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RECOMMENDED PRACTICE  
DNV-RP-J201

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QUALIFICATION PROCEDURES  
FOR CO<sub>2</sub> CAPTURE TECHNOLOGY

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APRIL 2010

DET NORSKE VERITAS

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## Amendments and Corrections

This document is valid until superseded by a new revision. Minor amendments and corrections will be published in a separate document normally updated twice per year (April and October).

For a complete listing of the changes, see the “Amendments and Corrections” document located at: <http://webshop.dnv.com/global/>, under category “Offshore Codes”.

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## INTRODUCTION

### — Background

Over the last decade, substantial resources have been directed towards developing cost-efficient solutions that involves CO<sub>2</sub> capture, transport, and storage (CCS).

The carbon capture technologies that are available today require large efforts to integrate, optimise, and to scale up the process components to an industrially mature process. Currently there are several different new technologies under development and testing for CO<sub>2</sub> capture. This development will accelerate over the coming decades.

New CO<sub>2</sub> capture technology is generally not adequately covered by established codes and procedures. It must therefore be qualified by a systematic process where its required performance is targeted and obtained by defining the expectations to the technology and identifying the risks

that need to be reduced through adequate qualification methods, such as analyses and testing.

This Recommended Practice (RP) has therefore been developed in order to address the need for guidance for the qualification of CO<sub>2</sub> capture technology.

### — Acknowledgment

The development of this RP was organized as a joint industry project with Aker (Aker Clean Carbon and Aker Solutions), Statoil, Statkraft and Det Norske Veritas AS as partners. The project gratefully acknowledges receiving 50% of its funding from Gassnova SF-the Norwegian state enterprise for carbon capture and storage. DNV further gratefully acknowledges the support by the project partners.



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# 1. General

## 1.1 Introduction

There is a growing concern that global warming and climate change are the anthropogenic results of greenhouse gas emissions from the combustion of fossil fuels, such as natural gas, oil and coal. The world's population is steadily growing, as are its energy needs. It is expected that a significant part of the world's future need for electrical energy and heat will come from burning of fossil fuels, implying increased carbon dioxide (CO<sub>2</sub>) emissions to the atmosphere.

Currently there are several different technologies under development and testing for CO<sub>2</sub> capture. Regarding the development work with large-scale CO<sub>2</sub> capture processes for CCS application, such as for energy production, consecutive scale up, validation and verification work are necessary. The full size plants are so large and expensive that an owner acting in a commercial environment cannot tolerate a technical failure.

Technology qualification is a systematic set of activities that contribute to managing the risk associated with the implementation of new technology. It will therefore play an important role in increasing the confidence in new and scaled-up CO<sub>2</sub> capture technologies.

Technology qualification is a confirmation by examination and provision of evidence that the new technology meets the specified requirements for the intended use. This Recommended Practice (RP) provides qualification procedures for how to prove that the new CO<sub>2</sub> capture technology is fit for purpose.

## 1.2 Objective

The objective of this RP is to provide a systematic approach for the qualification of fossil fuel power generation technologies with CO<sub>2</sub> capture.

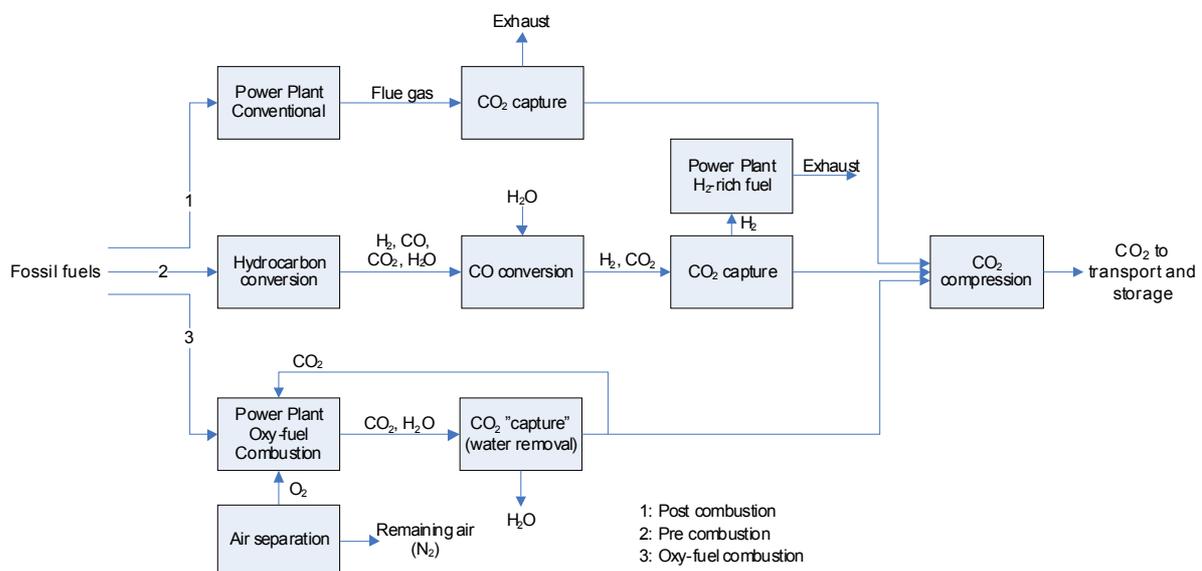
## 1.3 Scope

The scope of this RP is to provide a supplement to DNV's generic qualification procedures for new technology, DNV-RP-A203 /1/, by giving guidance for how to utilise these procedures for fossil fuel power generation technologies with CO<sub>2</sub> capture.

### 1.3.1 Application

This RP is applicable for components, equipment, processes, and process systems (assemblies) that can be defined as new CO<sub>2</sub> capture technology or concepts. The procedure covers, but is not limited to, the three main concepts for capturing CO<sub>2</sub> from power generation processes based on fossil fuels as illustrated in Fig. 1-1:

- Post combustion; the CO<sub>2</sub> is removed from the power plant flue gas after the combustion process
- Pre combustion; the CO<sub>2</sub> is captured before combusting the hydrogen-rich fuel
- Oxy-fuel combustion; the fuel is combusted using almost pure oxygen at near stoichiometric conditions producing a flue gas consisting mainly of CO<sub>2</sub> and H<sub>2</sub>O.

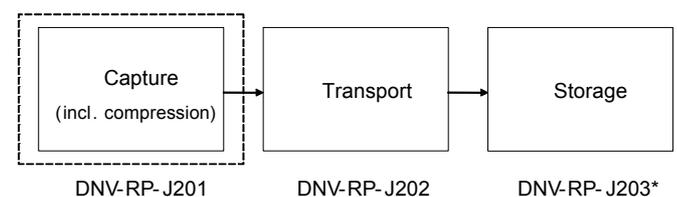


**Figure 1-1**  
Overview of CO<sub>2</sub> capture concepts in fossil fuel power production

### 1.3.2 Boundaries

The procedure covers the first step in the CO<sub>2</sub> capture, transport, and storage (CCS) value chain as shown by the dashed line in Fig. 1-2. The dashed line shows the scope of the present document. The transport and storage elements are covered by DNV-RP-J202 /3/ and DNV-RP-J203\*, respectively. The compression facilities needed to bring the captured CO<sub>2</sub> to the required transportation pressure are considered part of the scope.

\* Planned publication in October 2010.



**Figure 1-2**  
The CO<sub>2</sub> capture, transport, and storage (CCS) value chain

## 1.4 Use of the procedure

### 1.4.1 Users

Users of the procedure will typically be:

- The manufacturer, who offers the new CO<sub>2</sub> capture technology to the market
- The company, which integrates the new technology into a larger system
- The end-users, who must optimise the benefits of their investment through selection between competing technologies.

### 1.4.2 Project development phases

The qualification process can be run throughout the development of the new technology, or be started at any time in the development. However, if a significant modification (physical or operational) is planned during operation, a review should be made with regards to revisiting the qualification process. Examples of project development phases are: strategy, feasibility and concept selection, design, construction, installation and commissioning, operation and life extension, and decommissioning.

## 1.5 Structure of this document

This Recommended Practice is organised into three parts:

- An introductory part (Sec.1 to Sec.4) where CO<sub>2</sub> capture concepts and technologies are described, philosophy and principles of technology qualification are presented and the qualification process is introduced.
- The main body: the description of the qualification work process (Sec.5 to Sec.11).
- Appendices (Appendix A to Appendix E) that contain additional and supplemental information as well as examples and templates.

To get a first overview of the qualification work process, one could read through the introductory chapters (Sec.3 and Sec.4), and the first part (the sections called introduction and methodology) of each step in the qualification procedure (Sec.5 to Sec.11). The remaining body of each chapter after the methodology section, and the appendices, gives more detailed description and information.

## 1.6 Relationship to other codes

Generic qualification procedures for new technology are covered by DNV-RP-A203 /1/, whereas DNV-OSS-401 /2/ covers technology qualification management. While these procedures cover a generic approach, the present document provides a more specific qualification procedure on how to utilize DNV-RP-A203 for qualification of CO<sub>2</sub> capture technologies.

The present document covers the capture part of the CCS value chain. The transport part and the storage part are covered by DNV-RP-J202 “*Design and Operation of CO<sub>2</sub> Pipelines*” /3/ and DNV-RP-J203 “*Selection and Qualification of Sites and Projects for Geological Storage of CO<sub>2</sub>*” (to be published) as shown in Fig. 1-2.

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## 1.8 Definitions

<i>Term</i>	<i>Definition</i>
Availability	For a repairable system: the probability that the system is operating at a specified time
Consequence	Resulting event from the happening of the failure. Consequence is measured by the magnitude of its effects. Consequence is expressed as the number of people injured or killed, area affected, outage time, mission delay, money lost, etc.
Failure	Termination of the ability of an item to perform the required (specified) function
Failure frequency	The number of failures divided by the time (calendar or operational)
Failure mechanism	The physical, chemical or other process which lead or have led to a failure
Failure mode	The observed manner of failure (on a specified level)
Failure probability	The probability of failure occurring within a specified time period, or at a specified condition (e.g. during start up or load changes)
FME(C)A	Failure modes, effect (and criticality) analysis
HAZOP	Hazard and operability study
New technology	Technology that has not been proven in the field with a documented track record for a defined application and defined operational environment
Performance margin	Tested or analyzed maximum performance divided by required/ design performance. For a qualified system it must be larger than one
Process	The transformation from one state to another, where state refers to the condition of a system as described by its properties (such as mass, volume, energy, pressure, and temperature)
Proven technology	Technology that has a documented track record in the field for a defined operational environment
Qualification	Qualification is the process of providing the evidence that the technology will function within specific limits or operating regime with an acceptable level of confidence
Reliability	The ability of an item to perform a required function under given environmental and operational conditions and for a stated period of time
Risk	The combined failure probability and consequence of failure
Technology	The scientific study and use of applied sciences, and the application of this to practical tasks in industry
Threat	A potential risk with significant uncertainty about the consequence of failure and/ or likelihood of occurrence that requires further investigation to either quantify as a risk or remove from further consideration
Unit operation	A structure of logic used for synthesizing and analyzing processing schemes in the chemical and allied industries, in which the basic underlying concept is that all processing schemes can be composed from and decomposed into a series of individual or unit steps
Verification	Confirmation by examination and provision of objective evidence that specified requirements have been fulfilled

## 1.9 Abbreviations

CAP	Chilled Ammonia Process	MEA	MonoEthanolAmine
CCS	Carbon Capture and Storage	OPERA	Operational Problem Analysis
CFD	Computational Fluid Dynamics	PFD	Process Flow Diagram
CLC	Chemical Looping Combustion	P&ID	Process piping and Instrumentation Diagram
DEA	DiEthanolAmine	PSA	Pressure Swing Adsorption
DNV	Det Norske Veritas	QA	Quality Assurance
EOR	Enhanced Oil Recovery	QB	Qualification Basis
FEM	Finite Element Method	QC	Quality Control
FMECA	Failure Mode, Effects, and Criticality Analysis	R&D	Research and Development
FMIRR	Failure Mode Identification & Risk Ranking	RAM	Reliability, Availability and Maintainability
FTA	Fault Tree Analysis	RP	Recommended Practice
HAZID	Hazard Identification	SWIFT	Structured What-If Checklist
HAZOP	Hazard and Operability Study	TA	Technology Assessment
SHE	Safety, Health and Environment	TSA	Temperature Swing Adsorption
IPCC	Intergovernmental Panel on Climate Change	TQP	Technology Qualification Plan
JIP	Joint Industry Project	ZEP	Zero Emissions Platform: The European Technology Platform for Zero Emission Fossil Fuel Power Plant
MDEA	MethylDiEthanolAmine		

## 2. CO<sub>2</sub> CAPTURE CONCEPTS AND TECHNOLOGIES

### 2.1 Introduction

Sectors where CO<sub>2</sub> capture is relevant are fossil fuel electricity generation, industry such as iron, steel and cement production, and fossil fuel production and transformation. The main technological concepts for CO<sub>2</sub> capture contain a majority of processes and components that are predominantly commercially available today. These processes and components, however, are not operated at conditions or scale planned for CCS applications. The carbon capture technologies that are available today require large efforts to integrate, optimise, and to scale up the process components to an industrially mature process. There are also some novel carbon capture concepts that use new components that are not known in industry today. These novel technologies will need a longer development and qualification program before commercial deployment.

The main challenges within the development and implementation of large-scale CO<sub>2</sub> capture technologies are to ensure that they are cost-efficient and reliable, safe, and environmentally friendly. It will be of major interest for technology vendors, operators, as well as governments, that these technologies can be implemented with technological risks adequately understood and managed to an acceptable level so as to give confidence, and that they will work as intended over the lifetime of the project.

Managing the risk by scaling up CO<sub>2</sub> capture technologies was described by ZEP as /4/:

*Concerning the development work with large-scale industrial processes as for energy production, consecutive scale up, validation and verification work is necessary. Although principles and mechanisms are well known, verification is necessary to reduce risks, since the full size plants are so large and expensive that an owner acting in a commercial environment cannot tolerate a technical failure.*

Technology qualification is a systematic set of activities that contribute to managing the risk associated with the implementation of new technology. Technology qualification will therefore play an important role in increasing the confidence in new and scaled-up CO<sub>2</sub> capture technologies.

Technology qualification is used to confirm that a technology meets certain requirements within specific limits with an acceptable level of confidence. This can be done by identification, assessment, and management of potential risks through implementation of the qualification process.

### 2.2 CO<sub>2</sub> capture concepts - an overview

For fossil fuel power production, there are three main concepts to reducing the CO<sub>2</sub> content in the combustion gases. These are post-combustion, pre-combustion, and oxy-fuel combustion. A schematic illustration is shown in Fig. 1-1.

In *post-combustion capture*, the CO<sub>2</sub> is removed from the power plant flue gas. The state-of-the-art technique for separ-

ating CO<sub>2</sub> from flue gases is via chemical solvent scrubbing (usually with an amine). The CO<sub>2</sub> reacts with the amine in the absorber and is later separated from the amine solution in the stripper, then dried, compressed, and transported to the storage site. For flue gases with a low partial pressure, a large amount of energy is needed to regenerate the solvent. Improved solvents and optimized processes are currently being developed. Alternative methods for separating CO<sub>2</sub> from flue gases are also evolving. A more detailed overview of post combustion decarbonisation processes can be found in Ref. /4/, /5/, /6/.

*Pre-combustion capture* is a technique where the CO<sub>2</sub> is captured before burning the fuel in a combustor. It is commercially available for several applications, including hydrogen, ammonia, and synthetic gas production. The technique consists of a natural gas reforming or coal gasification step followed by water gas shift reforming of the gas, with subsequent steps for separation of CO<sub>2</sub> and H<sub>2</sub> to produce a H<sub>2</sub>-rich gas. The main challenge within this concept to make it economically feasible is to develop gas turbines that reliably can burn fuel with a high H<sub>2</sub> content /4/. Because of the world-wide interest in the hydrogen economy, a lot of R&D efforts are currently put into this field. A description of pre-combustion decarbonisation technology can be found in Ref. /4/, /5/, /7/.

In *Oxy-fuel carbon capture* (also called denitrogenation), the fuel is combusted using almost pure oxygen at near stoichiometric conditions. This creates a flue gas consisting of mainly CO<sub>2</sub> and H<sub>2</sub>O (and small amounts of SO<sub>x</sub> and NO<sub>x</sub>). A portion of the CO<sub>2</sub> in the flue gas is recycled in order to control the combustion temperature. Oxy-fuel combustion has been used within the metal and glass manufacturing industries for some time, but has so far not been applied to full-scale conventional steam boilers. The main challenges with this concept are the new combustion environment in the burner, and the high energy demand of the air separation unit. An overview of oxy-fuel processes can be found in Ref. /4/, /5/, /8/.

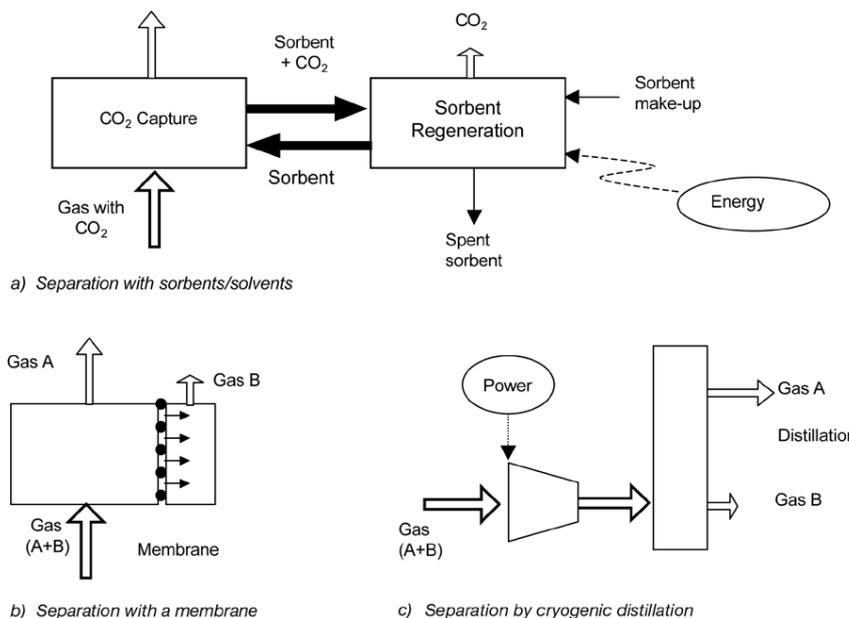
Each of the three pathways described above has inherent advantages and disadvantages (see Sec.2.4 below).

### 2.3 CO<sub>2</sub> capture technologies – state of the art

The technologies for capture of CO<sub>2</sub> can broadly be classified under four categories:

- Absorption by solvents
- Adsorption by sorbents
- Membranes
- Cryogenic separation.

In addition to these four main separation processes, there are several novel CO<sub>2</sub> capture technologies that cannot easily be grouped under these categories, such as biotechnological. These are denoted as *emerging technologies*. A brief description of the various CO<sub>2</sub> capture technology categories is given in Appendix A with further details in Ref. /4/, /5/, /6/, /7/, /8/. The main principle for separation in each of these four different processes is visualized in Fig. 2-1.



**Figure 2-1**  
General schemes of the main separation processes relevant for CO<sub>2</sub> capture (source: IPCC /5/)

The application of each capture technique depends mainly on the gas mixture that contains carbon dioxide. Its composition, temperature, pressure, CO<sub>2</sub> concentration and removal quantity of CO<sub>2</sub> are some of the criteria to decide the appropriate capture technology. Chemical absorption when carbon dioxide partial pressure is low (post-combustion capture), is currently considered state-of-the-art for separation.

The applicability of the different separation technologies to the different concepts can be visualized in a “CO<sub>2</sub> capture toolbox” as shown in Table 2-1 /4/, /5/, /9/. In this table, current and foreseen technology approaches are listed for the various capture concepts. The current leading commercial options are shown in bold italic. A more detailed description of the capture technologies is given in Appendix A.

Capture Route	Post combustion		Pre combustion		Oxy fuel combustion	
Separation task	CO <sub>2</sub> /N <sub>2</sub>		CO <sub>2</sub> /N <sub>2</sub>		CO <sub>2</sub> /N <sub>2</sub>	
Capture Technologies	Current	Future	Current	Future	Current	Future
Solvents (Absorption)	<b>Chemical solvents</b>	Improved solvents Novel contacting equipment Improved design of processes	<b>Physical solvent</b> <b>Chemical solvents</b>	Improved solvents Novel contacting equipment Improved design of processes	N. A.	Biomimetic solvents
Solid sorbents (Adsorption)	Zeolites Activated carbon	Carbonates Carbon based sorbents	Zeolites Activated carbon	Alumina Carbonates Hydrotalcites Silicates	Zeolites Activated carbon	Adsorbents for CO <sub>2</sub> /N <sub>2</sub> separation, Perovskites Oxygen chemical looping
Membranes	Polymeric	Ceramic Facilitated transport Carbon Contactors	Polymeric	Ceramic Palladium Reactors Contactors	Polymeric	Ion transport membranes Facilitated transport
Cryogenic	Liquefaction	Hybrid processes	Liquefaction	Hybrid processes	<b>Distillation</b>	Improved distillation
Emerging (bio-technological)		Algae production		High pressure applications		Biomimetic approaches
Energy conversion		Novel power cycles	Hydrogen combustion	Improved burner design	Combustion in O <sub>2</sub> /CO <sub>2</sub> /H <sub>2</sub> O atmosphere	Improved burner design

## 2.4 Challenges and uncertainties in CO<sub>2</sub> capture concepts

The three CO<sub>2</sub> capture concepts have different challenges and uncertainties. Major challenges and uncertainties with the different capture routes are summarized in Table 2-2.

<i>Concept</i>	<i>Major Challenges</i>
Post-combustion capture	<ul style="list-style-type: none"> <li>— High energy consumption for absorbent regeneration and CO<sub>2</sub> compression</li> <li>— Most major units need scale-up</li> <li>— Large-scale equipment needs optimizing and process integration</li> <li>— Extended “clean-up” of exhaust gas including desulphurization</li> <li>— Corrosion</li> <li>— Solvent degradation</li> <li>— Uncertainties of SHE properties of solvent (amines) degradations products.</li> </ul>
Pre-combustion capture	<ul style="list-style-type: none"> <li>— High energy consumption for CO<sub>2</sub> separation, fuel gas processing, and CO<sub>2</sub> compression</li> <li>— Large-scale equipment needs optimizing and process integration</li> <li>— Combustion of H<sub>2</sub>-rich fuel in gas turbine power plants</li> <li>— Coal gasification units need demonstration for power plant application</li> <li>— Low plant availability: high consequence of plant downtime</li> <li>— Extensive supporting systems requirements.</li> </ul>
Oxy-fuel combustion capture	<ul style="list-style-type: none"> <li>— High energy consumption for O<sub>2</sub> production and CO<sub>2</sub> compression</li> <li>— Large-scale equipment needs optimizing and process integration</li> <li>— Combustion process not demonstrated at a larger scale</li> <li>— Cooled CO<sub>2</sub> recycle required to maintain temperatures within limits of combustor materials</li> <li>— Low plant availability: high consequence of plant downtime</li> <li>— Corrosion</li> <li>— New thermodynamic properties for CO<sub>2</sub>/H<sub>2</sub>O mixtures.</li> </ul>

## 3. QUALIFICATION PHILOSOPHY AND PRINCIPLES

### 3.1 Introduction

Implementation of new technology introduces uncertainties and risks to technology developers, operators, and end-users. The procedure described in this document is a method to identify and analyse risks related to development, production and use of the new technology. Typically, concepts with well known and proven technology are often preferred to solutions with elements of non-proven technology, despite the fact that the latter may be the most cost-effective.

Business opportunities and growth are often revealed through new technology. Qualifying new technology and hence managing the risk by its implementation, increases the level of confidence and the potential profit.

### 3.2 Philosophy

The qualification shall be based on the following philosophy:

- The qualification process shall be based on a systematic risk based approach.
- Possible threats (or failure modes) to the technology shall be identified, and their relevance shall be determined based on their risk, i.e. the combined probability and consequences of a failure mode occurring. Risk in this context is related to the functionality of the new technology.
- Screening the technology based on the identified novel elements to focus the effort to areas where the uncertainty is most significant. The uncertainty can be associated with the technology itself and/or the operating conditions/ environment.
- The level of the qualification efforts will be proportional to the uncertainty associated with the technology, i.e. greater uncertainty requires a higher performance margin and more robust qualification methods.
- Analyses shall, when practical, be used to document fulfilment of the specifications and predict the performance margin. As a general principle, the analyses should be verified by experiments.
- The QA/ QC system for manufacturing, assembly, installation, start-up, commissioning, modification, repair and decommissioning of the technology is an integral part of the qualification process.

### 3.3 Principles

The following principles shall control the qualification:

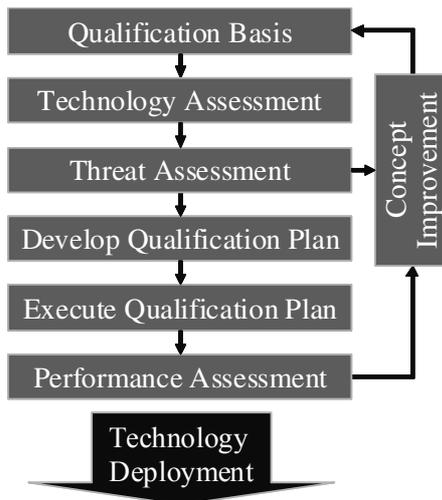
- Specifications and requirements shall be clearly defined, quantified and documented.
- A rigorous failure mode identification shall be conducted for the technology. Risk assessment tools shall be used to determine the consequence and likelihood of failure for a technology application. Failure modes that are not identified pose a significant risk to the successful implementation of the technology.
- The performance margin shall be established based on recognized methods, standards, or on combinations of all uncertainties used in the data, operation, calculations and tests.
- The qualification efforts (analysis, testing, previous experience, etc.) for each technology failure mode shall be documented and traceable, along with the established performance margin.
- When experience is used as proof of fulfilment of the specifications, then evidence shall be collated and validated. The experience must be at the relevant operating condition/ environment.
- The limiting material and functional parameters, such as yield strength, friction factors, and thermal expansion coefficient, to be used in analyses should be determined through tests, given by reference to recognized literature or expert judgement.

## 4. QUALIFICATION PROCESS

The steps in the technology qualification process are illustrated in Fig. 4-1 below. The amount of rigor or effort applied to step should be proportional to the uncertainty of the technology and the consequence of failure (technology classification, see Sec. 6.5).

The output from one step is input to the next. The process is iterative in nature in the way that concept improvements might be needed in order for the technology to be qualified.

A description of the various steps, including more specific issues regarding CO<sub>2</sub> capture process qualification, is given in Sec.5 to Sec.11.



**Figure 4-1**  
Main steps in the technology qualification process

## 5. QUALIFICATION BASIS

### 5.1 Introduction

*The purpose of the qualification basis is, in the absence of relevant codes and procedures, to define the expectations of the technology.*

The qualification basis document defines how the technology will be used and what the acceptance criteria will be in terms of a fully qualified product. It also specifies performance expectations and behaviour through out the life cycle of the technology. Through further qualification processes, the expectations described in the qualification basis shall be fulfilled.

### 5.2 Methodology

The technology shall be unambiguously and completely described, through text, calculation data, drawings and other relevant documents. It is important that the limits of the technology are stated and that all relevant interfaces are clearly defined. The specification shall identify all phases of the new technology's life and all relevant parameters.

The qualification basis should include the following key elements /1/:

- a) System description and specification with the available detail level at each phase of the development process. It should at least include:
  - System description of the technology to be qualified including system boundaries and boundary conditions
  - Functional/ operational limitations and main data
  - Interfacing system requirements
  - Authority requirements
  - Safety, Health and Environment (SHE) requirements
  - Reliability targets
  - Main principles for technology life cycle (such as design, construction, commissioning, operation and maintenance, and decommissioning)
  - Environment and loads
  - Main principles for manufacturing and quality assurance
  - List of assumptions and conditions to be fulfilled from the qualification process (generated in the qualification process).

- b) Functional requirements.

The specification and functional requirements shall be quantitative and complete. Note that these requirements must have been agreed upon by all relevant stakeholders.

Based on the specification, a review/ screening of all possible requirements and limitations to the technology shall be performed and the functional requirements specified. The critical parameters shall be identified and a critical parameters list shall be created (see Sec.5.6).

A more detailed description of how this can be done for CO<sub>2</sub> capture technologies is given in the remaining sections of this chapter (Sec.5.3 to Sec.5.6).

### 5.3 System description and specification of CO<sub>2</sub> capture technology

There exist no specific standard for the information needed to build a process plant based on, for instance, a chemical, mechanical, or a thermal process. A general guidance is that the description and specification in the qualification basis for CO<sub>2</sub> capture technology should follow the standard procedure given in Sec.5.2 as applicable to the carbon capture concept. A standardized scope of the information needed to build a commercial chemical process unit is given in Ref /10/ as:

- Project description
- Process description
- basis for the commercial plant
- Heat and material balance
- Process flow sheet
- Process piping and instrumentation diagrams
- Utility piping and instrumentation
- Plot plan
- Major equipment outline drawings and specifications
- Process safety
- Utilities requirements
- Environmental
- Instrument specifications
- Piping and line specifications.

Process scale-up should be approached at the first stage in describing the new technology, i.e. from the knowledge of what it is believed the commercial unit will look like.

In the evolution of a process system, from idea to commercial design, there is a continuous interaction between design/ economic studies and experimental program (such as laboratory, pilot plant, or mock-up). The process scale-up is rarely a simple and direct path, but rather a combination of theoretical models, correlations and empirical experience. Scale-up issues are briefly presented in Appendix C, whereas a more detailed description of how to describe a process system and the importance with regards to scale-up in process design development can be found in Ref. /11/, /12/, /13/. A description of different documentation types for describing a process system and their importance is given in Appendix B.

### 5.4 Requirements

A number of requirements must be achieved for a commercial plant to be successful. It is of crucial importance that the requirements, and the impact of setting them, are thoroughly discussed, understood, and agreed by all project participants. Functional requirements are described in Sec.5.5, whereas a description of interfacing and authority requirements, SHE requirements, and requirements to plant availability for CO<sub>2</sub> capture processes is given in Appendix B. A general description of state-of-the-art CO<sub>2</sub> capture concepts and technologies is given in Sec.2.

**Table 5-1 Examples of functional requirements for CO<sub>2</sub> capture concepts and system levels**

<i>Capture Concept</i>			
<i>System level</i>	<i>Post-combustion (absorption)</i>	<i>Pre-combustion</i>	<i>Oxy-fuel combustion</i>
Process	CO <sub>2</sub> capture rate CO <sub>2</sub> purity Power consumption Emissions (solvent)	Energy efficiency Power production CO <sub>2</sub> avoided CO <sub>2</sub> purity	Energy efficiency Power production CO <sub>2</sub> avoided CO <sub>2</sub> purity
Sub-process	Steam quality Solvent consumption Inhibitor addition	Reformer/shift conversion Turbine energy delivery H <sub>2</sub> dilution	Turbine energy delivery Steam generation O <sub>2</sub> purity
Component	Absorber packing material corrosion resistance CO <sub>2</sub> loading Stripper reboiler duty Flue gas blower duty	Catalyst performance Combustor flame temperature, flame flashback, auto ignition NO <sub>x</sub> emissions	Combustor flame temperature, radiation and soot levels, CO emissions Expander cooling Turbine material choice

### 5.5 Functional requirements for CO<sub>2</sub> capture technology

The following sections give guidance for how to identify the qualification goals for CO<sub>2</sub> capture technology such as the functional requirements.

Functional requirements describe the purpose(s) of the technology. The functional requirements of the system should:

- Clearly define what the technology should do
- Be quantifiable
- Be established as early as possible and updated throughout the qualification process.

Based on the system description and the flow diagrams, described in Sec. 5.3, the breakdown of the capture technology will enable identification of system requirements at different levels of detail. For example, the CO<sub>2</sub> capture performance, expressed as CO<sub>2</sub> avoidance or capture rate, is a high-level process parameter that is likely to be part of the qualification basis defined at an early stage of the qualification process. Beneath the high-level process system requirements, each sub-process and/or material and energy stream will have known specifications that are of importance to the overall performance or system integration. Furthermore, functional requirements on a component level should be established for components considered essential for the functionality of the total process. Table 5-1 exemplifies typical functional requirements for the different capture technology routes.

Note that the functional requirements are subject to continuous updating during the qualification process, as technology assessment and failure mode identification most likely will reveal functional requirements on sub-components, not foreseen at the initial stage of the qualification process.

**Guidance note:**

Review and possibly update of the requirements given in the qualification basis might be needed after each step in the qualification work process.

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### 5.6 Critical parameters list

The purpose of the critical parameters list is to document the vital governing parameters for the technology. Key issues such as dimensioning loads, capacities and functional requirements from the qualification basis shall be summarised in the list. This ensures that the relevant input parameters for analyses and tests are used and updated with possible changes in design during the qualification process.

The critical parameters list should cover all parameters that are governing for the identified failure modes of concern, and should specify the limits/ boundaries for these parameters within the scope of the qualification. Further, this list should

also specify the main concerns and uncertainties with the given parameters. The parameters and their limits should be established in the initial phase of the technology qualification process (defining of qualification basis). However, both the parameters and their limits might change as the qualification progresses. Upon conclusion of the qualification process, the critical parameters list will represent the qualification envelope of the technology, i.e. this list will define the boundaries within which the technology is considered qualified.

A critical parameters list template is shown in Appendix E.

## 6. TECHNOLOGY ASSESSMENT

### 6.1 Introduction

*The purpose of the technology assessment is to divide the technology into manageable elements in order to assess which elements involve aspects of new technology and identify the key challenges and uncertainties.*

Input to the technology assessment comes from the qualification basis, and the output is a list of the novel technology elements in the concept and the main challenges and uncertainties.

### 6.2 Methodology

The technology assessment shall include the following issues:

- Breaking down the technology into manageable elements
- Assessment of the technology elements with respect to novelty (technology classification)
- Identification of the main challenges and uncertainties related to the new technology aspects.

The technology break down shall be achieved by dividing the technology into one or more of the following types of elements, as relevant:

- Sub-systems and components with functions, and/or
- Unit operations with unit processes
- Process sequences
- Project execution phases based on procedures for manufacturing, installation and operation.

The degree of novelty of the technology shall be determined by classifying the technology elements with respect to application area and technology maturity. Elements classified as new technology shall be subject to the further assessment.

The main challenges and uncertainties related to the new technology aspects shall be identified. For complex systems, such as power plants with CO<sub>2</sub> capture processes, it is recommended that the main challenges and uncertainties are identified by carrying out a high level HAZID (Hazard Identification).

### 6.3 Technology breakdown for CO<sub>2</sub> capture processes

In order to fully understand the novel elements in a technology, the technology needs to be broken down into manageable elements. Two different routes for performing technology breakdown of CO<sub>2</sub> capture technologies are shown below. The most favourable division must be considered on a case-by-case basis.

#### 6.3.1 Sub-systems and components with functions

A technology breakdown for sub-systems and components with functions might often start with a general process flow diagram (PFD) for the process plant. Each unit operation in the PFD should then be listed and broken down into detailed parts, so technical expertise can judge the novelty. Fig. 6-1 gives an example of the technology breakdown for a typical post-combustion capture plant including an absorber.

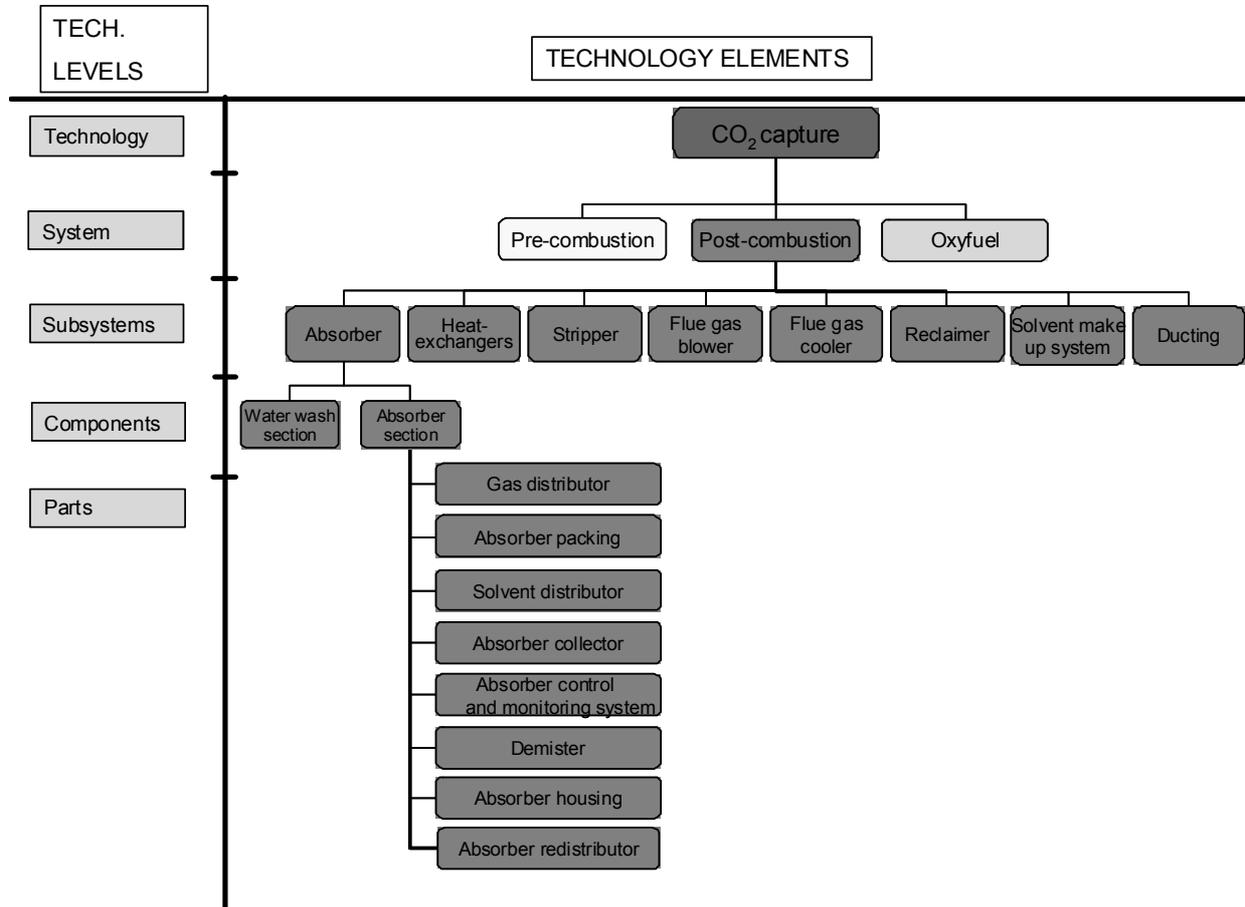


Figure 6-1  
Example of technology breakdown and levels for subsystems and components

#### 6.3.2 Unit operations with unit processes

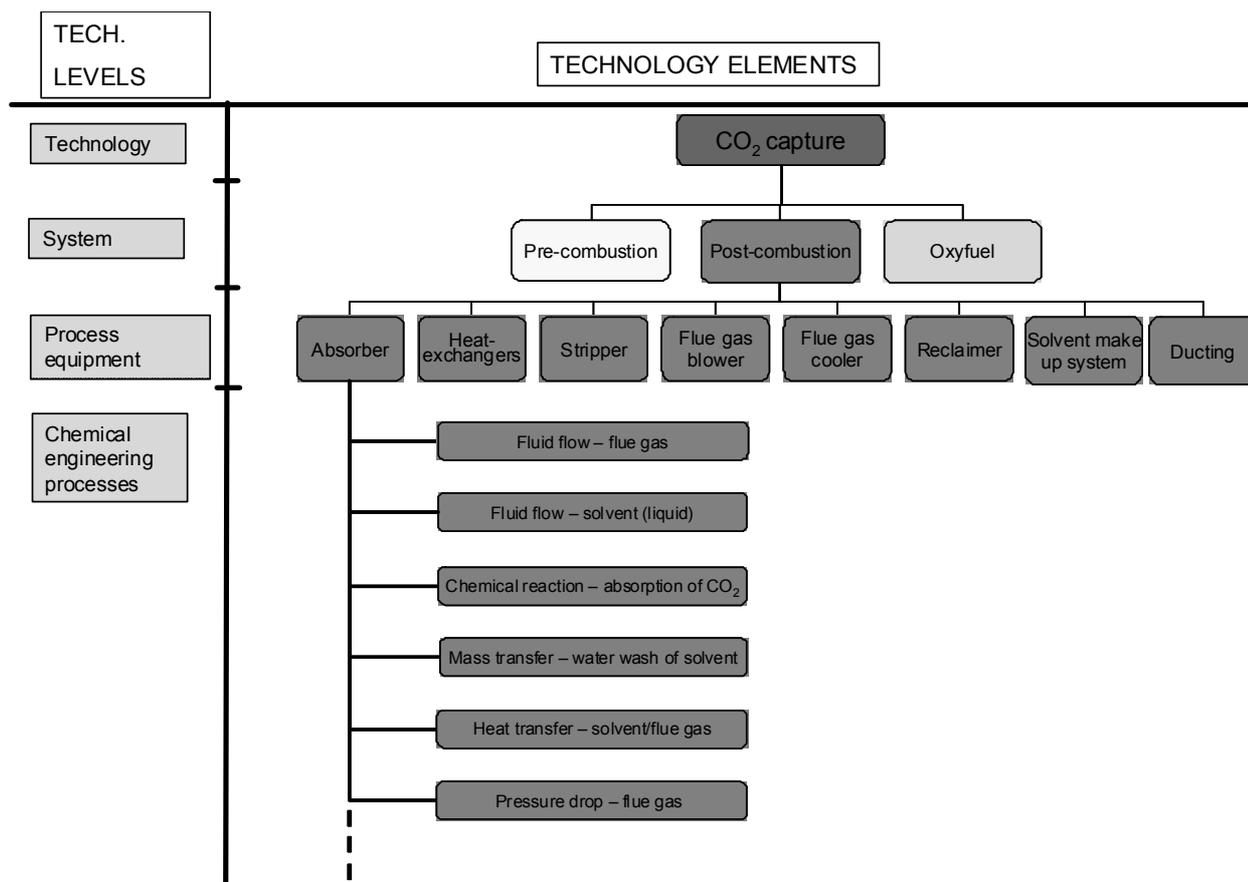
An alternative, or supplement to, technology breakdown into sub-systems and components with functions can be to start with the PFD, and for each unit operation in the PFD, divide into unit processes. Hence, a unit operation consists of a set of unit processes. Unit processes can be categorized as:

- 1) *Fluid flow processes*, including fluids transportation, filtration, solids fluidization etc.
- 2) *Heat transfer processes*, including evaporation, condensation etc.
- 3) *Mass transfer processes*, including gas absorption, distillation, extraction, adsorption, drying etc.
- 4) *Pressure change processes*, including gas compression,

expansion, etc.

- 5) *Thermodynamic processes*, including gas liquefaction, refrigeration etc.
- 6) *Mechanical processes*, including solids transportation, crushing and pulverization, sieving etc.
- 7) *Chemical reactions*, including combustion, oxidation, isomerisation etc.

This approach will increase the likelihood that new aspects not directly connected to single components, as shown in Sec.6.3.1, are discovered. An example of a technology breakdown into unit processes is shown in Fig. 6-2. Note that in the example shown in Fig. 6-2, the term process equipment is used instead of unit operations.



**Figure 6-2**  
Example of technology breakdown for CO<sub>2</sub> capture processes (the dashed line indicates other possible processes)

In CO<sub>2</sub> capture technologies where amines are used for separating the CO<sub>2</sub> from the flue gas, gas absorption, heat exchange, stripping, and gas compression are examples of unit processes.

### 6.4 Process sequences

In addition to the two methods described above (Sec.6.3.1 and Sec.6.3.2), breakdown of CO<sub>2</sub> capture technology into process sequences might reveal new aspects related to sequence (or cycle) interaction. This will be especially important for capture technology integrated in combined cycle power plants, but could also be important for studying interactions between the power plant and the capture plant when these are two separate units such as in post combustion capture.

### 6.5 Technology classification

New technology is typically evolved from existing proven technologies and as such only certain elements of the technology are considered new. The highest uncertainty is typically associated with such new elements. In order to identify and focus on the more uncertain elements of a technology, a classification rating has been defined below in Table 6-1. The maturity of the technology and its application area affect the uncertainty associated with the technology.

This classification applies to the totality of the applied technology as well as each separate part, function, process or subsystem forming it. Hence, breaking down the technology into subsystems (parts, functions, processes or subsystems) will simplify the identification of new elements of the technology. The technology classification will then be used to focus the qualification efforts on the elements that have the highest rank-

ing and thus highest uncertainty.

Application Area	Technology Maturity		
	Proven	Limited Field History	New or Unproven
Known	1	2	3
Limited Knowledge <sup>1)</sup>	2	3	4
New	3	4	4

<sup>1)</sup> E.g. proprietary information with no or limited accessibility

Technology rated as Class 1 is proven technology with no new technical uncertainties where proven methods for qualification, tests, calculations and analysis can be used to document the performance margins. It is important not to overlook the elements falling into this category, as they may be critical for the overall performance. These elements should be handled through the regular design process, using appropriate and robust engineering design, and implementing adequate Quality Assurance and Quality Control to ensure sound engineering design.

Technology rated as Class 2 to Class 4 is defined as new technology with increasing degree of technical uncertainty. Elements falling into these classes shall be qualified according to the work process described in this Recommended Practice. The defined classification ratings make it possible to distinguish between combinations of technology maturity and its application areas.

**Guidance note:**

Application area may refer to the experience with the operating condition, the environment or the application in which the tech-

nology shall be used. A change in the environment or in the use of the technology for a different application than before, will lead to increasing degree of uncertainty. The most uncertain case is no experience in the industry for a particular application of the technology in question, in which case the category “New” would be chosen for Application Area. The least uncertain case is when there is sufficiently documented knowledge for the use of the technology element for similar conditions and application, in which case the category “Known” would be chosen for “Application Area”.

“Technology Maturity” refers to the technology itself. A change in any of the elements of existing technology (parts, functions, processes, subsystems) will lead to increased uncertainty resulting in selecting the Technology Maturity level of “Limited Field History” or “New or Unproven”. This increased uncertainty may change the overall performance of the technology and the acceptance criteria.

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## 6.6 Technology classification for CO<sub>2</sub> capture processes

The basis for technology classification is described in Sec.6.5. The degree of novelty of the capture process shall be determined by classifying the technology elements with respect to Table 6-1, i.e. the level of technology maturity and experience with the operating conditions.

The objective of the categorization with respect to “level of technology maturity” is to establish to what degree the technology has been verified through field experience.

### Guidance note:

#### Example:

The absorber in Fig. 6-1 has been designed and manufactured in line with established engineering practice and has been operated with a documented track record. Consequently it is considered to be proven technology.

If the absorber has to be redesigned (using the same overall principles) to accommodate changes in the functional requirements (temperature, pressure, size, flow, etc.), the category for this absorber will change to limited field history

In the event that a new type of absorber is developed, which is conceptually different from the established design, the absorber will be categorised as new or unproven.

“Experience with the operating condition” or application area, relates to the working environment and functional requirements of the new technology. The application area should be defined for the total system, as well as for all the individual parts forming it.

#### Example:

If a new solvent is introduced in a traditional absorber, the application area for the absorber will be new. However, some of the components inside or outside of the absorber may not experience any change in environment as they will operate under the same conditions as before, thus the application area for these components will be known.

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## 6.7 Identification of main challenges and uncertainties (HAZID)

After the technology classification the main challenges and uncertainties can be identified. For complex systems like CO<sub>2</sub> capture plants, it is recommended that the main challenges and uncertainties are at this point in the process, identified by carrying out a high level HAZID (HAZard IDentification).

A high level HAZID is a means of obtaining a better understanding of a system at an early stage, and to identify which

parts of the system that need to be further developed and/ or documented in more detail, prior to the failure mode identification and risk ranking.

The need for a high level HAZID is related to the stakeholders’ need to identify the main challenges at an early stage. The HAZID has similarities to the failure mode identification and risk ranking, and if the technology is well documented and ready to perform this step, a high level HAZID might not be justified at this stage in the qualification process.

## 7. Threat assessment

### 7.1 Introduction

*The objective of this step is to identify all relevant threats, here defined as failure modes of concern, for the elements defined as new technology in the technology assessment and, for each, judge the associated risks.*

The inputs to the failure mode identification are the qualification basis (Sec.5) and the list of the new technology elements developed in the technology assessment. The output is a failure mode registry containing all identified failure modes of concern and their associated risk. Note that it is impossible to develop an adequate qualification plan unless the potential failure modes have been identified and are understood.

### 7.2 Methodology

The threat assessment consists of the following key steps:

- Qualitative definition of various classes of probability and classes reflecting the consequence severity. This is done prior to the identification of failure modes.
- Definition of acceptable risk by defining a risk matrix showing fully acceptable combinations (“low risk”) and unacceptable combinations (“high risk”) as well as intermediate combinations (“medium risk”) of the probability and consequence classes.
- Identification of all potential failure modes and their risk ranking.
- For each failure mode, rank the risk by assigning a probability class and a consequence class based on previous experience and expert judgements. In the latter case uncertainties shall be reflected by selecting conservative classes. This is done as an integral part of the failure mode identification and risk ranking (FMIRR) method.
- Storing the information for each failure mode in a failure mode registry.

For complex systems like CO<sub>2</sub> capture technologies, the failure mode identification and risk ranking process is recommended to be carried out as workshops, involving a panel of experts covering the necessary fields of competences and experiences.

### 7.3 Qualitative definition of probability classes

The probability classes should be developed to capture the span in failure rates from elements that fail every year to equipment that is designed to have one failure per 10 000 years (typically steel structures). Three classes can be defined between the extremes very high and very low. Low failure probability is the 1 000-year event, medium corresponds to the 100-year event and high corresponds to the 10-year event. Table 7-1 shows an example of failure probability classes. The classes must be chosen in each individual case using expert judgement and previous experience.

No.	Name	Description	Indicative Annual Failure Rate (up to)*
1	<i>Very Low</i>	Negligible event frequency	1.0E-04*
2	<i>Low</i>	Event unlikely to occur	1.0E-03*
3	<i>Medium</i>	Event rarely expected to occur	1.0E-02*
4	<i>High</i>	One or several events expected to occur during the lifetime	1.0E-01*
5	<i>Very high</i>	One or several events expected to occur each year	1.0E+00*

\* The numbers in this column are presented for exemplification purpose only and must not be used as quantitative guidelines.

No.	Name	Impact on:		
		Injury	Pollution	Production*
1	<i>Very Low</i>	No or superficial injuries	No effect	No effect*
2	<i>Low</i>	Slight injury, a few lost work days	Minor consequences	Some reduced capacity*
3	<i>Medium</i>	Major injury, long term absence	Moderate consequences	Up to 2 days down time*
4	<i>High</i>	Single fatality or permanent disability	Considerable consequences	Up to 2 weeks down time*
5	<i>Very high</i>	Multiple fatalities	Severe consequences	More than 2 months down time*

\* The numbers in this column are presented for exemplification purpose only and must not be used as quantitative guidelines.

#### 7.4 Qualitative definition of consequence classes

Similar to the probability classes, consequence classes must be chosen in each individual case using expert judgement and previous experience. An example of consequence classes is shown in Table 7-2.

The number of defined classes has been reduced by combining several types of consequences into one set of classes. A single class could therefore represent specific impacts on human injury, pollution and/or production. Within one class, the consequences of the three types of impact could be defined to represent similar levels of severity.

For instance, a major injury, a moderate pollution, and up to 2 days of down time may be regarded (by the qualification process stakeholders) as equally severe events; consequence medium. For a particular event of more than one type of impact, the type of impact giving the highest class shall be governing in the selection of a single consequence class.

#### 7.5 Definition of acceptable risk

The risk of a failure mode is the product of combined probability and consequence. The critical failure modes shall be ranked according to the risk matrix shown in Table 7-3. In general, the risk levels indicate the attention the failure mode shall be given:

<i>Low risk</i>	Acceptable
<i>Medium risk</i>	May be accepted on an individual basis. Risk reducing measure should be considered
<i>High risk</i>	Unacceptable. Risk reducing measure shall be implemented.

Risk acceptance involves a subjective balancing of benefits with risks. Two people who may agree on the degree of risk involved may disagree on its acceptability. Hence, acceptable risk is a subjective measure. However, some risks may be efficiently mitigated with a limited amount of effort and cost (e.g. visit reference plants, consult documentation, etc). Hence, it is recommended that a conservative and a cost-benefit approach is taken when assessing the risks, so that risks are not left out from the remaining steps of the qualification process.

**Table 7-3 Example of a typical risk matrix. Risk levels “low”, “medium” and “high” and acceptability to be categorized on a case by case basis**

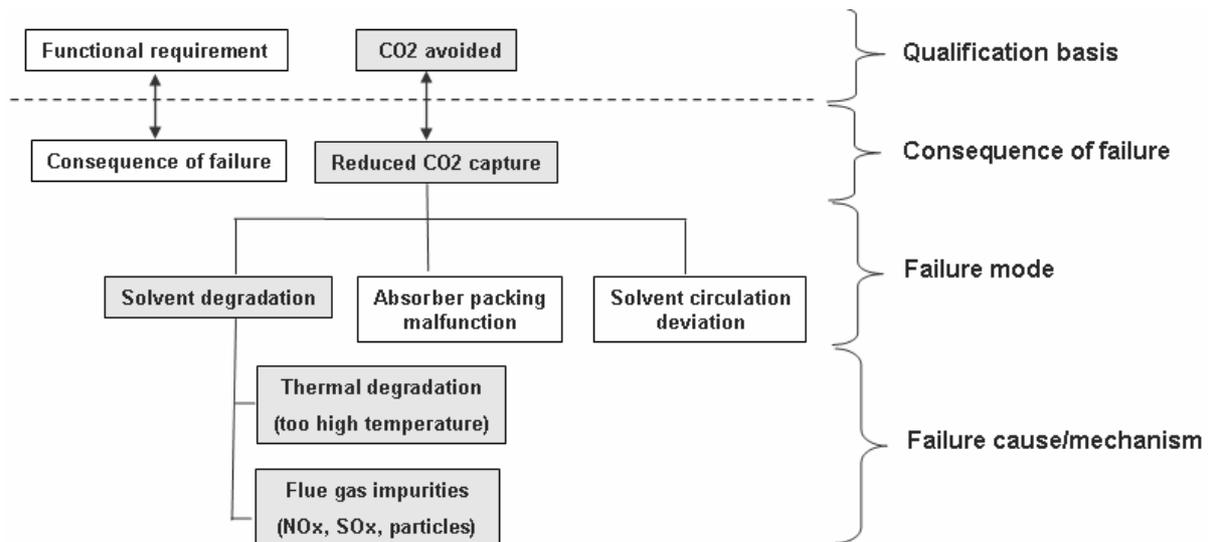
Probability	Consequence				
	1 Very low	2 Low	3 Medium	4 High	5 Very high
5 Very High	Low risk	Medium risk	High risk	High risk	High risk
4 High	Low risk	Medium risk	Medium risk	High risk	High risk
3 Medium	Low risk	Low risk	Medium risk	Medium risk	High risk
2 Low	Low risk	Low risk	Low risk	Medium risk	Medium risk
1 Very Low	Low risk				

**7.6 Assessment of acceptable risk for CO<sub>2</sub> capture processes**

The consequence of failure for CO<sub>2</sub> capture technologies can, as described in Sec.7.4, be coarsely divided into two main classes; personnel (injury) and operational (pollution or production issues).

The consequence of personnel injuries should be defined in accordance with the acceptance criteria set by the operator and commonly used in industry for similar process plants.

For the operational issues, the qualification basis (see Sec.5), should, when properly established, provide guidance towards establishing the consequence classes. This is because the requirements, which define the expectations to the technology, are likely to be strongly correlated with the consequence classes of a failure mode, found in the threat assessment step. This is exemplified in Fig. 7-1 in the case where the CO<sub>2</sub> capture rate is defined as a functional requirement to the technology. Here, the reduction in CO<sub>2</sub> capture is a typical consequence of a failure, which will influence the capture rate predefined in the qualification basis.



**Figure 7-1**  
Example of the inter-link between the requirements set in the qualification basis and the threat assessment step

Furthermore, deviations from the functional requirements, at different order of magnitude, should be reflected in the consequence classification. An example on how this classification can be arranged for operational issues is shown in Table 7-4. Similarly, consequence classes for personnel injury could be developed.

For a particular event with more than one type of impact, the

type of impact giving the highest class shall govern the selection of a single consequence class.

**Guidance note:**

The consequence classes shown in Table 7-4 should be quantified (as much as possible) on a project specific basis in order to come closer to a quantitative assessment.

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**Table 7-4 Example of how failure consequence classes could be developed in the qualification of a typical post combustion carbon capture process based on amine absorption**

No	Name	Consequence classes (production & pollution)			
		Emissions	Capture rate	Energy consumption	Reliability/on-stream factor
1	Very low	No effect/qualification basis	No effect/qualification basis	No effect/qualification basis	No effect/qualification basis
2	Low	Slight increase	Slight reduction	Slight increase	Slight reduction
3	Medium	Significant increase	Significant reduction	Significant increase	Significant reduction (days)
4	High	High increase	High reduction	High increase	High reduction (weeks)
5	Very high	Severe increase	Severe reduction	Severe increase	Severe reduction (months)

**Table 7-5 Advantages and disadvantages with different risk analyses methods**

Method	Advantages	Challenges and Disadvantages
Failure mode, effect and criticality analysis (FMECA)	Highly systematic as well as simple to apply	Investigating one failure mode at a time may not identify critical combinations of failures
Hazard and Operability study (HAZOP)	Highly systematic tool which enables identification of the most inconceivable incidents	Resource consuming Requires detailed information (PFDs at least) for producing useful results. Experienced facilitator required
Fault Tree Analysis (FTA)	Thorough investigation of (already) identified incident Can be used at different level of detail Can be a powerful tool when describing the failure mode structure and cause-and-effects	Might not be applicable for identifying (new) incidents. Time consuming to set up Not suitable for accurately modelling all types of systems
Structured what-if checklist (SWIFT)	Applicable even if detailed design information is not available	Experienced facilitator essential, as well as good checklists
Operational Problem Analysis (OPERA)	Emphasis on the product interfaces	Emphasis on technical problems and human error without going into details about causes

### 7.7 Failure mode identification & risk ranking methodologies

There are several hazard or failure mode identification techniques commonly used in the industry. The selection of method should take into consideration the complexity and maturity of the concept being considered. The failure mode identification & risk ranking should follow the technology break down described in Sec.6. The lists of novel elements identified in the TA step should be the starting point when going into the FMIRR. The output is a list (failure mode registry) of all identified failure modes, failure mechanisms and the uncertainties that are associated with an unacceptable risk. Various methods for risk analysis can be used for the threat assessment step. Table 7-5 lists some of the advantages and disadvantages with different methods.

### 7.8 Workshop guidelines

When using inter disciplinary workshops to identify and rank failure modes by their risk, it is crucial that these workshops have the relevant expertise present and are handled in a structured manner. It is of crucial importance that the qualifications of these members include the disciplines necessary to understand the potential failure modes of the technology.

## 8. Develop qualification plan

### 8.1 Introduction

*The objective of this step is to select qualification methods that adequately address the identified failure modes of concern with respect to its risk and determination of sufficient performance margins.*

The selected qualification methods will be input to a technology qualification plan where the various issues will be outlined

as qualification activities needed to be executed. These activities will generate the evidence that each failure mode is qualified with an adequate performance margin.

### 8.2 Methodology

The development of the qualification plan consists of the following main steps:

- Analysis and selection of qualification methods for each failure mode based on requirements set by the user or the customer in the qualification basis.
- Development of a technology qualification plan in order to show how each of the failure modes will be qualified and what the performance margin will be.
- Develop a detailed description of how to carry out each of the selected qualification methods.

The choice of methods to achieve qualification will depend on the nature of the requirement as stated in the QB. For instance, if a reliability target is set, this would require a quantitative reliability prediction and the methods to generate data will depend upon what type of input this predictive method requires.

### 8.3 Basis for the analysis and selection

Qualification shall be achieved by providing documented evidence that each specific requirement (as stated in the qualification basis) has been met, within a stated acceptance criteria.

Failure probabilities, and if relevant, consequences of failure, and performance margins shall be determined for each failure mode of concern. The determination shall be performed at the level of detail relevant for the respective development phase of the technology.

If a quantitative reliability target is stated in the qualification basis, then a quantitative reliability method is required to document fulfilment of the target.

For each failure mode of concern, it should be determined if the failure mechanisms can be simulated by recognized and generally accepted methods. In the case where recognized and generally accepted methods do not exist, the correctness of the suggested method should be qualified.

**Guidance note:**

When practical, a qualitative approach can be used in early development phases normally reflecting the first iteration of the qualification process. This may be done when the failure modes of concern have been listed in the failure mode registry in the course of the threat assessment step (see previous chapter). The expert panel goes through each failure mode and decides what types of qualification activities shall be conducted in each separate case. The choice of qualification activities will depend on the type of failure mode, its degree of uncertainty, and its risk level.

Consequence of failure shall, when required, be determined through recognized qualification methods. Consequence classes shall be described based on the data generated from these methods or the preliminary classes found in the threat assessment step shall be updated.

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**8.4 Qualification methods**

The following methods can be used for qualification:

- Failure mode avoidance, such as operational procedures or interlocks
- Previous documented experience with similar equipment and operating conditions
- Analytical methods such as handbook solutions, empirical correlations or mathematical formulas
- Numerical methods, such as process simulation models, CFD, FEM, corrosion models, etc.
- Experimental methods, such as:
  - Laboratory tests (simplified tests targeted towards a specific failure mode to enhance knowledge about for example material behaviour)
  - Test to reduce uncertainties in numerical and analytical models (such as erosion models, limited number of fatigue tests)
  - Scale-up studies using pilot plants, mock-ups or demonstration plants.

The methods listed above, and combination of these, can be employed to determine failure probability (and if relevant consequence of failure), and performance margin. Additional methods for qualification may also be relevant.

A general guidance to the selection of qualification activities for scaling up CO<sub>2</sub> capture processes is given in Appendix C.

**Guidance note:**

The selection of type and number of qualification methods depend on the risk for the failure mode, technology class, and level of confidence in the methods to be used.

The objective is to select the qualification methods that provide the most reliable and cost-effective combination (i.e. an optimal interaction). The selection of the methods should therefore be based on optimization of related cost versus accuracy, such as cost-benefit analysis. Each qualification method might often address several failure modes. Thus, the methods should be selected in a systematic manner to reduce unnecessary overlapping.

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**8.5 Development of the technology qualification plan**

The selected qualification methods will be specified further and outlined as activities in a technology qualification plan (TQP). The qualification activities shall be linked to the failure mode register developed during the failure mode identification and risk ranking. Objectives for each of the qualification activities shall be defined. Cost-benefit analysis may be required as decision support in order to assess the remaining degree of

uncertainty after the qualification activities have been executed for each of the failure modes. A qualification plan template is shown in Appendix E.

Upon completion of the activities of the technology qualification plan, the technology shall fulfil the requirements including the acceptance criteria set forth in the qualification basis.

**8.6 Detailed description of the selected activities in the TQP**

The means and purpose of the qualification activities must be described unambiguously. In this context this implies that the method for qualification is described at a level necessary to carry out the activities and obtain satisfactory results depending on technology maturity (development phase).

Guidance on relevant activities for scaling up CO<sub>2</sub> capture processes is given in Appendix C.

**9. Execute Qualification Plan**

**9.1 Introduction**

*The objective of this step is to carry out the qualification activities prescribed in the technology qualification plan developed in the previous step to document performance margins for the failure modes of concern.*

The execution of the technology qualification plan is likely to represent a significant part of the costs in the qualification process. It is also likely to be time consuming compared to the other steps. It is therefore of importance that the qualification activities are well chosen and planned in order to derive the information needed to address the identified failure modes, and to avoid spending resources on tests that do not give such information.

**9.2 Methodology**

The execution of the qualification plan consists of the following key steps:

- Carrying out the qualification activities in the technology qualification plan
- Collection and documentation of the data generated by the respective qualification activities
- Ensure traceability of the data
- For each failure mode, determine the performance margin.

**Guidance note:**

If there has been a time delay between the development of the TQP and the execution of it, it is recommended that a review is undertaken prior to execution to assure that the qualification activities in the TQP still properly address the failure modes of concern. Review and check of qualification activities can be to:

- Check / ask / verify if the planned activity for each failure mode will actually find the performance margins of concern, i.e.: will the planned test find the performance margin to the specified operational requirements with the desired level of confidence?
- Check that the operational limits that were specified in the qualification basis are correctly specified for each failure mode of concern (check with the critical parameters list)
- Ask how the planned tests will validate the analytical model(s)
- Check the level of accuracy of the planned activity. Is the accuracy of the desired level?
- Outline what is sufficient evidence and how evidence should be generated and documented.

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**9.3 Execution of the qualification activities**

The qualification activities outlined in the TQP shall be executed according to the guidelines outlined in Sec.8.6. The exe-

cution comprises the work needed to generate the type of evidence required for qualification. The objective of each qualification activity is to determine a performance margin.

#### 9.4 Collection and documentation of data

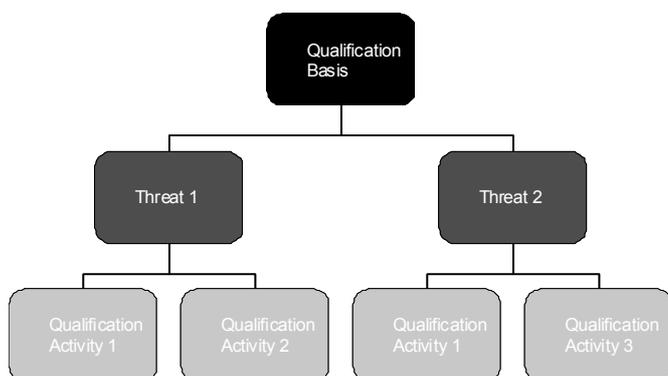
The documented evidence from the execution of the technology qualification plan should enable the performance assessment step to be carried out. The data collection and its documentation should be performed at the level of detail relevant for the development phase of the technology.

The quality of the data generated and how it shall be used in the different qualification methods shall be evaluated.

#### 9.5 Traceability of data

In order to ensure traceability of data, an “audit trail” shall be provided for the qualification process.

By audit trail it is meant that the data shall be organized in such a manner that there is a link from the qualification basis to the failure mode identification to the qualification activities (see Fig. 9-1).



**Figure 9-1**  
**Data hierarchy**

In other words: someone outside the project should be able to follow what failure modes have been identified, how they have been addressed (test, analysis, previous experience, etc.), what evidence has been developed (test and analysis reports) and how conclusive they are (adequate performance margin).

A benefit of this is that it will enable future projects to assess the scope of the qualification and therefore its applicability to the project specific requirements. If the project has functional or operational requirements beyond what the technology has been qualified for then these can be easily assessed and a smaller qualification program can be established to close the gap.

#### 9.6 Determination of performance margin

The determination of the performance margin will vary depending on the level of uncertainty with the technology. The uncertainty in turn depends on the level of confidence in understanding the failure modes and mechanisms of the system(s), and the uncertainty in the operating conditions. For qualification of CO<sub>2</sub> capture processes, process stability, the sensitivity to perturbation or disturbance should be considered.

## 10. PERFORMANCE ASSESSMENT

### 10.1 Introduction

*The objective of this phase is to confirm that the performance, functional requirements, or target reliability as stated in the qualification basis are met.*

The performance assessment is carried out to quantify the overall performance of the technology, and to compare it against the defined margins stated in the qualification basis. If the final acceptance of the technology qualification process has not been achieved, recommendations for design improvements or further qualification activities can be made. Alternatively, the operating envelope for the technology can be reduced to ensure adequate performance margin based on the gathered evidence. As a worst case, the technology cannot be qualified against the qualification basis.

### 10.2 Methodology

Key steps of the performance assessment are to:

- Confirm that the qualification activities have been carried out, and that the acceptance criteria have been met. A key part of this confirmation is to carry out a gap analysis to ensure that all the identified failure modes have been adequately addressed.
- Assess the performance margin related to each identified failure mode of concern.

### 10.3 Decision analysis

Examples of various methods for decision analysis are:

- Assessment of performance margin
- Engineering judgement
- Sensitivity analysis
- Quantitative risk assessment
- System reliability assessment.

If a reliability target is stated in the qualification basis, then a quantitative reliability assessment shall be carried out taking information from the execution of the qualification plan into account. The need for such bottom-up analysis using the qualification results depends primarily upon the system architecture. The requirement for such analysis should be identified at the qualification basis stage if a reliability target is stated. A description of system reliability assessment is given in Ref. /14/.

## 11. CONCEPT IMPROVEMENT

The objective of the concept improvement step is to implement improvements that have been found necessary or beneficial during the failure mode identification and risk ranking or in the performance assessment (see Fig. 4-1). All concept improvements have to be analysed for cost benefit. When making modifications to the concept, care should be taken to ensure that the modification either:

- Removes a failure mode, or
- Reduces the probability or consequence of failure mode to an acceptable level, or
- Reduces the total concept cost without introducing new failure modes.

Improvements would normally imply that the previous steps in the qualification process need to be updated. The updates may range from limited update of parameters or risk data to major rework of all documents. Regardless of the scope of the updates, traceability of the process is important to reflect the qualification process (see Sec.9.5).

## APPENDIX A DESCRIPTION OF CO<sub>2</sub> CAPTURE TECHNOLOGIES

This appendix gives a more detailed description of the capture technologies outlined in Table 2-1. The different technology categories for CO<sub>2</sub> capture, as listed in Table A-1 are described below.

Capture Category	Specific Technology
Absorption	Chemical absorption (amine, hindered amine and inorganic)
	Physical absorption
Adsorption	Pressure swing adsorption
	Temperature swing adsorption
	Electric swing adsorption
	Vacuum swing adsorption
Membranes	Gas absorption membranes
	Gas separation membranes
	Membrane reactors/reformers
Cryogenics	Compression and refrigeration
Emerging technologies	Chemical looping combustion; Enzyme based systems; Solid sorbents

### A.1 Absorption

*Chemical absorption* uses organic and inorganic aqueous solutions to weakly bond with carbon dioxide forming intermediate compounds. *Organic amines* are able to react with carbon dioxide forming water soluble compounds from streams with low CO<sub>2</sub> partial pressure. They are distinguished in primary, secondary and tertiary forms. The primary amine, monoethanolamine (MEA), is currently the most widely used solvent. The MEA solution is contacted with flue gas in an absorber where CO<sub>2</sub> is absorbed by the solution. MEA reacts with CO<sub>2</sub> in the gas stream to form MEA carbamate. The CO<sub>2</sub>-rich MEA solution is then sent to a stripper where it is reheated to release almost pure CO<sub>2</sub>. This process is generally uneconomic as it requires large equipment size and intensive energy input. Besides MEA, diethanolamine (DEA) and methyldiethanolamine (MDEA) are often used as absorbents.

*Inorganic solvents* include potassium carbonate, sodium carbonate and aqueous ammonia. Soluble carbonate compound react with carbon dioxide to form bicarbonate. The latter, when heated, releases CO<sub>2</sub>, regenerating the initial carbonate. There are two available systems using ammonia, the ammonia-based wet scrubbing and the chilled ammonia process (CAP). In principle, ammonia and its derivatives react with CO<sub>2</sub> by a range of mechanisms. For instance, ammonium carbonate, water and CO<sub>2</sub> react and form ammonium bicarbonate.

In *physical absorption*, the solvents form a weaker bond to CO<sub>2</sub> than chemical solvents, with the advantage of lower cost of regeneration. Binding takes place at high pressure with the CO<sub>2</sub> released when the pressure is reduced. The only energy needed for CO<sub>2</sub> capture is the power required for gas pressurization. The amount of energy per tonne of CO<sub>2</sub> is proportional to the inverse of the CO<sub>2</sub> concentration in the gas. Specific physical solvents include cold methanol which is used in the Rectisol process, dimethylether or polyethylene glycol which is used in the Selexol process, propylene carbonate used in the Fluor process and n-methyl-2pyrrolidone.

Of the separation methods described above, chemical absorption is the preferred method at CO<sub>2</sub> concentrations lower

than 10% (such as flue gases from gas-fired power plants), because its energy use is not particularly sensitive to low CO<sub>2</sub> partial pressures. Physical absorption is the preferred method at higher CO<sub>2</sub> partial pressures.

### A.2 Adsorption

Some solid materials with high surface areas, such as zeolites, molecular sieves and activated carbon, can be used to separate CO<sub>2</sub> from gas mixtures by adsorption, where chemical reactions between the adsorbent and CO<sub>2</sub> may or may not occur during the separation process. These processes operate on repeated cycles with the basic steps being adsorption and regeneration. The regeneration can be done by reducing the pressure, by so-called *pressure swing adsorption (PSA)*, or by increasing the temperature, in *temperature swing adsorption (TSA)*. Electrical and vacuum swing adsorption are also available techniques for regeneration.

Currently, adsorption is not considered attractive for large-scale separation of CO<sub>2</sub> from flue gas because the capacity and CO<sub>2</sub> selectivity of available adsorbents are low.

### A.3 Membranes

Carbon dioxide may be recovered using membranes. *Gas separation membranes* are available as ceramic, polymeric and ceramic/polymeric hybrids. The driving force for separation is given by the difference in partial pressure of gas species between the feed side and permeate side of the membrane. Gas separation membrane energy efficiencies can be higher than for absorption separation systems, as a limited pressure drop across the membrane is sufficient to achieve separation. Their modular design also allows their use in combination with small-scale modular fuel cells, foreseen as a power plant concept for the future. While membranes are widely applied for gas separation, they have yet to be applied at power plant scale. The disadvantage of membrane separation systems for CO<sub>2</sub> capture is that their separation efficiency is relatively poor and the purity of CO<sub>2</sub> is relatively low [15].

Micro-porous solids are used as *gas absorption membranes* that work as contacting devices between the gas and the liquid phase, increasing the contact area, thus reducing the size of the scrubbing equipment. They have potential to reduce the mass transfer of undesirable gas phase components such as oxygen and nitrous oxide, which are known to degrade the alkanolamine solvent.

Membranes are also applied for *membrane reformers* for hydrogen production in pre-combustion capture concepts. The reformer consists of a steam reformer equipped with hydrogen selective membrane modules of palladium-based alloy and nickel-based catalyst and can perform steam reforming reaction, water gas shift reaction and hydrogen separation at the same time without a shift converter and PSA. This process is called membrane-enhanced steam reforming. The permeate (hydrogen) can be combusted, whereas the CO<sub>2</sub>-rich retentate is further purified as appropriate.

### A.4 Cryogenic separation

Cryogenics take advantage of the critical pressures and temperatures of specific elements and compounds in a mixture and are commonly used today for purification of CO<sub>2</sub> in gas streams that already have high CO<sub>2</sub> concentrations. Cryogenic separation offers high recovery of CO<sub>2</sub>, but the large amount of energy required to provide the refrigeration necessary for the process, particularly for dilute gas streams, is the major disadvantage. Cryogenic separation is the most common way of producing oxygen in the oxy-fuel combustion concept.

## A.5 Novel technologies

There are several novel CO<sub>2</sub> capture concepts being developed in the wake of the first large-scale commercial CO<sub>2</sub> capture projects. Some of these concepts are briefly delineated below:

*Chemical looping combustion (CLC)* is an oxygen supply concept based on the use of a metal/metal oxide system to provide a reversible chemical reaction for oxygen supply /16/. Note that the CLC technology is often also categorized under the oxy-fuel combustion concept. In one reactor the metal reacts with air to produce a metal oxide; in another reactor, the metal oxide reacts with the fuel to produce syngas and metal. Metal and metal oxide are transported from one reactor to the other. Such a system avoids energy intensive air separation for pure oxygen supply. CLC has several advantages compared with conventional combustion. The exhaust gas stream from air reactor is harmless, consisting mainly of nitrogen. In a well-designed system, there should be no thermal formation of NO<sub>x</sub> since the regeneration of oxygen carrier takes place at moderate temperatures (without a flame). The exhaust gas from the fuel reactor consists of CO<sub>2</sub> and H<sub>2</sub>O. Separation of CO<sub>2</sub> can be done by condensing H<sub>2</sub>O. This is the major advantage with CLC which avoids the huge energy penalty necessary in traditional amine scrubbing process to capture CO<sub>2</sub>.

*A number of solid sorbents* can be used to react with CO<sub>2</sub> to form stable compounds at one set of operating conditions and then, at another set of conditions, be regenerated to liberate the absorbed CO<sub>2</sub> and reform the original compound. For exam-

ple, lithium zirconate (Li<sub>2</sub>ZrO<sub>3</sub>) and lithium silicate (Li<sub>4</sub>SiO<sub>4</sub>) have been investigated as high temperature CO<sub>2</sub> absorbents. Desired features, such as large capacity, rapid absorption, wide range of temperature and concentrations of CO<sub>2</sub>, and stability, make these compounds strong candidates for developing commercially competitive CO<sub>2</sub> adsorbents. In another concept, solid CaO-based sorbents can be applied for high temperature CO<sub>2</sub> capture (>500°C) from flue gas to form CaCO<sub>3</sub>, which is regenerated in a parallel process to form pure CO<sub>2</sub> and the oxide is circulated back to the capture vessel. These types of sorbents are attractive for high temperature in-situ CO<sub>2</sub> capture in novel pre-combustion concepts. However, solids are inherently more difficult to work with than liquids, and no solid sorbent system for large scale recovery of CO<sub>2</sub> from flue gas has yet been commercialized.

*Biologically based capture systems* are another potential avenue for improvement in CO<sub>2</sub> capture technology. These systems are based upon naturally occurring reactions of CO<sub>2</sub> in living organisms. One of these possibilities is the use of enzymes. An *enzyme-based system*, utilizing carbonic anhydrase in a hollow fibre contained liquid membrane, can achieve CO<sub>2</sub> capture and release by mimicking the mechanism of the mammalian respiratory system /17/. The idea behind this process is to use immobilized enzyme at the gas/liquid interface to increase the mass transfer and separation of CO<sub>2</sub> from flue gas.

## APPENDIX B SPECIFICATION AND REQUIREMENTS

This appendix gives an additional description to the specification relevant for the qualification of fossil fuel-fired power plants equipped with CO<sub>2</sub> capture processes as described in Sec.5.

### B.1 Documentation describing the process system

For the purpose of defining the qualification basis, an overall study of the process system, expressed as a process flow diagram (PFD) with relevant additional information (specification) should form the basis for establishing the functional requirements for the process. The process flow diagram should be clear, comprehensive, accurate and complete. However, the

extent to which it can be drawn up before any work is done on the detailed design of equipment will depend on the complexity of the process and the information available, which is likely to reflect the maturity of the process development program, e.g. exploratory research, process research, pilot plant studies or development of a commercial unit. Process piping and instrumentation diagrams (P&IDs) and equipment specification sheets are only likely to be available at late stages of process development.

Table B-1 shows the documentation that detailed system description for CO<sub>2</sub> capture technology could include.

Documentation type		Description
Conceptual	Process description	A detailed description of how the process operates and all system interfaces.
	Basis for commercial plant	The basis for a commercial plant should be established, including items such as production rate, battery limits requirements, specifications on feed and product streams, etc.
	Heat and material balances	A heat, material and pressure balance including all the pertinent physical characteristics of the process fluids involved. Moreover, utility streams involved in heat transfer to the process system should be shown.
Drawings	Block diagrams	Simplest form of graphical presentation, where each block represent a single piece of equipment or a complete stage in the process. Useful for highlighting mass and energy stream interactions between subsystems.
	Process flow diagram (PFD)	The key document in process design, showing the equipment selected to carry out the process; the stream connections and operating conditions. The flow sequence should be presented in its simplest form. Principal control systems should be shown and all major equipment items clearly indicated. Operating conditions should be shown at principal points in the process: 1) Stream composition 2) Total stream flow rate 3) Stream temperature 4) Nominal operating pressure 5) Stream enthalpy ( <i>optional</i> ) 6) Physical property data, e.g. density and viscosity ( <i>optional</i> )
	Process piping and instrumentation diagrams (P&ID)	The P&ID shows the arrangement of the process equipment, piping, pumps, instruments, valves and other fittings. It should include: 1) All process equipment, identified by an equipment number 2) All pipes with size and material of construction 3) All valves, control and block valves, by size and type 4) Ancillary fittings that are part of the piping system, such as inline sight-glasses, strainers and steam traps 5) Pumps 6) All control loops and instruments  For simple processes, the utility (service) lines can be shown on the P&ID. For complex processes, separate diagrams should be used to show the service lines. The service connections to each unit, however, should be shown on the P&ID.
Specification sheets	Major equipment outline drawings and specifications	Specification sheets for major equipment, such as heat exchangers, pumps and vessels, should be used. For example, vessel sketches, including specified pressure and temperature ratings, metal thickness, nozzle orientation and special internals should be shown.

### B.2 Interfacing system requirements

There will be several types of interfaces that need to be considered prior to the construction and building of a process plant. Such interfaces could be physical interfaces, connections, or supply points, as well as documental interfaces such as contractual agreements, with external operators /18/.

An important interface for CO<sub>2</sub> capture systems is the integration between the capture unit/ capture plant and the power plant. For oxy-fuel, and pre-combustion concepts, the CO<sub>2</sub> capture processes are integrated within the power plant, whereas for the post combustion concept, the capture plant and the power plant would normally be two separate units. Hence, integration of a capture process into a power plant will intro-

duce different challenges depending on the chosen technology.

In all three capture concepts, the effects of the interactions between the power plant and the capture plant must be considered. For a gas power plant, with post combustion capture, conditions in the capture plant can influence the gas power plant (back pressure) or produce new requirements regarding steam production (effect on low pressure turbine).

The boundaries for the CO<sub>2</sub> capture process are in this document defined as the interface to the CO<sub>2</sub> transport element (see Sec.1.3.2). Typical interfacing requirement for this boundary would be specifications to the CO<sub>2</sub> product stream composition and pressure.

### B.3 Authority requirements

The authorities will require that the plant is built and operated according to national and international regulations, applicable codes, and standards, related to pollution, emissions, safety, etc. Such requirements are highly dependent on the country in which the plant is to be installed and operated.

General rules and regulations that need to be considered for a gas-fired power plant with CO<sub>2</sub> capture in Norway are for instance /18/:

- Consequence assessment requirements
- Safety rules and regulations
- Legislations on pollution and climate quotas
- The petroleum legislation
- Other new/special regulations.

It will be important to secure the necessary permissions from the government at an early stage in order to ensure the progress of the project. It is recommended these requirements are included as early as possible in the qualification basis.

### B.4 Requirements to safety, health and the environment

A CO<sub>2</sub> capture plant or power plant fitted with CO<sub>2</sub> capture technology will require to comply with considerable SHE regulations in design, construction, and operation. Examples of SHE requirements are emissions to air and technical safety /18/.

### B.5 Reliability, availability, and maintainability requirements

For CO<sub>2</sub> capture processes, plant availability is the most commonly used reliability parameter. *Availability requirements* are typically expressed as the fraction of time the equipment is able to perform its intended function under given operating conditions, whereas *maintainability requirements* are typically expressed as the mean time needed to return failed or shutdown equipment back to normal service.

Requirements for plant availability for a CO<sub>2</sub> capture process might vary based on the type of capture concept. The consequences for the downtime for a post combustion capture unit might be small compared to a process that is fully integrated with the power plant, such as in a pre-combustion process or an oxy-fuel combustion process.

Strict targets for reliability, availability, and maintainability (RAM) can strongly influence a project's economy by imposing very comprehensive tests and analyses in order to document fulfilment. It is of crucial importance that the impact of setting such requirements are thoroughly discussed, understood, and agreed by all project participants. Before setting targets, it can be instructive (or helpful) to investigate how a system's reliability or availability targets are met. A more detailed guidance on the prediction of system reliability can be found in Ref. /14/, /19/, /20/.

It is recommended that system availability is investigated as early as possible in the project. Before more detailed information is available, one could use fault-tree analysis or a simplified RAM analysis with the input from a HAZID for support in the decision making.

## APPENDIX C

### SCALE-UP OF CO<sub>2</sub> CAPTURE TECHNOLOGIES

This appendix describes scale-up issues related to CO<sub>2</sub> capture technologies, where a traditional chemical engineering approach to the scale-up path from laboratory to commercial design is described and compared to the principles of this Recommended Practice.

#### C.1 Introduction

Scale-up is essential in qualification of process systems. A CO<sub>2</sub> capture technology may be qualified and even well proven at a given scale. However, it will still need to be qualified for a larger scale.

The discussions are limited to scale-up of separation vessels typically used for physical and chemical absorption of CO<sub>2</sub> for post-combustion capture. Scaling issues related to oxy-fuel combustion and catalytic reforming reactors used in pre-combustion systems are not discussed, neither are any utility systems.

The idea of separating CO<sub>2</sub> from flue gas streams started back in 1970's, not with concern about the greenhouse effect, but as a possible economic source of CO<sub>2</sub>, mainly for enhanced oil recovery (EOR) operations. Other application areas for CO<sub>2</sub> usage include carbonated beverages, food industry, brewing, welding, chemical feed stocks, fire extinguisher and solvent extraction. Several plants are in commercial operation today, however, all existing plants are much smaller than proposed CCS plant for a typical power plant in terms of tonnage of CO<sub>2</sub> handled for the purpose of CCS.

#### C.2 Scale-up of post combustion CO<sub>2</sub> capture units

One of the most known, and frequently cited, commercial CO<sub>2</sub> post-combustion capture facilities that has been in recent operation, is the Bellingham (Massachusetts, US) facility, where capture rates of ~320 t CO<sub>2</sub>/day were experienced, in the period from 1991 to 2005. In order to capture 90% of a 400 MW natural gas fired combined cycle, units of approximately 3200 t CO<sub>2</sub>/day are required. For example, this would equal a scale-up ratio of 10, relative to the Bellingham plant.

In general, the critical aspects of scale-up relate to the impact of surface/ volume and height/diameter ratios on flow patterns, gas/liquid dispersion and heat transfer. Typical problems may be of physical nature, chemical nature, or involve some aspects of both. For chemical processes in general, some features considered to be of particular importance when moving from small-scale to commercial unit, are listed in Table C-1.

In addition to the issues listed in Table C-1, presence of impurities not considered at laboratory scale could be encountered for a commercial operation and foul or poison catalysts or solvents. Moreover, some impurities in recycle streams, e.g. solvent recycle, might accumulate over time and cause operational problems not foreseen at smaller scale.

<i>Scale-up issues</i>	<i>Challenges</i>
Shape and geometry of reactor	Fluid by-passing; Pressure drop; Stagnation zones resulting in changes in residence time distribution
Surface-to-volume ratios; height-to-diameter ratios	Gradients of concentration and temperature; Flow patterns; Gas/liquid distribution
Materials of construction	Different contaminant levels
Heat removal	Temperature profiles; Hot/cold-spots; Run-away reactions

The major challenge with CO<sub>2</sub> capture from flue gases from natural gas powered plants compared to coal fired power plants, is related to combustion with a large excess of air, resulting in:

- Large total volume of gas to be scrubbed
- Low concentrations of CO<sub>2</sub>
- High concentrations of oxygen that degrade amine solvents.

The most common separation vessels employed for CO<sub>2</sub> scrubbing are counter current absorbers. The design of counter current absorbers normally involves the following steps:

- Selection of contactor (type of trays or packing)
- Calculation of mass and heat balances
- Estimation of required column height (based on mass and heat transfer analysis)
- Calculation of required column diameter (based on gas/liquid flow rates and hydraulic considerations)
- Mechanical design of the hardware.

Detailed reviews on commonly used design procedures for absorbers, including theoretical equilibrium calculations, empirical correlations and computer-assisted models, are presented by *Kohl and Nielsen (1997) /22/*.

A common feature for absorbers is the optimum in operational conditions for gas and liquid flow rates, which should yield good wetting of the packing material and at the same time avoiding the occurrence of flooding. The diameter of a packed column is usually established on the basis of flooding correlations, whereas the height of the column relates to the mass transfer efficiency.

Increased volumetric flow of flue gas is likely to require larger absorbers to be designed and constructed, than previous experienced, as it is often desirable to treat the large volumes of gas in a single train rather than a number of parallel trains, due to economy of scale reasons (reduces the number of vessels, the quantity of piping, valves, and instrumentation). Hence, these larger columns will introduce practical challenges related to design and fabrication.

Uniform gas and liquid distribution is indispensable for a large size tower to obtain required performance. As the absorber cross sectional area increases, there is likely to be an increased number of challenges in maintaining uniform distribution of the solvent over the packing in packed columns, or of maintaining even distribution of solvent over large plate areas in plate columns. The most severe effects of uneven distribution in the absorber column on the capture performance can be summarized as:

- Uneven solvent distribution – If all the surface area of the packing is not wetted, then less surface area will be available for mass transfer of CO<sub>2</sub> from the flue gas to the solvent.
- Flue gas bypass – The flue gas will follow the path of least resistance. The parts of the tower with the greatest liquid flow will receive the least gas flow and the part with the least solvent will receive the most flue gas. This contributes to the loss of performance.

Also, as the diameter becomes large, heavy structural members must be employed to support the trays or packing, and such heavy structural members require an increased absorber column internal volume at great expense.

The previous discussions on design and size of large scale absorbers are also valid for the stripper vessel. However, the

sizes of stripper vessels are generally smaller than for absorbers, as the gas throughput is more dependent on the amount of CO<sub>2</sub> fixated in the recycled solvent. Furthermore, the above discussions are not meant to be a comprehensive and thorough assessment of scaling effects and design of large-scale CO<sub>2</sub> capture units. However, it highlights some challenging features likely to be encountered when scaling-up and designing very large absorption towers.

### C.3 Technology qualification and scale-up

To follow a direct path from laboratory scale to a commercial full-scale design requires either an enormous amount of information that often is unavailable or beyond scientific and engineering judgement normally considered possible and desirable. On the other hand, building intermediate-scale pilot plants is an expensive task. The pilot will require the same number of instruments and controllers as the full scale plant, and even more instrumentation will be required to gather data required for the scale-up studies. Moreover, the operating cost of a pilot is high as it is necessary to staff the pilot with both engineers and operators. There is always a limited amount of time and money for process development. Therefore, calculated risks will have to be taken in the design, construction and start-up of the “first commercial unit”. These calculated risks should be minimized and assessed in a systematic manner.

The current Recommended Practice provides a systematic procedure for managing the risks associated with CO<sub>2</sub> capture technologies, where in particular two aspects of scale-up are relevant:

1) *Scale-up as a source of risk.*

The scale-up ratios of future commercial post-combustion capture plants relative to previous experience could typically be in the order of magnitude of 10. This might not

seem like a very great figure, compared to historic scale-up data for other chemical processes /10/. However, considering the urgency of deployment of CCS as a greenhouse gas mitigation technology, the relatively short timeframe for scale-up development introduces additional challenges for technology developers. Moreover, novel pre-combustion and oxy-fuel capture systems, such as hydrogen membrane reactors or chemical looping combustion, are likely to have scale-up ratios of a much higher order of magnitude than for an amine-based post-combustion plant. Therefore, the scale of operation itself introduces risks, which should be identified, assessed and managed using technology qualification following the principles of the current Recommended Practice.

2) *Scale-up as a qualification method (pilot plants).*

The technology qualification plan, following the threat assessment step, is developed in order to show how each of the identified failure modes will be qualified. Qualification methods are selected to adequately address the identified failure modes of concern. This might be computer modelling, theoretical investigations, laboratory experimental investigations, previous experience, handbook solutions or pilot scale tests. Building a pilot plant is expensive and time consuming, and should only be justified if it contributes to the reduction of the risks and minimizes the chances of failure of the commercial plant. The selected qualification method should be directed primarily at attacking areas of doubt and uncertainty. Therefore, scale-up studies using pilots should address the failure modes of concern, rather than being a miniaturized commercial system. Technology qualification, following the principles of the current Recommended Practice, is an efficient methodology and tool in assessing whether a pilot plant should be built or not.

## APPENDIX D QUALIFICATION EXAMPLES

### D.1 Introduction

Examples have been created to show how the different steps in the Recommended Practice can be performed. These examples are not meant to be complete, but intended as a general guidance on:

- Technology Classification
- Failure Mode Identification & Risk Ranking
- Selection of Qualification Methods.

All technical details in the example have been taken from the paper “CO<sub>2</sub> removal from power plant flue gas – cost efficient design and integration study” by Choi et al. [23].

### D.2 Qualification basis

*For practical reasons, a full qualification basis has not been included, but sufficient details are given here to serve as basis for the technology assessment example.*

#### D.2.1 Process description

The CO<sub>2</sub> capture process is a post combustion amine absorption process shown in Fig. D-1. The design basis for the case study is CO<sub>2</sub> from the flue gas of a 400 MW gas fired combined cycle power plant. The flue gas leaves the power plant exhaust ducting at 85°C and 1.01 bar, and enters the flue gas cooler where it is cooled to approximately 40°C. A fan is required to provide sufficient pressure to overcome the pressure drop in the absorber and water wash section of the absorber tower. In the absorber, CO<sub>2</sub> in the flue gas will react with amine and remain in the liquid phase. To facilitate the mass transfer from the flue gas to the solvent, the absorber is equipped with structural packing.

The gas leaving the absorber will contain some amines due to gas phase equilibrium and droplet carryover. The water wash section is a recycle system where the water rich with amine is collected below the packing section and pumped via a cooler to the distributor above the packing. A small amount of water is added in the circuit to avoid too much build up of amine in the water wash section. This is required to control emission of amine via the stack.

The water/amine solution rich in CO<sub>2</sub> (rich amine) is collected in the bottom of the absorber and is pumped to the amine stripper via the lean/rich amine exchanger. The rich amine is heated by the water/amine solution lean in CO<sub>2</sub> (lean amine) leaving the amine stripper.

The CO<sub>2</sub> is recovered from the rich amine solution in the amine stripper. The stripper is a column with structural packing. The solution is heated in the reboiler located below the amine stripper. Steam and amine vapours leave the reboiler and enter the packed section of the stripper where the vapours liberate the CO<sub>2</sub> and heat the down flowing solution. The heat transfer from vapour/steam to rich amine leads to partial condensation. The uncondensed steam, vapour and liberated CO<sub>2</sub> enter the wash section of the stripper where the amine vapour

is condensed. The released CO<sub>2</sub> and excess steam leaves over the top of the amine stripper. The steam is condensed in the stripper condenser and separated from the CO<sub>2</sub> in gas phase in the stripper overhead receiver. The condensed water is returned to the water wash section of the amine stripper. The CO<sub>2</sub> in gas phase is available for downstream processing.

The bottom product of the amine stripper is lean amine. Part of the lean amine is circulated through the stripper reboiler producing steam required in the amine stripper. Flow is induced by thermal siphoning. The lean amine from the amine stripper is cooled by sea water in the lean/rich solution exchanger and is pumped via the lean solution cooler to the top of the flue gas absorber.

#### D.2.2 Functional requirements

Examples of functional requirements for this CO<sub>2</sub> capture plant are:

- CO<sub>2</sub> capture rate: 85%
- heat and power consumption: 4.2 GJ/tonne CO<sub>2</sub> + 6.5 MW electric power
- emissions (solvent): <3 ppm.

#### D.2.3 Critical parameters list

The critical parameter list ensures that the relevant input parameters for analysis and tests are used and updated with possible changes in design during the qualification process. Examples of critical parameters for the capture plant are given in Table D-1.

Critical parameter description	Unit of Measure	Goal values	Min	Max
CO <sub>2</sub> capture rate	%	85%	80%	-
Heat consumption	GJ/tonne CO <sub>2</sub>	4.2	-	4.5
Power usage	MW	6.5	-	7.5
Degradation rate	kg/hr			
CO <sub>2</sub> product composition:				
- CO <sub>2</sub>	vol%			
- H <sub>2</sub> O	vol%			
- trace components	vol%			

### D.3 Technology assessment

#### D.3.1 Technology breakdown

For each component the relevant functions shall be listed. The level of technology breakdown is determined by the complexity of the system. The objective is to identify the unique functions that contribute to the system functionality. Table D-2 shows a part of the technology breakdown of the absorber into components with functions.

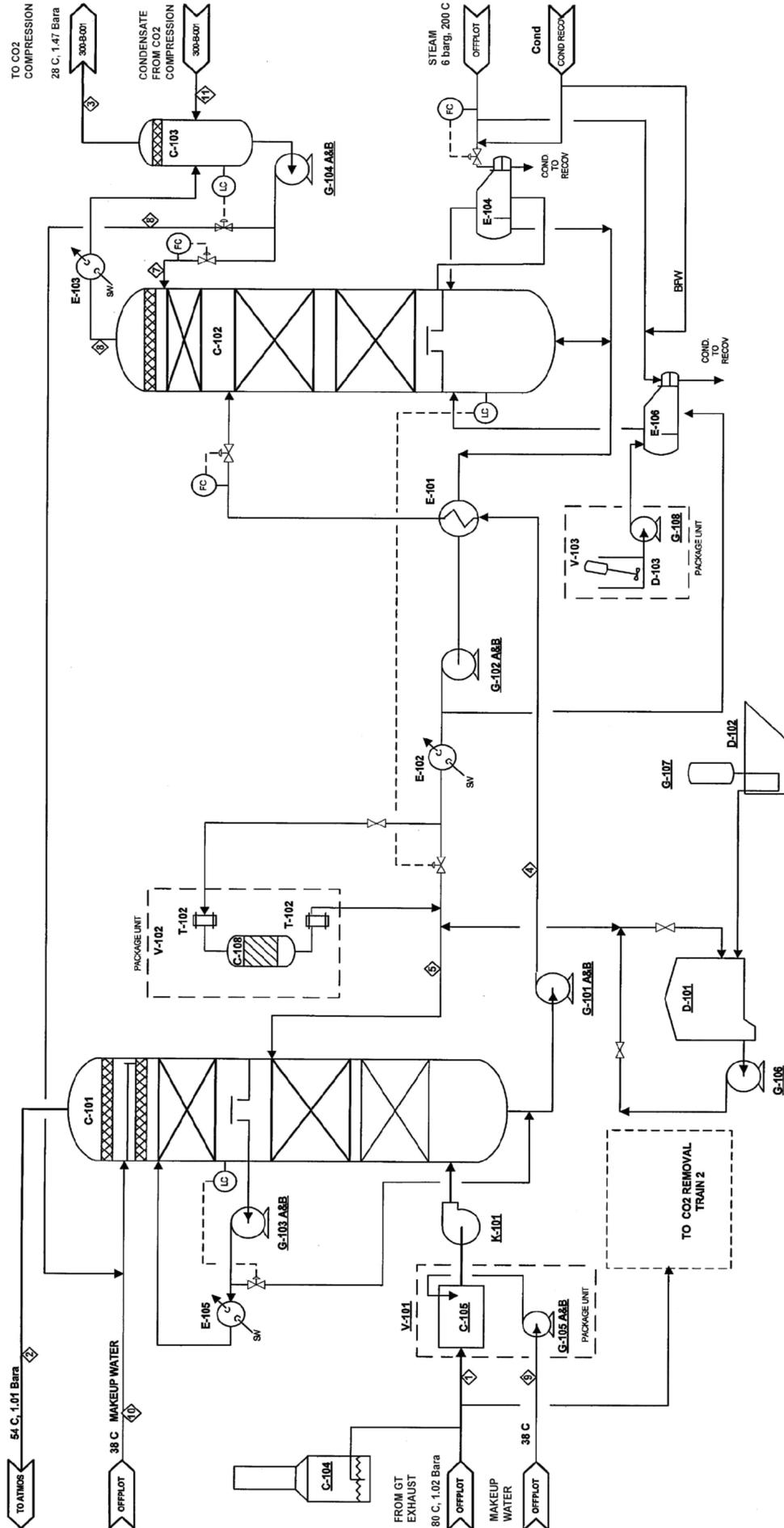


Figure D-1  
 Process Flow Diagram /23/

In order to identify all novel elements, and subsequently possible failure modes, it can be an advantage to perform the technology breakdown based on unit operations with unit processes in addition to components with functions.

### D.3.2 Technology classification

Table D-3 shows a technology classification of the absorber from the previous section. Table 6-1 in Sec.6.5 was applied to each of the technology elements from the technology breakdown.

The classification in Table D-3 shows that out of 5 technology elements, 3 of them have been classified as New Technology or with Limited Knowledge/Field History. The remaining 2 elements that are classified as Known Technology, will not

be forwarded into the next step in the qualification process, threat assessment (failure mode identification & risk ranking).

The technology classes 2, 3 and 4 indicated the degree of uncertainty related to the element, but not necessarily the technical challenges related to it.

### D.4 Failure mode identification and risk ranking

The failure mode, effect and criticality analysis (FMECA) methodology may form the basis for the failure mode identification. This methodology should be performed by an interdisciplinary team, involving personnel with relevant competence. An example of an FMECA worksheet for a specific component from Table D-3 is given in Table D-4.

**Table D-2 Absorber components with functions**

ID	Component	Function
1	Flue gas absorber (absorption section)	Absorb CO <sub>2</sub> from flue gas
1.1	Flue gas absorber	Containment
1.2	Flue gas absorber packing	Facilitate absorption of CO <sub>2</sub> to liquid solvent
1.3	Absorber distributor	Ensure uniform distribution of solvent in packing
1.4	Absorber collector	Collect solvent at bottom of packing section
1.5	Gas distributor	Ensure uniform distribution of gas in absorber

**Table D-3 Technology classification of components in the absorber**

ID	Component	Function	New aspect	Application			Technology			Techn. Class.
				Known	L. know.	New	Known	L. hist.	New	
1	Flue gas absorber (absorption section)	Absorb CO <sub>2</sub> from flue gas								
1.1	Flue gas absorber	Containment		x			x			1
1.2	Flue gas absorber packing	Facilitate absorption of CO <sub>2</sub> to liquid solvent	Has not been used with this type of solvent over the entire packing height. Uncertainty about necessary height			x		x		4
1.3	Absorber distributor	Ensure uniform distribution of solvent in packing	Very large distributor, no industry experience with so large distribution		x			x		3
1.4	Absorber collector	Collect solvent at bottom of packing section		x			x			1
1.5	Gas distributor	Ensure uniform distribution of gas in absorber	Large distributor compared to general industry experience		x		x			2

ID	Component	Function	Failure mode	Failure mechanism / root cause	Detection	Consequence	Risk Ranking		
							Cons.	Prob.	Risk
1	Flue gas absorber (absorption section)	Absorb CO <sub>2</sub> from flue gas							
1.3	Absorber distributor	Ensure uniform distribution of solvent in packing	Uneven liquid distribution resulting in a lower CO <sub>2</sub> capture rate	Modelling uncertainty leading to unsuitable distribution technology chosen	No detection (can be detected with visual inspections)	Work over on the distributor, several months of down time	5	3	High
				Solids build up in the distributor that clogs the distribution holes	No detection (can be detected in with visual inspections)	Increased maintenance intervals with 7 days down time more than expected	3	3	Medium

A general guidance for the various column headings is given below.

**ID**

For documentation purposes each failure mode shall be numbered.

**Component**

The technology is broken down to a level at which the root cause or failure mechanism is understood (see Sec.6.3).

**Function**

In order to fully understand the possible failure modes, all of the components' functions need to be identified. Components have often more than one function.

**Failure mode**

Failure modes and uncertainties shall be identified and documented. A failure mode can be understood as when a component fails to fulfil one of its functions.

**Failure mechanism / root cause**

An example of the relationship between failure cause, failure mode and effect is shown in Fig. D-2 below. It is vital that the technology breakdown is at a level where all failure mechanisms can be fundamentally understood.

**Detection**

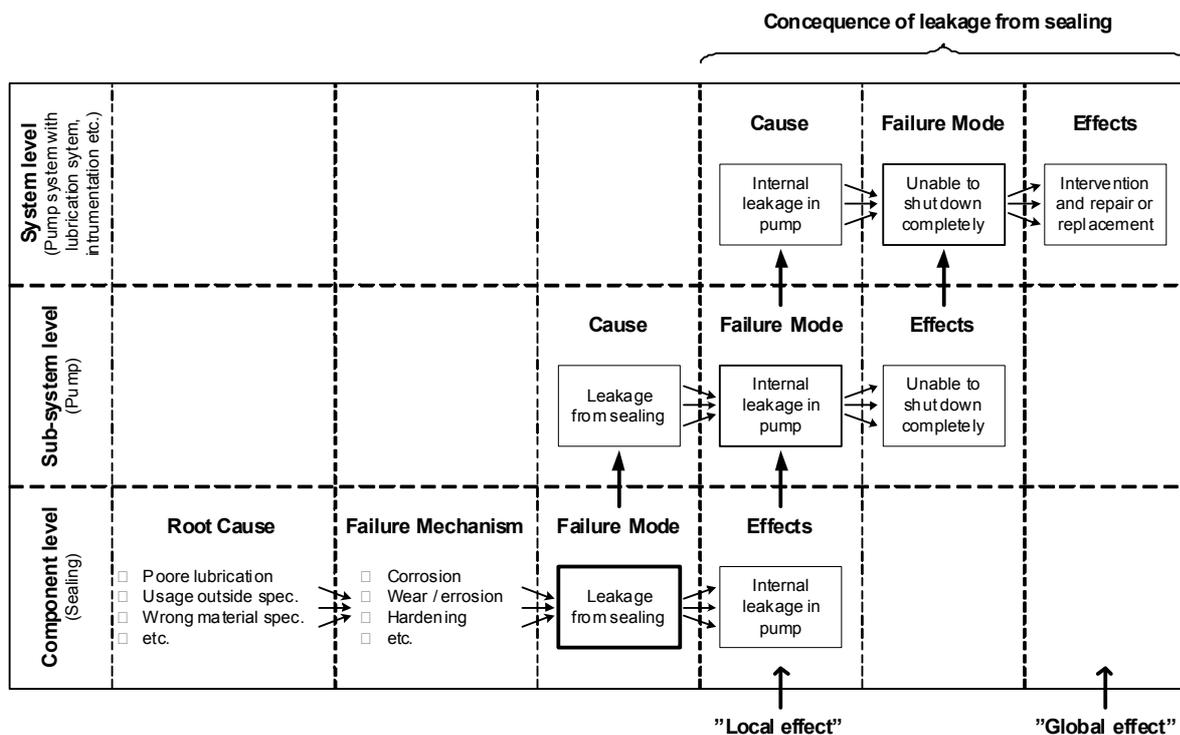
When and how you detect a failure mode can be of great influence to the consequence of it. The relevant detection should therefore be identified before the consequence classification.

**Consequence**

The consequence identified according to the principles given in Sec.7.4 and should be in written text for easier reference. Consequences of failure on neighbouring equipment and the environment should be evaluated.

**Unit operations with unit processes**

The failure mode identification & risk ranking for unit operations with unit processes may follow the same principles as for components, however, it is expected that, when looking at processes, different or additional failure modes might be identified.



**Figure D-2**  
Relationship between failure cause, mode and effect /1/

#### D.4.1 Risk ranking

The risk ranking should follow the principles given in Sec.7.5. The results from the risk ranking process should be summarized in a common risk matrix that shows the failure modes with medium and high risk (see Table 7-3).

#### D.5 Selection of qualification methods

Qualification activities have been selected to address the failure modes given medium and high criticality in the risk ranking. For failure modes with low risk, it is assumed that adequate reliability is ensured through conventional design.

The selection of activities is based on the assumption that best engineering practice is followed in the design and that adequate quality control and testing is applied.

Table D-4 shows one selection of a qualification method for a failure mode with high risk.

<i>Activity</i>	<i>ID</i>	<i>Component</i>	<i>Failure Mode</i>	<i>Failure Mechanism</i>
A sectioning of the absorber should be evaluated. If sectioning is not feasible, a full-scale mock-up of a distributor should be tested to ensure that the liquid distribution is uniform.	1.3	Absorber distributor	Uneven liquid distribution resulting in a lower CO <sub>2</sub> capture rate	Modelling uncertainty leading to unsuitable distribution technology chosen

## APPENDIX E TEMPLATES

### E.1 Critical parameters list

Table E-1 suggests a critical parameters list template. The list will be continuously updated and its dimension increased throughout the qualification process. See Sec.5.6 for further description.

<i>Qualification Basis</i>					<i>Failure Mode Registry</i>
<i>ID</i>	<i>Critical parameter description</i>	<i>Unit of Measure</i>	<i>Design Values/ Acceptance criteria</i>		<i>Failure Mode ID</i>
			<i>Min</i>	<i>Max</i>	<i>ID</i>
1	Functions	[ ]			
1,1					
1,2					
2	Performance				
2,1					
3	Geometry and Weight				
4	Boundary conditions and Environment				
5	Materials				
6	SHE				
7	Scale-up				
8	Reliability				
9	QA/QC				

### E.2 Technology qualification plan

A TQP template is suggested in Table E-2.

<i>No.</i>	<i>Activity description</i>	<i>ID</i>	<i>Component/ Process</i>	<i>Failure Mode</i>	<i>Failure Mechanism</i>	<i>Analytical method</i>	<i>Computational method</i>	<i>Experimental method</i>	<i>Handbook solution</i>	<i>Previous experience</i>	<i>Failure Mode avoidance</i>
1											
2											
3											
4											
5											