



Technical report describing the design of monitoring systems

Prepared by: D. Sijacic (TNO)

Reviewed by: A.F.B. Wildenborg

Approved by: J. Brouwer
(CATO-2 Director)

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1 Executive Summary (restricted)

CATO-2 program's mission is to facilitate and enable the integrated development of CCS demonstration sites in the Netherlands. Work Package 4.5 aims to develop and test risk management methods and tools supporting the qualification and certification procedures for long-term safe and effective CO₂ storage during all storage phases. Risk management which acts as the central driver for all safety related activities, consists of Risk Assessment, Risk-based Monitoring and Preventive and Corrective Measures. This deliverable focuses on developing a Risk-based Monitoring Plan which is a legal requirement as stipulated by the EU guidelines and required by the CCS directive.

This report lists the requirements for developing a monitoring plan as formulated in the Directive and the relevant Annex. Monitoring is brought into connection with the phases during the storage process (pre-injection, injection and post-injection phase). So are the different categories of the monitoring (mandatory, required and optional contingency monitoring). Even so, monitoring of CO₂ storage is by its nature site-specific, the existing (and any future) guidelines and regulations can never prescribe a fit-for-purpose monitoring plan for any concrete storage site. The construction of a Monitoring Plan must depend on the Risk Assessment, according to the Directives mentioned .

Risk Assessment is obviously site-dependent and has to be conducted by a team of experts. The results of this work will consist of the definitions of relevant (HSE linked) risks and scenario's which should be avoided. We assume this as a starting point, input for a supporting tool which can facilitate the development of a risk-based monitoring plan. The focus of this deliverable is development of such a tool.

This tool is built around two databases, one containing risk factors and associated parameters and another one containing monitoring techniques and the parameters they measure. The database with the risk factors is the product of a TNO risk assessment methodology referred to as CASSIF. The tool has been designed as a logical continuation of the risk and safety assessment performed by experts using the CASSIF process. The tool is meant to be part of a risk management framework which enables communication between the risk analysis results and the monitoring strategy.

The tool is driven by the user-selection of site-specific characteristics and scenarios which contain risk factors. The selection of the scenarios leads to a number of risk factors which are then matched with the monitoring techniques. Information about the monitoring techniques can be displayed, depending on the demands of the user. The resulting list provides insight into the suitability of certain monitoring techniques for particular risks. This list aids the user in creating a risk based monitoring plan. It is possible to specify the different monitoring categories, e.g. required, contingency and mandatory monitoring. The first web-enabled version of the tool has been implemented. The tool was tested by applying it to the Barendrecht project and comparing the outcome of the tool with the original Barendrecht monitoring plan. A second test was done on a potential storage site, offshore Norway.

In the future, additional functionality, such as information about the risk level and the time and space frames of the scenarios and FEPs will be taken into account.



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Document Change Record

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Version	Nr of pages	Short description of change	Pages

Table of Content

1	Executive Summary (restricted)	2
2	Applicable/Reference documents and Abbreviations	5
2.1	Applicable Documents	5
2.2	Reference Documents	5
2.3	Abbreviations	5
3	Introduction	6
4	Requirements for developing a monitoring plan	7
4.1	The legal basis	7
4.2	Monitoring plan: the requirements.....	7
4.2.1	Initial plan.....	7
4.2.2	Updated plan.....	8
4.3	Monitoring: additional explanations and categorisations	10
4.3.1	Categories.....	10
4.3.2	Monitoring in different stages of a CCS-project	11
4.4	Outline of a Monitoring Protocol.....	11
4.4.1	Pre-injection phase.....	12
4.4.2	Injection phase	12
4.4.3	Post-Injection phase.....	13
5	Monitoring planning tool	14
5.1	Introduction	14
5.2	The goal and the concept of the Tool.....	14
5.3	Risk Assessment.....	16
5.4	Detailed description of the Tool.....	18
5.5	What Does the Tool Do?	19
5.5.1	The Source of the FEPs	19
5.5.2	The Source of the Monitoring Techniques.....	20
5.6	User Interface of the Monitoring Planning Tool.....	20
5.6.1	The Introduction Screen Sheet	21
5.6.2	The Scenario Sheet(s).....	22
5.6.3	The Output Sheet.....	25
5.6.4	The Monitoring Techniques Sheet	27
5.7	Graph of the Tool	27
5.8	Tool Demonstration – The Barendrecht Case	27
5.8.1	Scenario Description	28
5.8.2	The Barendrecht Monitoring Plan	28
5.8.3	List of FEPs.....	29
5.8.4	Results of the Tool	30
5.9	Tool demonstration – Other cases.....	31
5.10	Online web version of the tool (Version 1)	32
5.11	Work in Progress	33
5.11.1	Quality check of indirect connections between FEPs and monitoring techniques... 33	
5.11.2	Using (and providing) extra information.....	34
5.11.3	Generating the list of Tools and displaying the results.....	34
5.11.4	Developing online web interface	34
5.11.5	Site-specific quantified monitoring plan (stage II)	34
6	Conclusion	35
7	References	36

2 Applicable/Reference documents and Abbreviations

2.1 Applicable Documents

(Applicable Documents, including their version, are documents that are the “legal” basis to the work performed)

	Title	Doc nr	Version
AD-01d	Toezegging CATO-2b	FES10036GXDU	2010.08.05
AD-01f	Besluit wijziging project CATO2b	FES1003AQ1FU	2010.09.21
AD-02a	Consortium Agreement	CATO-2-CA	2009.09.07
AD-02b	CATO-2 Consortium Agreement	CATO-2-CA	2010.09.09
AD-03g	Program Plan 2013b	CATO2-WP0.A-D03	2013.04.01

2.2 Reference Documents

(Reference Documents are referred to in the document)

	Title	Doc nr	Issue/version	date
R.01	Progress Report on Risk Management of CO ₂ Storage	CATO2-WP4.5-D4.5.03	2011.12.16	16.12.2011
R.02	Assessment of Risks and Uncertainties	CATO2-WP4.1-D4.1.08	2012.10.18	
R.03	Technical report describing the design of monitoring systems, and remediation	CATO2-WP4.5-D4.5.04	2013.02.15	

2.3 Abbreviations

(this refers to abbreviations used in this document)

FEP	Features Events Processes
HSE	Health Safety Environment
CASSIF	Carbon Sequestration Scenario Identification Framework

3 Introduction

CATO-2 program's mission is to facilitate and enable the integrated development of CCS demonstration sites in the Netherlands. The program's ambition is to support the realization of two or more demonstration sites where the complete integration of CO₂ capture, transport and storage will be demonstrated in the Netherlands before 2015. With this, CATO-2 will help build an internationally leading strong knowledge and technology position for CCS in the Netherlands (AD03: CATO2A Plan).

One of the CATO2 Sub Programmes is SP 4: Regulation and Safety, which addresses regulation, operational practices, environmental impacts, and the safety of CO₂ transport and geological storage.

This WP aims to develop and test risk management methods and tools supporting the qualification and certification procedures for long-term safe and effective CO₂ storage. They should be reliable, adequate, practical and flexible. The three main components of risk management are:

1. Risk assessment;
2. Risk-based monitoring;
3. Preventive and corrective measures.

This report focus on a protocol for designing the risk based monitoring plan and on a practical tool which can support the process.

The methods and tools are adjusted to the current industrial upstream HSE practice in the Netherlands. The level of detail and type of tools will be adapted to the specific conditions at a particular site (gas field or aquifer) and to regulatory (EIA/Storage Plan) or public needs (e.g. comparison with other man-induced or natural risks).

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The workflow for the risk based monitoring has been extended with the inclusion of monitoring categories and has been tested on a potential storage site , offshore Norway. Chapter 4 reviews legal requirements and the procedure for developing a monitoring plan. Chapter 5 provides the updated concept for a monitoring planning tool, a description of the new version of the tool and the results of the additional test example, offshore Norway. The first version of the web-enabled tool was implemented.

4 Requirements for developing a monitoring plan

In this chapter we describe how an operator of a prospective CO₂ storage site arrives at a suitable monitoring plan. We will describe the legal basis, and the legal requirements, relevant issues of monitoring as such, and then describe the road towards a monitoring plan.

4.1 The legal basis

The basis for a monitoring plan related to CO₂ storage is the 2009 EC Storage Directive [1]. Monitoring is addressed in Articles 13. and 17. of the Storage Directive. Article 13 sub 1. informs us that “Member States shall ensure that the operator carries out monitoring of the injection facilities, the storage complex (including where possible the CO₂ plume), and where appropriate the surrounding environment for the purpose of ...” and then the many purposes are henceforth mentioned. We will deal with them later on.

Article 13 sub 2. informs us that monitoring shall be based upon a monitoring plan by the operator, the requirements of which are given in the Annex II. At this point it is important to mention that the plan must be based upon risk assessment, which is site specific.

Article 17 details closure and post-closure obligations and continuing monitoring activities are among these obligations. They are to be in accordance to Annex II also.

4.2 Monitoring plan: the requirements

For reference, we lay down the requirements as formulated in the Directive and the relevant Annex. The Storage Directive requires a monitoring plan, drawn up by the operator, and approved by the competent authorities. A monitoring plan should meet the following requirements:

4.2.1 Initial plan

The monitoring plan shall provide details of the monitoring to be deployed at the main stages of the project, including baseline, operational and post-closure monitoring.

The following shall be specified for each phase:

- a. Parameters monitored;
- b. Monitoring technology employed and justification for technology choice;
- c. Monitoring locations and spatial sampling rationale;
- d. Frequency of application and temporal sampling rationale.

The parameters to be monitored are identified so as to fulfil the purposes of monitoring. However, the plan shall in any case include continuous or intermittent monitoring of the following items:

- a. Fugitive emissions of CO₂ at the injection facility;
- b. CO₂ volumetric flow at injection wellheads;
- c. CO₂ pressure and temperature at injection wellheads (to determine mass flow);

Design of Monitoring systems

- d. Chemical analysis of the injected material;
- e. Reservoir temperature and pressure (to determine CO₂ phase behaviour and state).

The choice of monitoring technology shall be based on *best practice available at the time of design*.

The following options shall be considered and used as appropriate:

- a. Technologies that can detect the presence, location and migration paths of CO₂ in the subsurface and at surface;
- b. Technologies that provide information about pressure-volume behaviour and areal/vertical saturation distribution of CO₂-plume to refine numerical 3D-simulation to the 3-D-geological models of the storage formation established pursuant to Article 4 and Annex I;
- c. Technologies that can provide a wide areal spread in order to capture information on any previously undetected potential leakage pathways across the areal dimensions of the complete storage complex and beyond, in the event of significant irregularities or migration of CO₂ out of the storage complex.

[Note: The yearly report to the competent authorities should encompass the above. If needed it comments on site-specific monitoring problems.]

4.2.2 Updated plan

The initially installed monitoring system and related procedures need to be updated on the basis of the evaluation and modelling activity, or the verification results. Monitoring plans must be *updated, at least every five years*, to take into account changes to assessed risk of leakage, changes to assessed risks to environment and human health, new scientific knowledge, and improvements in the best available technology. The national authorities may set a more stringent frequency.

According to Annex II of the Storage Directive one has the following *updating* requirements:

1. The data collected from the monitoring shall be collated *and interpreted*. The observed results shall be compared with the behaviour predicted in dynamic simulation of the 3D-pressure-volume and saturation behaviour undertaken in the context of the security characterisation.
2. Where there is a significant deviation between the observed and the predicted behaviour, the 3D-model shall be recalibrated to reflect the observed behaviour. The recalibration shall be based on the data observations from the monitoring plan, and where necessary provide confidence in the recalibration assumptions, additional data shall be obtained. Steps 2 and 3 of Annex I shall be repeated using the recalibrated 3D model so as to generate new hazard scenarios and flux rates and to revise and update the risk assessment. Where new CO₂ sources, pathways and flux rates *or observed significant deviations from previous assessments* are identified as a result of history matching and model recalibration, the monitoring plan shall be updated accordingly.
3. Post-closure monitoring shall be based on the information collected and modelled as in step 2. The plan must now also provide information needed for the transfer of responsibilities to



Doc.nr: CATO2-WP4.5-D05
Version: 2013.12.16
Classification: public
Page: 9 of 36

Design of Monitoring systems

the competent authority (long-term stewardship). Especially the site's permanent containment should be confirmed, based *on all available evidence*.

4.3 Monitoring: additional explanations and categorisations

In this section we bring together a number of monitoring-related issues that are helpful on the road to a monitoring protocol

The most important aspects of monitoring are *confirming the containment of CO₂, alerting for corrective measures in case of increased leakage risk and gathering evidence for the long-term containment of CO₂.*

Monitoring can be achieved either by measuring the absence of any leakage through direct detection methods, or by verifying indirectly that the CO₂ is behaving as expected in the reservoir based on modelling and comparison with monitoring data. A large part of the monitoring techniques depends on advanced (geo)physical theory, e.g. seismic monitoring. Static and dynamic models of the subsurface are necessary also for the interpretation of the measured results. However to properly assess uncertainties usually more than one model is needed (see R.02).

The challenge for measuring the absence of any leakage resides in the question: "Where and when do we need to monitor in order to be sure that no leakage occurs". The monitoring strategy should therefore be based on identified risks. This is an explicit requisite in the Annex II to the Directive, and it is scientifically cogent as well.

For the indirect model-based monitoring the emphasis is on scenario confirmation. As long as predictive models are behaving in agreement with monitoring data, the understanding of both the processes occurring and the behaviour of the storage complex are considered sufficient. In case of deviations, one should find the causes of the deviations and where necessary recalibrate the models. If, however, the deviations fall well beyond the uncertainty ranges of the predictive models, then additional monitoring and possibly contingency measures need to be taken.

4.3.1 Categories

As to the different monitoring categories we make the following distinction:

1. *Mandatory (for all sites) monitoring*

A number of parameters to be monitored is mandatory based on the Storage Directive (see Chapter 4.2.1).

2. *Required (site specific) monitoring*

This monitoring group is required to gather evidence for containment in the reservoir and to demonstrate the integrity of the seal, the fault and the wells in case of regular development.

3. *Optional contingency monitoring*

The third group refers to a contingency monitoring system which will only be called in action if irregularities show up. In the Storage Directive a "significant irregularity" is defined as '*...any irregularity in the injection or storage operations or in the condition of the storage complex itself, which implies the risk of a leakage or risk to the environment or human health*'. (Art.3.17)

Contingency monitoring needs to be taken into account already at the very early pre-injection stage based on the risk analysis of "What can go wrong".

4.3.2 Monitoring in different stages of a CCS-project

Monitoring during the pre-injection phase, the injection phase or the post-injection phase always serves the same goal as detecting and preventing undesired events. Particular risks may be deemed higher in (parts of) the injection phase, notably the beginning of the injection activities. The monitoring plan deals with these higher degrees of risk through requiring more frequent monitoring. The monitoring plan details requirements as laid down in the Storage Directive, and conforms to good scientific practice as described in guidelines issued by the IPCC [2] and the OSPAR [3].

Baseline and repeat measurement acquisition, processing and interpretation should be detailed in the monitoring plan. The relation with risk assessment and preventive / corrective measures should be borne out. At all times, the operator has the obligation to take appropriate corrective measures if and when needed; he operates on the basis of a corrective measures plan, agreed by the competent authorities.

In the pre-injection phase the main issue consists of *gathering baseline data*. At this stage it is of the utmost importance to identify all possible baseline data that might be needed later during the injection and post-injection phases both for required monitoring as well as for contingency monitoring. More precisely, the risk assessment and connected scenario definitions are crucial in this phase. It is crucial to predict what can go wrong and where in order to monitor the relevant parameters. Subsurface modelling is indispensable for the correct interpretation of monitoring results.

The Storage Directive requires the operator to provide a provisional plan with corrective measures. This plan must be produced before any operations have begun. The basis therefore depends largely on modelling exercises performed in the context of site characterization and risk assessment. The operator should comment on how models plus forthcoming data lead him to a diagnosis of the problem and, if the suspicion of a problem exists, which corrective measures will be taken. This will be largely a *site-specific* exercise, based on the aforementioned risk assessment.

4.4 Outline of a Monitoring Protocol

A storage plan has to fit situations as they present themselves in practice. It is important as a guide to go/no go decision making, for permit issuing, and possibly in preparing the qualification statements [4].

There are generally five aspects which play a role in the development of a monitoring plan. They are:

- 1) Legislation
- 2) The different phases of the storage process
- 3) Risk types
- 4) Available monitoring systems
- 5) Geological storage container type

In *structuring* the protocol we will typically follow these aspects as much as we can. The rationale for doing so is simple.

Legislation (EU directives) describes a “must do”. Choices do not exist here, at least not regarding the activities that are mandatory per work phase.

Design of Monitoring systems

The phases during the storage process are mentioned in this legislation. Now science and technology take over in defining, or rather detailing, **risk types and monitoring systems** that can be used for monitoring, verification (and accounting).
Geological storage container types, if suitably defined, further aid in making relevant choices.

4.4.1 Pre-injection phase

It is required that potential storage sites must be assessed with regards to their suitability for CCS purposes. This first requires the collection of relevant data, as specified in ANNEX I. This concerns data regarding Geology and Geophysics, Geomechanics, Geochemistry, Hydrogeology and Reservoir Engineering. These data are required for defining a **baseline set** of observations, once screening, characterisation, risk assessment, and documentation have been performed, and the “green light” has been given for the potential site to become an actual storage site. These data also aid the compulsory **static and dynamic modelling**.

Since the monitoring must be **risk-based** (EU Directive) it has to be decided which the prominent risks are for the site at hand **in the pre-injection phase**. This will generally depend on the type of storage complex and the site-specific details. Only these can give an indication of the nature of the risks involved and as such tell which technologies will likely deliver the required information. A rather important fact is that the effectiveness of all kinds of technological methods is at least in part *site-specific*. **This makes it difficult to prescribe technologies in a protocol.**

4.4.2 Injection phase

The EU Directive demands that during the **injection phase, at least every year monitoring results must be reported**. Any changes with respect to the baseline set must be monitored, at least in the injection phase. One should keep in mind the monitoring goals:

- 1) monitoring of performance confirmation
- 2) monitoring to detect possible leakages
- 3) monitoring of local environmental impacts on eco-systems

Using the OSPAR Guidelines [3], this amounts to monitoring of

- 1) injection rates
- 2) pressures
- 3) injectivity and fall-off testing
- 4) properties of the injected fluid (including temperature, phase, solid contents, incidental associated substances)
- 5) mechanical integrity seals
- 6) containment CO₂ stream

Finally, proxies must be defined that give information on the possible influence of CO₂ on the marine environment.

Since modelling of the storage complex must be a “continuous” activity, based on updated input, the modelling results will tell whether problems with 5) and 6) are present. If so, additional monitoring may be required.

Testing on items 1)- 4) must be performed on a daily-monthly-yearly basis, depending on the precise parameters involved..



Design of Monitoring systems

During this phase any “irregularities” must be immediately reported to the competent authorities. They shall order remediation activities deemed necessary.

The EU-Directive specifies a minimum reporting frequency of once per year. Testing the other items “semi-continuously” calls for specifying the sampling frequency in time. Any remediation activities ordered will give rise to special monitoring activities. The operator will probably have to revise the monitoring plan, which will in turn have to be approved by the competent authorities.

4.4.3 Post-Injection phase

At the start of the **post-injection phase** the same suite of variables must be obtained as with establishing the baseline in the pre-injection phase. Those data will then be regarded as reference data and any **differences** with subsequent monitoring data from the post-injection phase must be explained and reported; it must be made clear that no “irregularities” or CO₂ leakage has occurred. When, finally, steps are taken to hand over responsibilities from the operator to the authorities (in accordance with the Storage Directive), the procedure must be repeated.

Monitoring must continue at a level that enables any (sizable) CO₂ leakage, migration and “irregularities” to be discovered.

5 Monitoring planning tool

5.1 Introduction

CCS project operators will have to supply a monitoring plan as part of the regulatory requirements for licence applications and approvals, for instance as given in the EU Directives on CCS (April 2009). Because monitoring of CO₂ storage is by its nature site-specific, the existing (and any future) guidelines and regulations can never prescribe a fit-for-purpose monitoring plan. The construction of a Monitoring Plan must depend on the Risk Assessment, according to the Directives mentioned. This Risk Assessment is obviously site-dependent and has to be conducted by a team of experts. The results of this work will consist of the definitions of relevant (HSE linked) risks and scenario's which should be avoided. All this should be the basis of the Monitoring Plan as presented to the competent authorities.

During the first year of the CATO-2 project (Work Package 4.5) the basis of risk management and the overall workflow were described (ECN) [5]. The procedure for developing a monitoring plan was elaborated and the concept for a monitoring planning tool was developed including the evaluation of the tool concept on the basis of the Barendrecht monitoring plan (TNO) [5]. In R0.1 progress report (TNO)[6] a new chapter "Monitoring planning tool" provided a first insight into the preliminary setup of this tool, (henceforth 'monitoring tool').

In this chapter a new updated version of a preliminary monitoring tool is presented. While the concept stayed pretty much the same as before, the user interface has changed, some new features have been added and the data base has been extended. This chapter reviews the concept, goals and risk assessment protocol of the tool, especially elaborating on updated aspects of the tool.

5.2 The goal and the concept of the Tool

Risk management is considered to be essential in building the confidence that CO₂ storage will be effective and safe. The purpose of the monitoring tool is to support the development of a risk-based monitoring plan. The tool is built around a database containing risk factors and parameters and a database containing monitoring techniques and parameters. The tool is driven by the selection of site-specific characteristics and scenarios which contain risk factors referred to as FEPs (features events and processes). Through these FEPs or main risk attributes a link is made with a monitoring technique with the appropriate detection limits and costs. The chosen FEPs are based on a Risk Assessment based on expert analysis.

The tool should help to check, or audit, the monitoring solutions of the site operator against the risks identified and the regulatory monitoring requirements. The tool is designed to be an integral part of the Risk Management flow. The input comes from the Risk Assessment results, in particular the highest risks and the associated scenarios.

The tool is built up as a decision tree with control points allowing user choices. It guides the user from the Risk Assessment results to a set of monitor tool suggestions that are fit-for-purpose for the particular site. User input and options (selection or rejection) can be changed at any stage (also backwards).



Doc.nr: CATO2-WP4.5-D05
Version: 2013.12.16
Classification: public
Page: 15 of 36

Design of Monitoring systems

The concept of the risk based monitoring tool as described is parametric, meaning that there are at one side parameters associated with the risk factors, or FEPs, and at the other side monitoring parameters, which are connected with the monitoring techniques.
This is the basic set-up that we will now detail below.

5.3 Risk Assessment

Because of the uncertainties related to CCS, assessing the safety of a carbon sequestration storage site can be a tedious job. Moreover, every aspect of the site requires a different expertise and the discussion of the factors playing a role in sequestration performance of the site is often a complex process.

In order to facilitate a thorough and complete risk assessment, CASSIF has been developed. CASSIF (**Carbon Sequestration Scenario Identification Framework** [7]) utilizes Features, Events and Processes (FEP) for the purpose of qualitative risk assessments in CO₂ storage projects. The framework assists in describing and clarifying potential CO₂ release scenarios. CASSIF is designed to perform a *hazard analysis*. This hazard analysis focuses on performing a comprehensive inventory of risk factors (or FEPs) and a subsequent selection of the most critical factors. Those are grouped into discrete CO₂ leakage scenarios. The three major general leakage scenarios which form the basis for the relevant risk factors are well, fault and seal leakage.

A web interface has been created (<http://edison.nitg.tno.nl/fep/dev/index.php/>) to enable the hazard analysis in an interactive way. Every participant of an expert group meeting is invited to log on to the interface and connect to a workshop case. Every participant will make use of his/her own login so that later on, during the workshop, the results can be compared and discussed. One advantage of CASSIF is that it enables the experts to run through the complete list of risk factors, deciding to include or exclude them from being used in the scenario analysis. It is recommended to select a maximum total of 15 FEPs from the list which are thought to be most important for the site at hand by the experts. The results from every participant will be summarized on the workshop and used in discussions.

The workshop has several objectives, the most relevant one being to build consensus on the selected FEPs. When consensus is reached, the selected FEPs are combined using cause-consequence relations in order to build sub-scenarios for each major migration scenario. Based on the scenarios, the time frames for the operational phases can be selected (pre-injection, injection, post-injection).

The workshop is also a relevant step as it helps to identify the gaps in (mainly site-specific) knowledge, to gain confidence on *prima facie* suitability and feasibility of the site, and to bring traceability and transparency into the decision making process. The monitoring planning tool should use this knowledge to suggest which tools are appropriate to monitoring identified risks. As such, this tool allows the user to gain insight into which monitoring techniques are applicable for a specific situation. Therefore, risk assessment analysis *must* be performed prior to using the tool, and preferably using the CASSIF scenario approach (Figure 1).

Design of Monitoring systems

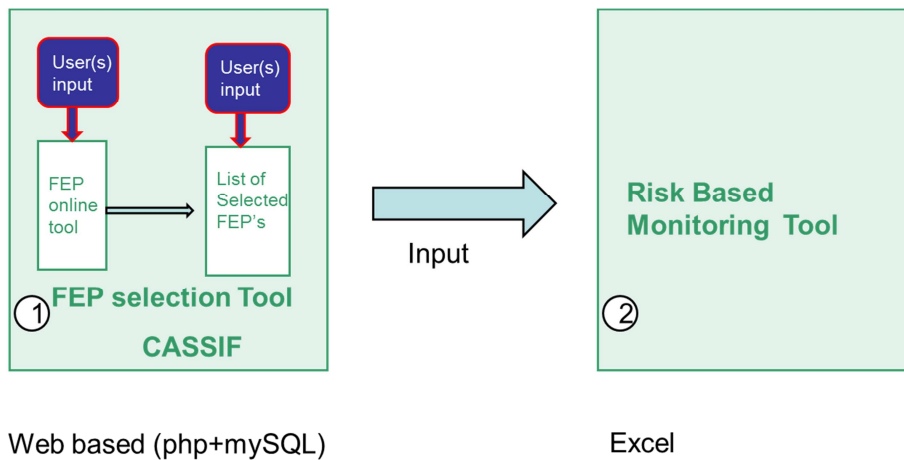


Figure 1: Appropriate work flow for designing risk based monitoring plan

In addition to selecting appropriate monitoring techniques, the tool provides details for each of these monitoring techniques, listing the parameters which are measured and explaining which information they provide. Other important features such as the monitoring area (well level, reservoir level, storage site level), the timing (for example pre-operational or operational), the frequency of measurements and the costs of the monitoring techniques can also be listed. In addition, an extra column with remarks has been added, where various things can be displayed such as the limitations of the techniques, information in connection with the EU regulative framework and other relevant method specific information (for example, for the DTS monitoring method it will be noted in the remarks column that DTS systems can locate the temperature to a spatial resolution of 1 m with accuracy to within $\pm 1^\circ\text{C}$ with a temperature resolution of 0.01°C . From the location managers we got advice to incorporate in a separate column all info about law and regulations since that is operationally very important; the user must know what he is obliged to do, etc.

The tool has initially been developed in Excel but can be easily converted to an online risk based monitoring tool. In that case, the workflow of the Excel tool can be used as a blueprint for the online tool.

The following table in Figure 2 shows an example of the output of the tool, containing the monitoring techniques, the parameters measured and the additional information such as monitoring area and timing.

Monitoring technique	Physical parameter measured	Informs about	Monitoring area	Timing	Monitoring frequency	cost indication	Maturity	Remarks
Differential pressure flow meters	injection pressure	flow rates	Local - well	operational phase	continuous	low to moderate	Standard	Mandatory monitoring
Temperature sensors	injected gas temperature	Local - well	operational phase	continuous	low to moderate	Standard	Mandatory monitoring	
Distributed temperature sensing	temperature profiles	Local - well	operational phase (in preoperational phase only baseline measurements)	usually continues, or very often (Permanent Downhole Monitoring)	low to moderate	Standard	DTS systems can locate the temperature to a spatial resolution of 1 m with accuracy within $\pm 1^\circ\text{C}$ at a resolution of 0.01°C	
SPTG (Static P & T gradient)	reservoir pressure and temperature	reservoir pressure and temperature / well	pre-operational, operational and verification phase	yearly	low to moderate	Standard		

Figure 2: An example of the type of information available for a resulting monitoring tool

5.4 Detailed description of the Tool

The next paragraphs describe in further detail the updated version of the previously defined [5] and developed [6] monitoring tool. Although not yet complete and fit for practical use, the fundamentals of the tool are in place and functional. The following sections describe how the tool works and the data flow. We also provide an example of how the tool functions when compared to the Barendrecht case [8,9]. Finally we discuss the improvements that should be made both on the short and long term and any additional functionality that might be included.

5.5 What Does the Tool Do?

As mentioned in the previous chapter, the tool consists of two databases; the first database contains a list of FEPs, each of them linked to one or more parameters which can be measured to monitor the FEP. The second database consists of the monitoring techniques and the parameters which they measure plus the additional info as shown in Figure 1. After the user has selected the relevant FEPs, the tool connects the parameters of the FEPs and the monitoring techniques. Although this concept seems straight forward it is not at all easy to implement it. The actual physical parameter measured with a certain monitoring technique is often not a direct parameter describing the FEP, but indirectly the results of that monitoring technique are relevant for monitoring that selected FEP. Often a selected parameter can be found with different monitoring techniques, not all of which are feasible for the site and the FEP at hand. To overcome these problems it is often more appropriate to use key words instead of parameters to smartly connect FEPs with the appropriate monitoring techniques. In any case the outcome of the tool is a scenario with a number of selected FEPs (i.e., risk factors), their corresponding parameters (and/or key words) and a list of monitoring techniques with all additional info if desired (as explained earlier) which can be used to monitor those risk factors.

5.5.1 The Source of the FEPs

The FEPs represent situations which could threaten the integrity of the CO₂ storage site and cause leakage. The TNO FEP data base consists of 667 FEPs, while the online tool CASSIF makes use of the 83 most relevant FEPs. There are two main groups: Specific level FEPs and System level FEPs. Specific level FEPs are the ones affecting well, seal and fault integrity directly, while system level FEPs are of a more general nature, influencing a number of other issues (like geochemical processes, geomechanical processes, thermal processes etc.). At this stage of development the monitoring tool has a list of 44 FEPs taken from CASSIF. All specific level FEPs (21) are included and a number of other general FEPs. The current FEP database is sufficient to cover all identified risk scenarios from the Barendrecht and de Lier fields. For consistency the list of FEPs imported from the CASSIF database contains the same ID numbers.

To start using Monitoring Planning Tool, it is required that a proper Risk assessment has been done, where all risk scenarios have been identified. Standardized input from the Risk Assessment is necessary for the Monitoring Planning Tool.

At this stage of development of monitoring tool, by the “scenario” we mean a list of FEPs which are a part of the scenario. Although we must add that a scenario is strictly speaking more than just a list of FEPs (it contains information such as intra-connections of FEPs, time frames, spatial estimation etc.).

In this version of the tool, it is possible to analyse several scenarios in parallel and compare the outcome. We assume that It should be possible to create all relevant scenarios from the list of selected FEPs.

In the future, it will be made possible that in addition to the list of FEPs, additional information related to the selected FEPs and scenarios will be available (see Figure3), such as:

- a) FEP type
- b) Risk level of scenario
- c) Time and space frames of the selected FEPs

Design of Monitoring systems

Scenarios and FEPs	characteristics		
Risk level of scenario	Spatial resolution	Timing	Time scale
negligible	Well	pre-operational	Seconds
low	reservoir	operational	Hours
medium	storage complex	post-operational	Days
	FEP type		Months
	initiating FEP		Years
	impact FEP		100 years
	specific level		
	system level		

Figure 3: Table displaying additional information and constrains on selected FEPs with the suggested classification

Characteristics of the FEPs in c) Time and space frames of the selected FEPs are already available in the Tool, but only as a drop-box for additional input user can select. In the next stage of the development those inputs will be used in the selection process of a suitable monitoring technique.

Also, all characteristics of the site used for the previous Risk Assessment (and FEP identification) are assumed to be known and in the future will be used for the selection of the appropriate monitoring tool.

5.5.2 The Source of the Monitoring Techniques

There are three main catalogues (databases) of monitoring techniques that are currently in use or in a developmental/experimental phase which are to be used for CCS monitoring:

- BGS/IEA-GHG monitoring techniques catalogue [10]
- NETL report: Monitoring, Verification and Accounting of CO2 Stored in Deep Geological Formations [11]
- NSBTF Catalogue of Monitoring tools [12]

Although each catalogue has a maximum of about 40 monitoring techniques, all together there are around 60 different methods that are potentially useful for detecting undesired scenario's. Our database so far contains 37 monitoring techniques coming from all three sources.

5.6 User Interface of the Monitoring Planning Tool

The tool consists of several Excel sheets. The first sheet is an introductory sheet and is called Introductory Screen. The user is required here to enter some administrative information such as the name of the user, the name of the organisation he is representing, date and number of scenarios (maximum 10) he wishes to analyse and their names.

The number of sheets following Introductory Screen depends on the number of analysed scenarios. If the user indicated in the Introductory Screen that he wishes to analyse 3 different scenarios, then there will be 3 sheets after the introductory one, called Scenario 1, Scenario 2, and Scenario 3 (See Figure 4). After the scenario analysis sheets there is one sheet showing in a concise way output of the tool (Figure 4).

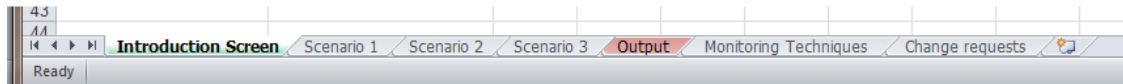


Figure 4: Different Excel sheets of the monitoring tool


The Monitoring Techniques sheet allows the user to browse through available techniques in the tool if so desired. Otherwise, this sheet does not require any action from the user and as such can be omitted from the analysis. The same holds for the Change requests sheet, which is intended for developers to track changes and improvements of the tool. If desired, the user can here also add his comments and wishes for the further developments of the tool .

In designing the tool, providing accurate information while at the same time keeping it user friendly was a top priority. Using the tool therefore requires only few actions from the user, where two main ones are here listed :

1. FEP Selection: The user thinks of a scenario and selects the corresponding FEPs using the checkboxes on the left side of the FEP. Clicking the checkbox activates or deactivates the FEP, marking it green when active and grey when inactive.
2. Scenario Analysis: The user has to press the “Refresh scenario” button in the top left corner of the Scenario. When pressing the refresh button, the tool compares the hidden parameters connected to the FEPs with the parameters related to the monitoring techniques and lists the resulting available techniques on the right side of the sheet.

5.6.1 The Introduction Screen Sheet

The Introduction Screen as previously explained, contains all basic information relevant for the documentation such as names and dates. The screen shot of the Introduction Screen is presented in Figure 5.

	A	B	C	D	E
1		WP 4.5 - Storage Risk			
2					
3					
4					
5	Storage name	Monitoring Tool Workshop			
6	Storage description	Halten Terrace Norway			
7	User	Danijela			
8	Organisation	TNO			
9	Date	10-12-2013			
10					
11	Number of Scenarios	2			
12					
13	Scenarios	Name of Scenario	Monitoring Category		
14	Scenario 1	fault reactivation	include		
15	Scenario 2	well failure	include		
16					
17					
18					
19					
20					
21					
22					
23					
24					

Introduction Screen
Scenario 1
Scenario 2
Output
Monitoring Techniques
Change requests

Figure 5. Screen shot of the Introduction Screen sheet of the Tool

As can be seen in Figure 5 it is required to enter the name of the storage site, storage description, user name, organisation and date. Furthermore there is a drop-box where the number of scenarios one wishes to analyse can be selected. In the next step, the name of those scenarios can be entered (but it is not necessary).

The Introduction Screen sheet also contains one button “Start” linked to a Macro which sets the correct number of Scenario sheets in the Tool (depending of selected Number of Scenarios).

It is to be noted that at least one scenario needs to be analysed. If the user first selects, for example, 4 scenarios for the analysis, but later wants to compare only two relevant scenarios, two sheets need to be deleted manually.

The 2013 version includes additional functionality on the assignment of monitoring categories, i.e. mandatory monitoring, required monitoring and optional contingency monitoring (more detail are given in the next two sections). The user has the choice to in- or exclude the monitoring categories (see the 3rd column in Figure 5).

5.6.2 The Scenario Sheet(s)

The Scenario Sheet contains the same heading as the Introduction Screen sheet: the logo of the CATO2 project and the name of the work package within which is the tool developed. The Scenario sheet also displays the name of the particular scenario as entered in the Introduction Screen sheet.

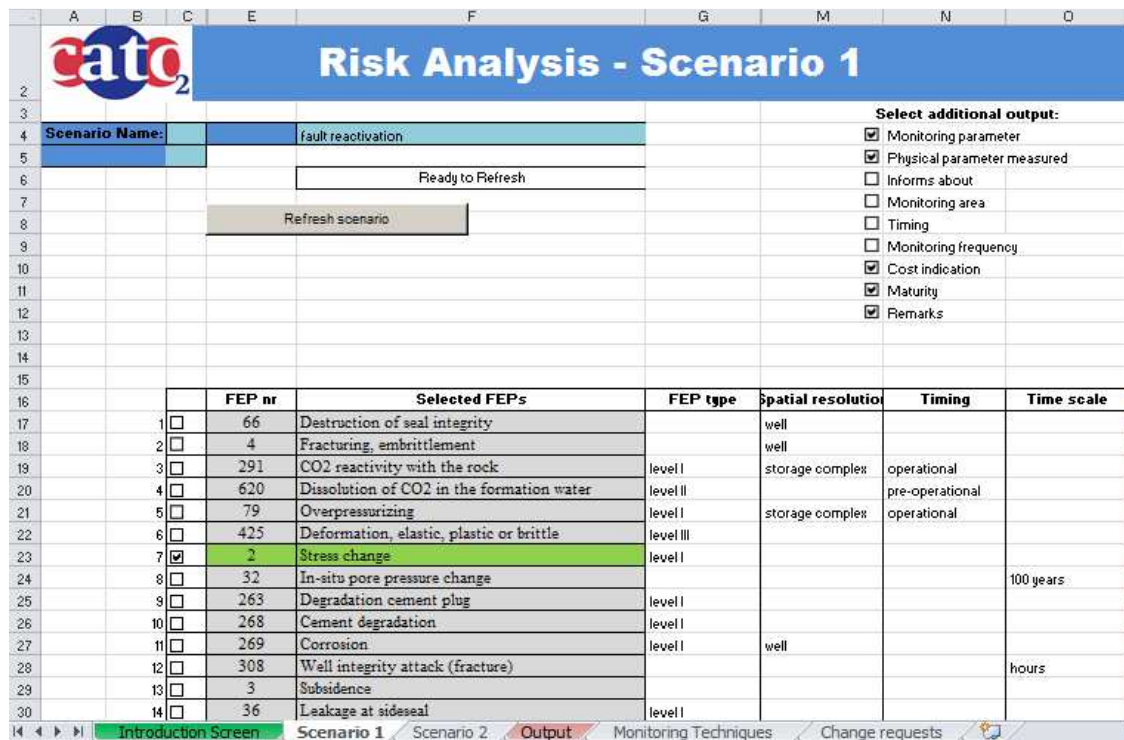
Design of Monitoring systems

The FEP Selection activity previously explained is part of the Scenario sheet. The Scenario sheet includes a list of the FEPs with checkboxes on the left side. Between the checkboxes and the Selected FEPs table/column is a hidden column which changes to TRUE if the checkbox is checked and FALSE if the checkbox is unchecked. Conditional formatting makes the FEPs which are TRUE green and the FEPs which are FALSE grey.

On the right side of the Selected FEPs table are 5 hidden columns (H - L) containing the parameters connected to the FEPs. That is, one FEP can be maximally connected to 5 parameters, although usually 1 or 2 will suffice.

On the right side of the Selected FEPs table is the Monitoring Techniques table, shown in blue. This table contains a list of the monitoring techniques that match the selected FEPs i.e., the scenario under investigation. It is refreshed by using the “Refresh Scenario” button.

The Scenario Sheet also contains the “Refresh Scenario” button, which should be used as soon as the FEPs are selected. (The workings of the button are explained later in this chapter.) When no FEPs are selected, the cell below the “Refresh Scenario” button shows the warning message “Please select FEP!”.

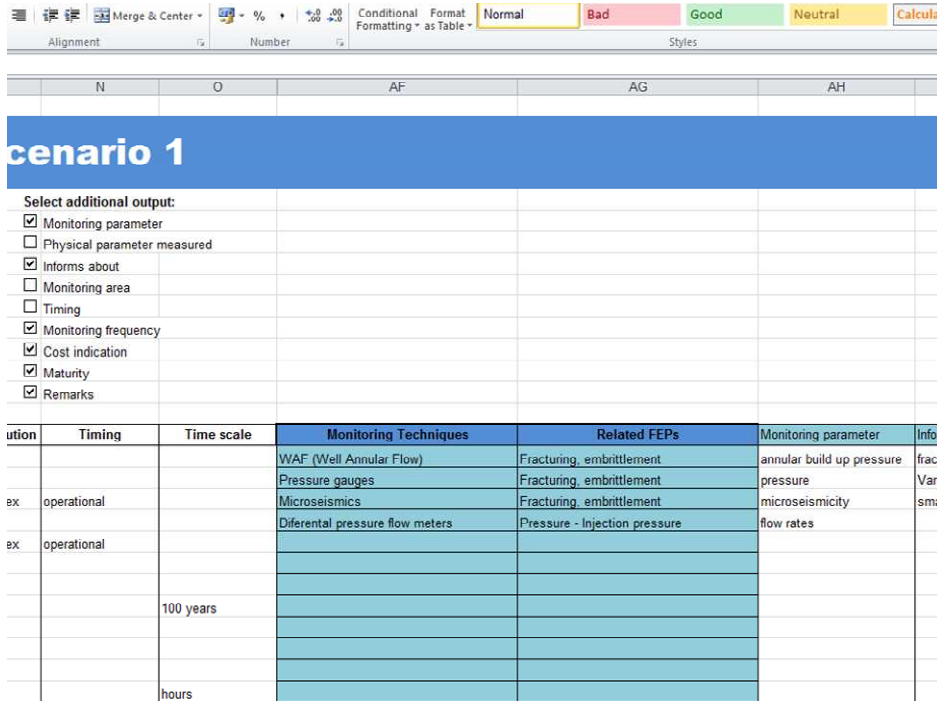


FEP nr	Selected FEPs	FEP type	spatial resolution	Timing	Time scale
<input type="checkbox"/> 66	Destruction of seal integrity		well		
<input type="checkbox"/> 4	Fracturing, embrittlement		well		
<input type="checkbox"/> 291	CO2 reactivity with the rock	level I	storage complex	operational	
<input type="checkbox"/> 620	Dissolution of CO2 in the formation water	level II		pre-operational	
<input type="checkbox"/> 79	Overpressurizing	level I	storage complex	operational	
<input type="checkbox"/> 425	Deformation, elastic, plastic or brittle	level III			
<input checked="" type="checkbox"/> 2	Stress change	level I			
<input type="checkbox"/> 32	In-situ pore pressure change				100 years
<input type="checkbox"/> 263	Degradation cement plug	level I			
<input type="checkbox"/> 268	Cement degradation	level I			
<input type="checkbox"/> 269	Corrosion	level I	well		
<input type="checkbox"/> 308	Well integrity attack (fracture)				hours
<input type="checkbox"/> 3	Subsidence				
<input type="checkbox"/> 36	Leakage at sideseal	level I			

Figure 6. Screen shot of part of the Scenario sheet

The screen shot of part of the Scenario sheet is presented in Figure 6. Between the Selected FEP column and the resulting blue Monitoring Techniques column there are three more columns: Spatial resolution, Timing and Time scale.. *In the 2012 version of the tool development those attributes are not used in the decision algorithm for the selection of appropriate monitoring techniques, but in the future they will be added to the equation.*

Design of Monitoring systems



Timing	Time scale	Monitoring Techniques	Related FEPs	Monitoring parameter	Information
ex operational		WAF (Well Annular Flow)	Fracturing, embrittlement	annular build up pressure	fract
		Pressure gauges	Fracturing, embrittlement	pressure	Varic
		Microseismics	Fracturing, embrittlement	microseismicity	smal
		Diferential pressure flow meters	Pressure - Injection pressure	flow rates	
	100 years				
	hours				

Figure 7. Alternative view of the Scenario sheet with the emphasis on the (selected) additional output

Figure 7 shows what else, besides the resulting monitoring technique and the Related FEPs, can be printed. At this stage of the development the user can select whether he wants any additional output next to the default output marked by the blue table. Additional output gives information on the monitoring parameter, the exact physical parameter measured, what the monitoring techniques actually informs you about, what is the monitoring area, the timing, monitoring frequency, the cost indication for employing the certain technique, its maturity and it furnishes some general remarks if needed.

The inner working of the Scenario sheets can be the best understood looking at the hidden columns Q – AE (see Figure 8).

Columns S and T are just another lay out of the FEP/parameter table hidden in table H – L. Column Q is counting this layout which is Number of FEPs x 5 (since for each FEP there is maximum 5 parameters and always 5 reserved spots).

Column S is the list of FEPs where each FEP is listed 5 times according to this layout.

All parameters are now listed in only one column T.

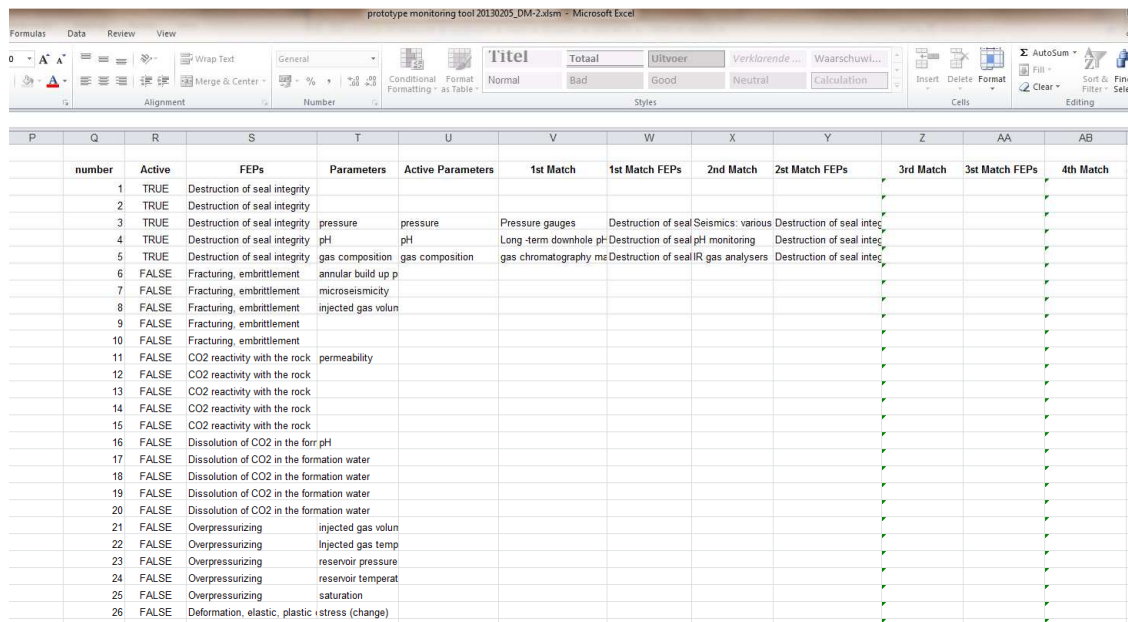
Column R indicates if those parameters are active (weather or not FEPs they belong to have been selected by the user). Active parameters are copied then into column U. Now it is easy to match active parameters from the column U to exactly the same parameters from Monitoring Techniques sheet (using functions IF, IFERROR, SMALL).

If the monitoring categories have been selected for one or more scenarios in the input sheet, additional information on the so-called FEP level has to be added (see Figure 6):

Design of Monitoring systems

- Level I: The most important FEPs. All Specific Level FEPs belong to this group (Specific Level FEPs are the FEPs that directly affect the integrity of the seal, faults and wells.
- Level II: If this FEPs are realized, the integrity of the system is already disturbed. These FEPs are consequence of some irregularities that should be detected by the required monitoring techniques, and they ask for the implementation of optional monitoring techniques and additional actions.
- Level III: FEPs of low probability and/or low consequence that still can be part of the scenario of medium risk.

The “Refresh Scenario” button activates a Macro which is called RefreshScenario. This Macro refreshes the scenario by looking for active FEPs and parameters, prints them separately as explained and matches them to the appropriate parameters from the Monitoring Techniques sheet.



The screenshot shows an Excel spreadsheet titled 'prototype monitoring tool 20130205_DM-2.xlsx'. The spreadsheet has columns labeled P through AB. The visible columns are P, Q, R, S, T, U, V, W, X, Y, Z, AA, and AB. The data in these columns is as follows:

P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
	number	Active	FEPs	Parameters	Active Parameters	1st Match	1st Match FEPs	2nd Match	2st Match FEPs	3rd Match	3st Match FEPs	4th Match
1	TRUE	Destruction of seal integrity										
2	TRUE	Destruction of seal integrity										
3	TRUE	Destruction of seal integrity	pressure	pressure	Pressure gauges	Destruction of seal	Seismics: various	Destruction of seal	intec			
4	TRUE	Destruction of seal integrity	pH	pH	Long-term downhole pH	Destruction of seal	pH monitoring	Destruction of seal	intec			
5	TRUE	Destruction of seal integrity	gas composition	gas composition	gas chromatography me	Destruction of seal	IR gas analysers	Destruction of seal	intec			
6	FALSE	Fracturing, embrittlement	annular build up p									
7	FALSE	Fracturing, embrittlement	microseismicity									
8	FALSE	Fracturing, embrittlement	injected gas volum									
9	FALSE	Fracturing, embrittlement										
10	FALSE	Fracturing, embrittlement										
11	FALSE	CO2 reactivity with the rock	permeability									
12	FALSE	CO2 reactivity with the rock										
13	FALSE	CO2 reactivity with the rock										
14	FALSE	CO2 reactivity with the rock										
15	FALSE	CO2 reactivity with the rock										
16	FALSE	Dissolution of CO2 in the forr	pH									
17	FALSE	Dissolution of CO2 in the formation water										
18	FALSE	Dissolution of CO2 in the formation water										
19	FALSE	Dissolution of CO2 in the formation water										
20	FALSE	Dissolution of CO2 in the formation water										
21	FALSE	Overpressurizing	injected gas volum									
22	FALSE	Overpressurizing	injected gas temp									
23	FALSE	Overpressurizing	reservoir pressure									
24	FALSE	Overpressurizing	reservoir temperat									
25	FALSE	Overpressurizing	saturation									
26	FALSE	Deformation, elastic, plastic	stress (change)									
27	FALSE	Deformation, elastic, plastic	stress (change)									

Figure 8. Hidden columns of the tool hiding the inner structure and functioning

5.6.3 The Output Sheet

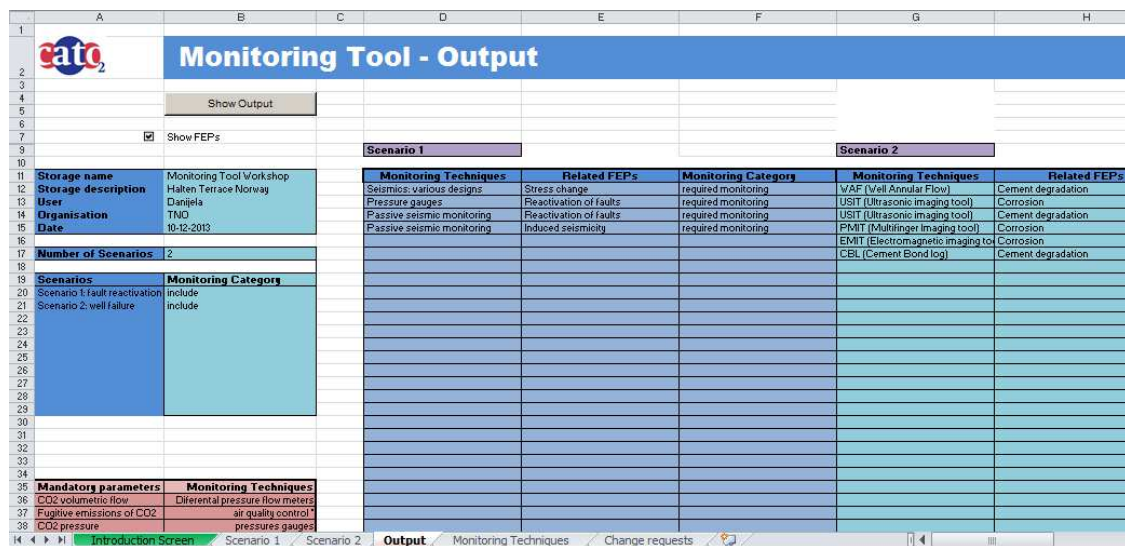
The screen shot of the output screen is presented in Figure 9. The main purpose of the sheet is to display a clean overview of results. It reviews the documentation information from the Introduction Screen sheet, and enables the user to compare resulting monitoring plans for different scenarios. In addition it is possible to hide or show FEPs related to monitoring techniques.

The Output sheet contains a button “Show Output” which is linked to the Macro under the same name. This Macro basically copies the relevant output from Scenario sheets and displays them

Design of Monitoring systems

next to each other in different shades of blue colour. Also, it copies administrative information from the Introduction screen sheet to output sheet.

If at the start of the analysis “Monitoring categories” has been selected in the input sheet, than, the monitoring category will be displayed next to the monitoring technique (Figure 9). In Section 4.3.1 three monitoring categories have been introduced (Mandatory, Required and Optional Contingency monitoring). Accordingly, the tool can specify which type of monitoring plan it suggests. In general risk-based monitoring is concerned only with the scenarios perceived as low and medium risks. If scenarios were identified as a high risk, it is a show stopper and therefore there is no need for developing a monitoring plan. In practice, negligible-risk scenarios can be omitted from the monitoring plan. Nevertheless, we define here one new monitoring category named “Optional according to ALARA plan which is relevant for negligible risk scenarios, or for the FEPs of low probability and low impact belonging to low or medium risk scenarios. Sometimes the technique used for monitoring negligible risks can be added to the monitoring plan with little effort (low cost), making the monitoring plan more complete and comprehensive.



Monitoring Tool - Output		Scenario 1			Scenario 2	
Storage name	Monitoring Tool Workshop	Monitoring Techniques	Related FEPs	Monitoring Category	Monitoring Techniques	Related FEPs
Storage description	Halten Terrace Norway	Seismics: various designs	Stress change	required monitoring	VAF (Well Annular Flow)	Cement degradation
User	Daniela	Pressure gauges	Reactivation of faults	required monitoring	USIT (Ultrasonic imaging tool)	Corrosion
Organisation	TNO	Passive seismic monitoring	Reactivation of faults	required monitoring	USIT (Ultrasonic imaging tool)	Cement degradation
Date	10-12-2013	Passive seismic monitoring	Induced seismicity	required monitoring	PMIT (Multifinger Imaging tool)	Corrosion
Number of Scenarios	2				EMIT (Electromagnetic imaging tool)	Corrosion
					CBL (Cement Bond log)	Cement degradation
Scenarios	Monitoring Categories					
Scenario 1: fault reactivation	include					
Scenario 2: well failure	include					
Mandatory parameters	Monitoring Techniques					
CO2 volumetric flow	Differential pressure flow meters					
Fugitive emissions of CO2	air quality control					
CO2 pressure	pressures gauges					

Figure 9. Screen shot of the Output sheet with clear presentation of results

Emphasising Mandatory monitoring according to the EU Directive

The EU Directive on CCS contains specifications about the monitoring plan, which should be based on a risk assessment. The parameters to be monitored are identified so as to fulfil the purposes of monitoring. According to the EU Storage Directive the plan shall in any case include continuous or intermittent monitoring of the following items (see Section 4.2.1):

- fugitive emissions of CO₂ at the injection facility;
- CO₂ volumetric flow at injection wellheads;
- CO₂ pressure and temperature at injection wellheads (to determine mass flow);
- chemical analysis of the injected material;
- reservoir temperature and pressure (to determine CO₂ phase behaviour and state).

The tool displays in the output sheet, in the left corner below, all mandatory parameters and monitoring methods in compliance with the EU storage Directive, in the form of the table (see Figure 12 and 9).

5.6.4 The Monitoring Techniques Sheet

The sheet located on the right of the last Scenario sheet, is called Monitoring Techniques. This sheet represents data base for monitoring techniques. It contains one column listing all the monitoring techniques and one column listing the corresponding monitoring parameters. This means that if more parameters are connected to the same monitoring techniques, these monitoring techniques will be listed more than once in the corresponding column (C). Next to this two columns, a monitoring techniques table contains also additional information as explained in chapter 5.3. Part of the data base is displayed in Figure 2.

5.7 Graph of the Tool

Figure 10 shows a simple graphical overview of the Tool. Start Process implies entering documentation information. The two steps of the user input, both on the Scenario(s) sheet, are shown in purple. The databases containing the FEPs and the monitoring techniques and their parameters are shown in dark blue. The processes of matching the FEPs and the monitoring techniques and showing the output are shown in light blue.

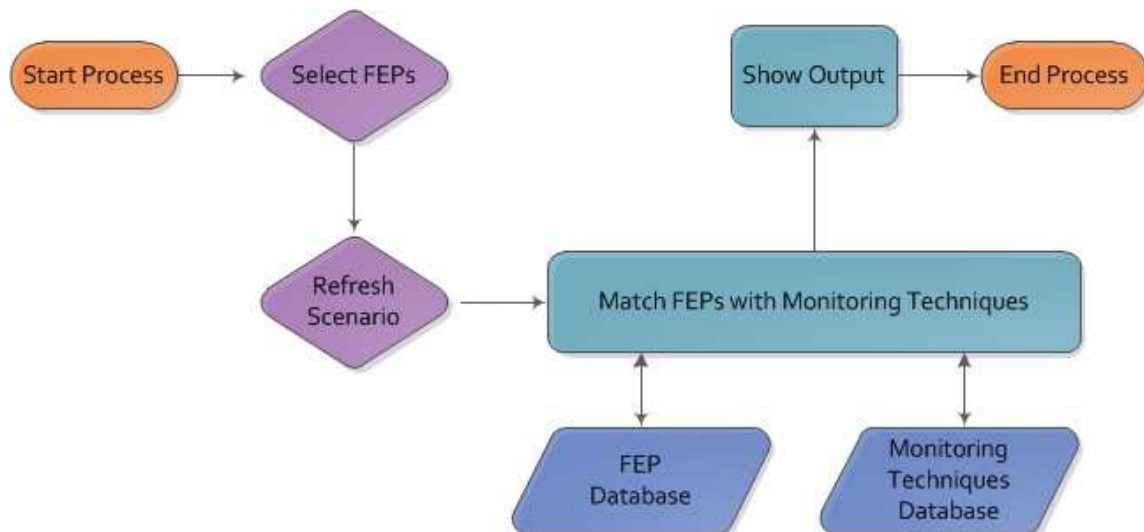


Figure 10. Graphical representation of the Tool. The start and the end of the process are shown in orange. User input is shown in purple. The processes are shown in light blue and the two databases are shown in dark blue.

5.8 Tool Demonstration – The Barendrecht Case

Design of Monitoring systems

Although the Barendrecht project was cancelled at an early stage, the risk analysis and monitoring plan were already completed beforehand [7 and 8]. The Barendrecht monitoring plan is, at the moment, the most comprehensive monitoring plan for CO₂ injection in the Netherlands available (Environmental Impact Assessment: Underground storage of CO₂ in Barendrecht & Concept Monitoringplan voor CO₂-emissiehandel). It was developed by Shell for intended geological CO₂ storage near Barendrecht. Many of the FEPs included in this version of the tool have been derived from the Barendrecht project.

The extensive information about the Barendrecht project has been used to demonstrate the effectiveness of the monitoring planning tool. We will not concentrate on the entire monitoring plan for Barendrecht, but only at a specific scenario with the aim of checking if our monitoring tool handles the scenario correctly.

For this purpose, a scenario from the Barendrecht monitoring plan has been analysed and recreated in the monitoring planning tool. By looking at the output of the tool and comparing it to the monitoring plan from Barendrecht, we can see whether our results match the outcomes of the Barendrecht case. In the following sections we first briefly describe the chosen scenario and the Barendrecht monitoring plan for the scenario.

5.8.1 Scenario Description

The scenario from the Barendrecht monitoring plan that we used to test the monitoring planning tool is a caprock failure due to a mechanical or chemical threat. This mechanical and chemical threat is defined as following:

Mechanical threat

A huge pressure change in the reservoir (due to gas production and CO₂ injection) can lead to an attack on the seal integrity. Furthermore, over-pressurization of the reservoir (due to too high injection rate or the overfilling of the reservoir) can do the same thing. Local over-pressuring due to reservoir inhomogeneity, density change or phase change can also lead to failure of seal integrity.

Chemical threat

The geochemical reaction of CO₂ (also CO₂ dissolved in water) with minerals from the caprock can change permeability leading to a leakage of the caprock and hence a caprock failure.

5.8.2 The Barendrecht Monitoring Plan

This paragraph contains an excerpt from the Barendrecht monitoring plan relevant for a caprock failure of a mechanical or chemical nature.

In order to make sure that injecting of CO₂ is not causing fracturing of the seal continuous monitoring and control of injection pressure and flow is required. Yearly measurements of in-situ pressure for correlation and calibration of surface pressure and regular testing of injectivity are needed.

In order to make sure that the injected CO₂ is pure and dry, the continuous measurement of CO₂ (gas) components and analysis is needed. In addition, monitoring the injected CO₂ is required to be sure that pressure during and after CO₂ injection stays lower than initial reservoir pressure. Yearly measurements of the downhole (bottom hole) pressure are needed.

Design of Monitoring systems

Furthermore, the monitoring plan should be designed in such a way to be able to detect leakage via the caprock by using mass balance techniques and following the CO₂ (and brine) migration via seismic measurements (if needed – when the mass balance technique is showing irregularities). If CO₂ is leaking, impact zones should be determined and CO₂ measurements in water and atmosphere should be applied.

5.8.3 List of FEPs

The following list contains the first 19 from total 53 FEPs which are included in the current version of the tool. According to the caprock failure scenario these FEPs will be selected as input for the monitoring planning tool.

66	Destruction of seal integrity
4	Fracturing, embrittlement
291	CO ₂ reactivity with the rock
620	Dissolution of CO ₂ in the formation water
79	Overpressurizing
425	Deformation, elastic, plastic or brittle
174	Injection rate
377	Pressure - Injection pressure
560	productivity and injectivity index
672	Composition of injection fluids
299	Impurity of CO ₂
282	Pressure – Initial pore (fluid) pressure
287	Pressure – pore (fluid) pressure
545	Pressure – leak off pressure
362	Porosity – effective porosity
360	Permeability – Kv/Kh ratio
666	Entry pressure
2	Stress change
32	In-situ pore pressure change

Formation of scenarios using FEPs (and/or grouping FEPs)

The following combinations of FEPs can lead to a caprock failure and hence CO₂ leakage. The first two situations, fracturing and overfilling/overpressurizing, are examples of mechanical threats. The last situation, dealing with CO₂ reactivity with rock and the composition of injection fluid are examples of a chemical threat.

32 + 4 + 66 = CO₂ leakage
 32 + 2 + 287 + 282 + 4 + 545 + 66 = CO₂ leakage

} Fracturing

174 + 79 + 66 = CO₂ leakage
 174 + 377 + 560 + 79 + 66 = CO₂ leakage

} Overfilling, overpressurizing

291 + 66 + CO₂ leakage
 672 + 299 + 291 + 360 + 66 = CO₂ leakage
 291 + (299) + 620 + 360 + 66 = CO₂ leakage

} Chemical threat

5.8.4 Results of the Tool

The following screenshots of the tool in Figure 11 are representing the results for a caprock failure scenario due to a chemical threat. At the first sheet (Scenario) one can see (part of) the list of FEPs and selected FEPs for caprock failure scenario due to a chemical threat and on the right one can see among the other things the monitoring techniques associated with these FEPs. The Output sheet presents the same result in a comprehensive way. In the previous version of the tool, the result was just a list of the monitoring techniques. Since this time we have chosen to show next to the monitoring technique also all the FEPs associated to it, the resulting list contains some duplicates (because different FEPs can be associated to the same parameter). Also if two different parameters lead to same monitoring method, it will be displayed in two separate times. This tool gives the same result as the previous tool, only that here FEPs parameters that were not matched to any monitoring techniques' parameter were shown as well (at the end of table, marked by red colour).

The resulting techniques are routine analytical techniques for gas measurements and standard pH monitoring techniques. These are also mentioned in the Barendrecht monitoring plan, albeit worded differently.

It can also be seen that the complex FEP "destruction of seal integrity" brings with it the suggestion to use seismic methods and pressure monitoring. It is true that these techniques can be used to measure the destruction of seal integrity, although this might not necessarily be caused by a chemical threat but rather as a result of a mechanical threat. Chemical threat is basically going to be monitored only by gas measurements and pH monitoring.

										<input checked="" type="checkbox"/> Monitoring frequency									
										<input checked="" type="checkbox"/> Cost indication									
										<input checked="" type="checkbox"/> Maturity									
										<input checked="" type="checkbox"/> Remarks									
	FEP nr	Selected FEPs	Spatial resolution	Timing	Time scale	Monitoring Techniques	Related FEPs	Monitoring parameter	Inform about										
1	<input checked="" type="checkbox"/> 66	Destruction of seal integrity	reservoir			Seismics: various designs	Destruction of seal integrity	pressure	geological structure, faults, cap rock thickness, fractures										
2	<input type="checkbox"/> 4	Fracturing, embrittlement	well			Pressure gauges	Destruction of seal integrity	pressure	Various pressure values (in the reservoir, well, entry pres										
3	<input checked="" type="checkbox"/> 291	CO2 reactivity with the rock	storage complex	operational		pH monitoring	Destruction of seal integrity	pH	formation water pH correlates to amount of dissolved CO2										
4	<input checked="" type="checkbox"/> 620	Dissolution of CO2 in the formation water	storage complex	operational		pH monitoring	Dissolution of CO2 in the formation water	pH	formation water pH correlates to amount of dissolved CO2										
5	<input type="checkbox"/> 79	Overpressurizing	storage complex	operational		Long term downhole pH	Destruction of seal integrity	pH	formation water pH correlates to amount of dissolved CO2										
6	<input type="checkbox"/> 425	Deformation, elastic, plastic or brittle				Disolution of CO2 in the formation water	Dissolution of CO2 in the formation water	pH	formation water pH correlates to amount of dissolved CO2										
7	<input type="checkbox"/> 174	Injection rate				IR gas analysers	Destruction of seal integrity	gas composition	gas composition										
8	<input type="checkbox"/> 377	Pressure - injection pressure			months	IR gas analysers	Composition of injection fluids	gas composition	gas composition										
9	<input type="checkbox"/> 840	Productivity and injectivity index				IR gas analysers	Impurity of CO2	gas composition	gas composition										
10	<input checked="" type="checkbox"/> 672	Composition of injection fluids				gas chromatography mass spectroscopy	Destruction of seal integrity	gas composition	gas composition										
11	<input checked="" type="checkbox"/> 299	Impurity of CO2	storage complex			gas chromatography mass spectroscopy	Composition of injection fluids	gas composition	gas composition										
12	<input type="checkbox"/> 282	Pressure - initial pore (fluid) pressure			hours	gas chromatography mass spectroscopy	Impurity of CO2	gas composition	gas composition										
13	<input type="checkbox"/> 287	Pressure - pore (fluid) pressure				No Match: permeability - Kv/Kh ratio	Permeability - Kv/Kh ratio												
14	<input type="checkbox"/> 545	Pressure - leak off pressure				No Match: permeability	CO2 reactivity with the rock												
15	<input type="checkbox"/> 362	Porosity - effective porosity																	
16	<input checked="" type="checkbox"/> 360	Permeability - Kv/Kh ratio																	
17	<input type="checkbox"/> 666	Initial pressure																	
18	<input type="checkbox"/> 2	Stress change																	
19	<input type="checkbox"/> 32	In-situ pore pressure change																	
20	<input type="checkbox"/> 263	Degradation cement plug																	
21	<input type="checkbox"/> 268	Cement degradation																	
22	<input type="checkbox"/> 269	Corrosion																	
23	<input type="checkbox"/> 308	Well integrity attack (fracture)																	

Monitoring Tool - Output																																									
Show Output																																									
<input checked="" type="checkbox"/> Show FEPs																																									
Scenario 1																																									
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Number of Scenarios	1																																								
Scenarios	Name of Scenario																																								
Scenario 1	caprock failure																																								

Figure 11. Result of the test case of the monitoring tool of Barendrecht seal failure scenario. Scenario Input (above) and Output (below) sheets

5.9 Tool demonstration – Other cases

In the EU FP7 SiteChar project several commercial scale approaches to monitoring plan development were compared, which were Quest, (Shell, CA), Kingsnorth (Shell, UK), ROAD (NL). The three plans are all risk-based which implies that the first step consists of risk assessment and the development of key scenarios. The approaches differ in categorization of monitoring tasks and risk, e.g. various definitions for terms like containment, conformance, contingency, mandatory and categories.

In the same study the monitoring planning tool was successfully applied to a potential storage site offshore Norway, Halten Terrace. Leakage of CO₂ through the caprock was assumed to be the main potential long-term, post-injection, risk for the site. The monitoring tool recommends time-lapse mode 3D seismic reflection surveys, and continuous pressure monitoring in the wells as the most appropriate monitoring techniques.

In addition, the tool was used to analyse two scenarios that would require contingency monitoring. The first scenario describes a long-term change in stress regime, leading to the re-activation of faults and associated triggered seismicity. In this scenario, additional monitoring of (micro)-seismicity is recommended. For instance, this could be achieved by a permanent seismic monitoring infrastructure on the sea-bed.

The second scenario involves the failure of a well in the injection phase. In this case the contingency monitoring consists of deployment of well inspection techniques to locate and assess the well failure. The output screen of the monitoring tool lists the FEPs related to those two scenarios and recommended monitoring options (Figure 12). More information can be derived from the SiteChar project.

Monitoring Tool - Output		Scenario 1	Scenario 2
<input type="checkbox"/> Show FEPs Monitoring Tool Test Case Examples Halten Terrace Philippe Steeghs TNO 10/7/2013		Monitoring Techniques Seismics: various designs Seismics: various designs Pressure gauges Passive seismic monitoring	Related FEPs Stress change Reactivation of faults Reactivation of faults Seismicity Reactivation of faults
Number of Scenarios : 2 Scenarios Scenario 1: stress change (post oper.) Scenario 2: well failure, geochemical		Monitoring Techniques WAF (Well Annular Flow) WAF (Well Annular Flow) WAF (Well Annular Flow) USIT (Ultrasonic imaging tool) USIT (Ultrasonic imaging tool) USIT (Ultrasonic imaging tool) PMIT (Multifinger imaging tool) EMIT (Electromagnetic imaging tool) CBL (Cement Bond log) CBL (Cement Bond log) CBL (Cement Bond log)	Related FEPs Degradation cement plug Cement degradation Well integrity attack (fracture) Corrosion Degradation cement plug Cement degradation Well integrity attack (fracture) Corrosion Degradation cement plug Cement degradation Well integrity attack (fracture)
Mandatory parameters CO2 volumetric flow Fugitive emissions of CO2 CO2 pressure CO2 temperature Ch. comp. of injection stream Reservoir pressure & temp.		Monitoring Techniques Diferental pressure flow meters air quality control pressures gauges temperature sensors gas composition SPTG (Static P & T gradient)	

Figure 12. Screen image of monitoring planning tool output. Note that the output screen also produces a list of the mandatory monitoring parameters with their recommended monitoring technologies.

Emphasising Mandatory monitoring according to the EU Directive

The EU Directive on CCS contains specifications about the monitoring plan, which should be based on a risk assessment. The parameters to be monitored are identified so as to fulfil the purposes of monitoring. According to the EU Storage Directive the plan shall in any case include continuous or intermittent monitoring of the following items (see Section 4.2.1):

- fugitive emissions of CO₂ at the injection facility;
- CO₂ volumetric flow at injection wellheads;
- CO₂ pressure and temperature at injection wellheads (to determine mass flow);
- chemical analysis of the injected material;
- reservoir temperature and pressure (to determine CO₂ phase behaviour and state).

The tool will display always all mandatory parameters and monitoring methods in compliance with the EU storage Directive.

5.10 Online web version of the tool (Version 1)

The 2012 version of the Excel monitoring planning tool was converted into a web-enabled version (Figure 132). This development version is accessible through <http://slappy.jbs-us.nl/~jkooijman/cato2/MPTool1.html>. Note this version is not meant for actual analysis of monitoring plans as the tool is still in development and not fully evaluated.

Design of Monitoring systems

Once the page has been opened, one can start selecting FEPs by double clicking the FEP numbers of choice. Double clicking again will deselect the FEP. The scrolling of the FEP table while the other tables are static is now more or less working in Firefox and Chrome. Internet Explorer refuses to separately scroll the FEP table, which is a known bug in IE.



FEP Table	
FEP Nr	Selected FEPs
66	Destruction of seal integrity
4	Fracturing, embrittlement
291	CO2 reactivity with the rock
620	Dissolution of CO2 in the formation water
79	Overpressurizing
425	Deformation, elastic, plastic or brittle
2	Stress change
32	In-situ pore pressure change
263	Degradation cement plug
268	Cement degradation
269	Corrosion
308	Well integrity attack (fracture)
3	Subsidence
36	Leakage at sideseal
223	Clay shrinkage
48	Change in permeability
330	Mineral precipitation and dissolution

Scenario composed of selected FEPs	
FEP Nr	Selected FEPs
79	Overpressurizing
2	Stress change
269	Corrosion

Inferred Monitoring Techniques and Related FEPs	
Monitoring Techniques	Related FEPs
Pressure gauges	Overpressurizing
Temperature sensors	Overpressurizing
SPTG (Static P & T gradient)	Overpressurizing
SPTG (Static P & T gradient)	Overpressurizing
Seismics: various designs	Overpressurizing
RST (Reservoir Saturation tool)	Overpressurizing
Seismics: various designs	Stress change
PMIT (Multifinger Imaging tool)	Corrosion
USIT (Ultrasonic imaging tool)	Corrosion

Figure 13. Printscreen of the interactive web-enabled monitoring planning tool, yellow marked txt in left-hand columns represent selected FEPs

5.11 Work in Progress

5.11.1 Quality check of indirect connections between FEPs and monitoring techniques

The novelty and complexity of the CO₂ storage process brings up the question to which extent it is possible to account for all relevant scenarios, sub-scenarios, FEPs interconnections and how to monitor that. The additional experience and insight in CCS with its practical implementation can result in new FEPs and/or new monitoring techniques. For the tool to remain useful, it is therefore

Design of Monitoring systems

important that the quality control of underlying information is regularly performed. Also it is important that the tool can be easily updated. Regular updates of the database for the monitoring techniques and updates of FEP connections monitoring parameters are expected. Where needed more specific info on FEPs and related monitoring techniques will be added, e.g. in relation to corrosion. This can be done by the designer of the tool, but possibly also by the user itself, making sure that the workings of the tool are not negatively affected in the process. *The creation of a user friendly process of updating the tool will be part of the next update.* At this version there is a space for the user to leave his comments in the last sheet Change Request. Here the user can also request developing of new features or installing certain updates.

5.11.2 Using (and providing) extra information

The detailed information included in the monitoring techniques database can be used to make a more specific selection based on the spatial distribution, the timing and the costs associated with the monitoring techniques. Selections could be made using drop boxes and filters. Also the possibility of additional questionnaires for some specific issues might be implemented (such as questions to determine what is a best design for a seismic acquisition).

5.11.3 Generating the list of Tools and displaying the results

Compared to the previous version of the tool, generating the list of Tools and displaying the results has been improved but it is still not satisfactory. Although displaying one monitoring method several times in the list of results can be useful to get the overview of the risks it can monitor, it is not an elegant solution. The user should be able to view the list of tools without duplicates. Also, displaying additional information is sometimes in a sub-optimal format. That needs to be corrected.

In the next stage of development of the tool, these improvements must be taken into account and the final monitoring plan should be concise and without redundancies. The final output could be in a form of clickable table with links to detailed explanation and some technical details.

5.11.4 Developing online web interface

For user convenience and as a continuation of the CASSIF risk assessment, it has been decided to enable online use of the Monitoring Tool. For that purpose, a new source code (either php or java) needs to be developed using the Excel tool as a blue print. A first version has been implemented (see section 5.10).

5.11.5 Site-specific quantified monitoring plan (stage II)

After implementation and consolidation of the previously mentioned tool improvements, a more site-specific, quantified version of the monitoring planning tool will be developed. This will include a planning scheme and a spatial representation of the monitoring techniques to be deployed.

6 Conclusion

In a broad sense *Risk management* acts as the central driver for all safety related activities, just as stipulated by the EU guidelines. Although developing a risk management plan in itself is not a legal requirement, most of the components (site characterisation, risk assessment, monitoring and preventive and corrective measures) are required by the CCS Directive.

To facilitate this process, a monitoring planning tool has been developed which results in a list of possible monitoring techniques based on user (experts) defined scenarios and risk factors. The tool has been designed as a logical continuation of the risk and safety assessment performed by experts using the CASSIF process. The tool can be part of a risk management framework which enables communication between the risk analysis results and the monitoring strategy.

The Tool has been built in Excel and consists of several Excel sheets. It has been designed as a supporting tool helping and advising the users on how to design a reliable and cost effective monitoring plan. The tool has been built around a database with risk factors and parameters and a database with monitoring techniques and parameters. The tool is driven by site-specific characteristics and selected scenarios with risk factors (FEPs). A test run "mimicking" the Barendrecht monitoring plan and a test for a potential storage site offshore Norway (EU SiteChar project) show that the monitoring tool developed here is a feasible development.

It is possible to design different monitoring plans (required and contingency) and mandatory monitoring is separately displayed. The first version of the web-enabled tool is available.

In the future, additional functionality, such as information about the risk level and the time and space frames of the scenarios and FEPs will be taken into account.

7 References

Chapter 4: Requirements for developing a monitoring plan

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Chapter 5: Monitoring planning tool

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