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TNO Monitoring plan development tool

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Abstract

TNO has developed a software tool that supports the design of a risk-based monitoring plan for a CO_2 storage site. The purpose of the tool is to aid storage site operators by facilitating a structured monitoring technologies selection or evaluation process. The tool makes a selection this recommended monitoring technologies, based on a set of rules that link a monitoring technology to a particular risk factor or regulatory requirement. In our paper we describe conceptual framework of the tool and its functionality. The starting point of the tool is the selection of site-specific characteristics and scenarios which contain risk factors referred to as FEPs (Features, Events, and Processes). These FEPs are matched with monitoring technologies that fulfill a set of pre-specified requirements, for instance, related to performance criteria or operational costs. The tool is built around two databases: one consisting of risk factors and associated parameters and another one containing monitoring technologies and the information they provide. The database with the risk factors is the product of a TNO risk assessment methodology (CASSIF). The user-defined inputs for the monitoring plan development tool are site-specific characteristics and the scenarios which contain risk factors. Site characteristics are for instance the type of storage reservoir or the storage site location (e.g. on-shore or offshore). The individual risk factors in each scenario are then translated into measurement parameters, which are subsequently matched with the monitoring technologies. Additional information about the monitoring technologies can be displayed, depending on user preferences and requirements.

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1. Introduction

CO_2 storage site operators are required to submit a monitoring plan as part of the regulatory requirements, such as a storage permit application. For instance, under the EU Storage Directive a monitoring plan, drawn up by the operator, and approved by the Competent Authorities [1], has to be in place at the start of a storage project. This monitoring plan should be risk based, and has to provide details of the monitoring to be deployed at the main stages of the project, including baseline, operational, and post-closure monitoring. For each phase the plan has to specify:

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 purpose of the monitoring planning 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). These FEPs are linked to a monitoring technology that can provide information that is relevant for these risk factors and in addition meets certain requirements concerning performance or operational costs.

The monitoring planning tool supports checking, or auditing, the monitoring options for the site operator against the risks identified and requirements in connection with the regulatory context. The software tool is set up as a decision tree, with control points allowing user choices. It guides the user from the risk assessment results to a set of suggested monitoring technologies.

In our paper we will describe the underlying conceptual framework and illustrate the tool's functionality. We will first describe how the tool is integrated into a risk assessment workflow. We will then discuss the functionality of the tool in detail and show how the software can be used to support the development or evaluation of a risk-based monitoring plan.

2. The framework and concept for the monitoring plan development tool

The tool has been designed to be an integral part of a risk management workflow. Its main input data are the outcome of a site-specific risk assessment. The currently implemented workflow uses CASSIF (Carbon Sequestration Scenario Identification Framework [2]) to guide the risk assessment. The CASSIF approach is structured around the concept of Features, Events and Processes (FEPs) for qualitative risk assessments of CO_2 storage projects. The framework assists in describing and clarifying potential CO_2 leakage scenarios. CASSIF is designed to perform a hazard analysis. This hazard analysis starts with the creation of a comprehensive inventory of site-specific risk factors (or FEPs), followed by a selection of the most critical factors. The FEPs are then grouped into discrete CO_2 leakage scenarios. The methodology recognizes three major general leakage scenarios, associated with well, fault, or seal leakage, for the site specific risk factors have to be identified and described.

The monitoring planning tool uses the significant FEPs as identified by CASSIF process as its main user defined input. From a risk management perspective, the tool gives the user to insight into which monitoring technologies are to be considered to relate a monitoring approach to a particular risk scenario. Figure 1 illustrates the relation between the risk assessment and monitoring plan development tool.

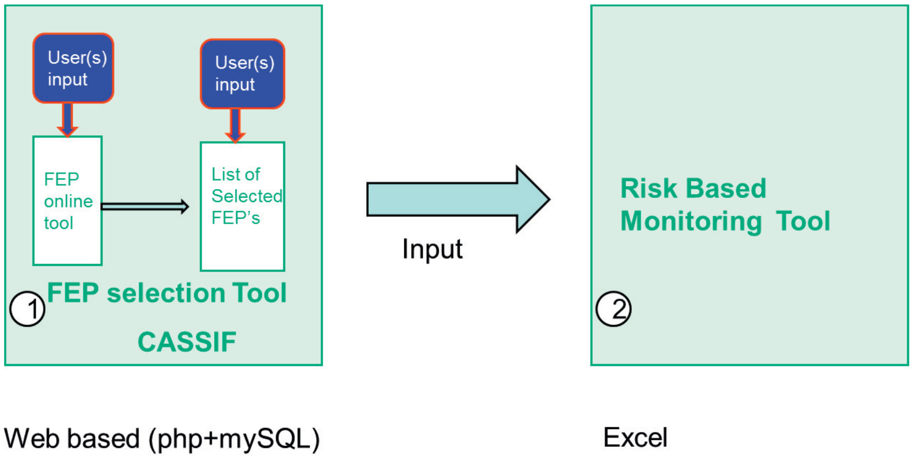

Fig. 1. Work flow for development of a risk-based monitoring plan with the planning tool.

The tool connects two databases. The first database is a list of FEPs, each of them linked to one or more parameters which can be measured to monitor that particular FEP. The second database consists of the monitoring technologies and the parameter they measure. After the user has selected the relevant FEPs, the tool connects the parameters of the FEPs and the monitoring technologies. Although this basic concept is straightforward, implementation is not. The actual physical parameter measured with a certain monitoring technology often cannot be directly linked to a FEP, but only indirectly. Hence, the FEPs should also be connected to monitoring technologies that provide more indirect observations of that particular FEP. In addition, there is no straightforward way to unambiguously weed out monitoring technologies that are not feasible for a particular the site or FEP. This issues can be dealt with by using key words rather than (physical) parameters to connect FEPs with the appropriate monitoring technologies.

The output of the tool is a scenario with a number of selected FEPs, their corresponding parameters (and/or key words), and a list of proposed monitoring technologies.

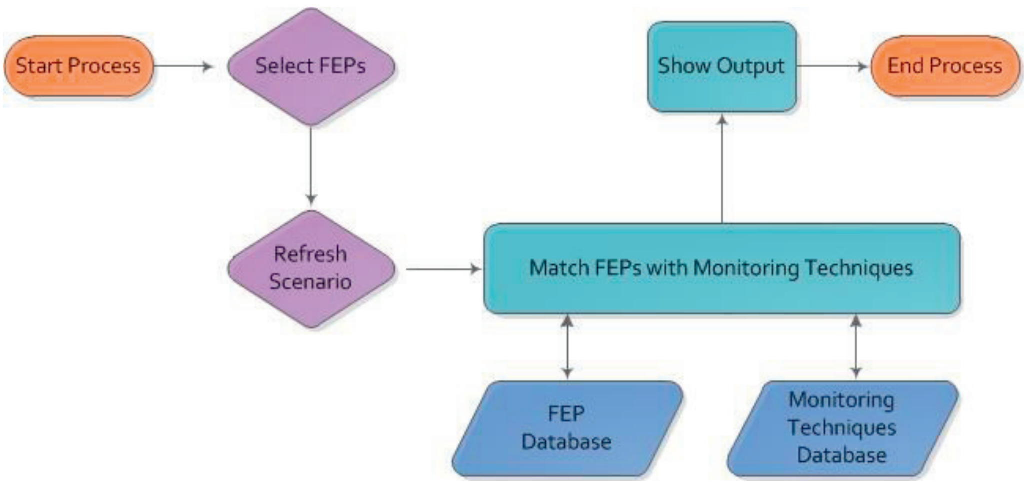

Fig. 2. Flow chart of monitoring plan development tool.

In addition to selecting appropriate monitoring technologies, the tool provides additional detail, such as listing the parameters that are measured and a brief explanation of the type of information that can be derived from the measurements. Important features, such as the monitoring area (well, reservoir, storage site), the timing (for example pre-operational or operational), the frequency of measurements, and indications for costs, can also be listed. In addition, an extra column with remarks has been added, where additional information can be displayed, such as limitations of the technologies, information in connection with the EU regulative framework, and other relevant features, such as measurement accuracy or other performance indicators.

The workflow has been implemented in Microsoft Excel but would be easily converted into a web-based monitoring planning tool.

Table 1 gives an example of the output of the tool, consisting of the monitoring technologies, the parameters measured, and the additional information, such as monitoring area, timing and frequency, and a cost indication.

Table 1. Example of the output of the monitoring planning tool.

Monitoring technologies	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	temperature	injected gas temperature	local - well	operational phase	continuous	low to moderate	Standard	Mandatory monitoring
Distributed temperature sensing	temperature	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 to within ±1°C at a resolution of 0.01°C
SPTG (Static P & T gradient)	temperature	reservoir pressure and temperature	reservoir/ well	pre-operational, operational and verification phase	yearly	low to moderate	Standard	

2.1. Sources for input data

The FEPs represent situations which could threaten the integrity of the CO_2 storage site could ultimately result in 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 (e.g., geochemical processes, geomechanical processes, thermal processes, etc.).

At this stage of development of monitoring tool, a ‘scenario’ consists of a list of FEPs, that are associated with a leakage scenario. It is possible to analyse several scenarios in parallel and compare the outcomes.

The monitoring technologies have been selected from several existing databases and sources. Currently, there are three catalogues of monitoring technologies that are widely used:

- BGS/IEA-GHG monitoring techniques catalogue [3] ;
- NETL report: Monitoring, Verification and Accounting of CO_2 Stored in Deep Geological Formations [4];
- NSBTF Catalogue of Monitoring tools [5].

We have found approximately 60 different monitoring technologies in these sources, from which we have selected 37 for our database.

3. Examples of input and output screens

Figure 3 gives an example of the input screen for the tool. The user selects a set of FEPs that belong to a particular risk scenario. If desired, the input screen also provides the list of monitoring technologies and the parameters and keyword that will link them to a particular FEP. The user can evaluate several scenarios, each with their corresponding FEP list, in parallel.

C	F	G	AF	AG	AH	AI
	Selected FEPs	FEP type	Monitoring Techniques	Related FEPs	Physical parameter measur	Informs about
☐	Destruction of seal integrity		well-head CO2 detectors	Migration of CO2 or brine along injector	co2 concentration	CO2 concentration
☑	Fracturing, embrittlement		WAF (Well Annular Flow)	Fracturing, embrittlement	annular build up pressure	fracturing around well casing
☐	CO2 reactivity with the rock	level I	WAF (Well Annular Flow)	Degradation cement plug	annular build up pressure	fracturing around well casing
☐	Dissolution of CO2 in the formation water	level II	WAF (Well Annular Flow)	Cement degradation	annular build up pressure	fracturing around well casing
☐	Overpressurizing	level I	WAF (Well Annular Flow)	Well integrity attack (fracture)	annular build up pressure	fracturing around well casing
☐	Deformation, elastic, plastic or brittle	level III	WAF (Well Annular Flow)	primary well barrier failure	annular build up pressure	fracturing around well casing
☐	Stress change	level I	USIT (Ultrasonic imaging tool)	Corrosion	acoustic impedance	cement sheath and casing
☐	In-situ pore pressure change		USIT (Ultrasonic imaging tool)	Steel expansion/contraction	acoustic impedance	cement sheath and casing
☑	Degradation cement plug	level I	USIT (Ultrasonic imaging tool)	Erosion of casing	acoustic impedance	cement sheath and casing
☑	Cement degradation	level I	USIT (Ultrasonic imaging tool)	Migration of CO2 or brine along injector	acoustic impedance	cement sheath and casing
☑	Corrosion	level I	USIT (Ultrasonic imaging tool)	Degradation cement plug	acoustic impedance	cement sheath and casing
☑	Well integrity attack (fracture)		USIT (Ultrasonic imaging tool)	Cement degradation	acoustic impedance	cement sheath and casing
☐	Subsidence		USIT (Ultrasonic imaging tool)	Well integrity attack (fracture)	acoustic impedance	cement sheath and casing
☐	Leakage at sideseal	level I	USIT (Ultrasonic imaging tool)	Cement bound loss	acoustic impedance	cement sheath and casing
☐	Clay shrinkage		USIT (Ultrasonic imaging tool)	Erosion of casing	acoustic impedance	cement sheath and casing
☐	Change in permeability	level II	USIT (Ultrasonic imaging tool)	Inadequate cement job	acoustic impedance	cement sheath and casing
☐	Mineral precipitation and dissolution		USIT (Ultrasonic imaging tool)	Alteration of borehole completion	acoustic impedance	cement sheath and casing
☐	Dewatering of host rock	level III	Temperature sensors	Steel expansion/contraction	temperature	temperature
☐	Compositional change	level II	Temperature sensors	Migration of CO2 or brine along injector	temperature	temperature
☐	Formation enhancement (fracing, acid jobs)		Pressure gauges	Fracturing, embrittlement	pressure	Various pressure values (in the re
☐	CO2 phase behaviour		Pressure gauges	Instantaneous material failure	pressure	Various pressure values (in the re
☐	Pressurization of the reservoir		Pressure gauges	Migration of CO2 or brine along injector	pressure	Various pressure values (in the re
☐	Fluid density contrast		PMIT (Multifinger Imaging tool)	Corrosion	Thickness of the pipe	pipe corrosion
☐	Geochemical widening of pref pathways		monitoring annulus pressure	primary well barrier failure	annulus pressure	annulus pressure
☐	Reactivation of faults		Microseismic monitoring	Fracturing, embrittlement	acoustic impedance	small seismic events due to for e
☐	Seismicity		EMIT (Electromagnetic imaging tool)	Corrosion	resistivity	corrosion in pipes
☐	Under pressurizing		EMIT (Electromagnetic imaging tool)	Steel expansion/contraction	resistivity	corrosion in pipes
☐	Adiabatic processes		EMIT (Electromagnetic imaging tool)	Erosion of casing	resistivity	corrosion in pipes
☑	Steel expansion/contraction		Distributed temperature sensing	Steel expansion/contraction	temperature	temperature profiles
☑	Cement bound loss		CBL (Cement Bond log)	Degradation cement plug	amplitude of acoustic signa	cement integrity
☑	Erosion of casing		CBL (Cement Bond log)	Cement degradation	amplitude of acoustic signa	cement integrity

Fig. 3. Input sheet of monitoring plan development tool.

Figure 4 shows a typical output screen of the tool. For three scenario, the tool produces a list of proposed monitoring technologies and the FEP they have been linked to. Another type of output is shown in Fig. 5, which is a ranked list of monitoring technologies. In this example, the monitoring technologies are ranked according to the number of individual risk factors they have been linked to. Also other ranking schemes can be implemented in the tool, for instance facilitating a cost-benefit analysis. In addition, it is possible to let the tool list the monitoring parameters that are mandatory within the regulatory context for which the plan is to be developed. The tool then separately outputs a set of proposed monitoring technologies to address the mandatory monitoring requirements.

Monitoring Tool - Output

Show Output

☑ Show FEPs

Storage name	Monitoring Tool Test Case
Storage description	Examples from Barendrecht
User	Danijela
Organisation	TNO
Date	21-6-2012
Number of Scenarios	4

Scenarios	Monitoring Category
Scenario 1: well	do not include
Scenario 2: geochemical threa	do not include
Scenario 3: mechanical threat	

Mandatory parameters	Monitoring Techniques
CO2 volumetric flow	Diferental pressure flow meters
Fugitive emissions of CO2	air quality control *
CO2 pressure	pressures gauges
CO2 temperature	temperature sensors
Ch. comp. of injection stream	gas composition **
Reservoir pressure & temp.	SPTG (Static P & T gradient)

Scenario 1		Scenario 2	
Monitoring Techniques	**Related FEPs**	**Monitoring Techniques**	**Related FEPs**
well-head CO2 detectors	Migration of CO2 or brine along injector	Time-lapse seismic survey	Reactivation of faults
WAF (Well Annular Flow)	Fracturing, embrittlement	Time-lapse seismic survey	Migration of CO2 or brine via matrix pathways
WAF (Well Annular Flow)	Degradation cement plug	Tiltmeters	Compositional change
WAF (Well Annular Flow)	Cement degradation	Temperature sensors	CO2 phase behaviour
WAF (Well Annular Flow)	Well integrity attack (fracture)	Temperature sensors	CO2 phase behaviour
WAF (Well Annular Flow)	primary well barrier failure	Pressure gauges	Destruction of seal integrity
USIT (Ultrasonic imaging tool)	Corrosion	Pressure gauges	Leakage at sideseal
USIT (Ultrasonic imaging tool)	Steel expansion/contraction	Pressure gauges	Change in permeability
USIT (Ultrasonic imaging tool)	Erosion of casing	Pressure gauges	Reactivation of faults
USIT (Ultrasonic imaging tool)	Migration of CO2 or brine along injector	Pressure gauges	Migration of CO2 or brine via matrix pathways
USIT (Ultrasonic imaging tool)	Degradation cement plug	plt (spinner)	CO2 reactivity with the rock
USIT (Ultrasonic imaging tool)	Cement degradation	plt (spinner)	Change in permeability
USIT (Ultrasonic imaging tool)	Well integrity attack (fracture)	plt (spinner)	Geochemical widening of pref pathways
USIT (Ultrasonic imaging tool)	Cement bound loss	pH monitoring	Destruction of seal integrity
USIT (Ultrasonic imaging tool)	Erosion of casing	pH monitoring	Dissolution of CO2 in the formation water
USIT (Ultrasonic imaging tool)	Inadequate cement job	pH monitoring	Mineral precipitation and dissolution
USIT (Ultrasonic imaging tool)	Alteration of borehole completion	Passive seismic monitoring	Reactivation of faults
Temperature sensors	Steel expansion/contraction	Microseismic monitoring	Reactivation of faults
Temperature sensors	Migration of CO2 or brine along injector	lab testing of samples	Mineral precipitation and dissolution
Pressure gauges	Fracturing, embrittlement	lab testing of samples	Geochemical widening of pref pathways
Pressure gauges	Instantaneous material failure	IR gas analysers	Destruction of seal integrity
Pressure gauges	Migration of CO2 or brine along injector	InSAR (Synthetic Aperture Radar inte	Reactivation of faults
PMIT (Multifinger Imaging tool)	Corrosion	InSAR (Synthetic Aperture Radar inte	Migration of CO2 or brine via matrix pathways
monitoring annulus pressure	primary well barrier failure	gas chromatography / mass spectros	Destruction of seal integrity
Microseismic monitoring	Fracturing, embrittlement	Distributed temperature sensing	CO2 phase behaviour
EMIT (Electromagnetic imaging tool)	Corrosion	Differential pressure flow meters	Change in permeability
EMIT (Electromagnetic imaging tool)	Steel expansion/contraction		Mineral precipitation and dissolution
EMIT (Electromagnetic imaging tool)	Erosion of casing		
Distributed temperature sensing	Steel expansion/contraction		
CBL (Cement Bond log)	Degradation cement plug		
CBL (Cement Bond log)	Cement degradation		
CBL (Cement Bond log)	Well integrity attack (fracture)		

Fig. 4. Output screen of the monitoring plan development tool, showing the monitoring technologies and related FEPs.

	Final List of sudgested Monitoring Techniques	No. Risks
1	Pressure gauges	15
2	USIT (Ultrasonic imaging tool)	11
3	CBL (Cement Bond log)	9
4	pH monitoring	6
5	Temperature sensors	5
6	Distributed temperature sensing	2
7	SPTG (Static P & T gradient)	2
8	WAF (Well Annular Flow)	5
9	Microseismic monitoring	5
10	Passive seismic monitoring	3
11	Time-lapse seismic survey	4
12	Seismics: various designs	2
13	plt (spinner)	3
14	EMIT (Electromagnetic imaging tool)	3
15	InSAR (Synthetic Aperture Radar interferometry)	4
16	lab testing of samples	2
17	gas chromatography / mass spectroscopy / IR gas ar	3
18	well-head CO2 detectors	1
19	PMIT (Multifinger Imaging tool)	1
20	monitoring annulus pressure	1
21	Differential pressure flow meters	1
22	Tracers	1
23	soil CO2 gas flux surveys	1
24	soil CO2 gas concentration surveys	1
25	RST (Reservoir Saturation tool)	1
26	Tiltmeters	1
27		
28		
29		

Mandatory parameters	Monitoring Techniques
CO2 volumetric flow	Diferental pressure flow meters
Fugitive emissions of CO2	air quality control *
CO2 pressure	pressures gauges
CO2 temperature	temperature sensors
Ch. comp. of injection stream	gas composition **
Reservoir pressure & temp.	SPTG (Static P & T gradient)

* standard methods as gas detectors
or new technologies such as
portable leak imaging camere, or
DIAL (differential absorption light
detection and ranging)

** standard methods such as
IR gas analysers or
gas chromatography mass spectroscopy

Fig. 5. Output screen of the monitoring plan development tool, showing the monitoring technologies ranked by the number of risks they relate to and separate output showing suggested monitoring technologies for monitoring mandatory parameters.

4. Conclusions

CO_2 storage project operators are required to submit a monitoring plan as part of the regulatory requirements for license applications and approvals. For instance, the EC Guidance document [1] prescribes that a monitoring plan is to be drawn up by the operator and approved by the Competent Authorities. This monitoring plan should be risk based. To facilitate the process of developing a risk-based monitoring plan, we have developed a software tool that produces an annotated list of recommended monitoring technologies. The tool has been designed function as part of a workflow that starts with a risk and safety assessment based on the CASSIF process [2]. As such, the tool can be considered to be an element of a larger risk management framework. Within this framework, the main role of the tool is to aid in translating the outcomes of a site-specific risk assessment into recommendations for a monitoring plan.

Simulation runs with the tool, using risk assessments and monitoring plans from several large scale CO_2 storage projects, have shown that the tool can consistently reproduce the main components of a comprehensive monitoring plan. As a result, we expect that our tool will evolve into an effective and widely used tool for the development of a monitoring plan for a CO_2 storage site.

Acknowledgements

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