

**Technical Report**

**TR-10-51**

**Model summary report for  
the safety assessment SR-Site**

Svensk Kärnbränslehantering AB

December 2010

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## Update notice

The original report, dated December 2010, was found to contain both factual and editorial errors which have been corrected in this updated version. The corrected factual errors are presented below.

Location	Original text	Corrected text
Page 26, Heading 3.2.6	"Rationales for using the code in SR-Can"	"Rationales for using the code in SR-Site"
Page 54, second last paragraph, line 2	/Grivé et al. 2010/.	/Grivé et al. 2010b/.
Page 55, paragraph 2, line 1	/Grivé et al. 2010/.	/Grivé et al. 2010b/.
Page 55, paragraph 3, last line	/Grivé et al. 2010/.	/Grivé et al. 2010b/.

# Preface

This document gives an overview of computer codes used in the safety assessment SR-Site and the quality assurance procedures and documents relating to the codes. It supports the safety assessment SR-Site, which will support the licence application for a final repository in Sweden.

The report has been produced by Fredrik Vahlund, SKB (project leader) in collaboration with Lena Zetterström Evins, SKB and Maria Lindgren, Kemakta Konsult AB.

Stockholm, December 2010

*Allan Hedin*

Project leader SR-Site

## Summary

This document is the model summary report for the safety assessment SR-Site. In the report, the quality assurance (QA) measures conducted for assessment codes are presented together with the chosen QA methodology.

In the safety assessment project SR-Site, a large number of numerical models are used to analyse the system and to show compliance. In order to better understand how the different models interact and how information are transferred between the different models Assessment Model Flowcharts, AMF's, are used. From these, different modelling tasks can be identify and the computer codes used.

As a large number of computer codes are used in the assessment the complexity of these differs to a large extent, some of the codes are commercial while others are developed especially for the assessment at hand. QA requirements must on the one hand take this diversity into account and on the other hand be well defined. In the methodology section of the report the following requirements are defined for all codes:

- It must be demonstrated that the code is suitable for its purpose.
- It must be demonstrated that the code has been properly used.
- It must be demonstrated that the code development process has followed appropriate procedures and that the code produces accurate results.
- It must be described how data are transferred between the different computational tasks.

Although the requirements are identical for all codes in the assessment, the measures used to show that the requirements are fulfilled will be different for different types of codes (for instance due to the fact that for some software the source-code is not available for review).

Subsequent to the methodology section, each assessment code is presented together with a discussion on how the requirements are met.

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# 1 Introduction

In the current chapter, the SR-Site safety assessment and the current document is initially introduced, followed by a brief presentation of other documents within the SR-Site series of reports and an outline for current report.

## 1.1 Objectives and scope of the SR-Site assessment

The role of the safety report SR-Site in SKB's licence application is to demonstrate that the repository SKB intends to build at the Forsmark site is safe in the long term. If safety is demonstrated, the SR-Site report can serve its intended purpose in the licence application.

The main purposes of the safety assessment project SR-Site are:

- To assess the safety, as defined in applicable Swedish regulations, of the proposed KBS-3V repository at Forsmark;
- To provide feedback to design development, to SKB's R&D programme, to detailed site investigations and to future safety assessment projects.

The SR-Site report supports the licence application. The objective of the SR-Site report is to investigate whether the KBS-3V method has the potential of fulfilling regulatory safety criteria at the Forsmark site, with the host rock conditions emerging from the surface based site investigations. The assessment is based on a reference design of the engineered parts of the repository, including reference methods to achieve the specified design, taking into account methods of controlling that the specifications of the reference design have been achieved. Another important purpose is to give feedback for further developments to that specification, in particular by giving input to the development of updated design premises.

## 1.2 Objectives and scope of the current report

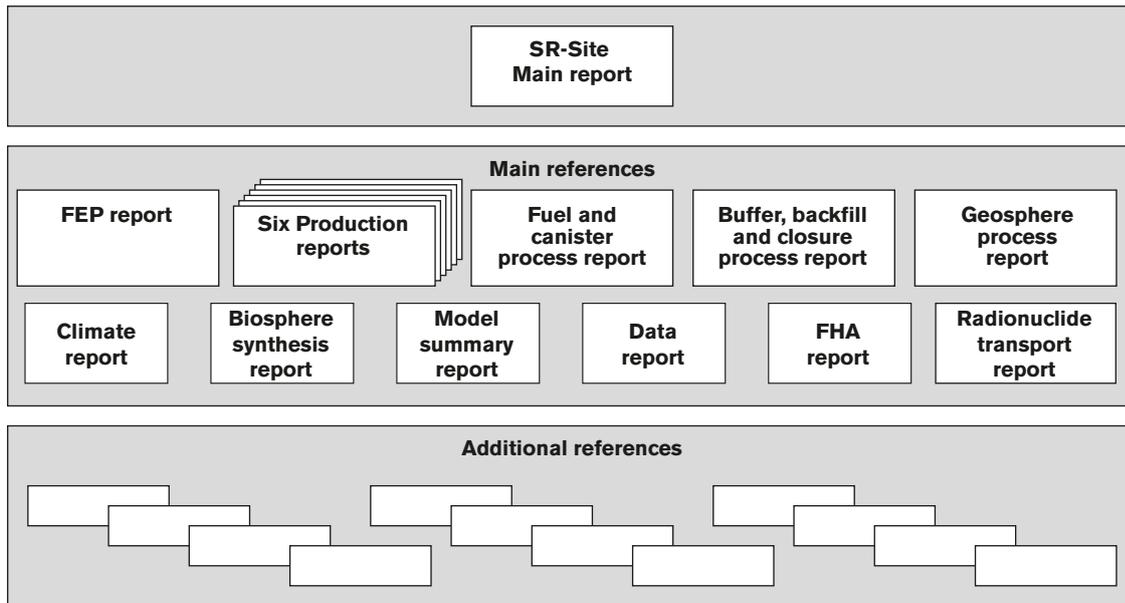
The purpose of this report is to give an overview of the modelling tasks and computer codes used in the safety assessment SR-Site and the quality assurance procedures and documents relating to the codes. More specifically, the report contains.

- Assessment model flow charts (AMF's) that describe the modelling tasks in SR-Site and how the different modelling tasks are associated.
- The principles behind the QA measures regarding the codes and the calculations.
- A brief presentation of each code used for modelling tasks identified in the AMF, with references to other documents that describe the mathematical model (the equations solved), verification measures, QA routines for input data handling and storage of results, QA routines for code development, version control, etc.

The aim is, however, not to give rationales for including a certain process in the modelling or to support the selected input data. This is done in the three **Process reports** and the **Data report**, respectively.

## 1.3 Key reports in the assessment

Several of the steps carried out in the SR-Site safety assessment result in specific reports that are of central importance for the conclusions and analyses in the SR-Site **Main report**. These specific reports, referred to as main references, are 16 in number. Besides the main references there are about 80 additional references, treating more narrow issues, supporting the main report and/or one or more of the main references. The SR-Site report hierarchy is illustrated in Figure 1-1.



**Figure 1-1.** The hierarchy of the Main report, main and additional references to the SR-Site project. The six production reports include for example the Spent fuel report and the Underground openings construction report (reproduced from Figure 2-3 of the SR-Site Main report).

In addition to the dedicated SR-Site reports, references are made to a variety of documents, articles and publications, either from SKB or from other organisations, or as part of the open literature.

In this report, the **Main report** and main references of the SR-Site project are referenced by using abbreviations. The abbreviations of the discussed reports, as well as their full references, are given in Table 1-1.

## 1.4 Outline of the report

In the current chapter, the purpose of the report and of the SR-Site project in general is presented. In Chapter 2, the basic ideas for this report and requirements on codes used for assessment calculations are presented. The different modelling tasks and flow of information can be identified in the Assessment Model Flow charts (AMF's).

While some of the modelling tasks identified in the AMF's are simple scoping calculations other require complex computer codes. As it would be impractical to include all kinds of modelling tasks performed within the framework of the safety assessment and to apply the same QA requirements on all computer codes used for modelling, the codes are subdivided into categories on which the requirements are formulated differently. The methods used for distinguishing between the different categories of codes are presented in Chapter 2. The QA requirements on codes used for the calculation tasks are also described in Chapter 2 together with a template used when describing each code.

Finally, in Chapter 3, the different codes used for the assessment calculations are presented following the outline presented in Chapter 2. Modelling data used in the safety assessment are archived at SKB, see Table 1-2.

**Table 1-1. Abbreviations and full references of SKB reports, used in SR-Site.**

Abbreviation used when referenced in SR-Site	Full reference, as given in the reference list
Main report	<b>Main report, SKB 2011.</b> Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. TR-11-01, Svensk Kärnbränslehantering AB.
FEP report	<b>FEP report, SKB 2010.</b> FEP report for the safety assessment SR-Site. SKB TR-10-45, Svensk Kärnbränslehantering AB.
Spent fuel report	<b>Spent fuel report, SKB 2010.</b> Spent nuclear fuel for disposal in the KBS-3 repository. SKB TR-10-13, Svensk Kärnbränslehantering AB.
Canister production report	<b>Canister production report, SKB 2010.</b> Design, production and initial state of the canister. SKB TR-10-14, Svensk Kärnbränslehantering AB.
Buffer production report	<b>Buffer production report, SKB 2010.</b> Design, production and initial state of the buffer. SKB TR-10-15, Svensk Kärnbränslehantering AB.
Backfill production report	<b>Backfill production report, SKB 2010.</b> Design, production and initial state of the backfill and plug in deposition tunnels. SKB TR-10-16, Svensk Kärnbränslehantering AB.
Closure production report	<b>Closure production report, SKB 2010.</b> Design, production and initial state of the closure. SKB TR-10-17, Svensk Kärnbränslehantering AB.
Data report	<b>Data report, SKB 2010.</b> Data report for the safety assessment SR-Site. SKB TR-10-52, Svensk Kärnbränslehantering AB.
Underground openings construction report	<b>Underground openings construction report, SKB 2010.</b> Design, construction and initial state of the underground openings. SKB TR-10-18, Svensk Kärnbränslehantering AB.
Fuel and canister process report	<b>Fuel and canister process report, SKB 2010.</b> Fuel and canister process report for the safety assessment SR-Site. SKB TR-10-46, Svensk Kärnbränslehantering AB.
Buffer, backfill and closure process report	<b>Buffer, backfill and closure process report, SKB 2010.</b> Buffer, backfill and closure process report for the safety assessment SR-Site. SKB TR-10-47, Svensk Kärnbränslehantering AB.
Geosphere process report	<b>Geosphere process report, SKB 2010.</b> Geosphere process report for the safety assessment SR-Site. SKB TR-10-48, Svensk Kärnbränslehantering AB.
Climate report	<b>Climate report, SKB 2010.</b> Climate and climate related issues for the safety assessment SR-Site. SKB TR-10-49, Svensk Kärnbränslehantering AB.
Radionuclide transport report	<b>Radionuclide transport report, SKB 2010.</b> Radionuclide transport report for the safety assessment SR-Site. SKB TR-10-50, Svensk Kärnbränslehantering AB.
Model summary report	<b>Model summary report, SKB 2010.</b> Model summary report for the safety assessment SR-Site. SKB TR-10-51, Svensk Kärnbränslehantering AB.
FHA report	<b>FHA report, SKB 2010.</b> Handling of future human actions in the safety assessment SR-Site. SKB TR-10-53, Svensk Kärnbränslehantering AB.
Biosphere synthesis report	<b>Biosphere synthesis report, SKB 2010.</b> Biosphere analyses for the safety assessment SR-Site – synthesis and summary of results. SKB TR-10-09, Svensk Kärnbränslehantering AB.

**Table 1-2. List of SR-Site modelling data archived at SKB.**

SKBdoc, id, version	Title	Issuer, year
1256019 ver 1.0	Hydrogeological model data and results – Forsmark	SKB, 2010
1258988 ver 1.0	Canister and buffer shear – App 10 I TR-10-34	SKB, 2010
1260295 ver 1.0	Results from radionuclide transport calculations with COMP23 and FARF31	SKB, 2010
1260297 ver 1.0	Scripts and input data used for the radionuclide transport calculations with COMP23 and FARF31	SKB, 2010
1262945 ver 1.0	Hydrogeochemistry: SR-Site and comparative analysis	SKB, 2010
1263189 ver 1.0	Data used in SR-Site Biosphere	SKB, 2010
1264505 ver 1.0	Scripts and input data used in 3DEC modelling reported in TR-10-23	SKB, 2010
1264508 ver 1.0	Scripts and input data used in 3DEC modelling reported in TR-08-11	SKB, 2010
1264530 ver 1.0	Matlab scripts used in EFPC Development and Benchmarks (FPI chapter in MSR)	SKB, 2010
1264531 ver 1.0	Matlab scripts used in EFPC/FPI modelling in SR-SITE (FPI chapter in MSR)	SKB, 2010
1264532 ver 1.0	General Matlab codes used in EFPC/FPI modelling (FPI chapter in MSR)	SKB, 2010
1265606 ver 1.0	CODE_BRIGHT Input files to the models used in SR-Site	SKB, 2010
1265608 ver 1.0	Scripts and data used for Abaqus modelling of buffer in SR-Site	SKB, 2010
1265612 ver 1.0	Scripts and data used for Analytical erosion corrosion calculations	SKB, 2010
1265613 ver 1.0	Data used in the SR-Site Climate program	SKB, 2010
1265616 ver 1.0	Simple Functions calculations and data used in SR-Site	SKB, 2010
1265618 ver 1.0	Scripts and data used for TOUGHREACT modelling in SR-Site	SKB, 2010
1265689 ver 1.0	Oxygen ingress at Forsmark	SKB, 2010
1265807 ver 1.0	PHAST data used for water saturated bentonite in SR-Site (TR-10-59)	SKB, 2010
1266150 ver 1.0	Radionuclide transport calculations with MARFA	SKB, 2010

## **2 Principles for quality assurance of computer codes**

In this chapter, principles relating to quality assurance of computer codes used in the safety assessment SR-Site are described. To provide an overview of the modelling activities and the flow of information between them, assessment model flow charts, AMF's, are used. The majority of the modelling activities identified in the AMF's are associated with different computer codes. For the different codes, QA requirements are identified and a template for documenting how these apply for the different codes is presented.

### **2.1 Assessment model flow chart**

To illustrate how major modelling tasks in the assessment are related, two Assessment Model Flow charts (AMF's), have been constructed for SR-Site assessment. The first illustrates modelling of the excavation and operation phase and the initial temperate period, Figure 2-1, while the second illustrates modelling of permafrost and glacial conditions, Figure 2-2. In the AMF's, modelling activities, input and output to and from the activities and assessments based on model output are identified for different parts of the repository system.

In addition to the models presented in the flow chart, minor calculations are performed, for instance when post processing results or when preparing input data. These are not included in the present document as described in subsequent sections.

### **2.2 Computer codes and AMF activities**

While the AMF's show the different modelling activities performed within the framework of the safety assessment, Table 2-1 and Table 2-2 show computer codes used for each modelling task. In the tables, the section in the present report where the code is reported is listed together with the reference to the report in which the results of the calculations are presented.

### **2.3 Types of codes used in the assessment**

In the AMF's, a large number of modelling activities can be identified. Table 2-1 and Table 2-2 show these together with the different codes that are used for the modelling activities. The complexity of the computer codes ranges from simple routines written in scripts languages in commercially available codes like MATLAB or Microsoft Excel to large programs (thousands of lines) written in programming languages like C++ and Fortran. Also the origin of the codes differs substantially. While some are commercial, have a large world-wide user base and can be regarded as well tested, others are written exclusively for the safety assessment at hand.

For codes developed within the framework of the SKB safety assessments, the source codes are generally available for review as opposed to commercially available codes where the quality assurance procedures of the developer have to be accepted. A differentiated approach to quality assurance, with adaptations to the types of codes used in the assessment, is thus required.

The following categories of computer codes have been identified:

1. Commercial system software such as operating systems, compilers and data base software. Although necessary for the assessment, these codes are not regarded as assessment codes and are hence not included in the AMF or in the model documentation.
2. Software used to solve problems that can be verified by simple hand calculations. This category also includes codes used for unit conversion and pre- and post-processing of data. This category is not included in this document.
3. Wide-spread commercial or open source codes. These have a large user base and are therefore considered to be sufficiently well tested. Therefore, the need for verification tests within SR-Site is limited. These codes are not written exclusively for the safety assessment and the user of the code may in many cases be an expert on using the code in general. The documentation for these codes is generally extensive but may not be written with any particular application in mind. Source codes for the commercial codes are generally not available for review and the development process has been carried out independent of the SR-Site project. Using these codes for assessment calculations implies that the QA procedures used by the developer of the codes are accepted.
- 4a. Modified commercial codes. Some commercially available codes allow the user to add functionality to the original code through standardised methods with the extension working as an integrated part of the original code. Since functionality is added, the need for verification studies is larger than for codes in the previous category. Verification studies within SR-Site are however only required for the added functionality and not for the original code. Using these codes for assessment calculations implies that the QA procedures used by the developer of the codes are accepted, but also that good developing practices are followed for the part of the code developed within the safety assessment.
- 4b. Calculations performed with codes developed within the safety assessment, frequently written in languages like C++ and Fortran. These codes are in general written with the safety assessment application in mind and have a considerably smaller user base than codes in category 3. The need for verification is thus larger for these codes.

There may be cases where it is not evident whether a code should be in category 4a or in category 4b. Codes developed within the project may for instance contain routines from mathematical libraries (like ODE solvers etc) which are well tested and have a large user base. However, the basic requirement (showing QA compliance for the parts that is not part of the original code) is the same for 4a and 4b.

Based on these categories, the quality assurance procedures for each type of code are presented in the following section.

## 2.4 Requirements on assessment codes

Four basic requirements regarding quality assurance of codes and calculation results apply:

1. It must be demonstrated that the code is suitable for its purpose. This is required for all categories defined above.
2. It must be demonstrated that the code has been properly used. This is required for all categories defined above.
3. It must be demonstrated that the code development process has followed appropriate procedures and that the code produces accurate results. This requirement applies to codes in category 4 since these have been developed by the implementer. For codes in categories 1 to 3, the procedures of the developer are accepted.
4. It must be described how data are transferred between the different computational tasks. Note that this does not include a description on how data are handled internally by the model (covered in point 1 and 2 above and in documents where the calculations are presented), instead this section addresses data transfer between modelling activities. Due to the large number of modelling activities, it is possible that data is passed between activities in many different ways.

The requirements are further described below and a template to be used when writing the code presentation for the model summary report is given in Section 2.5. Of the six headings in the template, four relate directly to the basic requirements stated above.

## **2.5 Template used for reporting the codes in Chapter 3**

### **2.5.1 Introduction**

The code is briefly introduced and the categorisation according to the definition in Section 2.4 is given. This section should contain the following:

- A brief description of the problem solved by the code in the SR-Site assessment.
- The usage of the code in previous performance assessments (at SKB or elsewhere) and, if relevant, which previously used code it supersedes and the reason for this.
- The version of the code and the platform used in the assessment calculations.
- The category chosen for the code, based on the definition in Section 2.3, and a description of how the code has been developed.

This part may be written either by the SR-Site team or by subcontractors using the code.

### **2.5.2 Suitability of the code**

It needs to be shown that the code is suitable for solving the problem at hand. One indication of suitability included in this description concerns the used input parameter ranges. The parameter ranges should be within those for which the computer code gives acceptable results. This section should contain the following information:

- A description (or references to supporting documents) of mathematical models (the equations to be solved) and a description of the methods by which the solution is obtained.

This part may be written either by the SR-Site team or by subcontractors using the code.

### **2.5.3 Usage of the code**

It needs to be shown that sufficient information on the usage of the code is available. This section should contain the following:

- A description of how the code is documented. Clearly, the format of the documentation may differ considerably between different codes and is hence not specified in this template. In some cases, for instance spreadsheet codes in Microsoft Excel, the documentation may be included in the spreadsheet/code itself and no additional documentation is required. For commercial codes, the existing documentation is in most cases sufficient.

This part may be written either by the SR-Site team or by subcontractors using the code.

### **2.5.4 Development process and verification**

For codes that have been developed for the SR-Site project (category 4) it needs to be shown that the development process has been carried out in an appropriate manner. This section should contain the following:

- The measures that have been taken to ensure that the code produces the correct solution to the mathematical problem. This can e.g. be achieved by comparison to solutions obtained with other codes or to analytic solutions for special cases, if available.
- A description of how consistency of results between different versions of the code is demonstrated. This may be done using a test batch with examples that proves the functionality of the code.

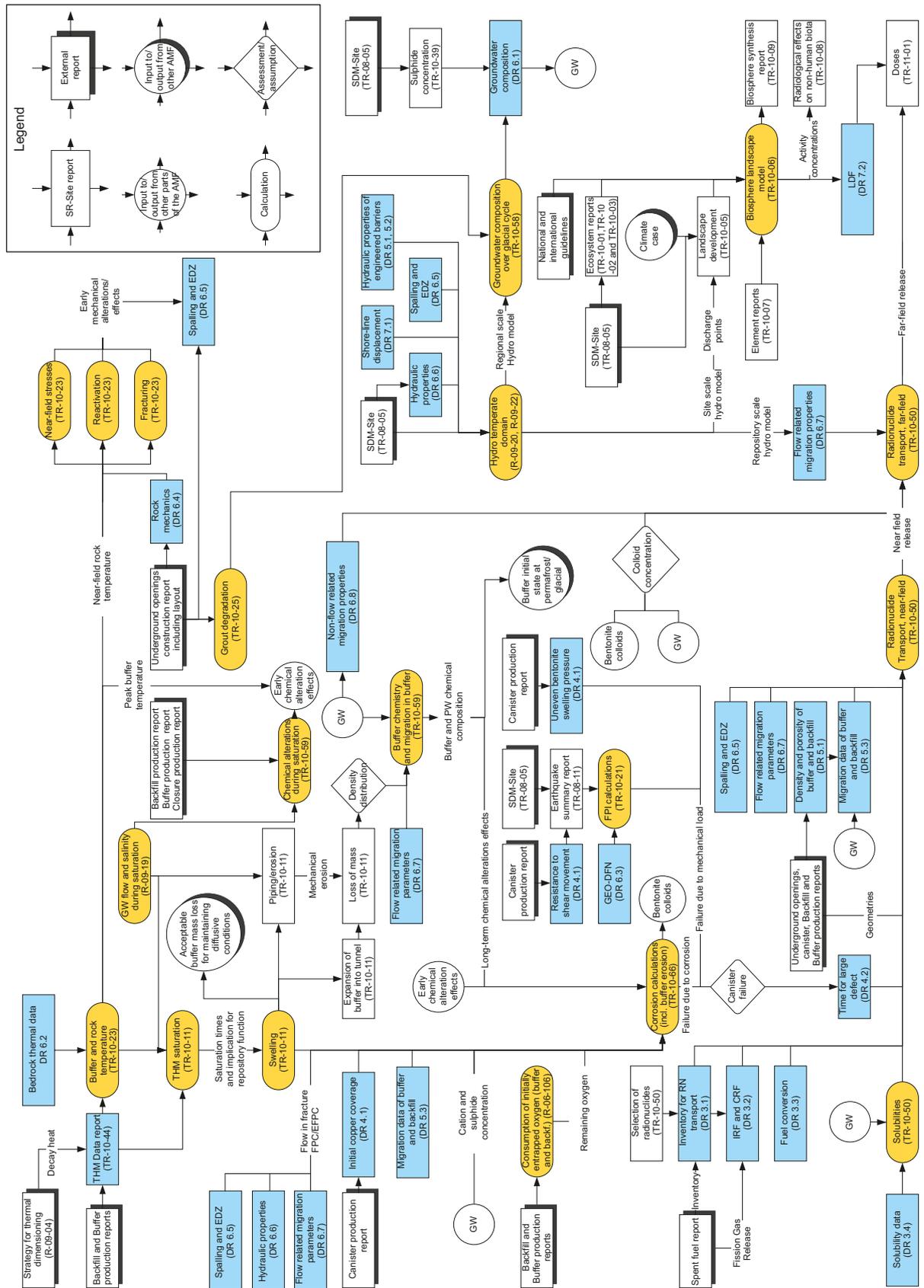
This part may be written either by the SR-Site team or by subcontractors using the code.

### **2.5.5 Handling of input data, computational results and scripts**

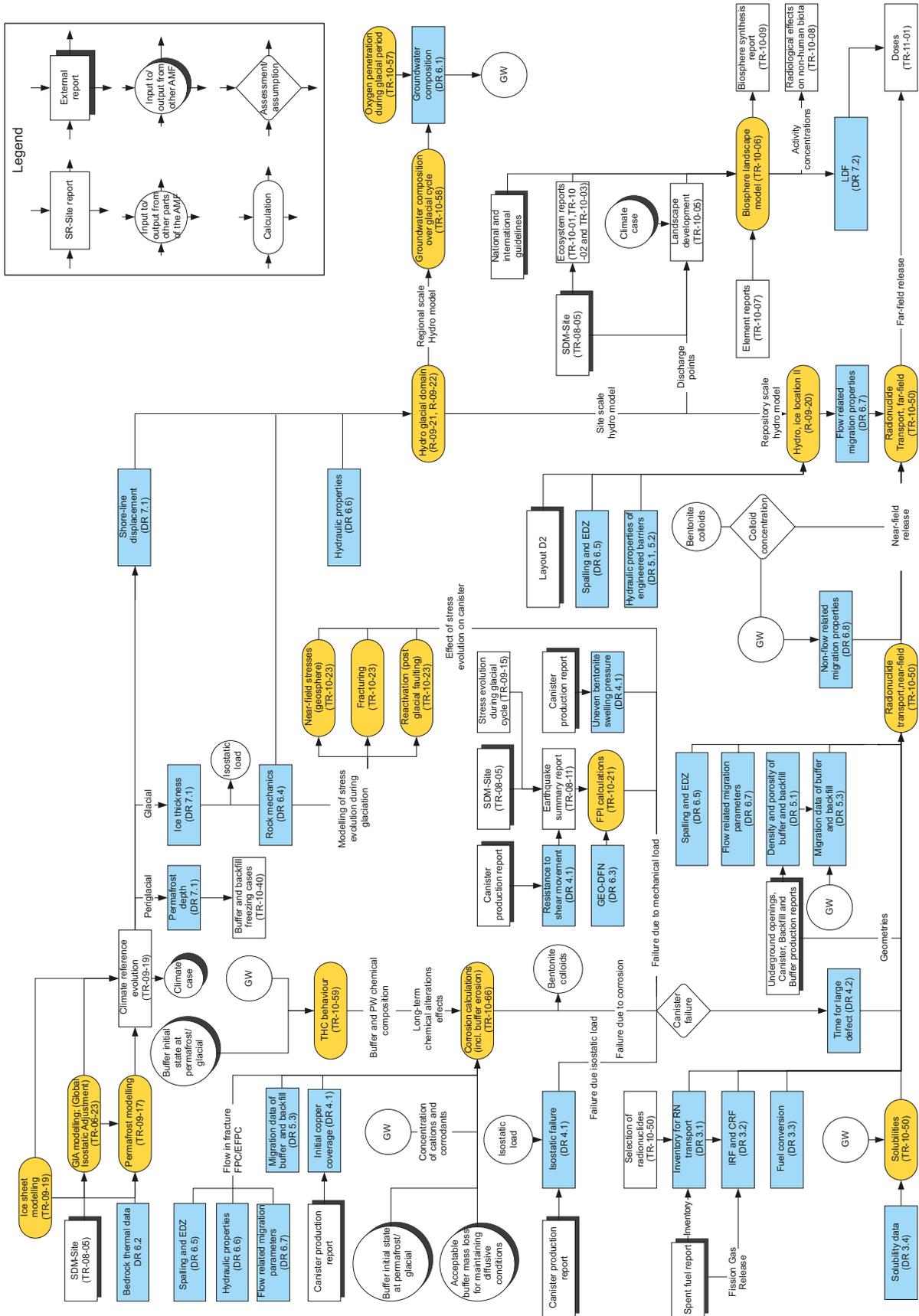
In this section it is described how data are passed between the model at hand and other models in the AMF. In this section it is also described how results and scripts used in the calculations are archived. It is also recommended to describe how the working process is controlled, for example if the version management system Subversion SVN /Küng and Onken 2009/ is used to keep track of changes. This part may be written either by the SR-Site team or by subcontractors using the code.

### **2.5.6 Rationales for using the code in the assessment**

Under this heading, the formal decision to use the code in the assessment is provided together with a brief motivation (this text is written by the SR-Site team).



**Figure 2-1.** The assessment model flow chart for the excavation/operation period and the initial temperate period after closure. In the AMF, modelling activities covered in the present report can be seen as yellow rounded rectangles. Input data and results (input data to other models) presented in the **Data report (DR)** appears as blue rectangles (with reference to the section in the Data report). Data in other reports are presented as rectangles.



**Figure 2-2.** The assessment model flow chart for permafrost and glacial conditions. In the AMF, modelling activities covered in the present report can be seen as yellow rounded rectangles. Input data and results (input data to other models) presented in the Data report (DR) appears as blue rectangles (with reference to the section in the **Data report**). Data in other reports are presented as rectangles.

**Table 2-1. Links between modelling activities in the AMF for excavation/operation and temperate periods (Figure 2-1) and the computer codes used. The modelling activities in the left column correspond to yellow objects in Figure 2-1.**

Modelling activity in AMF	Code used	Presented in section	Modelling report Reference	In AMF
Buffer and rock temperature	3DEC	3.1	Hökmark et al. 2010	TR-10-23
THM saturation (buffer and backfill)	Abaqus	3.2	Åkesson et al. 2010	TR-10-11
Near-field stresses (geosphere)	3DEC	3.1	Hökmark et al. 2010	TR-10-23
Reactivation	3DEC	3.1	Hökmark et al. 2010	TR-10-23
Fracturing (spalling)	3DEC	3.1	Hökmark et al. 2010	TR-10-23
FPI calculations: calculation of the occurrence of Full Perimeter Intersecting fractures in deposition tunnels	FPI script in MATLAB	3.11, 3.13	Munier 2010	TR-10-21
Chemical alterations during saturation (geosphere)	PHAST	3.18	Sena et al. 2010	TR-10-59
Grout degradation	CODE_BRIGHT	3.4	Grandia et al. 2010	TR-10-25
Groundwater flow and salinity during saturation	DarcyTools	3.6	Svensson and Follin 2010	R-09-19
Swelling	Abaqus	3.2	Åkesson et al. 2010	TR-10-11
	CODE_BRIGHT	3.4	Åkesson et al. 2010	TR-10-11
Buffer chemistry and migration in buffer	PHAST, TOUGHREACT	3.18, 3.21	Sena et al. 2010	TR-10-59
Consumption of initially entrapped oxygen (buffer and backfill)	PHAST	3.18	Grandia et al. 2006	TR-06-106
Corrosion calculations (including buffer erosion calculations)	Analytical expressions (Excel)	3.3	SKB 2010	TR-10-66
Hydro temperate domain	ConnectFlow	3.5	Joyce et al. 2010 Selroos and Follin 2010	R-09-20 R-09-22
Groundwater composition over glacial cycle	PHREEQC	3.19	Salas et al. 2010	TR-10-58
Solubilities	Simple Functions	3.20	<b>Radionuclide transport report</b>	TR-10-50
Radionuclide transport, near-field	COMP23	3.12	<b>Radionuclide transport report</b>	TR-10-50
Radionuclide transport, far-field	FARF31	3.9	<b>Radionuclide transport report</b>	TR-10-50
	MARFA	3.10	<b>Radionuclide transport report</b>	TR-10-50
Biosphere landscape model	Ecolego	3.7	Avila et al. 2010	TR-10-06
	MIKE_SHE	3.15	Avila et al. 2010	TR-10-06
	Pandora	3.14	Avila et al. 2010	TR-10-06
	Erica	3.8	Avila et al. 2010	TR-10-06

**Table 2-2. Links between modelling activities in the AMF for permafrost and glacial periods (Figure 2-2) and the computer codes used. The modelling activities in the left column correspond to yellow objects in Figure 2-2.**

Modelling activity in AMF	Code	Code presented in section	Modelling report Reference	In AMF
Permafrost modelling	Numerical permafrost model	3.17	<b>Climate report</b> , details in Hartikainen et al. 2010	TR-09-17
Ice sheet modelling	UMISM	3.22	<b>Climate report</b>	TR-09-19
GIA modelling (Global Isostatic Adjustment)	Numerical GIA model	3.16	<b>Climate report</b> , details in SKB 2006a	TR-06-23
FPI calculations; calculation of the occurrence of Full Perimeter Intersecting fractures in deposition tunnels	FPI script in MATLAB	3.11, 3.13	Munier 2010	TR-10-21
Near-field stresses (geosphere)	3DEC	3.1	Hökmark et al. 2010	TR-10-23
Reactivation	3DEC	3.1	Hökmark et al. 2010	TR-10-23
Fracturing	3DEC	3.1	Hökmark et al. 2010	TR-10-23
Groundwater composition over glacial cycle	PHREEQC	3.19	Salas et al. 2010	TR-10-58
Hydro, glacial domain	DarcyTools	3.6	Vidstrand et al. 2010 Selroos and Follin 2010	R-09-21 R-09-22
Hydro, ice location II	DarcyTools	3.6	Joyce et al. 2010	R-09-20
Oxygen penetration during glacial period	PHREEQC, PHAST	3.19, 3.18	Sidborn et al. 2010	TR-10-57
THC behaviour	PHAST	3.18	Sena et al. 1020	TR-10-59
Corrosion calculations (including buffer erosion calculations)	Analytical expressions (Excel)	3.3	SKB 2010	TR-10-66
Solubilities	Simple functions	3.20	<b>Radionuclide transport report</b>	TR-10-50
Radionuclide transport near-field	COMP23	3.12	<b>Radionuclide transport report</b>	TR-10-50
Radionuclide transport far-field	FARF31	3.9	<b>Radionuclide transport report</b>	TR-10-50
	MARFA	3.10	<b>Radionuclide transport report</b>	TR-10-50
Biosphere landscape model	Ecolego	3.7	Avila et al. 2010	TR-10-06
	MIKE_SHE	3.15	Avila et al. 2010	TR-10-06
	Pandora	3.14	Avila et al. 2010	TR-10-06
	Erica	3.8	Avila et al. 2010	TR-10-06

## 3 Description of the codes

This chapter provides a description of the codes used in the SR-Site safety assessment based on the models identified in the assessment model flowcharts. Each modelling activity and its associated code are presented in Table 2-1 and Table 2-2. The text for each code follows the outline presented in Section 2.5.

### 3.1 3DEC

#### 3.1.1 Introduction

3DEC simulates the mechanical and thermo-mechanical response of discontinuous media subjected to either static or dynamic loading. 3DEC is a three-dimensional numerical program based on the distinct element method for discontinuum modelling /Itasca 2003, 2007/. The program is based on the extensively tested formulation used by the two-dimensional version UDEC /Itasca 2005/.

3DEC was originally developed for stability analyses of rock slopes. It has been used for studies related to mining engineering and for studies related to deep disposal of nuclear wastes. Both static and dynamic analyses for deep underground openings have been performed, see for instance /Stephansson et al. 1991, Sjöberg 1992, Senseny 1993/. 3DEC has been used by SKB in earlier studies regarding thermo-mechanical effects on the bedrock around a deep repository /Hakami et al. 1998/. Much of the rock mechanics analyses referred to in SR 97 were conducted using 3DEC. In SR-Can, 3DEC was used for static analyses of mechanical effects on rock and rock fractures within and around the repository /Fälth and Hökmark 2007/, and for dynamic analyses of fracture shear displacements induced by post-glacial fault movements /Fälth and Hökmark 2006/.

In SR-Site 3DEC is used for similar analyses as those carried out in SR-Can:

- Static analyses of mechanical effects on rock and rock fractures within and around the repository. Effects caused by excavation of the repository openings, by pore pressures, by heat generation and glacial loads are considered. Effects of particular interest are creation of stress concentrations around the repository openings and fracture displacements that may change the hydraulic conditions. Both near-field and large-scale models are analysed /Hökmark et al. 2010/. For these analyses, version 4.1 of 3DEC is used /Itasca 2007/.
- Dynamic earthquake simulations are carried out in order to make estimates of the possible effects that post-glacial seismic events in pre-existing deformation zones may have on nearby fractures in terms of induced shear displacements /Fälth et al. 2010/. For these analyses, version 3.0 of 3DEC is used /Itasca 2003/.

The SR-Site 3DEC analyses are run on Windows-based PC-systems. Since 3DEC is a wide-spread commercial code which allows the user to add functionality by use of the built-in programming language FISH, and since specifically developed FISH routines are integral parts of the SR-Site application calculations, 3DEC is regarded as a category 4a code.

#### 3.1.2 Suitability of the code

3DEC is specially designed for mechanical analysis of jointed rock masses. The discontinuous medium is represented by an assemblage of discrete blocks and the discontinuities are treated as boundary conditions between the blocks. Large displacements along discontinuities and large rotations of blocks are allowed. The blocks may be either rigid or deformable. Deformable blocks are subdivided into a mesh of finite difference elements, which respond according to either linear or non-linear stress-strain laws /Itasca 2003/. The relative displacements along the discontinuities are also governed by linear or non-linear force-displacement laws, both in the normal- and shear directions. 3DEC also has a thermal logic implemented, which is specially oriented for solving design problems related to nuclear waste disposal. The temperatures at all node locations are calculated for specified “snapshots” in time by use of analytical point- and line source solutions. The temperatures (and temperature increments) are

then used by the mechanical logic in 3DEC for the calculation of thermal stresses. The thermal logic is based on linear thermal conduction and superposition of temperature contributions from different heat sources. The material is assumed to be thermally homogenous and isotropic with constant properties.

In the assessment work, the rock continuum, i.e. the intact rock between the discontinuities, is modelled as a linear elastic material. For the mechanical response of the discontinuities (fractures), an elastic and ideal-plastic law is applied assuming linear behaviour in the elastic range combined with the Mohr-Coulomb failure criterion.

The embedded programming language FISH is used for a number of tasks:

- The coordinates for each heat source are imported into 3DEC using FISH.
- It is used to reduce computer run time when analyzing thermo-mechanical static near-field models. 3DEC temperatures are calculated once for each set of models and then imported into different model versions using a specifically developed FISH routine.
- FISH is used for the development of a technique for defining circular-shaped fractures by assigning specific fracture material properties to selected parts of the discontinuities. This functionality is used in both the static analyses and in the dynamic earthquake simulations.
- In order to suppress irrelevant fracture shear movements in static thermo-mechanical models, a FISH routine is used to control fracture shear strength after each step-wise change of thermal stresses. It is also used to set pore pressures in the fractures.
- FISH is used to control boundary movements in the thermo-mechanical static near-field models.

In the earthquake simulations, FISH is used to control the initiation and propagation of fault rupture. Parameter values used in the SR-Site applications, i.e. values of rock mass and intact rock elastic parameters, values of fracture strength and fracture stiffness as well as values of rock thermal properties, are well within ranges covered by verified examples of analyses found in the extensive 3DEC literature, see e.g. /Last and Harper 1990, Kulatilake et al. 1992, Cappa et al. 2006/.

### **3.1.3 Usage of the code**

The documentation of 3DEC /Itasca 2003, 2007/ is provided by Itasca Consulting Group Inc. The documentation contains a complete description of the code and of the constitutive models that are implemented. A specific part of the documentation contains a description of the FISH language.

Text files containing all model data (geometries, material data, initial- and boundary conditions, solution strategies) are used as input to the code. In the input files, specific results to be monitored and recorded during the analysis can be specified. These results can be plotted or exported as text files. The FISH scripts are also written as text files. The scripts are activated by data calls in the input files.

3DEC has a plotting tool, which can be used for control of the model (geometry, application of boundary conditions etc) during model building. The plotting tool also have a wide range of possibilities for producing vector- and contour plots used during post processing of calculation results.

### **3.1.4 Development process and verification**

The formulation and development of the distinct element method, which is the core in 3DEC, begun in 1971 with the initial presentation /Cundall 1971/ and the development has been in progress since then. The 3DEC documentation includes a suite of systematic comparisons between 3DEC results and corresponding analytical solutions. Models with different types of geometry, different types of material behaviour and different types of boundary conditions are included. At present time, the code is subject for progressive development.

The specific FISH routines developed for use in the safety assessment calculations were rigorously tested and verified in small test models before implementation into the assessment models. Information regarding some specific FISH routines can be found in /Fälth et al. 2010/.

### 3.1.5 Handling of input data, computational results and scripts

The results from the static models analysed by /Hökmark et al. 2010/ were documented and evaluated within that study. They were used to make estimates of the potential for thermally induced spalling around the repository openings and of transmissivity changes in fractures and fracture zones. The text files containing all model input data and the corresponding FISH scripts are stored at Clay Technology's data server (administrativa dokument\Projekt\3DEC SR-Site\data) as well as at the record management system at SKB (SKBdoc 1264505, see Table 1-2).

The results from the dynamic earthquake models analysed by /Fälth et al. 2010/ were documented and evaluated within that study where they were used for the development of schematic deposition rules. The text files containing all model input data and the corresponding FISH scripts are stored at Clay Technology's data server (administrativa dokument\Projekt\3DEC dynamik\data\Input files (TR-08-11)) as well as at the record management system at SKB (SKBdoc 1264508, see Table 1-2).

### 3.1.6 Rationales for using the code in SR-Site

The code 3DEC has been thoroughly tested within the framework of SR-Can and shown to be adequate for the intended purpose. Models and scripts have been successively developed and backward traceability is thereby warranted. The SR-Site team still considers 3DEC being the code that best fulfil the purpose of the modelling and has therefore chosen to continue using 3DEC as the main tool both for static analyses and dynamic earthquake analyses.

## 3.2 Abaqus

### 3.2.1 Introduction

Abaqus is a suite of powerful engineering simulation programs, based on the finite element method, that can solve problems ranging from relatively simple linear analyses to the most challenging nonlinear simulations. Abaqus contains an extensive library of elements that can model virtually any geometry. It has an equally extensive list of material models that can simulate the behaviour of most typical engineering materials including metals, rubber, polymers, composites, reinforced concrete, crushable and resilient foams, and geotechnical materials such as soils and rock. Designed as a general-purpose simulation tool, Abaqus can be used to study more than just structural (stress/displacement) problems. It can simulate problems in such diverse areas as heat transfer, mass diffusion, thermal management of electrical components (coupled thermal-electrical analyses), acoustics, soil mechanics (coupled pore fluid-stress analyses), piezoelectric analysis, and fluid dynamics.

Abaqus offers a wide range of capabilities for simulation of linear and nonlinear applications. Problems with multiple components are modelled by associating the geometry defining each component with the appropriate material models and specifying component interactions. In a nonlinear analysis Abaqus automatically chooses appropriate load increments and convergence tolerances and continually adjusts them during the analysis to ensure that an accurate solution is obtained efficiently.

#### ***Interaction***

Manufacturing processes, bolted assemblies, snap-fits, and impact events all involve interaction between contacting bodies. Understanding the behaviour of components when they come into contact is critical to designing better products. The Abaqus Unified FEA product suite provides comprehensive contact modelling capabilities such as the ability to model interactions between deformable bodies, rigid bodies, and self-contact.

The general contact capability in Abaqus automatically detects contact between different bodies with little need for user intervention. Solution accuracy is improved by eliminating the possibility of missed contact definitions. This powerful capability dramatically reduces the time needed to define contact for complex assemblies such as those found in automobiles, aircraft, consumer products, and portable electronics.

### ***Abaqus/Standard***

Abaqus/Standard is a general-purpose analysis product that can solve a wide range of linear and nonlinear problems involving the static, dynamic, thermal, and electrical response of components. Abaqus/Standard solves a system of equations implicitly at each solution “increment.” In contrast, Abaqus/Explicit marches a solution forward through time in small time increments without solving a coupled system of equations at each increment (or even forming a global stiffness matrix).

### ***Abaqus/Explicit***

Abaqus/Explicit is a special-purpose analysis product that uses an explicit dynamic finite element formulation. It is suitable for modelling brief, transient dynamic events, such as impact and blast problems, and is also very efficient for highly nonlinear problems involving changing contact conditions, such as forming simulations.

### ***Abaqus/CFD***

Abaqus/CFD is a computational fluid dynamics analysis product. It can solve a broad class of incompressible flow problems including laminar and turbulent flow, thermal convective flow, and deforming mesh problems.

### ***Abaqus/CAE***

Abaqus/CAE (Complete Abaqus Environment) is an interactive, graphical environment for Abaqus. It allows models to be created quickly and easily by producing or importing the geometry of the structure to be analyzed and decomposing the geometry into meshable regions. Physical and material properties can be assigned to the geometry, together with loads and boundary conditions. Abaqus/CAE contains very powerful options to mesh the geometry and to verify the resulting analysis model. Once the model is complete, Abaqus/CAE can submit, monitor, and control the analysis jobs. The Visualization module can then be used to interpret the results.

### ***Abaqus/Aqua***

Abaqus/Aqua is a set of optional capabilities that can be added to Abaqus/Standard. It is intended for the simulation of offshore structures, such as oil platforms. Some of the optional capabilities include the effects of wave and wind loading and buoyancy.

### ***Abaqus/Design***

Abaqus/Design is a set of optional capabilities that can be added to Abaqus/Standard to perform design sensitivity calculations.

### ***Geometry translators***

Abaqus provides the following translators for converting geometry from third-party CAD systems to parts and assemblies for Abaqus/CAE:

- The CATIA V5 Associative Interface creates a link between CATIA V5 and Abaqus/CAE that allows you to transfer model data and propagate design changes from CATIA V5 to Abaqus/CAE.
- The SolidWorks Associative Interface creates a link between SolidWorks and Abaqus/CAE that allows you to transfer model data and propagate design changes from SolidWorks to Abaqus/CAE.
- The Pro/ENGINEER Associative Interface creates a link between Pro/ENGINEER and Abaqus/CAE that allows you to transfer model data and propagate design changes between Pro/ENGINEER and Abaqus/CAE.
- The Geometry Translator for CATIA V4 allows you to import the geometry of CATIA V4-format parts and assemblies directly into Abaqus/CAE.
- The Geometry Translator for I-DEAS converts parts and assemblies in I-DEAS to geometry files that can be imported by Abaqus/CAE.
- The Geometry Translator for Parasolid allows you to import the geometry of Parasolid-format parts and assemblies directly into Abaqus/CAE.

In addition, the NX Associative Interface creates a link between NX and Abaqus/CAE that allows you to transfer model data and propagate design changes between NX and Abaqus/CAE. The NX Associative Interface can be purchased and downloaded from the Elysium web site.

### **Translator utilities**

Abaqus provides the following translators for converting entities from third-party preprocessors to input for Abaqus analyses or for converting output from Abaqus analyses to entities for third-party postprocessors:

- abaqus fromansys translates an ANSYS input file to an Abaqus input file.
- abaqus fromnastran translates a Nastran bulk data file to an Abaqus input file.
- abaqus frompamcrash translates a PAM-CRASH input file into an Abaqus input file.
- abaqus fromradioss translates a RADIOSS input file into an Abaqus input file.
- abaqus tonastran translates an Abaqus input file to Nastran bulk data file format.
- abaqus toOutput2 translates an Abaqus output database file to the NastranOutput2 file format.
- abaqus tozaero enables the exchange of aeroelastic data between Abaqus and ZAERO.

Abaqus is a widely spread commercial Finite element code developed and supported by Dassault Systèmes that has been available on the market for more than 40 years.

In the SR-Site assessment, Abaqus has been used for a large range of applications, e.g. analyzing coupled thermo-hydro-mechanical (THM) problems or when simulating the response of the canister and buffer due to earthquake induced shear load. For the earthquake simulation, glacial load has also been included. These modelling activities have been presented in the following supporting documents to the assessment:

- Buffer homogenization /Åkesson et al. 2010a/.
- Canister sinking /Åkesson et al. 2010a/.
- Modelling and analysis of canister and buffer for earthquake induced rock shear and glacial load /Hernelind 2010/.

The buffer homogenisation modelling activities are part of the Canister Retrieval Test (CRT) within the Task Force for Engineered Barrier Systems (TF-EBS). The test was, in this context, used to study material models for unsaturated bentonite blocks and calculation techniques. Very similar results were reached with the Abaqus and the CODE\_BRIGHT model, see Section 3.4 /Åkesson et al. 2010a/ where a more detailed description of the modelling activity is given. Abaqus has been used for solving THM problems since SR97 /Börgesson and Hernelind 1999/.

For modelling of canister sinking, Abaqus was used to simulate the vertical movement of a canister emplaced in a deposition hole due to creep. The equations to be solved and the material models used is presented in the modelling report /Åkesson et al. 2010a/, corresponding problems were solved using Abaqus in SR-Can /Börgesson and Hernelind 2006a/. In SR-Can, Abaqus was used to simulate Rock shear through a deposition hole /Börgesson et al. 2003, Börgesson and Hernelind 2006b/. Abaqus is regarded to belong to category 3 and category 4a when user defined subroutines are used to extend the functionality.

Different versions of Abaqus (e.g 6.6-PR3, 6.7-5 and 6.8-1) has been used, mainly due to which latest version is available when the analyses are performed.

### **3.2.2 Suitability of the code**

Abaqus is used for a number of tasks in SR-Site, the equation solved are further described in each modelling report /Åkesson et al. 2010a, Hernelind 2010/. The code is especially well suited for large, non-linear models including general interaction between different components involving several different fields such as displacement, temperature and pore pressure.

### **3.2.3 Usage of the code**

Due to the large, world-wide user base there exists numerous user guides for the code, produced by the developer of the code and also by independent companies. The code is commonly used for different kind of mechanical modelling and there are common to find consultants specialised in using the code itself. Training classes are available at different levels both at universities and at private companies besides Dassault Systèmes.

### **3.2.4 Development process and validation**

No dedicated verification or validation tests of the Abaqus code have been performed within the SR-Site project (the code has however been used to study material models in the Canister retrieval test with good results). A description of the QA procedures of the manufacturer of the code is available on their webpage as listed below.

The formal Quality Assurance Management System is the foundation of their efforts to deliver high quality products and services at an acceptable cost.

There are two principal reasons they impose strict quality assurance: customer satisfaction and product reputation. The approach to quality assurance meets the ISO 9001:2008 standard. The processes in their Quality Management System are designed to meet the requirements set forth by the International Organization for Standardization as defined within the ISO 9001:2008 Standard and also to facilitate customer compliance with US Nuclear Regulatory Commission's quality assurance requirements for software used for calculations associated with the design of nuclear power facilities in the USA.

Their Quality Management System is founded on a collection of well-documented processes that incorporate multiple checks and balances. The development process, for example, ensures that development is performed as a collaborative effort with proposal, design, code, and test review performed by a team representing developers, technical writers, the Quality Assurance group, management, and customers. Similarly, the bug management process calls for each bug to be reviewed by the Bug Manager, Quality Assurance Manager, and development group manager. Throughout the products' lifecycles, documented plans, formal signoffs, and dashboard-like status tracking facilitate establishing, communicating, and achieving clearly defined quality objectives.

There is no question that these efforts are resource intensive. Equally, there is no question that they are firmly committed to these processes, because the quality of their products and services is central to the long-term health of their relationships with their customers.

When user defined subroutines are used these have been verified by using simple test examples with known solutions (if possible) or by careful inspection of the obtained results.

### **3.2.5 Handling of input data, computational results and scripts**

#### ***Buffer homogenisation and canister sinking***

Input-files are stored on disk-systems at 5T Engineering and are archived at SKB's record management system (SKBdoc 1265608, see Table 1-2).

#### ***Modelling and analysis of canister and buffer for earthquake induced rock shear and glacial load***

Scripts and input-files used for the analyses presented in /Hernelind 2010/ have been archived in SKB's record management system (SKBdoc 1258988, see Table 1-2).

### **3.2.6 Rationales for using the code in SR-Site**

The SR-Site team and the contractors involved in the modelling task consider Abaqus to be a suitable code for the applications, the code is regarded to be one of the dominating softwares in its field and is widely spread and commonly used by the subcontractors.

### **3.3 Analytical model for quantification of buffer erosion and canister corrosion**

#### **3.3.1 Introduction**

This model uses simple analytical expressions, derived and qualified elsewhere in the SR-Site documentation, for calculations of the extent of buffer erosion and canister corrosion /SKB 2010/. The calculations are performed in Microsoft Excel.

The code is developed specifically for SKB and is classified as category 4b. A first version of the code was used in the safety assessment SR-Can /SKB 2006b/. The final calculations in SR-Site were done with versions 0.7 and 0.8. The final SR-Site version 1.0 differs from v 0.8 only with respect to the comments in the Excel sheet.

#### **3.3.2 Suitability of the code**

The SR-Site mathematical models for buffer erosion and canister corrosion are simple analytical expressions, described in /SKB 2010/, that are readily implemented in this spreadsheet code. This code is thus suitable for calculations of the two processes in the safety assessment SR-Site.

#### **3.3.3 Usage of the code**

The code is implemented as a Microsoft Excel-file (SKBdoc 1265612, see Table 1-2). Simple user instructions are provided in the file.

#### **3.3.4 Development process and verification**

A first version of the code was developed for the safety assessment SR-Can /SKB 2006/. The SR-Site version of the code has been developed in several steps as documented in a history sheet in the Excel-file (SKBdoc 1265612, see Table 1-2). The mathematical expressions for erosion and corrosion are presented in /SKB 2010/. It has been verified that the code yields identical results as example calculations referred to in /SKB 2010/.

#### **3.3.5 Handling of input data, computational results and scripts**

Most input data are entered manually in the Excel-file and have default values that are write-locked in a specific version of the code. Hydrogeological input data (SKBdoc 1260297, 1256019, see Table 1-2) are provided in separate Excel files that are linked to the calculation file.

Key results of the extent of erosion and corrosion are obtained in a few output cells in the Excel file.

Results to be used as input to radionuclide transport calculations are automatically generated in a dedicated sheet, on a format suitable for that purpose. These data are stored in SKBdoc 1265612 (see Table 1-2).

The code is basically run in a single realisation mode. An Excel script (macro) is available to automatically run a number of realisations of a particular hydrogeological model. The Excel add-in @Risk is then used in combination with the script.

#### **3.3.6 Rationales for using the code in the assessment**

The code is tailor made for the needs in the SR-Site assessment. It has been developed and is used by members of the SR-Site project.

## 3.4 CODE\_BRIGHT

### 3.4.1 Introduction

In the SR-Site safety assessment, CODE\_BRIGHT (COupled DEformation BRIne, Gas and Heat Transport) is utilized for solving coupled thermo-hydro-mechanical (THM) problems in geological media. A large part of the TH, HM and THM simulations presented in /Åkesson et al. 2010a/ has been produced using CODE\_BRIGHT. Some examples from /Åkesson et al. 2010a/ where CODE\_BRIGHT is used are: Backfill saturation (H), Buffer saturation (TH), Buffer homogenization (THM), Backfill homogenization (HM) and Tunnel plug saturation (H). In addition, CODE\_BRIGHT has been used in model calculations of grout degradation /Grandia et al. 2010/.

In the SR-Can safety assessment, CODE\_BRIGHT was used for investigating the influence of trapped air in the backfill /Börjesson et al. 2006/. For references to other work concerning radioactive waste disposal where CODE\_BRIGHT has been used, see /CODE\_BRIGHT v3 Validation document 2009/. CODE\_BRIGHT has been extensively verified and validated in international benchmark exercises, documented in /CODE\_BRIGHT v3 Validation document 2009/, and has been applied to the analysis of different geoenvironmental schemes, waste disposal designs and geotechnical problems involving saturated/unsaturated soil behaviour.

CODE\_BRIGHT is a Fortran code. Four different versions of the code, running on Windows platforms, have been used in the work with SR-Site assessment:

- Version 2.2 (category 3).
- Version 3beta (category 3).
- Version 3beta with modification 1 (category 4a).
- Version 3beta with modifications 1 and 2 (category 4a).

The unmodified code versions belong to category 3, whereas the modified code versions belong to category 4a. The modifications concern one of the mechanical constitutive laws, based on the Barcelona Basic Model (BBM).

In modification 1 the swelling modulus  $\kappa_s$  of BBM is made dependent on the void ratio by using experimental swelling pressure curves, see /Åkesson et al. 2010a, Appendix C/. Modification 2 consists of incorporation of a varying critical state line slope parameter  $M$  that is governed by an experimentally motivated deviatoric failure stress curve, see /Åkesson et al. 2010a, Appendix D/.

Research and development of the code is supported by the UPC (Technical University of Catalonia) and CIMNE (International Center for Numerical Methods in Engineering at UPC). A consortium of international companies contributes financially to these developments and checks the efficiency and quality of the resulting software. The consortium also provides a valuable link with geoenvironmental and geotechnical engineering practice.

### 3.4.2 Suitability of the code

CODE\_BRIGHT is a tool designed to handle coupled THM problems in geological media. The code is able to solve non-saturated multiphase flow under non-isothermal conditions. The equations that govern the THM problem are categorized into four main groups, namely, balance equations, constitutive equations, equilibrium restrictions and definition constraints. Equations for mass balance were established following the compositional approach /Olivella et al. 1994/. That is, mass balance is performed for water, air and mineral species instead of using solid, liquid and gas phases. Equation for balance of energy is established for the medium as a whole. The equation of momentum balance for the porous medium is reduced to that of stress equilibrium /Olivella et al. 1996/.

The constitutive equations establish the link between the independent variables (or unknowns) and the dependent variables. There are several categories of dependent variables depending on the complexity with which they are related to the unknowns. Basic constitutive laws are divided in thermal, hydraulic and mechanical. The governing equations are finally written in terms of the unknowns when the constitutive equations are substituted into the balance equations. The unknowns are obtained by solving the system of PDE's (Partial Differential Equations) numerically in a coupled way. From state variables, dependent variables are calculated using the constitutive equations or the equilibrium restrictions.

For the numerical treatment of the different terms of the balance equations, the first step is the approximation of the material derivative with respect to the solid as an Eulerian derivative, owing to the assumption of small strain rate. Details related to the discretisation of the problem and the numerical technique used can be found in /CODE\_BRIGHT User's Guide 2009/. In summary, it can be mentioned that the numerical approach can be viewed as divided into two parts: spatial and temporal discretisation.

Regarding the boundary conditions of the mechanical problem, forces and displacement rate can be enforced in any spatial direction and at any node. In the hydraulic problem, mass flow rate of water and dry gas can be prescribed at any node, and liquid/gas pressure can be also enforced at any node. Finally, regarding the thermal problem, heat flow and temperature can be prescribed at any node of the mesh /CODE\_BRIGHT User's Guide 2009/.

For modelling the mechanics of buffer and backfill material, which consist of expansive bentonite clay, a thermo-elastoplastic law, based on BBM /Alonso et al. 1990/ which was developed to describe the hydro-mechanical behaviour of partially saturated soils, is used. In the safety assessment SR-Can /SKB 2006b/, the relevance of the thermo-elastoplastic model for highly expansive clays was identified as a subject for developments. The modifications made on this constitutive law, as described in /Åkesson et al. 2010a, Appendix C and Appendix D/, are results of the investigations made on this topic.

The parameter setting is discussed in detail in the SR-Site THM Data Report /Åkesson et al. 2010b/.

### **3.4.3 Usage of the code**

The documentation of CODE\_BRIGHT is provided by /CODE\_BRIGHT User's Guide 2009/. The documentation contains a description of the code and the models that are implemented.

CODE\_BRIGHT uses GiD system for preprocessing and post-processing. GiD is an interactive graphical user interface that is used for the definition, preparation and visualisation of all the data related to numerical simulations. This data includes the definition of the geometry, materials, conditions, solution information and other parameters. The program can also generate the finite element mesh and write the information for a numerical simulation in its adequate format for CODE\_BRIGHT. It is possible to run the numerical simulation directly from the GiD system and to visualise the results without transfer of files. Detailed information will be found in /CODE\_BRIGHT User's Guide 2009, chapters CODE\_BRIGHT Preprocess and Postprocess/.

### **3.4.4 Development process and verification**

CODE\_BRIGHT was developed at the UPC in the beginning of the 1990s /Olivella et al. 1994, 1996, Olivella 1995/. The code has been verified and validated through comparisons with analytical solutions for a number of problems, see /Olivella 1995, CODE\_BRIGHT v3 Verification document 2009/. In /CODE\_BRIGHT v3 Validation document 2009/ numerous references are given where CODE\_BRIGHT has been used.

The implemented modifications of the BBM-based mechanical constitutive law in the code are only active when mechanical problems are solved using this specific mechanical law. The code modification is contained within the part of the code describing the constitutive law. Thus, the foundation of the code has not been altered by the implementation of the modification. The implementations have been tested and validated for special cases where the solution is known. Where isotropic problems have been solved, the CODE\_BRIGHT solutions have been compared to solutions obtained by MathCad implementations. The modifications of the swelling modulus  $\kappa_s$  and critical state line slope parameter  $M$  are described in /Åkesson et al. 2010a, Appendix C and Appendix D, respectively/.

### **3.4.5 Handling of input data, computational results and scripts**

The results from the CODE\_BRIGHT models used for THM analyses by /Åkesson et al. 2010a/ were documented and evaluated within that study. They were used to analyse the saturation time, the homogenisation process and maximum temperatures for different system components. All input files to the CODE\_BRIGHT models are stored at Clay Technology's data server (Administrativa dokument\Projekt\THM SR-Site modellering\data) and archived at SKB (SKBdoc 1265606, see Table 1-2).

In the data archive the different tasks sorted in specific folders. These folders are divided in two folders, one for all CODE\_BRIGHT models and one for all additional documentation (\Task n (description)\FE-models, \Task n (description)\Other documents).

### **3.4.6 Rationales for using the code in the assessment**

CODE\_BRIGHT is regarded as a suitable code for solving the problem at hand. The contractor performing the calculations has a long experience in using the code.

## **3.5 ConnectFlow**

### **3.5.1 Introduction**

ConnectFlow is the suite of Serco's groundwater modelling software /Serco 2008a/ that includes the NAMMU /Serco 2008b/ continuous porous medium (CPM) module and the NAPSAC /Serco 2008c/ discrete fracture network (DFN) module. ConnectFlow is also the name given to the concept of nesting CPM and DFN sub-models into a combined CPM/DFN model. A further module, GeoVisage, is a dedicated 3D visualisation application for interpreting the results from ConnectFlow. Hence, ConnectFlow is a very flexible tool for modelling groundwater flow and transport in both fractured and porous media on a variety of scales. NAMMU was originally developed as part of UK Nirex programme. NAPSAC was initially developed as part of the international Stripa project /Herbert et al. 1991, Herbert and Lanyon 1992/. Integration of the DFN and CPM concepts started as part of UK Nirex programme /Jackson et al. 1997/ and the Äspö Task Force /Holton and Milický 1997/. ConnectFlow is now maintained and developed through the international *iCONNECT* club /Holton et al. 2003/ (including SKB, Posiva, NAGRA and Obayashi) and by other commercial users.

ConnectFlow has a long track-record of being used in the SKB programme since SR 97 /Boghammar et al. 1997, Hartley et al. 1998/. Bespoke developments have been made to suit the needs of site modelling and safety assessment calculations /Marsic et al. 2001, Marsic et al. 2002/. The role of the software in the safety assessment was proposed in /SKB 2003/ and illustrated in the SR-Can interim assessment /Hartley et al. 2004, SKB 2004/. The use of ConnectFlow within SR-Site is a natural progression from its application in the site-descriptive modelling /Follin 2008/. Connectflow version 9.6 is used in SR-Site.

The simulations for SR-Site have been run on a Linux cluster at Serco, Harwell, UK. Due to the relatively large user base, the software is of category 3 within SR-Site.

### **3.5.2 Suitability of the code**

The fractured nature of the rocks in the Östhammar and Oskarshamn areas requires the consideration of both DFN and equivalent CPM models, both to interpret the hydraulic properties of the rocks and to construct realistic models of flow and transport. ConnectFlow is unique in offering both these capabilities in the same package and allowing both approaches to be combined. In addition, ConnectFlow allows the modelling of a wide range of physical processes of relevance to SR-Site such as: transient groundwater flow; saturated and unsaturated groundwater flow; coupled groundwater flow and salt transport; transport of reference waters with rock matrix diffusion; coupled groundwater flow and heat transport; variable-density flow and transport in fracture networks; and radionuclide transport.

### **3.5.3 Usage of the code**

The capabilities of ConnectFlow are described in the Technical Summary Document /Serco 2008a/. Input data is supplied to the code as text files and results are output as binary files and as an ASCII log-file which can be checked for errors, warnings and issues such as convergence. The syntax of the input data and the input language is documented in the HTML Command Reference Manual. The code can also be run using a Graphical User Interface (GUI) which is documented by an on-line User Manual. Checking of input files is recorded by the originator and then cross-checked by a second user.

### 3.5.4 Development process and verification

ConnectFlow is maintained and developed under an appropriate QA programme /Serco 2008g/ by the Waste Management and Environment Department within Serco. The QA Programme conforms to the international standard BS EN ISO 9001 (2000) and to the TickIT Guidelines. The Concurrent Versions System (CVS) version management system is used to store all source code and test data for ConnectFlow. This automatically logs the author and date of each change to the system, and enables previous versions of the code to be accessed and recreated if necessary. All changes are thoroughly tested, and must be approved by the Software Manager before they are accepted. Through the ConnectFlow QA programme, Serco Assurance seeks to continually improve the quality and reliability of the program.

NAMMU has been verified within several international project including HYDROCOIN and INTRACOIN /SKI 1984, SKI 1986, NEA/SKI 1988/. NAPSAC has been verified within the STRIPA project /Herbert et al. 1991, Herbert and Lanyon 1992/. A full description of the verification of NAMMU and NAPSAC are given in /Serco 2008d, e/. Testing of combined models is reported in the ConnectFlow Verification Manual /Serco 2008f/. Each release of ConnectFlow is verified by running a full test set for all modules of the software with over 200 test cases.

### 3.5.5 Handling of input data, computational results and scripts

ConnectFlow runs are carried out using data sets written in ConnectFlow's command language. The input files for each run are specified in the header of the data set. Each input file is stored under the project directory on Serco's Linux cluster at Harwell, UK and is either generated by a previous ConnectFlow run or is downloaded from SKB's Trac system (svn/SR-SiteDataStorage). Some input files are processed by Java programs to produce input suitable for ConnectFlow, e.g. the IFZ files for the hydraulic conductor domains (HCD) and the grids for the repository layout. All Java programs and Perl scripts are kept under the project directory on Serco's Linux cluster at Harwell, UK.

Output files are also stored under the project directory on Serco's Linux cluster at Harwell, UK. Some of these are processed by Perl scripts to produce output suitable for delivery to other teams. The final output for delivery is uploaded to SKB's Trac system (svn/SR-SiteDataStorage).

The ConnectFlow input and output data used in SR-Site are archived at SKB (SKBdoc 1256019, see Table 1-2).

### 3.5.6 Rationales for using the code in SR-Site

ConnectFlow is used in SR-Site for saturated groundwater flow calculations to provide groundwater flow and transport inputs to safety assessment calculations. Since the code allows alternative conceptual models, such as a DFN, it has some advantages over a purely porous medium approach. There are several experienced users familiar with the SKB programme available to work on SR-Site.

## 3.6 DarcyTools

### 3.6.1 Introduction

DarcyTools is a computer code for simulation of flow and transport in porous and/or fractured media. The fractured media in mind is a fractured rock and the porous media the soil cover on the top of the rock.

DarcyTools is a general code for this class of problems, but the analysis of a repository for nuclear waste is the main intended application.

A number of novel features are introduced in DarcyTools. The most fundamental is perhaps the method to generate grid properties (DarcyTools is a continuum porous-media code); a fracture network, with properties given to each fracture, is represented "directly" in the computational grid. This method is believed to result in very accurate anisotropy and connectivity properties. Another key feature is the grid system; an unstructured Cartesian grid which accurately represents objects, read into the code as CAD-files, is used in DarcyTools v3.4.

DarcyTools is developed through collaborative effort by SKB, CFE AB (Computer-aided Fluid Engineering AB) and MFRDC (Michel Ferry Research&Development Consulting) with SKB as the owner of the code. DarcyTools builds upon earlier development of groundwater models, carried out by CFE AB during the last twenty years. One such early development is represented by /Svensson 1991/, where predictions of inflows to the Äspö HRL, prior to its construction, are reported. At this time the general purpose equation solver PHOENICS /Spalding 1981/ was used. DarcyTools is based on the solver MIGAL /Ferry 2002/ and the development work on DarcyTools was initiated early 2001. The first well documented version of DarcyTools is v2.1, which was released in 2004. Version 3.4 is the version presently in use and the updated documentation of this version is scheduled for the end of 2010. Both Windows and Red Hat Linux versions are available. The code is regarded as a category 4b code as the user base is small and limited to SKB projects. The SR-Site application of the code is described in recent publications /Svensson et al. 2010, Svensson 2010, Svensson and Ferry 2010/.

### **3.6.2 Suitability of the code**

Due to the collaborative (SKB and CFE AB/MFRDC) development of DarcyTools, it was from start decided that DarcyTools should be “the tailor-made SKB code”. It is hence not surprising that the key features of the code match the requested capabilities in for example site investigation or glaciation studies. It is beyond the scope of the present text to describe these features (see Svensson et al. 2010) but one may anyway mention: DFN-generation, free surface algorithm, multirate diffusion model and coupled groundwater flow and salt transport. In addition to useful features, a code needs to be efficient. The earlier mentioned unstructured grid in combination with the equation solver MIGAL (an unstructured multigrid solver) ensures that DarcyTools v3.4 is a state of the art code with respect to efficiency.

These features make DarcyTools v3.4 a suitable code for a wide range of problems that needs to be considered by SKB.

### **3.6.3 Usage of the code**

Three main documents /Svensson et al. 2010, Svensson 2010, Svensson and Ferry 2010/ describe the code and its use in detail. Recent real world applications, for example /Follin et al. 2005, Svensson and Follin 2010, Svensson and Rhén 2010, Vidstrand et al. 2010a, b/ provide other valuable sources of information.

One of the documents is a User’s Guide, which describe all input parameters. These input parameters make up the so called CIF (Compact Input File), which is written in XML format. DarcyTools also includes a Fortran input file, where more advanced features (transient boundary conditions, new source/sink terms, etc) can be introduced. Tecplot has been selected as the standard tool for post processing. Input files for Tecplot are readily generated.

An important part in the usage of the code is the monitoring of the simulation on the computer screen. Convergence parameters, development of variables in control points or profiles are plotted on the screen during the simulation. In v3.4 it is even possible to plot the distribution of variables in specified planes.

### **3.6.4 Development process and verification**

One of the three documents mentioned above, /Svensson 2010/, deals with verification, validation and demonstration. About thirty simple test cases, most with an analytical solution, are used to ensure that the equations are solved correctly. When a new major version of the code is released, all test cases are updated and checked to ensure both consistency with the old version and to make sure that the new version is correct. Validation is considered to be the process by which the code is shown to agree with measured data (“the right equations are solved”). A number of comparisons with field data are included in the above mentioned report. So far, no attempt to show that DarcyTools conforms to any international QA standard has been made.

### **3.6.5 Handling of input data, computational results and scripts**

Input files are downloaded from `svn/SR-SiteDataStorage` and stored on the working directory. In this directory, which is backed-up regularly, also output files and scripts for running various parts of the code are stored. DarcyTools results used by other models and analyses within SR-Site are stored in `svn/SR-SiteDataStorage`.

The DarcyTools input and output data used in SR-Site are archived at SKB (SKBdoc 1256019, see Table 1-2).

### **3.6.6 Rationales for using the code in SR-Can**

DarcyTools has been developed by CFE AB and MFRDC in cooperation with SKB especially for solving the problem at hand. The calculations have been performed by several consultants with assistance by the main developer of the code.

## **3.7 Ecolego**

### **3.7.1 Introduction**

Ecolego is a flexible software tool for modelling of dynamic systems and performing deterministic or probabilistic simulations. Ecolego is used in SR-Site for probabilistic and supporting simulations for generating Landscape Dose Factors (LDF's) /Avila et al. 2010/. Thus, Ecolego is used as a complement to Pandora (see Section 3.15).

Ecolego has been developed by Facilia AB and was originally sponsored by the Swedish Radiation Safety Authority (SSM) and the Norwegian Radiation Protection Authority (NRPA). Ecolego is now commercial software and is being used by companies and institutions all over the world. The version used within the SR-Site project is Ecolego 4.0.

Since Ecolego is a commercial code with a large user-base it belongs to category 3.

### **3.7.2 Suitability of the code**

Ecolego has been designed to maximize transparency and flexibility, while at the same time offer powerful numerical solvers. Large models with many compartments, expressions, parameters and species are easily managed with the user interface. Ecolego also has many features for quality assurance, such as:

- An integrated radionuclide database.
- An integrated parameter database, as well as the possibility to set up an external (shared) parameter database.
- Sub-system library.
- Unit checking.
- Sub-version support.

Ecolego supports both deterministic and probabilistic simulations. Sensitivity analysis can be performed on probabilistic results. The mathematical model is described in detail in /Andersson 2010/.

### **3.7.3 Usage of the code**

Ecolego has a thorough web-based user guide ([www.ecolego.facilia.se](http://www.ecolego.facilia.se)) which is continuously updated using the Wiki-concept. The user guide provides sufficient guidance for the use of the code, with step by step tutorials for the novice user and also full description of all implemented methods and features. At the same web site, there is also access to other resources such as a forum for support, ideas, answers and community talk as well as an issue tracker to report eventual bugs and request improvements.

The correct usage of the code is assured since Ecolego is used, in the SR-Site project, in close collaboration with the developer of the code (see /Avila et al. 2010/ for a description of the version used in SR-Site).

### **3.7.4 Development process and verification**

Ecolego has been developed since 2002 and has been verified and validated through several comparisons with both analytical solutions as with benchmarks of other software such as Amber and Simulink /Maul et al. 2004/. The SR-Site models have been implemented in both Pandora (Simulink, see Section 3.15) and Ecolego to validate the simulation results. The Ecolego software is continuously tested using standard unit testing algorithms.

### **3.7.5 Handling of input data, computational results and scripts**

After a simulation, an Ecolego model is saved together with its input data and the results as an assessment file. Each simulation performed for SR-Site has been stored as an assessment at SKB's subversion server.

Input data used for simulations are stored within the assessment file and originally extracted from the version handled Pandas assessments files representing the base cases at SKB subversion server using Java-scripts. The scripts used to perform batch simulations are archived at Facilia's internal concurrent versioning system (CVS).

The Ecolego input and output data used in SR-Site are archived at SKB (SKBdoc 1263189, see Table 1-2).

### **3.7.6 Rationales for using Ecolego in SR-Site**

Ecolego is used in SR-Site since the code is suitable for risk assessments of complex dynamic systems evolving over time with any number of species. Ecolego has databases and other add-ons especially designed for the field of radiological risk assessment.

The models used for biosphere modelling in SR-Site involve large number of parameters and complex relationships between the inputs and the outputs. In addition, Ecolego enables quick modifications and simulation of large number of assessments.

## **3.8 ERICA Tool**

### **3.8.1 Introduction**

The ERICA Tool is used in SR-Site as a tool for estimation of dose rates to non-human biota /Torudd 2010/. It was developed to support the ERICA Integrated Approach in the ERICA EURATOM project in the area of radiological environmental protection ([www.ERICA-project.org](http://www.ERICA-project.org)). The ERICA Integrated Approach can be applied in planned and existing exposure situations. The use of the ERICA Integrated Approach is facilitated by the ERICA Tool, which is a software programme that guides the user through the various steps, keeps records and communicates with a number of purpose-built databases /Beresford et al. 2007/.

The ERICA Tool is being maintained by a consortium comprising the Norwegian Radiation Protection Authority, Environment Agency (England and Wales), Centre for Ecology & Hydrology (UK), IRSN (France) the Swedish Radiation Safety Authority and CIEMAT (Spain).

The ERICA Tool is freely available (<http://www.project.facilia.se/ERICA/download.html>) and has a large international user base. Since it not written exclusively for the SKB safety assessment, the code is regarded as a category 3 code.

### **3.8.2 Suitability of the code**

The ERICA Tool is a software programme that guides the user through the environmental impact assessment process, keeps records and performs the necessary calculations to estimate dose rates to selected biota. The implementation of the code in SR-Site is described by /Torudd 2010/.

The Tool interacts with a number of databases and other functions that help the assessor to estimate environmental media activity concentrations, activity concentrations in biota, and dose rates to biota. The databases consider the majority of the radionuclides included in Publication 38 of the International Commission on Radiological Protection (ICRP) /ICRP 1983/. The ERICA Tool also interfaces with the FREDERICA radiation effects database ([www.frederica-online.org](http://www.frederica-online.org)), which is a compilation of the scientific literature on radiation effect experiments and field studies, organised around different wildlife groups and, for most data, broadly categorized according to four effect umbrella endpoints: morbidity, mortality, reproduction, and mutation.

The databases of the ERICA Tool are built up around a number of reference organisms. Each reference organism has its own specified geometry and is representative of either terrestrial, freshwater or marine ecosystems. The approach is compatible with that used by ICRP; some of the geometries proposed for the ICRP 'reference animals and plants' are used as defaults in the ERICA Tool.

### **3.8.3 Usage of the code**

A thorough web-based user guide, found at [www.ERICA-project.org](http://www.ERICA-project.org), is continuously updated. The user guide provides sufficient guidance for the use of the code, with step by step tutorials and also full description of all implemented methods and features. The detailed help assists the user in making appropriate choices and inputs, as well as interpret the outputs. At the same web site, there is also access to other resources such as a forum for support, ideas and answers as well as an issue tracker to report eventual bugs and request improvements.

### **2.8.4 Development process and verification**

This is a freely available code used in several international projects, developed and maintained by an international consortium and the developer grant for the development process and verification of the code.

### **3.8.5 Handling of input data, computational results and scripts**

After a simulation, an ERICA model is saved together with its input data and the results as an assessment file. Each simulation performed for SR-Site has been stored and is found in SKB doc 1263189 (see Table 1-2).

### **3.8.6 Rationales for using the code in SR-Site**

The ERICA Tool is used in SR-Site since it is a well documented and internationally used and reviewed tool for estimation of dose rates to non-human biota.

## **3.9 FARF31**

### **3.9.1 Introduction**

FARF31 /Lindgren et al. 2002/ is a code used for radionuclide migration calculations in the far-field, i.e. the geosphere. It is based on a model with a one-dimensional advection-dispersion equation along a, possibly curved, stream tube coupled to a pure diffusion equation in the direction perpendicular to the centroid of the stream tube, for a number of radionuclides. Chain decay and ingrowth are included in the model. The concept of a stream tube can be compared to the combined effect of a large number of individual fractures all sharing the same inlet and outlet. The transversal dimension of the stream tube, the penetration depth, must be chosen by the user.

FARF31 has been used by SKB in the SR 95 /SKB 1995/, the SR 97 /SKB 1999/ the SR-Can Interim /SKB 2004/ and SR-Can /SKB 2006b/ safety assessments of a final repository of the KBS-3 type. In addition, the code has been used by Andra /Andra 2005/ and the European Commission's Joint Research Centre /Prváková 2005/.

The code was initially developed by SKB in the early 1990's as a submodel of the SKB safety assessment framework Proper. This framework is a collection of codes used for migration and consequence calculations through the near-field, the far-field and the biosphere, and uses standardised methods to transfer data and results between the different submodels. FARF31 has been continuously developed by SKB and subcontractors from its conception until the present version 1.2.1. FARF31 is a Fortran 77 code. In SR-Site a stand-alone version of the code, called from MATLAB scripts, is used.

Since the code has been developed by SKB, the code is belonging to category 4b.

### **3.9.2 Suitability of the code**

The governing equations are solved in the Laplace domain using the groundwater travel time in the longitudinal direction as the independent variable to obtain a unit response function, which is subsequently convoluted with the input function to obtain the output function. A detailed description of the solution method can be found in /Norman and Kjellbert 1990/.

The FARF31 code has been developed by SKB to be a reasonably accurate, simplified model of the fully three-dimensional far-field transport problem, which still is fast enough to allow for probabilistic calculations. The solution method, based on Laplace transformation of the governing equations and numerical inversion, limits its applicability to cases with constant transport properties, but this poses no problem at the present level of knowledge. However, a different solution method must be used to include colloid facilitated transport in the model. This is possible to handled in a version of the code called FARF33, where the governing equations are discretised in space using a first order finite volume scheme in both the longitudinal and the transversal direction /Vahlund and Hermansson 2006b/. However, in SR-Site the MARFA code is used for colloid facilitated transport (see Section 3.10).

In a dedicated test batch (Appendix B in the FARF31 User's Guide /Lindgren et al. 2002/) and in previous assessments, the capability of solving problems for the expected input data ranges has been shown.

### **3.9.3 Usage of the code**

In the FARF31 User's Guide /Lindgren et al. 2002/ the program and its implementation and usage details are explained. Text files are used to pass input data to the code and results from the code. During each run log files are produced, which makes it possible to ensure the right parameter values have been used after the simulation has finished.

### **3.9.4 Development process and verification**

In the validity document /Elert et al. 2004/ it is shown that the results are equal to analytical solutions and results from other numerical codes.

In order to ensure the functionality of the code on new machines, batch scripts are used to check out the desired version from the version control system SCCS /Boghammar 1999/ and to set up the build environment. After every major code change resulting in a new version, the problems of the FARF31 test batch /Lindgren et al. 2002/ are used in regression tests of the code to ensure that its accuracy and reliability is intact.

### **3.9.5 Handling of input data, computational results and scripts**

In SR-Site, FARF31 runs are handled with MATLAB scripts. The release from the near-field calculated with COMP23, see Section 3.12, is transferred to FARF31 in the MATLAB scripts. Results from the hydrogeological calculations with ConnectFlow given as ASCII-files (ptb-files) (SKBdoc 1256019, see Table 1-2) are simply converted to MATLAB input-data.

Input data, results and scripts are stored in Subversion. The used input data and scripts are documented in SKBdoc 1260297 (Table 1-2). The main results are available in SKBdoc 1260295 (Table 1-2).

### **3.9.6 Rationales for using the code in SR-Site**

The SR-Site team has selected the FARF31 code for the SR-Site safety assessment since it has been designed to solve the radionuclide transport problem at hand and since the knowledge of the code is good.

## **3.10 MARFA**

### **3.10.1 Introduction**

MARFA 3.2.2 /Painter and Mancillas 2009/ is a Fortran 95 code used for radionuclide migration calculations in the geosphere. It represents transport along one-dimensional flowpaths extracted from a ConnectFlow or similar flow model. The solution method is a particle-based Monte Carlo approach /Painter et al. 2008/. Advection, longitudinal dispersion, limited or unlimited diffusion in rock matrix adjacent to the flow path, equilibrium sorption, and decay/ingrowth are represented. Colloid-facilitated transport may be represented in MARFA by appropriate manipulation of input parameters. Full heterogeneity is supported. That is, the code allows an arbitrary (user input) number of flowpaths and each flowpath may be divided into an arbitrary number of segments with different flow and transport properties within each segment. Different segments may have different retention models (e.g. matrix diffusion in some segments and equilibrium sorption in others). MARFA 3.2.2 also supports temporal variability in flowpath properties. Specifically, different flow velocities and non-flow related transport parameters may be entered for different time periods. However, the three-dimensional flowpath trajectories themselves are assumed fixed in MARFA 3.2.2.

MARFA is a category 4b code.

### **3.10.2 Suitability of the code**

MARFA 3.2.2 accurately represents processes that are expected to be dominant transport processes in the Forsmark geosphere, similar to the FARF31 code (Section 3.9). MARFA was developed to represent certain features, events and processes that are not represented in the FARF31 code. Specifically, the solution method in MARFA does not require the flowpath to be homogenised into an effective constant-property pathway. Theoretical justification for such homogenisation has been demonstrated for single nuclides, but not for radionuclides linked through decay chains. In addition, MARFA also allows for different retention models in different parts of the flowpath, thus making it possible to represent sorption in backfilled tunnels or near-surface soils. MARFA also allows flow velocities and retention parameters to change with time.

### **3.10.3 Usage of the code**

Data input to MARFA is through a series of input files, as described in the MARFA User's Manual /Painter and Mancillas 2009/.

### **3.10.4 Development process and verification**

MARFA was developed at the Geosciences and Engineering Division (GED) of Southwest Research Institute (SwRI) in Texas, USA. The GED conducts all quality affecting activities in compliance with applicable requirements of Title 10 of the US Code of Federal Regulations Part 50, Appendix B (10 CFR Part 50, Appendix B; Domestic Licensing of Production and Utilization Facilities, Quality Assurance Requirements for Nuclear Power Plants and Fuel Reprocessing Plants). More specifically, quality affecting research and development activities related to geological disposal of high-level radioactive waste and spent nuclear fuel comply with the requirements of 10 CFR Part 63, Subpart G (Disposal of High-Level Radioactive Wastes in a Geologic Repository at Yucca Mountain, Nevada, Quality Assurance). The industry implementing standard for 10 CFR Part 50, Appendix B is American Society of Mechanical Engineers (ASME) NQA-1, Quality Assurance Requirements for Nuclear Facilities Applications (1986).

Software is developed, controlled, and modified using GED Technical Operating Procedure (TOP)-018, Development and Control of Scientific and Engineering Software. This procedure invokes the US Nuclear Regulatory Commission (NRC) regulatory guidance documents NUREG/BR-0167, Software Quality Assurance Programs and Guidelines, and NUREG-0856, Final Technical Position on Documentation of Computer Codes for High-Level Waste Management. Furthermore, TOP-018 identifies appropriate processes and documentation to control appropriate elements of the software development process. These measures include but are not limited to preparation of a software requirements description, software development plan, software validation plan, software release notices, software change notices, and similar documentation, as appropriate taking into consideration the size, complexity, and importance of the software being developed or modified. TOP-018 also provides guidance on preparation of a user guide.

Software validation tests are summarized in the MARFA user's manual /Painter and Mancillas 2009/.

### **3.10.5 Handling of input data, computational results and scripts**

MARFA requires flowpath definitions, radionuclide mass release rates from the near field, and retention parameters for the far field. MARFA is designed to directly accept ConnectFlow (see Section 3.5) ptv-files to define flowpaths. However, some modelling cases required the ConnectFlow-generated ptv-files to be modified to remove certain segments of the calculated flowpaths or to remap rock type numbering. Non-flow related transport parameters are input through the definition of certain parameters of the retention model. These are input through an ASCII file as described in the MARFA users manual /Painter and Mancillas 2009/. Non-flow related transport parameters sampled with the @RISK code (add-in to Microsoft Excel) were reformatted in the MARFA input format. Similarly, radionuclide release rates from COMP23, Section 3.12, were reformatted to the required MARFA input format. MARFA generates results in units of Bq/yr for each radionuclide. These results are saved in ASCII files and were also converted to units of Sv/yr for display purposes using SR-Site landscape dose factors (LDF's) for the temperate period. A complete input/output set for each MARFA calculation completed in support of SR-Site is archived in the QA system of the Geosciences and Engineering Division of Southwest Research Institute (for growing pinhole cases) and in SKB's record management system (SKBdoc 1256019, 1266150, see Table 1-2).

### **3.10.6 Rationales for using the code in SR-Site**

The SR-Site team has selected MARFA for the SR-Site safety assessment since it was specifically designed to integrate with the safety assessment workflow used by SKB. In contrast to FARF31 the MARFA code supports full spatial variability for all pathway properties as well as colloidal-facilitated transport. The results produced by MARFA have been shown to be in good agreement with results from other codes, for example FARF31.

## **3.11 MATLAB**

### **3.11.1 Introduction**

MATLAB /MathWorks 2010a/ is an interactive environment and computing language for numeric computation, analysis and visual presentation. MATLAB has been developed since the late 1970's and is globally widespread. MATLAB (versions R2008a, R2008b and R2010a) has been used for a variety of tasks in SR-Site for instance, migration calculations in all parts of the repository system (COMP23, Section 3.12), landscape models (Pandora, Section 3.14) and FPI-calculations (Section 3.13), and also for pre- and post-processing of data and their visualisation.

Simulink /MathWorks 2010b/, an extension integrated with MATLAB, is an environment for multidomain simulation and model-based design for dynamic and embedded systems. It provides an interactive graphical interface to MATLAB and implements MATLAB with a customisable set of block libraries.

While MATLAB and Simulink on their own are regarded as a category 3 code, the advanced applications using MATLAB are regarded as category 4 codes.

### **3.11.2 Suitability of the code**

As MATLAB and Simulink only provide the platform for different codes, the suitability is shown for each separate calculation task.

### **3.11.3 Usage of the code**

MATLAB and Simulink are both well documented codes and courses in using the codes are available.

### **3.11.4 Development process and verification**

This is a commercial code and the developer grant for the development process and verification of the code. The large number of users worldwide warrants swift reactions on programming errors.

### **3.11.5 Handling of input data, computational results and scripts**

In the SR-Site assessment, MATLAB is not used as a separate code, instead MATLAB provides mathematical solving capability and, together with Simulink, graphical environment for the codes developed or tuned for SR-Site.

### **3.11.6 Rationales for using the code in SR-Site**

When performing numerical analysis tasks, MATLAB and Simulink are one of few available codes and are well suited for their tasks.

## **3.12 MATLAB – COMP23**

### **3.12.1 Introduction**

In SR-Site an implementation of the COMP23 model written in MATLAB/Simulink, is used for the near-field migration calculations. This implementation of the COMP23 is also called Compulink /Vahlund and Hermansson 2006a/.

COMP23 has been used by SKB in the SR 95 /SKB 1995/, the SR 97 /Lindgren and Lindström 1999, SKB 1999/, the SR-Can Interim /SKB 2004/ and SR-Can /SKB 2006b/ safety assessments of a final repository of the KBS-3 type. A closely related code, NUCTRAN/NUCFLOW, (which origins from the same source but allows for multiple sources as opposed to COMP23 which only handles single sources) was used in the safety assessment SAFE of the SFR repository for operational waste /Lindgren et al. 2001/. In addition, the code has been used by Andra /Andra 2005/ and the European Commission's Joint Research Centre /Prváková 2005/ and, to some extent, by the Lithuanian Energy Institute (LEI) /Neerdael and Finsterle 2010/.

COMP23 /Cliffe and Kelly 2006/ is originally a Fortran77 code used for radionuclide migration calculations in the near-field (the canister and the engineered systems) and includes models for fuel dissolution, handling of element specific solubility, and migration through advection and dispersion in the different parts of the engineered system. The code was initially developed as NUCTRAN /Romero 1995/ and was subsequently incorporated into the SKB safety assessment calculation framework Proper as the submodel COMP23. Proper is a collection of codes used for migration and consequence calculations through the near-field, the far-field and the biosphere and uses standardised methods to transfer data and results between the different submodels. COMP23 has been continuously developed by SKB and subcontractors until the present version 1.2.2.

The code is considered a category 4b code.

### **3.12.2 Suitability of the code**

COMP23 has been developed by SKB with the main objective to solve the problem at hand and includes all essential models needed when modelling radionuclide migration through the engineered system. Some of the models have been used temporarily in the development process of the KBS-3 repository and can be regarded as being obsolete based on the present level of knowledge. The code

contains for instance several models of different complexity used to calculate the dissolution rate for the fuel matrix. However, for SR-Site a linear model is used, which corresponds best to the present level of knowledge of the actual processes suggested in the **Data report** and the **Fuel and canister process report**. For the solubility limits inside the canister which is a mechanism limiting the concentration inside the canister, a shared solubility model is used where the solubility limit for an element is shared proportionally between the different isotopes of the same element. For radionuclides embedded in the metal parts of the fuel assemblies the releases are determined by constant corrosion rates. Sorption coefficient, diffusivity and porosity are given for each nuclide which allows cations and anions to be treated differently. The validity of the different models used in the code is discussed in the **Fuel and canister process report** and the **Buffer, backfill and closure process report**.

The spatial discretisation used in the modelling of the KBS-3 system (the sub-division of the near-field into compartments) is described in appendix in the **Radionuclide transport report**. The discretisation is mainly based on an earlier study /Lindgren and Widén 1998/ where different discretisation techniques have been tested in order to find a discretisation that is coarse enough to allow for the problem to be solved using probabilistic calculations, but yet fine enough allowing for the problem to be solved with acceptable accuracy. In order to be able to have a relative coarse spatial discretisation, analytical expressions are possible to use at the mouth of the canister defect and at the fracture bentonite interface /Neretnieks 1986, Romero 1995, Kelly and Cliffe 2005/.

In a dedicated test batch /Lindgren et al. 2008/, in the validity document, /Kelly and Cliffe 2006/ and in previous assessments, the capability in solving problems for the expected input data ranges has been shown. Compulink uses a subset of the COMP23 test batch /Vahlund and Hermansson 2006a/.

### 3.12.3 Usage of the code

In the COMP23 user's manual /Romero et al. 1999, Cliffe and Kelly 2006/ the program and the models implemented are explained in detail. For the MATLAB-version used in SR-Site /Vahlund and Hermansson 2006a/ provides additional documentation on the usage. MATLAB scripts are used to handle input and output.

### 3.12.4 Development process and verification

In a validity document /Kelly and Cliffe 2006/, the features of the code are presented and some of these are benchmarked against analytical solutions and in some cases to other codes. In addition to the validity document, a test batch /Lindgren et al. 2008, Vahlund and Hermansson 2006a/ has been prepared in which the features of the code are demonstrated both for simple test cases which can be verified with analytical solutions or other codes and also for realistic KBS-3 cases using realistic data. Using the test batch the accuracy between different versions may be verified to ensure that code modifications does not change the capability of the code to solve the problem at hand.

The Matlab/Simulink version of COMP23 uses Subversion for version handling. The Fortran version of the COMP23 uses the version control system SCCS /Boghammar 1999/ and batch scripts are used to set up the computational environment.

### 3.12.5 Handling of input data, computational results and scripts

In this section it is described how data are passed between COMP23 and other models identified in the AMF, see Figure 2-1 and Figure 2-2. Table 3-1 summarises the data and how it is passed to COMP23 and if other model activities are performed to obtain the input data. The used input data and scripts are version controlled in Subversion and documented in SKBdoc 1260297 (Table 1-2). The results are stored in Subversion and the main results are available in SKBdoc 1260295 (Table 1-2).

### 3.12.6 Rationales for using the code in SR-Site

The SR-Site team has selected the MATLAB/Simulink version of COMP23 code for the SR-Site safety assessment since it has been designed to solve the radionuclide transport problem at hand and since the knowledge of the code is good.

**Table 3-1. Input data passed to COMP23.**

Data	Other model activity	Data passing
Inventory for RN transport (DR 3.1)		Subversion, <b>Data report</b> Section 3.1
IRF, CRF and Corrosion time for metal parts (DR 3.2)		Subversion, <b>Data report</b> Section 3.2
Fuel conversion (DR 3.3)		Subversion, <b>Data report</b> Section 3.3
Solubility data (DR 3.4)	Solubilities, Section 3.20	Subversion
Time for large defect (DR 4.3)	Corrosion calculations (incl. buffer erosion), Section 3.3	Subversion, <b>Data report</b> Section 4.3, (SKBdoc 1265612)
Geometries		Underground openings production report, <b>Canister production report, Buffer production report, Data report</b> Section 4.1
Flow related migration parameters (DR 6.7)	Hydro, Section 3.5 (Connectflow)	Subversion (ptb-files), <b>Data report</b> Section 6.7 (SKBdoc 1256019)
Density and porosity of buffer and backfill (DR 5.1)		Subversion, <b>Data report</b> Section 5.1
Migration data of buffer and backfill		Subversion, <b>Data report</b> Section 5.3

### 3.13 MATLAB – FPI

#### 3.13.1 Introduction

The full perimeter intersection criteria (FPI) were used in the safety assessment SR-Can /SKB 2006b/ as a proxy for large fractures. This enabled a quantitative estimate of the number of canisters that might fail due to earthquakes.

Using site descriptive models as input, the codes compute the probability of intersection between fractures, idealised as infinitely thin, circular discs, and either canisters, deposition holes or tunnels of various shapes and orientations /Munier 2010/. The critical fracture radii, i.e. radii sufficiently large to host slip exceeding the canister failure criterion, are dependent on the distance to deformation zones and the dip of the fracture, as demonstrated in /Fälth et al. 2010/. Combined with estimates of earthquake frequencies /e.g. Bödvarsson et al. 2006/ it is possible to compute an average number of potentially damaged canister for various time frames.

The codes are implemented as MATLAB /MathWorks 2010a/ scripts (see also Section 3.11), using the parallel processing toolbox /MathWorks 2010c/ for computation speed. A few subroutines were compiled in C++ for additional speed, using the compiler Visual Studio /Microsoft 2008/. The version of the code used in SR-Site is “version SR-Site”.

FPI is considered as a category 4b code.

#### 3.13.2 Suitability of the code

The codes were tailor-made for the sole purpose of computing fracture/canister intersection probabilities. The method is described in /Munier 2010/.

#### 3.13.3 Usage of the code

The codes require MATLAB (see also Section 3.11) and the parallel processing toolbox. The compilation of certain subroutines to C++ was targeted to a 64 bit platform and would need to be recompiled to run on a 32 bit platform. The code is documented in /Munier 2010/.

#### 3.13.4 Development process and verification

The notion of using full perimeter intersections as proxies for large fractures was originally introduced in /Munier 2006/ in which the terminology, geometrical framework and first versions of the codes were presented. In /Munier 2007/ a sensitivity analysis was published together with some fundamental benchmark cases /Hedin 2008/. The number of cases to consider, and their output, forced a radical rewriting of the codes and a need to compile some slow routines into native C++. These early reports

were complemented in /Munier 2010/ with a large number of analytical and semi-analytical benchmarks e.g. /Hedin 2010/, more sensitivity analyses and an application to both the Forsmark and Laxemar sites. The codes, presented in /Munier 2010/, were radically rewritten to enable parallel processing, in particular with regards to simulation logic. The version of the codes in /Munier 2010/ are those used in SR-Site though the simulation output has been complemented with additional realisations to stabilise results further.

### **3.13.5 Handling of input data, computational results and scripts**

There are several sources of input to the simulations. The most important ones are the DFN models for each site. All DFN models of the site description reside in SKB's model database as Microsoft Excel sheets, described in detail in the **Data Report**. However, the FPI codes require ASCII input files with a special formatting. These ASCII-versions of the DFN models are stored together with the MATLAB scripts.

The output also consists of ASCII-files of various formats. These are concatenated into Workbooks in Statistica /Statsoft Inc. 2009/ in which they are analysed. Statistica also provides the graphical output in terms of tables, diagrams and charts.

All files, which includes compiled subroutines, MATLAB scripts, input, output and Statistica workbooks are handled in Subversion, and are archived at SKB (SKBdoc 1264530, 1264531, 1264532, see Table 1-2).

### **3.13.6 Rationales for using the code in SR-Site**

The FPI codes were thoroughly tested within the framework of SR-Can and shown to be adequate for the intended purpose. Models and scripts have been successively developed and backwards traceability is thereby warranted. The SR-Site team still considers the FPI codes adequate to fulfil the purpose of the simulations and has therefore chosen to continue using the FPI codes as the main tool for analyses of canister/fracture intersection probabilities.

## **3.14 MATLAB – Pandora**

### **3.14.1 Introduction**

The software package Pandora is used in SR-Site for deterministic simulations for derivation of the Landscape Dose Factors (LDF's) for SR-Site /Åstrand et al. 2005, Avila et al. 2010, Ekström 2011/. Pandora is an extension of the well-known codes MATLAB and Simulink /Mathworks 2010a, b/. Pandora simplifies the development of compartment models consisting of large systems of ordinary differential equations and the handling of radionuclide decay chains. The Pandora tool comprises a library of Simulink blocks that facilitates the creation of compartment models, a Manager as an aid in the model building phase and a standalone assessment tool called Pandas for the model simulation phase. Pandora has been developed by Facilia AB and financed by SKB and Posiva OY. Pandas and the Manager have been financed by SKB alone. Pandora is also used for biosphere modelling by Posiva OY. In SR-Site, Pandora svn revision number 5172 is used.

Pandora is considered as a category 4b code.

### **3.14.2 Suitability of the code**

Pandora was developed for the specific needs of the biosphere modeling required for the safety assessments of high level nuclear waste repositories. It has all required functionalities, including:

- handling of large sets of parameters,
- handling of time evolving parameters,
- representation of discrete transitions between states,
- handling of large number of radionuclides and decay chains,
- consideration of time evolving and spatially distributed discharges,
- version handling of parameters, models and assessments,
- capability to perform probabilistic simulations and sensitivity analysis.

Pandora extends the Simulink graphical user interface as to allow the user to easily inspect and modify the conceptual and mathematical models implemented. The equations on which the model is built are described in /Andersson 2010/.

### **3.14.3 Usage of the code**

The Pandora code has an internal user guide with step by step tutorials as to build models as well as a general description report /Ekström 2011/, which provides sufficient guidance for the additional functionalities that have been incorporated to the commercial codes MATLAB and Simulink. MATLAB and Simulink are well documented and has good support and updating is provided by the developers /Mathworks 2010a, b/.

The path to build a landscape model starts by creating a library of ecosystem models in Pandora, which facilitates handling several instances of the ecosystem models in the landscape model. For each landscape object, a Simulink subsystem is created, which includes models of all ecosystem types that may exist in the object during the whole simulation period. An eventual discrete transition between ecosystem models is implemented using switches available in Simulink. The decay and ingrowth of radionuclides in decay chains are handled with the help of the Pandora Radionuclide block.

For integrating the model, the user can choose from a large list of solvers available in Simulink, including solvers that are appropriate for stiff systems of equations with discrete events. In SR-Site the solver ode15s was used, this due to the high stiffness of the implemented models. The activity concentrations and doses were calculated from the amounts of activity in different compartments predicted with the Pandora model by using a post-processing routine created in MATLAB and incorporated with Pandas assessment. Since Pandora is integrated with the assessment tool Pandas, it also allows for performing sensitivity and uncertainty analyses of the implemented models.

### **3.14.4 Development process and verification**

Pandora has been benchmarked, tested and compared with other similar tools /Åstrand et al. 2005, Ekström 2011/. The solutions with the predecessor of Pandora (Tensit) were compared with analytical results, as well as with numerical results obtained with other simulation tools /Jones et al. 2004, 2005/. These comparisons have shown that Pandora provides reliable solutions.

### **3.14.5 Handling of input data, computational results and scripts**

In SR-Site, Pandora runs are handled with Matlab scripts. Input data (universal constants, time specific-, site specific- or generic parameter values) are transferred from Excel tables to Pandora in the Matlab scripts.

Input data, results and scripts are stored at SKB's subversion server. These files are archived in the SKB record management system (SKBdoc 1263189, see Table 1-2).

### **3.14.6 Rationales for using the code in SR-Site**

Pandora was developed by SKB and Posiva OY for their specific needs in biosphere modelling. Both SKB and Posiva have been active in the development of the code, as to assure that the code satisfies all requirements, including quality assurance requirements. The decision to develop Pandora was taken after it was concluded that other available commercial tools did not have all required functionalities.

## **3.15 MIKE SHE**

### **3.15.1 Introduction**

In SR-Site, MIKE SHE (Système Hydrologique Européen) is used for hydrology and near surface hydrogeology calculations. MIKE SHE makes it possible to model the integration between surface water, groundwater and evaporation processes and makes it possible to describe and understand the complexity of the water flows in the surface system. The MIKE SHE model provides the dose-model with data on water fluxes in and between different compartments of the dose-model.

MIKE SHE is developed by the Danish Hydraulic Institute (DHI). The code describes the main processes in the land phase of the hydrological cycle, from rainfall to river flow /Graham and Butts 2005/. The model consists of five different compartments; saturated zone, unsaturated zone, overland flow, evapotranspiration and channel flow, Figure 3-1, in which the water flow is calculated separately. In addition to the different compartments there is a frame component that takes care of the coupling and water exchange between the different compartments which runs simultaneously with the other components of the model. Transport calculations, particle tracking and advection-dispersion calculations, can also be performed within the MIKE SHE modelling tool.

MIKE SHE Version 2009 /DHI 2009/ is used within the SR-Site modelling. The system is certified for Windows 2000 Professional and Windows XP Professional X64 Edition. MIKE SHE was also used in SR-Can but the code has been developed since then. The coupling between the river flow model and the groundwater flow model in the present version has been updated, so that the water can be transported from the aquifer to the river either via the bottom sediment or over the river bank, as well as allowing water to flood from the river to the ground surface and then infiltrate. Also the evapotranspiration module has been developed. In the MIKE SHE version 2009 it is possible for plants to extract water from the saturated zone which better describes the water turnover in wetlands /Vikström and Gustafsson 2006/. It is possible to define a water tolerance for each vegetation type, if the water tolerance is high the plant can extract all its water from the groundwater zone.

MIKE SHE is used in the hydrological and near surface hydrological modelling within SR-Site. The SDM MIKE SHE model /Bosson et al. 2008/ has been the basis for the models developed within the framework of SR-Site where both models describing present and future conditions have been developed. Different climate cases and the effect on the hydrology of the shore line displacement and development of the landscape have been analysed. The MIKE SHE modelling is reported in /Bosson et al. 2010, Lindborg 2010/.

The code is commercial and is regarded as a category 3 code.

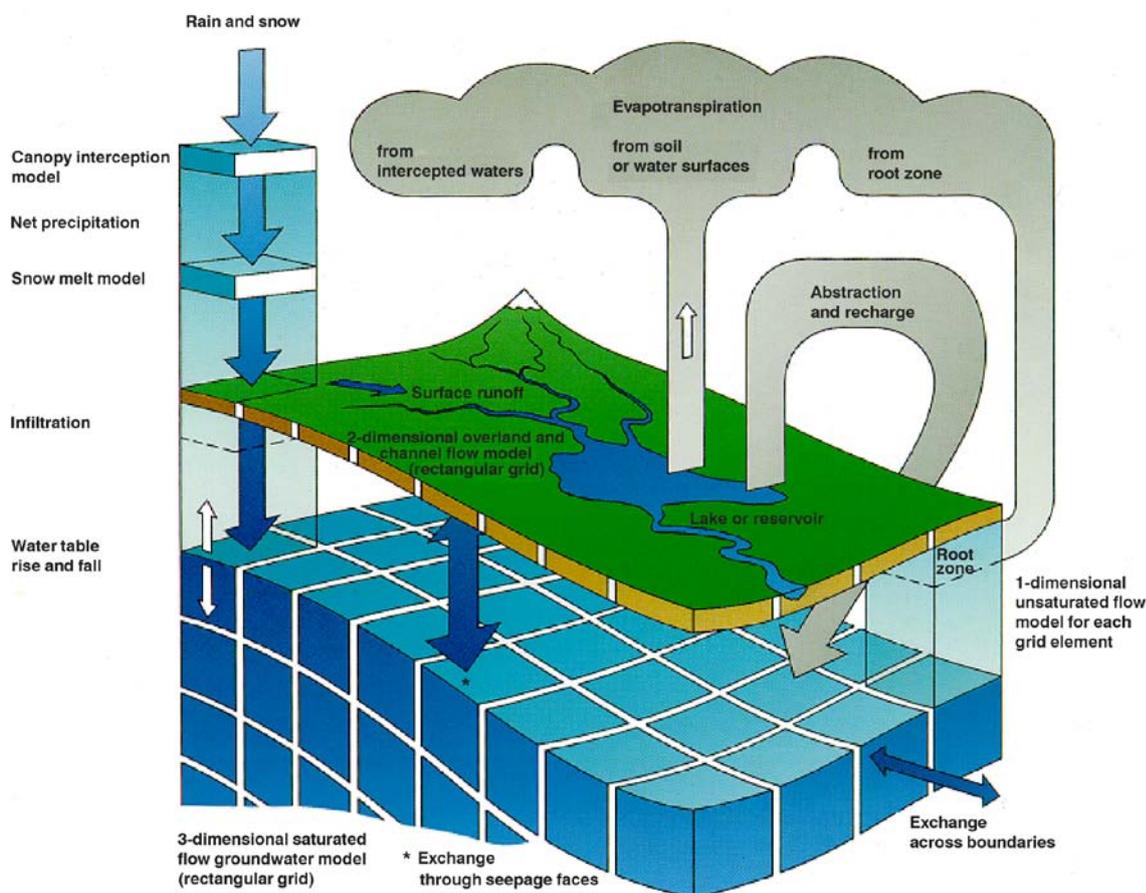


Figure 3-1. The MIKE SHE model /Abbott et al. 1986/.

### 3.15.2 Suitability of the code

MIKE SHE is an advanced integrated hydrological system capable to simulate both surface and groundwater with the same precision as models focused on either groundwater or surface waters. The model is able to simulate the interaction between the surface water and the groundwater which is important when studying potential flow paths from the repository, i.e the water flow from the geosphere to the biosphere.

The precipitation can either be intercepted by leaves or fall to the ground. The water on the ground surface can infiltrate, evaporate or form overland flow. Once the water has infiltrated the soil, it enters the unsaturated zone. In the unsaturated zone, it can either be extracted by roots, and leave the system as transpiration, or it can percolate down to the saturated zone, see Figure 3-1. MIKE SHE is fully integrated with a channel-flow program, MIKE 11. When using the MIKE 11 code together with MIKE SHE, the two programs run simultaneously allowing for water exchange between the two codes during the whole simulation. The water exchange between M11 and MIKE SHE is further described in /Gustafsson et al. 2009/.

Based on the calculated flow field, particle tracking calculations (in the saturated zone) and advection-dispersion calculations can be performed. Within the SR-Site application both particle tracking and advection-dispersion calculations have been performed. The solute transport in the advection-dispersion module can be calculated for all the components (river, overland, unsaturated zone, groundwater).

The following processes are included in the MIKE SHE advection-dispersion module:

- Water and solute transport in macro pores.
- Sorption of solutes described by either equilibrium sorption isotherms or kinetic sorption isotherms.
- Attenuation of solutes described by exponential decay.
- Plant uptake of solutes.

There is a direct coupling between MIKE SHE and the GIS program ArcMap which is part of the ArcGIS framework. This is a large advantage since most of the input data to the present modelling can be obtained in GIS format. It is possible to use both shape-files and ESRI-grid files as input. Both pre- and post processing can be made in the ArcGIS program. The program has been developed to calculate the integrated ground- and surface-water system (flow and transport in porous medium, the unsaturated zone and flow and transport of surface water). Hence, the parameter ranges used when simulating are within the ranges for which the program is valid.

### 3.15.3 Usage of the code

The MIKE SHE user manual /DHI 2009/ consists of two documents;

- The MIKE SHE user guide:  
The document describes how to set up a model and how to process input and output data.
- The MIKE SHE reference guide:  
The document describes in detail the individual tools and dialogs the user is encountered to when working in the MIKE SHE user interface. The document also includes detailed descriptions of the numeric engines and governing equations used in the MIKE SHE modelling system.

The MIKE SHE user manual follows as a pdf-file with the installation media. The manuals are not available in a printed version.

### 3.15.4 Development process and verification

The MIKE SHE model has its origin in the SHE model, Système Hydrologique Européen, which became operational 1982. The model was developed by three organisations; the British institute of Hydrology, the French consulting company SOGREAH and the Danish hydraulic institute, DHI. Today DHI markets the MIKE SHE code. The code is developed as new modelling ideas and needs are identified by the users. The latest version of the model is MIKE SHE version 2010.

The coupling between MIKE SHE and ArcGIS leads to a close integration with SKB's GIS-database. This ensures a good quality as well as high level of traceability for the input data to the model.

Many organisations have reviewed and evaluated the MIKE SHE code. MIKE SHE has been selected as the best modelling tool for integrated groundwater/surface water modelling in many independent reviews, /e.g. CDM 2001/. Each review has had different objectives and has used different criteria in the review process. A number of references are available at DHI website ([www.dhigroup.com](http://www.dhigroup.com)).

### **3.15.5 Handling of input data, computational results and scripts**

Input data is supplied to the code as text files, shape-files or ESRI-grid files. Result files are time series files, \*.dfs0 or grid-files, \*.dfs2 and \*.dfs3. Both dfs0-files, dfs2-files and dfs3-files are easily converted to text files. The dfs2-files can also directly be converted to GIS-format, shape-files or ESRI-grid files. An ASCII log-file is produced for each simulation, this file can be used to check for errors, warnings and issues such as convergence. The MIKE SHE model can also be run using a Graphical User Interface (GUI) which is documented by an on-line user manual.

Several modelling activities have provided the various external input data and models required for the SR Site hydrological and near surface hydrogeological numerical modelling. The MIKE SHE SDM model is the starting point for all model cases simulated within the SR-Site MIKE SHE modelling. The input data used in the SR-Site MIKE SHE modelling is described in /Bosson et al. 2010/.

All time series data from the site investigations, used as input data to the MIKE SHE model, are stored in the SKB Sicada database. Spatial distributed input data to the MIKE SHE models are stored in the SKB GIS database. Models and data from other scientific disciplines in the SR-Site project that are used in the MIKE SHE SR-Site modelling are stored at SKB's subversion server.

The MIKE SHE model generates numerous result data files. For practical reasons the model result files cannot be uploaded on svn. A separate server at SKB has therefore been in use for storing the MIKE SHE results files (G:\skb\modellering\mikeshe). The scripts used in MIKE SHE for SR-Site are archived at SKB (SKBdoc 1263189, Table 1-2).

Details about all input data to the MIKE SHE SR-Site model and references to specific data extractions from each database mentioned above are found in /Bosson et al. 2010/.

### **3.15.6 Rationales for using the code in SR-Site**

MIKE SHE is regarded as a suitable code for solving the problem at hand, since it is a well documented and internationally used and reviewed tool for calculating waterflows in the surface system.

## **3.16 Numerical GIA model**

### **3.16.1 Introduction**

The GIA (Glacial Isostatic Adjustment) code is used to calculate the isostatic adjustment of the solid earth due to loading by ice and water during a glacial cycle. The gravitationally-consistent redistribution of water within the oceans is a central component of the algorithm, allowing accurate relative sea-level and shoreline migration to be calculated.

In SR-Site the GIA code is used to reconstruct relative sea-level and shoreline positions in the region of interest. It is also used to carry out sensitivity tests regarding e.g. the influence of earth and ice model parameters on the output, see the **Climate report**.

The GIA code has been used in an extensive range of research projects. These include constraining mantle viscosities /Milne et al. 2001, 2004/, constraining former ice sheet volumes /Milne et al. 2002/, understanding Holocene sea-level change and modelling GIA effects around the world /Mitrovica and

Milne 2002, Gehrels et al. 2004, Milne et al. 2005, 2006/, testing global melt scenarios /Clark et al. 2002, Bassett et al. 2005/, investigating the effect of 3D earth structure on GIA predictions /Whitehouse et al. 2006/, and identifying present-day melt sources and constraining the recent mass balance of polar ice sheets /Mitrovica et al. 2001, Tamisiea et al. 2001, 2003/. The GIA code was also used for the SR-Can safety assessment /SKB 2006a/.

The GIA code is a category 4b code, written in Fortran, and has been developed by Dr. G.A. Milne over a number of years in collaboration with Prof. J.X. Mitrovica at the University of Toronto /Milne 1998, Milne and Mitrovica 1998, Milne et al. 1999/. The complete version of the code, which includes all of the advances described below, is used by a small user base of postgraduate students and postdoctoral researchers working in either Milne's or Mitrovica's research groups. The version of the code used for SR-Site is the one described in /Mitrovica and Milne 2003/.

### 3.16.2 Suitability of the code

The GIA code solves the sea-level equation /Farrell and Clark 1976/ via the pseudospectral approach developed by /Mitrovica and Peltier 1991/. The code has been significantly extended since this time to account for several different processes and thus improve the accuracy of the computation. Firstly, time-dependent shoreline positions are taken into account when calculating the ocean-loading function. Secondly, the water influx to regions vacated by retreating, marine-based ice is carefully accounted for in the distribution of the load /Milne et al. 1999/. Thirdly, changes to the rotational state of the Earth as a result of both surface and internal mass redistributions are considered /Mitrovica et al. 2005/. And fourthly, the impact of lateral variations in Earth structure is taken into account when calculating the solid Earth response to loading. The theory that the most recent version of the code is based on, and the algorithm employed to solve the governing equations, are described in /Mitrovica and Milne 2003/ and /Kendall et al. 2005/, the extension of the code to include lateral structure is described in /Latychev et al. 2005/. These publications define the state-of-the-art in computing sea-level changes associated with glaciation.

The code has a number of built-in analytical checks to ensure that the output is correct.

### 3.16.3 Usage of the code

Due to the nature of the development of the GIA code, and the intended user base, there is no formal documentation available. The correct usage of the code is assured since the numerical GIA model is used, in the SR-Site project, by scientists working in close collaboration with the developer of the code. The version used in SR-Site is described in /Mitrovica and Milne 2003/.

The input data and parameters required by the GIA model are: 4D (spatial and temporal) global ice history for the duration of the model run; various radial Earth properties including the viscous properties of the Earth's mantle, the thickness of the Earth's lithosphere, elastic structure, density structure, and gravitational acceleration, as well as data relating to the shape of the Earth and its rotation (flattening coefficient and spin rate); and a global topography data set. The model was run over a range of time periods when carrying out the sensitivity tests, and time steps varied between 500 and 7,000 years, depending on the level of resolution required. Details of model setups and input data for individual SR-Site simulations are found in the **Climate report**.

At each time step, output data relating to relative sea-level, the height of the equilibrium sea surface, and solid earth deformation are calculated at each grid node. The computations are performed in the spherical harmonic domain at a truncation suitable for the region of study. For Fennoscandia, a truncation of 256 degree and order enables accurate predictions of relative sea-level and solid Earth deformation (vertical and horizontal). The model output is stored as an array of spherical harmonic coefficients and so predictions can be generated for any point on the surface of the Earth at each time step.

### 3.16.4 Development process and verification

In developing the code, a number of comparisons were made to analytical solutions wherever possible to test the accuracy of the numerical schemes employed.

A small number of research groups have developed their own sea-level code based on the results presented in the papers referenced above. However, not all versions include the latest developments discussed in the most recent papers (e.g. /Mitrovica and Milne 2003/). The solid earth response to GIA-loading has recently been successfully benchmarked between several groups ([http://www.fis.uniurb.it/spada/GIA\\_benchmark\\_results.html](http://www.fis.uniurb.it/spada/GIA_benchmark_results.html)), but a systematic benchmark of the full sea-level equation is still in progress.

For the SR-Site work it was necessary to determine shoreline positions within the Gulf of Bothnia during periods when the Gulf was cut off from the oceans, and a lake formed above sea level. The code was adapted to meet this specific requirement.

### 3.16.5 Handling of input data, computational results and scripts

Data were transferred between the ice sheet (UMISM, see Section 3.22), GIA, and permafrost simulations (see Section 3.17) by text or Excel-files. Figure 3-2 shows the input and output data shared between the three models. Data are archived in SKBdoc 1265613 (Table 1-2).

### 3.16.6 Rationales for using the code in SR-Site

The GIA code was used in SR-Site for simulating isostatic changes during the last glacial cycle for input to safety assessment calculations. The code was selected for the SR-Site safety assessment since it is one of the world-leading in its field.

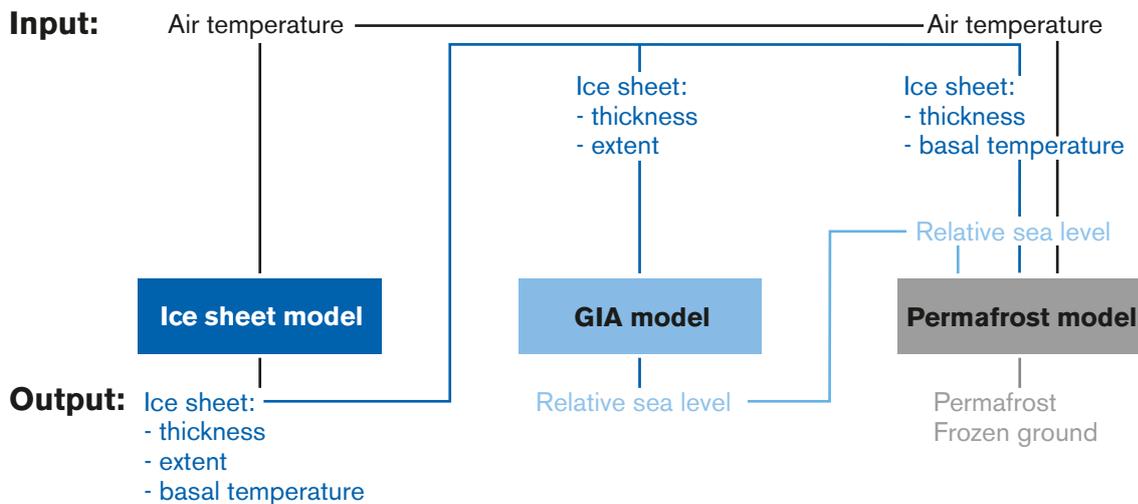


Figure 3-2. Data transferred between the ice sheet (UMISM), GIA, and permafrost simulations.

## 3.17 Numerical permafrost model

### 3.17.1 Introduction

The numerical permafrost model code, written in Fortran, is used to calculate the development of permafrost and perennially frozen ground. Originally, the code was developed at the Helsinki University of Technology for soil freezing problems /Hartikainen 1994/ being built on a general finite element solver code for non-linear non-stationary problems /Freund and Lempinen 1994/. The first version of the numerical permafrost model code was written for the international project DECOVALEX III in order to investigate thermo-hydro-mechanical impacts of processes associated with freezing and thawing of subsurface during periods of glaciation/deglaciation on the long-term performance of a hypothetical post-closure repository /Hartikainen 2004, Chan et al. 2005/. Thereafter, the code has been used in SR-Can /SKB 2006a/ to make a 1D reconstruction of the development of permafrost and perennially frozen ground at Forsmark during the last glaciation cycle and to perform sensitivity analyses on the important factors and parameters affecting the development of permafrost and frozen ground.

For SR-Site the code was updated to deal with spatially varying surface conditions and salt transport as well as to solve large systems of equations. The second version of the code was then used to investigate and demonstrate effects of multidimensional features of surface and subsurface conditions on the occurrence, development and distribution of permafrost and perennially frozen ground in a 2D vertical cross-section at Forsmark /Hartikainen et al. 2010/. The study included features such as varying climate conditions, water bodies and topography, lateral variations in physical properties and heat generation from the spent fuel as well as effects of the phase change of saline water, groundwater flow and salt transport. The code is classified as a category 4b code.

### 3.17.2 Suitability of the code

The second version of the code solves the equations of energy balance and mass balance of groundwater, ice and salts together with the generalized Clausius-Clapeyron equation of the phase change between water and ice, the Darcy equation of groundwater flow and the equation of non-Fickian salt diffusion /Hartikainen et al. 2010/. The model, considering the ground as saline water saturated porous medium, includes a description of the following physical processes:

- heat and mass transfer in freezing and thawing ground,
- phase change of groundwater being affected by groundwater pressure and salt concentration,
- exclusion of salt during freezing,
- density dependent groundwater flow in unfrozen and partially frozen ground.

Anisotropies of material properties such as permeability and thermal conductivity are allowed. Information on surface conditions including air temperature, ice-sheet thickness, basal temperature, shoreline migration, and vegetation are given as time varying boundary conditions.

The code is based on the finite element method and implicit time integration schemes, and solves the above-mentioned coupled nonlinear partial differential equations using a consistent regularisation technique for discontinuities due to phase changes and the Newton-Raphson method for the nonlinear problem /Mikkola and Hartikainen 2002/, and the preconditioned stabilized bi-conjugate gradient algorithm /van der Vorst 1992/ for the system of linearized equations.

Prior to the SR-Site project, the code has been used in several research projects including soil freezing problems /Hartikainen and Mikkola 1997, 2006, Mikkola and Hartikainen 2001, 2002/, and development of permafrost and perennially frozen ground /Hartikainen 2004, 2006, Chan et al. 2005, SKB 2006a/.

### 3.17.3 Usage of the code

Description of the first version of the code is given in /Freund and Lempinen 1994, Hartikainen 1994, 2004/, while the model settings for the second version of the code, as well as SR-Site input and output data to the model, are described in /Hartikainen et al. 2010/.

### 3.17.4 Development process and verification

The model development and verification for the second version of the code as well as the consistency of results between the second and first version of the code can be found in /Hartikainen et al. 2010/.

### 3.17.5 Handling of input data, computational results and scripts

In the code, both input and output data as well as the runtime information of solution convergence and progress are dealt with in ASCII format, how data is transferred between the ice sheet (UMISM), GIA, and permafrost simulations is shown in Figure 3-2. MATLAB and COMSOL are used to pre- and post-process the data. Data are archived in SKBdoc 1265613 (Table 1-2).

### 3.17.6 Rationales for using the code in SR-Site

The code was selected for the SR-Site safety assessment since it is one of the world-leading in its field. The code was used in SR-Site for simulations of freezing of saturated bedrock for a reconstructing last glacial cycle conditions and for a number of sensitivity tests.

## 3.18 PHAST

### 3.18.1 Introduction

PHAST v.1 /Parkhurst et al. 2004/ simulates multi-component, reactive transport in 3D saturated groundwater flow systems. PHAST is a versatile groundwater flow and solute transport simulator with capabilities to model a wide range of equilibrium and kinetic geochemical reactions. The flow and the transport calculations are based on a modified version of HST3D /Kipp 1987, 1997/ that is restricted to constant fluid density and constant temperature. The geochemical reactions are simulated with the geochemical code PHREEQC /Parkhurst and Appelo 1999/, which is imbedded in PHAST.

PHAST has been used in the SR-Site assessment for modelling oxygen transport (melt water enriched in oxygen) during episodes of a glaciation cycle.

PHAST has also been used for the assessment of the interaction of the fully water-saturated bentonite with groundwater through a series of three-dimensional (3D) numerical models /Sena et al. 2010a /.

PHAST has been also used as numerical tool in previous performance assessment studies at SKB /Arcos et al. 2006, Grandia et al. 2006, Luna et al. 2006, Domènech et al. 2006, Grandia et al. 2007, Sena et al. 2008/.

The version of the code is regularly updated. The code and revision history is available at ([http://wwwbrr.cr.usgs.gov/projects/GWC\\_coupled/phast/index.html](http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phast/index.html)). The latest version is PHAST v.2.0.2. Due to the frequent release of new revisions of the code, different versions of the code has been used, but most of the work performed in the SR-Site has been carried out using the version v.1.5.1.

Since the code is an open source code, of a large user base and not written exclusively for the SR-Site project, the code is regarded as a category 3 code.

### 3.18.2 Suitability of the code

PHAST is a robust geochemical code able to model the different geochemical processes of interest in the SR-Site assessment.

The PHAST simulator is a general computer code with the capability to model various reaction chemistry formulations (homogeneous equilibria using an ion-association thermodynamic model, heterogeneous equilibria between the aqueous solution and minerals, gases, surface complexation sites, ion exchange sites, solid solutions, and kinetic reactions). It can handle various equation-discretisation, types of boundary conditions (specified-head, flux and leaky conditions), source-sink, and equation-solver options. Four types of flow and reactive transport simulations can be performed with PHAST:

steady-state simulation of groundwater flow, transient simulation of groundwater flow, steady-state simulation of flow followed by reactive transport and transient simulation of flow with reactive transport. PHAST is applicable to the study of natural and contaminated groundwater systems at a variety of scales ranging from laboratory experiments to local and regional field scales /Parkhurst et al. 2004/. However, PHAST is not suitable for some types of reactive transport modelling, in particular for unsaturated zone flow, and simulating transport of gas phases and non-aqueous liquid phases. On the other hand, PHAST is restricted to constant temperature and density.

PHAST solves a set of partial differential equations for flow and transport and a set of nonlinear algebraic and ordinary differential equations for chemistry. The equations that are solved numerically are the saturated groundwater flow equation for conservation of total fluid mass, a set of solute-transport equations for conservation of mass of each solute component of a chemical-reaction system, and a set of chemical-reaction equations comprising mass balance equations, mass-action equations and kinetic-rate equations. The groundwater flow and solute-transport equations are coupled through the dependence of advective transport on the interstitial fluid-velocity field. The solute-transport equations and the chemical equations are coupled through the chemical concentrations terms. The chemical equations are fully coupled through the concentration terms and must be solved simultaneously.

By using a sequential solution approach for flow, transport and reaction calculations, numerical solutions are obtained for each of the dependent variables. Operator splitting is used to separate the solute-transport calculations from the chemical reactions calculations. Finite differences techniques are used for the spatial and temporal discretisation of the flow and transport equations.

The aqueous model for PHAST is an ion-association model that is applicable to ionic strengths to 1 molal. Thus, PHAST is not an appropriate simulator for many systems and processes, including transport of volatile organic compounds in a soil zone, hydrothermal systems, most high ionic-strength brines, or heat storage and recovery in aquifers. More detailed information on the geochemical and transport equations that can be solved using this code can be obtained from the PHAST user's manual /Parkhurst et al. 2004/.

### 3.18.3 Usage of the code

In the PHAST user's manual /Parkhurst et al. 2004/ the program is explained in detail and a lot of examples are provided. In addition to this document the web page of the authors ([http://www.wr.usgs.gov/projects/GWC\\_coupled/phast/index.html](http://www.wr.usgs.gov/projects/GWC_coupled/phast/index.html)) also contains a lot of information and well documented examples as well as an active and interactive section of FAQ.

Reactive-transport simulations with PHAST require three input files: a flow and transport data file, a chemistry data file, and a thermodynamic data file. All data files are built with modular keyword data blocks. Each data block defines a specific kind of information (e.g. grid locations, boundary-conditions information, or initial chemical composition). All spatial data are defined by zones, which are rectangular volumes. All this information is easily introduced by means of .dat files.

Simulation results can be saved in a variety of file formats (ASCII or binary HDF). Results can be thus, easily post-processed by using the program PHASTHDF to extract subsets of the data stored in the HDF file and the program MODEL VIEWER (only for Windows) to produce 3D visualizations of the problem definition and of the simulation results. Both programs are distributed together with PHAST.

### 3.18.4 Development process and verification

This is an open source computer code developed by the United States Geological Survey. The code is widely used and its algorithm has been checked through several scientific publications and through the example files distributed with the computer program.

### 3.18.5 Handling of input data, computational results and scripts

All input and output files to PHAST are ASCII text files. Three types of input files are needed: a thermodynamic data base, described in the **Data Report**, and two input files. One of them describes

the initial composition of the aqueous solutions in each volume (for each material), and the mineral precipitation/dissolution reactions to be modelled. The other input file describes the grid, the transport parameters, including the time discretisation, and the boundary conditions.

For the modelling of oxygen intrusion along a fracture and into the rock matrix, the input files were created with a text editor. The output file, which consists of lines of text with column data, may be directly imported into other programs, such as Microsoft's Excel, for plotting.

The data used for modelling of oxygen ingress in SR-Site are archived at SKB (SKBdoc 1265689, see Table 1-2). The data used for modelling of bentonite – groundwater interaction are archived in SKBdoc 1265807 (Table 1-2).

### **3.18.6 Rationales for using the code in SR-Site**

The SR-Site team has selected the PHAST code since it is useful to solve 3D fluid flow and reactive transport problems (advection, diffusion and dispersion) under water saturated conditions. The level of knowledge of this program is high and well-supported.

## **3.19 PHREEQC**

### **3.19.1 Introduction**

PHREEQC v.2 /Parkhurst and Appelo 1999/ is a computer program written in the C programming language that is designed to perform a wide variety of low-temperature aqueous geochemical calculations.

It has been used in the near-field (canister and the engineered systems) in several ways. In some cases it has been directly used to perform simple 1D transport modelling but in most cases has been used as a pre-conditioning tool for large scale 2D simulations performed with other codes. In SR-Site, it has been used for simulations of the evolution of the groundwater composition within the candidate repository site of the Forsmark and Laxemar areas assuming different climate conditions and hydrological situations. The hydrochemical calculations have been performed by simulating mixing of five end-member waters and mineral equilibrium reactions.

PHREEQC has been also used as numerical tool in previous performance assessment studies at SKB and elsewhere /Duro et al. 2006, Grivé et al. 2010a, Guimerà et al. 2006/.

The version of the code is regularly updated. The code and revision history is available at ([http://wwwbrr.cr.usgs.gov/projects/GWC\\_coupled/phreeqc/index.html](http://wwwbrr.cr.usgs.gov/projects/GWC_coupled/phreeqc/index.html)). The latest version of the code is PHREEQC 2.17 (SIT “Specific Interaction Theory”). Due to the frequent release of new revisions of the code, different versions of the code has been used. However, most of the work performed has been carried out using PHREEQC v.2.10.

Since the code is an open source code, of a large user base and not written exclusively for the SR-Site project, the code is regarded as a category 3 code.

### **3.19.2 Suitability of the code**

For the modelling of chemical behaviour at the candidate repository sites (Forsmark and Laxemar), under different climatic periods and hydrological assumptions, PHREEQC is a suitable tool. It can be used as a speciation program to calculate saturation indices as well as spatial and temporal distribution of aqueous species by mixing of solutions and considering equilibrium with mineral phases (including redox elements).

PHREEQC is based on equilibrium chemistry of aqueous solutions interacting with minerals, gases, solid solutions, exchangers and sorption surfaces, but also includes the capability to model kinetic reactions with rate equations specified in the form of Basic statements. It also includes a 1D transport

algorithm that comprises dispersion, diffusion and various options for dual porosity media. More detailed information on the geochemical and transport equations that can be solved using this code can be obtained from the PHREEQC v.2 user's manual /Parkhurst and Appelo 1999/.

Several limitations need to be considered. PHREEQC uses ion-association and Debye-Hückel expressions to account for the non-ideality of aqueous solutions /Parkhurst and Appelo 1999/. This type of aqueous model is adequate at low ionic strength, but may break down at higher ionic strengths (in the range of seawater). Other limitation of the aqueous model is lack of internal consistency in the data in the databases. On the other hand, in reference to surface complexation calculations, PHREEQC incorporates the generalized two-layer model, a two-layer model that explicitly calculates diffuse-layer compositions, and a non-electrostatic surface-complexation model. Other model have not been implemented. With respect to solid solution simulations, ternary non-ideal solid solutions are not also implemented.

### 3.19.3 Usage of the code

In the PHREEQC v.2 user's manual /Parkhurst and Appelo 1999/ the program is explained in detail and a lot of examples are provided. In addition to this document, the web pages of both authors (<http://www.xs4all.nl/~appt/a&p/> and [http://www.wr.usgs.gov/projects/GWC\\_coupled/phreeqc/](http://www.wr.usgs.gov/projects/GWC_coupled/phreeqc/)) also contain a lot of information and well documented examples as well as an active and interactive section of FAQ.

Input data is easily introduced by means of the edit tool provided by the same program. Selected output data can be obtained in ASCII-text formatted files that can be read and modified with Microsoft Excel program or similar.

### 3.19.4 Development process and verification

This is an open source computer code developed by the United States Geological Survey. The code is widely used and its algorithm has been checked through several scientific publications and through the example files distributed with the computer program.

### 3.19.5 Handling of input data, computational results and scripts

All input and output files to PHREEQC are ASCII text files. Two types of input files are needed: a thermodynamic data base, described in the **Data Report**, and an input file describing the mineral precipitation/dissolution reactions to be modelled (either equilibrium or kinetically controlled), and mixing if included in the model. Diffusion processes can also be specified in this input file.

For the modelling of the geochemical evolution of the groundwaters at Forsmark during a glacial cycle, simple computer programs were devised to create input files and to read and extract data from the output files. These programs and the procedure is described in detail in the Appendix of /Salas et al. 2010/. The output from the hydrogeological models, in terms of spatial coordinates, salinities and, if available, mixing proportions of reference waters, together with the composition of these reference waters, was used to construct the input files to PHREEQC /Salas et al. 2010/.

For the modelling of oxygen intrusion into the rock matrix, the format of an output file from PHREEQC ("selected output") is controlled through the input file. The selected output file, which consists of lines of text with column data, may be directly imported into other programs, such as Microsoft's Excel, for plotting.

The data used for SR-Site are archived at SKB (SKBdoc 1262945 and SKBdoc 1265689, see Table 1-2).

### 3.19.6 Rationales for using the code in SR-Site

The SR-Site team has selected the PHREEQC code because it is useful to characterize mixtures of solutions in equilibrium with mineral phases, considering simplistic 1D transport calculations, and for a high number of simulated points characterised by different mixing fractions. The level of knowledge of this program is high and well-supported.

## 3.20 Solubility model (Simple Functions)

### 3.20.1 Introduction

The Simple Functions spreadsheet is a tool to determine the solubility limits of radionuclides especially designed for Performance Assessment exercises. This tool has been developed in an Excel spreadsheet, and as such, it belongs to category 4b.

The development of this tool was promoted by the necessity of having a confident and easy-to-handle tool to calculate solubility limits in an agile and relatively fast manner. It was originally built up by Amphos 21 in the frame of the SR-Can project as a request by SKB. Later, it was improved by adding uncertainty calculation. The most recent update /Grivé et al. 2010b/ incorporates recent thermodynamic data changes and provides two versions, which differ in the conditions under which the solubility assessment is done:

- VERSION A is designed to calculate radionuclide solubility limits in *representative groundwater compositions supplied by the user*.
- VERSION B is designed to calculate radionuclide solubility limits in a *groundwater that has interacted with Fe-corrosion products*.

### 3.20.2 Suitability of the code

This tool is an Excel spreadsheet that contains the simple algorithms needed to determine the solid phase that may exert the solubility control under the conditions of interest for a given radionuclide and its solubility.

The aim of the Simple Functions spreadsheet is to facilitate the calculation of the solubility limits. Current geochemical codes calculate the speciation of many different elements in solution, and use an associated thermodynamic database containing the stoichiometry and stability of every aqueous and solid species. Most of these thermodynamic databases are exhaustive, in an attempt to cover a wide range of water compositions and they contain information on aqueous species that only appear under very specific water compositions which have been judged to be of no interest for the current solubility assessment.

The Simple Functions spreadsheet is tailored for the conditions of interest and contains only those species accounting for at least 10% of the total element in solution under the following range of conditions:

- $T = 25^{\circ}\text{C}$ .
- $I \leq 0.2\text{m}$  (ionic strength (I) in molality units (m)).
- $6 < \text{pH} < 11$ .
- $-8 < \text{pe} < 14$ .
- $5 \cdot 10^{-5} < [\text{SO}_4] < 5 \cdot 10^{-2}$  (range of interest for SR-Site).
- $10^{-4} < [\text{CO}_3] < 5 \cdot 10^{-3}$  (range of interest for SR-Site).
- In VERSION A,  $[\text{Fe}]_{\text{aq}}$  range given by the user; in VERSION B  $[\text{Fe}]_{\text{aq}}$  is given by the equilibrium magnetite/goethite at the pH of interest.

The elements included in the Simple Functions spreadsheet are Sr, Ra, Ni, Sn, Se, Ag, U, Zr, Nb, Pa, Np, Pu, Am, Cm, Tc, Pd, Sm, Ho, Th and Pb. Moreover the aqueous speciation of the following major elements is also considered:  $\text{HCO}_3^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$ ,  $\text{Ca}^{2+}$ ,  $\text{Na}^+$  and  $\text{Fe}^{2+}$ .

### 3.20.3 Usage of the code

The capabilities of Simple Functions spreadsheet are described in the Simple Functions Spreadsheet tool presentation report /Grivé et al. 2010b/. Input data are directly supplied into the Excel spreadsheet where the user can also find the output results.

This tool can be used together with the @RISK application (add-in to Microsoft Excel, see <http://www.palisade.com/risk/>) to perform probabilistic calculations.

### **3.20.4 Development process and verification**

The Simple Functions spreadsheet has been developed as an easy-handling tool to calculate ranges and distributions of solubility limits to be used in the radionuclide transport calculations. Because of its simplicity, calculations are less complete than those used in other geochemical codes.

Simple Functions Spreadsheet tool presentation report /Grivé et al. 2010b/ includes results of a benchmarking exercise in which the solubilities calculated with Simple Functions spreadsheet have been compared with the solubilities calculated with the code PHREEQC /Parkhurst and Appelo 2001/ and in some cases calculated with the code HYDRA-MEDUSA /Puigdomènech 2002/.

The validity of the activity correction approach used in the Simple Functions spreadsheet to calculate solubility values at high ionic strengths and the uncertainty associated with the Simple Functions spreadsheet calculations in the case of groundwater temperatures different from 25°C (in the range 0 to 100°C) have also been tested and reported in /Grivé et al. 2010b/.

The influence of temperature appears to be more important than that of the ionic strength, but in view of the results of the validation process, the Simple Functions spreadsheet can be considered a good tool for an easy and fast calculation of the solubility of radionuclides under the different groundwater compositions and temperatures of interest for SR-Site, always used with caution and keeping in mind its limitations.

### **3.20.5 Handling of input data, computational results and scripts**

The Simple Functions spreadsheet code is an Excel file. It is a user-friendly tool that requires the input of a groundwater composition and provides the concentration of radionuclides in equilibrium with their respective solubility limiting phases under the conditions of the groundwater composition. Therefore, any groundwater composition (calculated or measured) can be introduced in the tool. Calculated radionuclide concentrations can be directly used in other codes.

In SR-Site, groundwater data is supplied to the tool, which contains the uncertainties in thermodynamic data for the relevant reactions. The output produced is the solubility limit for the radioelements. Together with the @RISK tool, Simple Functions is used to calculate distributions of solubility to be used in the radionuclide transport calculations in SR-Site.

The data used for SR-Site are archived at SKB (SKBdoc 1265616, see Table 1-2).

### **3.20.6 Rationales for using the code in SR-Site**

The SR-Site team has selected the Simple Functions Spreadsheet for the SR-Site safety assessment since it is a tailor-made tool for the production of probabilistic distributions of radioelement solubilities. The results produced by the tool are in good agreement with those from conventional geochemical codes (e.g. PHREEQC).

## **3.21 TOUGHREACT**

### **3.21.1 Introduction**

TOUGHREACT is used in SR-Site for simulations of reactive transport in the buffer /Sena et al. 2010a/.

TOUGHREACT v.1.2 /Xu et al. 2008/ results from coupling the calculation of geochemical reactions to the THOUGH2 code /Pruess et al. 1999/, which solves multiphase, non-isothermal fluid flow, heat flow and multi-component transport. Aqueous complexation, gas dissolution/ex-solution and cation exchange are modelled under local equilibrium. Mineral precipitation/dissolution may be modelled either under equilibrium or kinetics assumptions. Additionally, changes in porosity, permeability and capillary pressure may be computed /Pruess et al. 1999/.

TOUGHREACT has been used by SKB in the “SKB-NF-2009” /Sena et al. 2010a/ and “LOT-A2 experiment”/Sena et al. 2010b/ projects. In the project “LOT-A2 experiment”, a 1D axis-symmetric model was developed to simulate the thermo-hydraulic, transport and geochemical processes that

have been observed during the LOT A2 test. In the SKB-NF-2009 project, the effect of the thermal period and the water saturation are analysed. These simulations are based on the outcomes of the previous numerical model built for the simulation of the LOT-A2 experiment.

Since the code is not written exclusively for the SKB projects, the code is regarded as a category 3 code.

### **3.21.2 Suitability of the code**

The first version of the code was developed by introducing reactive geochemistry into the framework of the existing multi-phase fluid and heat flow code TOUGH2 /Pruess 1991/. The present version of TOUGHREACT provides the following equation-of-state modules: EOS1, with typical applications to hydrothermal problems, EOS2 for multiphase mixtures of water and CO<sub>2</sub> with typical applications to hydrothermal problems, EOS3 for multiphase mixtures of water and air with typical applications to nuclear waste disposal problems, EOS4 with the same capabilities as EOS3 but with vapour pressure lowering effects due to capillary pressure, EOS9 with typical applications to ambient temperature and pressure reactive geochemical problems, and ECO2N for multiphase mixtures of water, CO<sub>2</sub> and NaCl with typical applications to CO<sub>2</sub> disposal in deep brine aquifers.

More detailed information on the geochemical and fluid flow and transport equations solved can be obtained from the TOUGHREACT User's Guide /Xu et al. 2008/ and the TOUGH2 User's Guide, version 2.0 /Pruess et al. 1999/.

### **3.21.3 Usage of the code**

In the TOUGHREACT User's Guide /Xu et al. 2008/ different examples have been included as test problems (geothermal systems, diagenetic and weathering processes, subsurface waste disposal, acid mine drainage remediation, contaminant transport and groundwater quality). The major processes for fluid and heat flow are: (1) fluid flow in both liquid and gas phases under pressure, viscous and gravity forces, (2) interactions between flowing phases represented by characteristic curves (relative permeability and capillary pressure), (3) heat flow by conduction and convection, and (4) diffusion of vapor and air /Pruess et al. 1999/. Aqueous complexation, acid-base, redox, gas dissolution/ex-solution, and cation exchange are considered under local equilibrium. Mineral dissolution and precipitation can proceed either subject to local equilibrium or kinetic conditions /Xu et al. 2008/. Linear adsorption and decay can be included.

### **3.21.4 Development process and verification**

The code was developed by the Earth Sciences Division of the Lawrence Berkeley National Laboratory (University of California) as a comprehensive non-isothermal multi-component reactive fluid flow and geochemical transport simulator to be applied to many geologic systems and environmental problems. The code is widely used and its algorithm has been checked through several scientific publications and through the example files distributed with the computer program.

### **3.21.5 Handling of input data, computational results and scripts**

Input data and output results are easily treated by means text editors. Output data can be also easily selected and obtained in .txt or .dat files that can be read and modified with Microsoft Excel program or similar.

Three input files are required: (1) flow.inp, including rock properties, time-stepping, grid, initial and boundary conditions and data related to a multi-phase fluid and heat transport simulations /Pruess et al. 1999/; (2) solute.inp, containing flags and input parameters for reactive transport calculations (diffusion coefficients, tolerances, e.g.); and (3) chemical.inp, defining the geochemical system, initial water compositions, material zones, and kinetic data for minerals. In addition, the program requires a thermodynamic database file.

The data used for SR-Site are archived at SKB (SKBdoc 1265618, see Table 1-2).

### 3.21.6 Rationales for using the code in SR-Site

The SR-Site team has selected the TOUGHREACT code because it is useful to solve non-isothermal and multicomponent reactive fluid flow and geochemical transport calculations. The level of knowledge of this program is high and well-supported.

## 3.22 UMISM

### 3.22.1 Introduction

UMISM (University of Maine Ice Sheet Model) is a dynamic ice-sheet model capable of simulating realistic ice sheets that are typically not in balance with climate (advances and retreats given changes in external forcing).

UMISM is used in SR-Site for reconstructing the ice sheet for the last glacial for the construction of the reference glacial cycle, and for input to simulations of other phenomena such as permafrost, isostatic changes, crustal stress, and ground water flow. The UMISM code was also used for sensitivity tests regarding e.g. maximum ice sheet thickness, see the SR-Site **Climate report**.

The UMISM has previously been used for simulations of Fennoscandian ice sheets for various purposes, cf /Fastook and Holmlund 1994, Holmlund and Fastook 1995, Näslund et al. 2003/ and in SKB safety assessments /SKB 2006a, 2008/.

The UMISM finite-element code (Fortran) has been developed by Prof. J. Fastook, at the Computer Science Department at University of Maine, U.S.A., e.g. /Fastook and Chapman 1989, Fastook 1990, 1994, Fastook and Holmlund 1994, Fastook and Prentice 1994, Johnson 1994/. In SR-Site, the version of UMISM as of October 2004/April 2005 was used. The code is classified as a category 4b code.

### 3.22.2 Suitability of the code

The climate input, forcing the ice sheet evolution, is the mean annual air temperature at sea level, and its variation over time. The mass balance is determined from an empirical relationship constituting a simple parameterisation of the ice sheet's effect on local climate /Fastook and Prentice 1994/. Distributed air temperatures over the model domain are determined from height over sea level and distance from the pole. The UMISM model includes a mathematical description of precipitation from a number of other parameters; distance from the pole, saturation vapour pressure (function of altitude and lapse-rate), and surface slope. This is an empirical relationship developed from the Antarctic ice sheet /Fastook and Prentice 1994/. Over a certain model domain, with a topography described from a Digital Elevation Model (DEM), this climate description gives a spatial pattern of air temperatures at ground level and a pattern of precipitation. Given a suitable climate forcing, the model develops a thermo-dynamic ice sheet over the DEM. Derived ice temperatures, together with density variations with depth, control ice hardness and ice flow. The thermodynamic calculation accounts for vertical diffusion, vertical advection, and heating caused by internal shear.

The UMISM ice sheet model includes a simplified isostatic description for the deformation of the crust due to the weight of the modelled ice sheet configuration. The UMISM code also includes a high-resolution modelling option by nesting.

### 3.22.3 Usage of the code

In the SR-Site ice sheet reconstruction simulations, inputs parameters to the model are: landscape topography, geothermal heat flux, global sea-level variations, thermo-mechanical properties of the ice, isostatic properties of the Earth's crust, and annual air temperature at sea level. In these runs, the program simulates the ice sheet for 120,000 years with 5 year time steps. For each time step, output data calculated for each grid cell and grid node are, for example,: ice thickness, englacial and basal ice temperatures, ice velocity, direction of ice movement, isostatic depression of crust, and amount of basal melting or freeze-on of water.

Output data from UMISM can be saved in, e.g., txt format or NetCDF (Network Common Data Form) format.

Descriptions of model setups, as well as input data to the model, for SR-Site simulations are found in the **Climate report**. The close collaboration with the developer of the code assures the correct usage of the code in SR-Site.

#### **3.22.4 Development process and verification**

UMISM was part of the EISMINT (European Ice Sheet Modelling Initiative) model intercomparison experiment and yielded output in agreement with many other major ice sheet models /Huybrechts et al. 1996, Payne et al. 2000/.

#### **3.22.5 Handling of input data, computational results and scripts**

The code was adapted to meet specific requirements during the modelling work, for instance to produce certain type of output data related to the production of glacial melt water. Specific output data formats were also produced for data export to other SR-Site activities, such as the permafrost modelling /Hartikainen et al. 2010 and **Climate report**, Section 3.4/, Global Isostatic Adjustment (GIA) modelling conducted at University of Durham by P. Whitehouse /**Climate report**, Section 3.3/, and for modelling of crustal stresses performed at university of Uppsala performed by B. Lund /Lund et al. 2009/. How data is transferred between the ice sheet (UMISM), GIA, and permafrost simulations is shown in Figure 3-2.

Data were transferred from the UMISM model to other SR-Site activities in Excel spread sheets. Data are archived in SKBdoc 1265613 (Table 1-2).

#### **3.22.6 Rationales for using the code in SR-Site**

The UMISM code was selected for the SR-Site safety assessment since a very large number of simulations of the Fennoscandian ice sheet have been done with the UMISM model over the years. This has resulted in considerable experience and understanding of how to do model calibrations against geological observations in order to obtain more realistic ice sheet configurations, which is highly relevant for the SR-Site safety assessment. An additional reason for choosing this model is the recognized ability and interest of the model developer to engage in validating and assessing model results against real-world observations and phenomena related to the ice sheet system that is being modelled. This is important in phases of model calibration as well as when adopting and developing the model to specific needs of the project.

## 4 References

SKB's (Svensk Kärnbränslehantering AB) publications can be found at [www.skb.se/publications](http://www.skb.se/publications).

### *References with abbreviated names*

**Buffer, backfill and closure process report, SKB 2010.** Buffer, backfill and closure process report for the safety assessment SR-Site. SKB TR-10-47, Svensk Kärnbränslehantering AB.

**Climate report, SKB 2010.** Climate and climate-related issues for the safety assessment SR-Site. SKB TR-10-49, Svensk Kärnbränslehantering AB.

**Data report, SKB 2010.** Data report for the safety assessment SR-Site. SKB TR-10-52, Svensk Kärnbränslehantering AB.

**Fuel and canister process report, SKB 2010.** Fuel and canister process report for the safety assessment SR-Site. SKB TR-10-46, Svensk Kärnbränslehantering AB.

**Geosphere process report, SKB 2010.** Geosphere process report for the safety assessment SR-Site. SKB TR-10-48, Svensk Kärnbränslehantering AB.

**Main report, SKB 2011.** Long-term safety for the final repository for spent nuclear fuel at Forsmark. Main report of the SR-Site project. SKB TR-11-01, Svensk Kärnbränslehantering AB.

**Radionuclide transport report, SKB 2010.** Radionuclide transport report for the safety assessment SR-Site. SKB TR-10-50, Svensk Kärnbränslehantering AB.

**Spent fuel report, SKB 2010.** Spent nuclear fuel for disposal in the KBS-3 repository. SKB TR-10-13, Svensk Kärnbränslehantering AB.

**Underground openings construction report, SKB 2010.** Design, construction and initial state of the underground openings. SKB TR-10-18, Svensk Kärnbränslehantering AB.

### *Other public references*

**Abbott M B, Bathurst J C, Cunge J A, O'Connell P E, Rasmussen J, 1986.** An introduction to the European Hydrological System – Systeme Hydrologique Europeen, "SHE", 2: Structure of a physically-based, distributed modelling system. *Journal of Hydrology*, 87, pp 61–77.

**Alonso E E, Gens A, Josa A, 1990.** A constitutive model for partially saturated soils. *Géotechnique*, 40, No. 3, pp 405–430.

**Andersson E (ed), 2010.** The limnic ecosystems at Forsmark and Laxemar-Simpevarp. SR-Site Biosphere. SKB TR-10-02, Svensk Kärnbränslehantering AB.

**Andra, 2005.** Dossier 2005 Granite – safety analysis of a geological repository. Châtenay-Malabry: Agence nationale pour la gestion des déchets radioactifs (ANDRA).

**Arcos D, Grandia F, Domènech C, 2006.** Geochemical evolution of the near field of a KBS-3 repository. SKB TR-06-16, Svensk Kärnbränslehantering AB.

**Avila R, Ekström P-A, Åstrand P-G, 2010.** Landscape dose conversion factors used in the safety assessment SR-Site. SKB TR-10-06, Svensk Kärnbränslehantering AB.

**Bassett S E, Milne G A, Mitrovica J X, Clark P U, 2005.** Ice sheet and solid Earth influences on far-field sea-level histories. *Science*, 309, pp 925–928.

**Beresford N, Brown J, Copplestone D, Garnier-Laplace J, Howard B, Larsson C-M, Oughton D, Pröhl G, Zinger I (eds), 2007.** D-ERICA: an INTEGRATED APPROACH to the assessment and management of environmental risks from ionising radiation. Description of purpose, methodology and application. ERICA Project, contract number FI6R-CT-2004-508847, European Commission.

**Boghammar A, Grundfelt B, Hartley L, 1997.** Investigation of the large scale regional hydrogeological situation at Ceberg. SKB TR 97-21, Svensk Kärnbränslehantering AB.

**Boghammar A, 1999.** Säkerhet och Vetenskap. Implementation and version control for software developed by SKB. User's Guide rev 2. SKB Arbetsrapport TS-99-13, Svensk Kärnbränslehantering AB.

- Bosson E, Gustafsson L-G, Sassner M, 2008.** Numerical modelling of surface hydrology and near-surface hydrogeology at Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-09, Svensk Kärnbränslehantering AB.
- Bosson E, Sassner M, Sabel U, Gustafsson L-G, 2010.** Modelling of present and future hydrology and solute transport at Forsmark. SR-Site Biosphere. SKB R-10-02, Svensk Kärnbränslehantering AB.
- Bödvarsson R, Lund B, Roberts R, Slunga R, 2006.** Earthquake activity in Sweden. Study in connection with a proposed nuclear waste repository in Forsmark or Oskarshamn. SKB R-06-67, Svensk Kärnbränslehantering AB.
- Börgesson L, Hernelind J, 1999.** Coupled thermo-hydro-mechanical calculations of the water saturation phase of a KBS-3 deposition hole. Influence of hydraulic rock properties on the water saturation phase. SKB TR-99-41, Svensk Kärnbränslehantering AB.
- Börgesson L, Hernelind J, 2006a.** Canister displacement in KBS-3V. A theoretical study. SKB TR-06-04, Svensk Kärnbränslehantering AB.
- Börgesson L, Hernelind J, 2006b.** Earthquake induced rock shear through a deposition hole. Influence of shear plane inclination and location as well as buffer properties on the damage caused to the canister. SKB TR-06-43, Svensk Kärnbränslehantering AB.
- Börgesson L, Johannesson L-E, Hernelind J, 2003.** Earthquake induced rock shear through a deposition hole. Effect of the canister and the buffer. SKB TR-04-02, Svensk Kärnbränslehantering AB.
- Börgesson L, Fälth B, Hernelind J, 2006.** Water saturation phase of the buffer and backfill in the KBS-3V concept. Special emphasis given to the influence of the backfill on the wetting of the buffer. SKB TR-06-14, Svensk Kärnbränslehantering AB.
- Cappa F, Guglielmi Y, Rutqvist J, Tsang C-F, Thoraval A, 2006.** Hydromechanical modelling of pulse tests that measure fluid pressure and fracture normal displacement at the Coaraze Laboratory site, France. *International Journal of Rock Mechanics and Mining Sciences*, 43, pp 1062–1082.
- CDM, 2001.** Evaluation of integrated surface water and groundwater modelling tools. Camp Dresser and McKee, Cambridge MA.
- Chan T, Christiansson R, Boulton G S, Ericsson L O, Hartikainen J, Jensen M R, Mas Ivars D, Stanchell F W, Vistrand P, Wallroth T, 2005.** DECOVALEX III BMT3/BENCHPAR WP4: The thermo-hydro-mechanical responses to a glacial cycle and their potential implications for deep geological disposal of nuclear fuel waste in a fractured crystalline rock mass. *International Journal of Rock Mechanics and Mining Sciences*, 42, pp 805–827.
- Clark P U, Mitrovica J X, Milne G A, Tamisiea M E, 2002.** Sea-level fingerprinting as a direct test for the source of global meltwater pulse IA. *Science*, 295, pp 2438–2441.
- Cliffe K A, Kelly M, 2006.** COMP23 version 1.2.2 user's manual. SKB R-04-64, Svensk Kärnbränslehantering AB.
- CODE\_BRIGHT User's Guide, 2009.** Geotechnical Engineering Department, Technical University of Catalunya, Spain.
- CODE\_BRIGHT v3 Validation document, 2009.** Geotechnical Engineering Department, Technical University of Catalunya, Spain.
- CODE\_BRIGHT v3 Verification document, 2009.** Geotechnical Engineering Department, Technical University of Catalunya, Spain.
- Cundall P A, 1971.** A computer model for simulating progressive, large scale movements in blocky rock systems. In: *Rock Fractures: Proceedings of the International Symposium on Rock Mechanics*, Nancy, France, October 1971, paper II-8.
- DHI, 2009.** MIKE SHE – User Manual. DHI Water & Environment, Hørsholm, Denmark.
- Domènech C, Arcos D, Duro L, Grandia F, 2006.** Effect of the mineral precipitation-dissolution at tunnel walls during the operational and post-operational phases. SKB R-06-108, Svensk Kärnbränslehantering AB.
- Duro L, Grivé M, Cera E, Gaona X, Domènech C, Bruno J, 2006.** Determination and assessment of the concentration limits to be used in SR-Can. SKB TR-06-32, Svensk Kärnbränslehantering AB.

- Ekström P-A, 2011.** Pandora – a simulation tool for safety assessments. Technical description and user's guide. SR-Site Biosphere. SKB R-11-01, Svensk Kärnbränslehantering AB.
- Elert M, Gylling B, Lindgren, M, 2004.** Assessment model validity document FARF31. SKB R-04-51, Svensk Kärnbränslehantering AB.
- Farrell W E, Clark J A, 1976.** On postglacial sea level. *Geophysical Journal of the Royal Astronomical Society*, 46, pp 647–667.
- Fastook J L, 1990.** A map-plane finite-element program for ice sheet reconstruction: a steady-state calibration with Antarctica and a reconstruction of the Laurentide ice sheet for 18,000 BP. In: Brown H U (ed). *Computer assisted analysis and modeling on the IBM 3090*. White Plains, N.Y.: IBM Scientific and Technical Computing Department.
- Fastook J L, 1994.** Modeling the ice age: the finite-element method in glaciology. *Computational Science & Engineering*, 1, pp 55–67.
- Fastook J L, Chapman J E, 1989.** A map plane finite-element model: three modeling experiments. *Journal of Glaciology*, 35, pp 48–52.
- Fastook J L, Holmlund P, 1994.** A glaciological model of the Younger Dryas event in Scandinavia. *Journal of Glaciology*, 40, pp 125–131.
- Fastook J L, Prentice M, 1994.** A finite-element model of Antarctica: sensitivity test for meteorological mass-balance relationship. *Journal of Glaciology*, 40, pp 167–175.
- Ferry M, 2002.** MIGAL. [www.mfrdc.com](http://www.mfrdc.com)
- Follin S, 2008.** Bedrock hydrogeology Forsmark. Site descriptive modelling, SDM-Site Forsmark. SKB R-08-95, Svensk Kärnbränslehantering AB.
- Follin S, Stigsson M, Svensson U, 2005.** Variable-density groundwater flow simulations and particle tracking – Numerical modelling using DarcyTools, Preliminary site description Simpevarp subarea – version 1.2. SKB R-05-11, Svensk Kärnbränslehantering AB.
- Freund J, Lempinen A, 1994.** A general purpose finite element solver. Report 40, Institute of Computational Dynamics, Helsinki University of Technology.
- Fälth B, Hökmark H, 2006.** Seismically induced slip on rock fractures. Results from dynamic discrete fracture modeling. SKB R-06-48, Svensk Kärnbränslehantering AB.
- Fälth B, Hökmark H, 2007.** Mechanical and thermo-mechanical discrete fracture near-field analyses based on preliminary data from the Forsmark, Simpevarp and Laxemar sites. SKB R-06-89, Svensk Kärnbränslehantering AB.
- Fälth B, Hökmark H, Munier R, 2010.** Effects of large earthquakes on a KBS-3 repository. Evaluation of modelling results and their implications for layout and design. SKB TR-08-11, Svensk Kärnbränslehantering AB.
- Gehrels W R, Milne G A, Kirby J R, Patterson R T, Belknap D F, 2004.** Late Holocene sea-level changes and isostatic crustal movements in Atlantic Canada. *Quaternary International*, 120, pp 79–89.
- Graham D N, Butts M B, 2005.** Flexible, integrated watershed modelling with MIKE SHE. In: Singh V P, Frevert D K (eds). *Watershed Models*. Boca Raton: CRC Press, pp 245–272.
- Grandia F, Domènech C, Arcos D, Duro L, 2006.** Assessment of the oxygen consumption in the backfill. Geochemical modelling in a saturated backfill. SKB R-06-106, Svensk Kärnbränslehantering AB.
- Grandia F, Sena C, Arcos D, Molinero J, Duro L, Bruno J, 2007.** Quantitative assessment of radionuclide retention in the near-surface system at Forsmark. Development of a reactive transport model using Forsmark 1.2 data. SKB R-07-64, Svensk Kärnbränslehantering.
- Grandia F, Galindez J-M, Arcos D, Molinero J, 2010.** Quantitative modelling of the degradation processes of cement grout. Project CEMMOD. SKB TR-10-25, Svensk Kärnbränslehantering AB.
- Grivé M, Domènech C, Montoya V, Garcia D, Duro L, 2010a.** Determination and assessment of the concentration limits to be used in SR-Can. Supplement to TR-06-32. SKB R-10-50, Svensk Kärnbränslehantering AB.

- Grivé M, Domènech C, Montoya V, García D, Duro L, 2010b.** Simple Functions Spreadsheet tool presentation. SKB TR-10-61, Svensk Kärnbränslehantering AB.
- Guimera J, Duro L, Delos A, 2006.** Changes in groundwater composition as a consequence of deglaciation. Implications for performance assessment. SKB R-06-105, Svensk Kärnbränslehantering AB.
- Gustafsson L-G, Gustafsson A-M, Aneljung M, Sabel U, 2009.** Effects on surface hydrology and near surface hydrogeology of an open repository in Forsmark. Results of modelling with MIKE SHE. SKB R-08-121, Svensk Kärnbränslehantering AB.
- Hakami E, Olofsson S-O, Hakami H, Israelsson J, 1998.** Global thermo-mechanical effects from a KBS-3 type repository. Summary report. SKB TR 98-01, Svensk Kärnbränslehantering AB.
- Hartikainen J, 1994.** Maan routimisen termomekaaninen malli ja sen laskelmat (Thermomechanical model for freezing soil and its computer implementation) (in Finnish). Master's thesis. Department of Civil Engineering and Surveying, Helsinki University of Technology.
- Hartikainen J, 2004.** Permafrost modelling in DECOVALEX III for BMT3. In: Eloranta E (ed). DECOVALEX III, 1999–2003. An international project for the modelling of coupled Thermo-Hydro-Mechanical processes for spent fuel disposal. Finnish national contributions. Helsinki: Radiation and Nuclear Safety Authority. (STUK-YTO-TR 209), Appendix IV.
- Hartikainen J, 2006.** Numerical simulation of permafrost depth at Olkiluoto. Working Report 2006-52. Posiva Oy, Finland.
- Hartikainen J, Mikkola M, 1997.** General thermomechanical model of freezing soil with numerical application. In: Knutsson S (ed). Ground freezing 97: frost action in soils: proceedings of the International Symposium on Ground Freezing and Frost Action in Soils, Luleå, Sweden, 15–17 April 1997. Rotterdam: Balkema, pp 101–105.
- Hartikainen J, Mikkola M, 2006.** Thermomechanical modelling for freezing of solute saturated soil. In: Gladwell G M L, Huyghe J M, Raats P A C, Cowin S C (eds). IUTAM symposium on physicochemical and electromechanical interactions in porous media. Dordrecht: Springer. (Solid Mechanics and its Applications 125), pp 335–341.
- Hartikainen J, Kouhia R, Wallroth T, 2010.** Permafrost simulations at Forsmark using a numerical 2D thermo-hydro-chemical model. SKB TR-09-17, Svensk Kärnbränslehantering AB.
- Hartley L, Boghammar A, Grundfelt B, 1998.** Investigation of the large scale regional hydrogeological situation at Beberg. SKB TR-98-24, Svensk Kärnbränslehantering AB.
- Hartley L, Cox I, Holton D, Hunter F, Joyce S, Gylling B, Lindgren M, 2004.** Groundwater flow and radionuclide transport modelling using CONNECTFLOW in support of the SR Can assessment. SKB R-04-61, Svensk Kärnbränslehantering AB.
- Hedin A, 2008.** Semi-Analytic Stereological Analysis of Waste Package/Fracture Intersections in a Granitic Rock Nuclear Waste Repository. *Mathematical Geosciences*, 40, 619–637.
- Hedin A, 2011.** Stereological Method for Reducing Probability of Earthquake-Induced Damage in a Nuclear Waste Repository. *Mathematical Geosciences* 43, 1–21.
- Herbert A, Gale J, Lanyon G, MacLeod R, 1991.** Modelling for the Stripa site characterization and validation drift inflow: Prediction of flow through fractured rock. Stripa Project Technical Report 91-35, Svensk Kärnbränslehantering AB.
- Herbert A W, Lanyon G W, 1992.** Modelling tracer transport in fractured rock at Stripa. Stripa Project Technical Report 92-01, Svensk Kärnbränslehantering AB.
- Hernelind J, 2010.** Modelling and analysis of canister and buffer for earthquake induced rock shear and glacial load. SKB TR-10-34, Svensk Kärnbränslehantering AB.
- Holmlund P, Fastook J, 1995.** A time dependent glaciological model of the Weichselian ice sheet. *Quaternary International*, 27, pp 53–58.
- Holton D, Milický M, 1997.** Simulating the LPT2 and Tunnel Drawdown Experiment at Äspö using a coupled continuum-fracture network approach. SKB HRL International Cooperation Report ICR 97-05, Svensk Kärnbränslehantering AB.

- Holton D, Hartley L J, Hautojärvi A, Marschall P, Selroos J-O, 2003.** iCONNECT Club: Integrated Continuum and Network Approach to Groundwater flow and Contaminant Transport. MRS 2003. Scientific basis for nuclear waste management XXVII, Kalmar, Sweden.
- Huybrechts P, Payne T, EISMINT Intercomparison Group, 1996.** The EISMINT benchmarks for testing ice-sheet models. *Annals of Glaciology*, 23, pp 1–12.
- Hökmark H, Lönnqvist M, Fälth B, 2010.** THM-issues in repository rock. Thermal, mechanical, thermo-mechanical and hydro-mechanical evolution of the rock at the Forsmark and Laxemar sites. SKB TR-10-23, Svensk Kärnbränslehantering AB.
- ICRP, 1983.** Radionuclide transformations : energy and intensity of emissions: report of a task group of committee 2 of the International commission on radiological protection on data used in ICRP publication 30. Oxford: Pergamon. (ICRP Publication 38; *Annals of the ICRP* 11-13).
- Itasca, 2003.** 3DEC – 3-Dimensional Distinct Element Code, User’s guide, Version: 3. Itasca Consulting Group Inc. Minneapolis, USA.
- Itasca, 2005.** UDEC, Universal Distinct Element Code, Version: 4. Itasca Consulting Group Inc. Minneapolis, USA.
- Itasca, 2007.** 3DEC – 3-Dimensional Distinct Element Code, User’s guide, Version: 4.1. Itasca Consulting Group Inc. Minneapolis, USA.
- Jackson C P, Watson S P, et al. 1997.** Nirex 97. An assessment of the post-closure performance of a deep waste repository at Sellafield. Volume 2: Hydrogeological model development – Effective parameters and calibration. UK Nirex Report no S/97/012 [Volume 2], UK Nirex Limited.
- Johnson J, 1994.** A basal water model for ice sheets. Ph. D. thesis. University of Minnesota.
- Jones J, Vahlund F, Kautsky U, 2004.** Tensit – a novel probabilistic simulation tool for safety assessments. Tests and verifications using biosphere models. SKB TR-04-07, Svensk Kärnbränslehantering AB.
- Jones J, Kautsky U, Vahlund F, 2005.** Tensit – a simulation tool for nuclide transport, risk and dose calculations. *Radioprotection*, 40, Suppl. 1, pp S933–S938.
- Joyce S, Simpson T, Hartley L, Applegate D, Hoek J, Jackson P, Swan D, Marsic N, Follin S, 2010.** Groundwater flow modelling of periods with temperate climate conditions – Forsmark. SKB R-09-20, Svensk Kärnbränslehantering AB.
- Kelly M, Cliffe K A, 2006.** Validity document for COMP23. SKB R-06-76, Svensk Kärnbränslehantering AB.
- Kendall R A, Mitrovica J X, Milne G A, 2005.** On post-glacial sea level – II. Numerical formulation and comparative results on spherically symmetric models. *Geophysical Journal International*, 161, pp 679–706.
- Kipp K L, 1987.** HST3D – a computer code for simulation of heat and solute transport in three dimensional ground-water flow systems. Denver, Co: U.S. Geological Survey. (Water-resources investigations report 86-4095).
- Kipp K L, 1997.** Guide to the revised heat and solute transport simulator HST3D – Version 2. Denver, Co: U.S. Geological Survey. (Water-resources investigations report 97-4157).
- Kulatilake P H S W, Ucpirti H, Wang S, Radberg G, Stephansson O, 1992.** Use of the distinct element method to perform stress analysis in rock with non-persistent joints and to study the effect of joint geometry parameters on the strength and deformability of rock masses. *Rock Mechanics and Rock Engineering*, 25, pp 253–274.
- Küng S, Onken L, 2009.** TourtoiseSVN. Version: 1.6.10, Build 19898 – 32 Bit, 2010/07/16 15:46:08. Tigris.org. <http://subversion.tigris.org/>
- Last N C, Harper T R, 1990.** Response of fractured rock subject to fluid injection part I. Development of a numerical model. *Tectonophysics*, 172, pp 1–31.
- Latychev K, Mitrovica J X, Tamisiea M E, Tromp J, Moucha R, 2005.** Influence of lithospheric thickness variations on 3-D crustal velocities due to glacial isostatic adjustment. *Geophysical Research Letters*, 32, L01304, doi:10.1029/2004GL021454.

- Lindborg (ed), 2010.** Landscape Forsmark – data, methodology and results for SR-Site. SKB TR-10-05. Svensk Kärnbränslehantering AB.
- Lindgren M, Lindström F, 1999.** SR 97 – Radionuclide transport calculations. SKB TR-99-23, Svensk Kärnbränslehantering AB.
- Lindgren M, Widén H, 1998.** Discretization in COMP23 for SR97. SKB R-98-03, Svensk Kärnbränslehantering AB.
- Lindgren M, Gylling B, Elert M, 2002.** FARF31 Version 1.2 – User’s guide. SKB TS-02-03, Svensk Kärnbränslehantering AB.
- Lindgren M, Pettersson M, Cliffe A, Kelly M, 2008.** COMP23 Test batch. SKB R-06-112, Svensk Kärnbränslehantering AB.
- Lindgren M, Pettersson M, Karlsson S, Moreno L, 2001.** Project SAFE. Radionuclide release and dose from the SFR repository. SKB R-01-18, Svensk Kärnbränslehantering AB.
- Luna M, Arcos D, Duro L, 2006.** Effects of grouting, shotcreting and concrete leachates on backfill geochemistry. SKB R-06-107, Svensk Kärnbränslehantering AB.
- Lund B, Schmidt P, Hieronymus C, 2009.** Stress evolution and fault stability during the Weichselian glacial cycle. SKB TR-09-15, Svensk Kärnbränslehantering AB.
- Marsic N, Hartley L, Jackson P, Poole M, Morvik A, 2001.** Development of hydrogeological modelling tools based on NAMMU. SKB R-01-49, Svensk Kärnbränslehantering AB.
- Marsic N, Hartley L, Sanchez-Friera P, Morvik A, 2002.** Embedded regional/local-scale model of natural transients in saline groundwater flow: Illustrated using the Beberg site. SKB R-02-22, Svensk Kärnbränslehantering AB.
- Maul P, Robinson P, Broed R, Avila R, 2010.** Further AMBER and Ecolego intercomparisons. SKI Report 2004:05, Statens kärnkraftinspektion (Swedish Nuclear Power Inspectorate), SSI Report 2004:01, Statens strålskyddsinstitut (Swedish Radiation Protection Authority).
- MathWorks, 2010a.** Matlab R2010b (v. 7.11). Natick, MA: MathWorks Inc.
- MathWorks, 2010b.** Simulink. Natick, MA: MathWorks Inc.
- MathWorks, 2010c.** Parallel processing toolbox. Version: V5.0 (R2010b). Natick, MA: MathWorks Inc.
- Microsoft, 2008.** Visual C++ 2008. Version: 2008 Express edition. Bellevue, WA: Microsoft Corp.
- Mikkola M, Hartikainen J, 2001.** Mathematical model of soil freezing and its numerical implementation. *International Journal for Numerical Methods in Engineering*, 52, pp 543–557.
- Mikkola M, Hartikainen J, 2002.** Computational aspects of soil freezing problem. In: Mang H A, Rammerstorfer F G, Eberhardsteiner J (eds). *Proceedings of the Fifth World Congress on Computational Mechanics*, Vienna, 7–12 July 2002.
- Milne G A, 1998.** Refining models of the glacial isostatic adjustment process. Ph. D. thesis. University of Toronto.
- Milne G A, Mitrovica J X, 1998.** Postglacial sea-level change on a rotating Earth. *Geophysical Journal International*, 133, pp 1–19.
- Milne G A, Mitrovica J X, Davis J L, 1999.** Near-field hydro-isostasy: the implementation of a revised sea-level equation. *Geophysical Journal International*, 139, pp 464–482.
- Milne G A, Davis J L, Mitrovica J X, Scherneck H-G, Johansson J M, Vermeer M, Koivula H, 2001.** Space-geodetic constraints on glacial isostatic adjustment in Fennoscandia. *Science*, 291, pp 2381–2385.
- Milne G A, Mitrovica J X, Schrag D P, 2002.** Estimating past continental ice volume from sea-level data. *Quaternary Science Reviews*, 21, pp 361–376.
- Milne G A, Mitrovica J X, Scherneck H G, Davis J L, Johansson J M, Koivula H, Vermeer M, 2004.** Continuous GPS measurements of postglacial adjustment in Fennoscandia: 2. Modeling results. *Journal of Geophysical Research*, 109, B02412, doi:10.1029/2003JB002619.

- Milne G A, Long A J, Bassett S E, 2005.** Modelling Holocene relative sea-level observations from the Caribbean and South America. *Quaternary Science Reviews*, 24, pp 1183–1202.
- Milne G A, Shennan I, Youngs B A R, Waugh A I, Teferle F N, Bingley R M, Bassett S E, Cuthbert-Brown C, Bradley S L, 2006.** Modelling the glacial isostatic adjustment of the UK region. *Philosophical Transactions of the Royal Society A – Mathematical, Physical & Engineering Sciences*, 364, pp 931–948.
- Mitrovica J X, Milne G A, 2002.** On the origin of late Holocene sea-level highstands within equatorial ocean basins. *Quaternary Science Reviews*, 21, pp 2179–2190.
- Mitrovica J X, Milne G A, 2003.** On post-glacial sea level: I. General theory. *Geophysical Journal International*, 154, pp 253–267.
- Mitrovica J X, Peltier W R, 1991.** On post-glacial geoid subsidence over the equatorial oceans. *Journal of Geophysical Research*, 96, pp 20053–20071.
- Mitrovica J X, Tamisiea M E, Davis J L, Milne G A, 2001.** Recent mass balance of polar ice sheets inferred from patterns of global sea-level change. *Nature*, 409, pp 1026–1029.
- Mitrovica J X, Wahr J, Matsuyama I, Paulson A, 2005.** The rotational stability of an ice-age earth. *Geophysical Journal International*, 161, pp 491–506.
- Munier R, 2006.** Using observations in deposition tunnels to avoid intersections with critical fractures in deposition holes. SKB R-06-54, Svensk Kärnbränslehantering AB.
- Munier R, 2007.** Demonstrating the efficiency of the EFPC criterion by means of Sensitivity analyses. SKB R-06-115, Svensk Kärnbränslehantering AB.
- Munier R, 2010.** Full perimeter intersection criteria. Definitions and implementations in SR-Site. SKB TR-10-21, Svensk Kärnbränslehantering AB.
- NEA/SKI, 1988.** The international HYDROCOIN project. Groundwater hydrology modelling strategies for performance assessment of nuclear waste disposal. Level 1: Code verification. Oecd/Nea; SKI.
- Neerdael B, Finsterle S, 2010.** The use of numerical models in support of site characterization and performance assessment studies for geological repositories. *Nuclear Engineering and Technology*, 42, pp 145–150.
- Neretnieks I, 1986.** Stationary transport of dissolved species in the backfill surrounding a waste canister in fissured rock: some simple analytical solutions. *Nuclear Technology*, 72, pp 194–200.
- Norman S, Kjellbert N, 1990.** FARF31 – A far field radionuclide migration code for use with the PROPER package. SKB TR 90-01, Svensk Kärnbränslehantering AB.
- Näslund J O, Rodhe L, Fastook J L, Holmlund P, 2003.** New ways of studying ice sheet flow directions and glacial erosion by computer modelling – examples from Fennoscandia. *Quaternary Science Reviews*, 22, pp 245–258.
- Olivella S, 1995.** Nonisothermal multiphase flow of brine and gas through saline media. Ph. D. thesis. Geotechnical Engineering Department, Technical University of Catalunya, Spain.
- Olivella S, Carrera J, Gens A, Alonso E E, 1994.** Non-isothermal multiphase flow of brine and gas through saline media. *Transport in Porous Media*, 15, pp 271–293.
- Olivella S, Gens A, Carrera J, Alonso E E, 1996.** Numerical formulation for a simulator (CODE\_BRIGHT) for the coupled analysis of saline media. *Engineering Computations*, 13, pp. 87–112.
- Painter S, Mancillas J, 2009.** MARFA version 3.2.2 user’s manual: migration analyses of radionuclides in the far-field. SKB R-09-56, Svensk Kärnbränslehantering AB.
- Painter S, Cvetkovic V, Mancillas J, Pensado O, 2008.** Time domain particle tracking methods for simulating transport with retention and first-order transformation. *Water Resources Research*, 44, W01406, doi:10.1029/2007WR005944.
- Parkhurst D L, Appelo C A J, 1999.** User’s guide to PHREEQC (version 2): a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. Denver, Co: U.S. Geological Survey. (Water-resources investigations report 99-4259).

- Parkhurst D L, Appelo C A J, 2001.** User's guide to PHREEQC (Version 2.4.6). A computer program for speciation, batch reaction, one dimensional transport and inverse geochemical calculations. Denver, Co: U.S. Geological Survey.
- Parkhurst D L, Kipp K L, Engesgaard P, Charlton S R, 2004.** PHAST: a program for simulating ground-water flow, solute transport, and multicomponent geochemical reactions. U.S. Geological Survey Techniques and Methods 6-A8. Denver, Co: U.S. Geological Survey.
- Payne A J, Huybrechts P, Abe-Ouchi A, Calov R, Fastook J L, Greve R, Marshall S J, Marsiat I, Ritz C, Tarasov L, Thomassen M P A, 2000.** Results from the EISMINT model intercomparison: the effects of thermomechanical coupling. *Journal of Glaciology*, 46, pp 227–238.
- Pruess K, 1991.** TOUGH2 – A general purpose numerical simulator for multiphase fluid and heat flow. Report LBL-29400, Lawrence Berkeley Laboratory.
- Pruess K, Oldenburg C, Moridis G, 1999.** TOUGH2 User's Guide, Version 2.0. Report LBNL-43134, Lawrence Berkeley National Laboratory, University of California.
- Prváková S, 2005.** Deep geological disposal and its long-term safety. EUR 22100, European Commission.
- Puigdomènech I, 2002.** MEDUSA (Make Equilibrium Diagrams Using Sophisticated Algorithms) Windows interface to the MS-DOS versions of INPUT, SED and PREDOM (FORTRAN programs drawing chemical equilibrium diagrams) Vers. 31 July. 2002. Royal Institute of Technology (KTH), Stockholm.
- Romero A L, 1995.** The near-field transport in a repository for high-level nuclear waste. Ph. D. thesis. Department of Chemical Engineering and Technology, Royal Institute of Technology, Stockholm, Sweden.
- Romero L, Thompson A, Moreno L, Neretnieks I, Widén H, Boghammar A, 1999.** Comp23/ Nuctran user's guide – Proper version 1.1.6. SKB R-99-64, Svensk Kärnbränslehantering AB.
- Salas J, Gimeno M J, Auqué L F, Molinero J, Gómez J, Juárez I, 2010.** SR-Site – hydrogeochemical evolution of the Forsmark site. SKB TR-10-58, Svensk Kärnbränslehantering AB.
- Selroos J-O, Follin S, 2010.** SR-Site groundwater flow modelling methodology, setup and results. SKB R-09-22, Svensk Kärnbränslehantering AB.
- Sena C, Grandia F, Arcos D, Molinero J, Duro L, 2008.** Complementary modelling of radionuclide retention in the near-surface system at Forsmark. Development of a reactive transport model using Forsmark 1.2 data. SKB R-08-107, Svensk Kärnbränslehantering AB.
- Sena C, Salas J, Arcos D, 2010a.** Aspects of geochemical evolution of the SKB near field in the frame of SR-Site. SKB TR-10-59, Svensk Kärnbränslehantering AB.
- Sena C, Salas J, Arcos D, 2010b.** Thermo-hydro-geochemical modelling of the bentonite buffer, LOT A2 experiment. SKB TR-10-65, Svensk Kärnbränslehantering AB.
- Senseny P E, 1993.** Stress wave loading of a tunnel: a benchmark study. In: Hossain Q A (ed). Dynamic analysis and design considerations for high-level nuclear waste repositories: proceedings of the symposium held in San Francisco, 19–20 August 1992. New York: American Society of Civil Engineers, pp 311–338.
- Serco, 2008a.** ConnectFlow Release 9.6 Technical Summary Document. SA/ENV/CONNECTFLOW/15, Serco Assurance, UK.
- Serco, 2008b.** NAMMU Release 9.6 Technical Summary Document. SA/ENV/CONNECTFLOW/8, Serco Assurance, UK.
- Serco, 2008c.** NAPSAC Release 9.6 Technical Summary Document. SA/ENV/CONNECTFLOW/12, Serco Assurance, UK.
- Serco, 2008d.** NAMMU Release 9.6 Verification Document. SA/ENV/CONNECTFLOW/9, Serco Assurance, UK.
- Serco, 2008e.** NAPSAC Release 9.6 Verification Document. SA/ENV/CONNECTFLOW/13, Serco Assurance, UK.

- Serco, 2008f.** ConnectFlow Release 9.6 Verificiation Document. SA/ENV/CONNECTFLOW/16, Serco Assurance, UK.
- Serco, 2008g.** ConnectFlow Quality Plan. SA/ENV/CONNECTFLOW/1, Serco Assurance, UK.
- Sidborn M, Sandström B, Tullborg E-L, Delos A, Molinero J, Hallbeck L, Pedersen K, 2010.** SR-Site: Oxygen ingress in the rock at Forsmark during a glacial cycle. SKB TR-10-57, Svensk Kärnbränslehantering AB.
- Sjöberg J, 1992.** Failure modes and pillar behavior in the zinkgruvan mine. In: Tillerson J A, Wawersik W R (eds). Proceedings of 33rd U.S. Rock Mechanics Symposium, Sante Fe, June 1992. Rotterdam: Balkema, pp 491–500.
- SKB, 1996.** SR 95. Template for safety reports with descriptive example. SKB TR 96-05, Svensk Kärnbränslehantering AB.
- SKB, 1999.** Deep repository for spent nuclear fuel. SR 97 – Post-closure safety. Main report. SKB TR-99-06 Vol. I, Vol. II and Summary, Svensk Kärnbränslehantering AB.
- SKB, 2003.** Planning report for the safety assessment SR-Can. SKB TR-03-08, Svensk Kärnbränslehantering AB.
- SKB, 2004.** Interim main report of the safety assessment SR-Can. SKB TR-04-11, Svensk Kärnbränslehantering AB.
- SKB, 2006a.** Climate and climate-related issues for the safety assessment SR-Can. SKB TR-06-23, Svensk Kärnbränslehantering AB.
- SKB, 2006b.** Long-term safety for KBS-3 repositories at Forsmark and Laxemar – a first evaluation. Main report of the SR-Can project. SKB TR-06-09, Svensk Kärnbränslehantering AB.
- SKB, 2008.** Safety analysis SFR 1. Long-term safety. SKB R-08-130, Svensk Kärnbränslehantering AB.
- SKB, 2010.** Corrosion calculations report for the safety assessment SR-Site. SKB TR-10-66, Svensk Kärnbränslehantering AB.
- SKI, 1984.** INTRACOIN. International Nuclide Transport Code Intercomparison study. Final report level 1. Code verification. SKI 84 3, Intracoin/Ski.
- SKI, 1986.** INTRACOIN. International Nuclide Transport Code Intercomparison study. Final report levels 2 and 3. Model validation and uncertainty analysis. SKI 86 2, Intracoin/Ski.
- Spalding D B, 1981.** A General Purpose Computer Program for Multi-Dimensional One- and Two-Phase Flow. Mathematics and Computers in Simulation XXIII: pp 267–276.
- Statsoft Inc., 2009.** Statistica 9.1. Version: 9.1.210.0. Statsoft Inc. 2300 East 14:th st. Tulsa OK, 74104, USA <http://www.statsoft.com/>
- Stephansson O, Shen B, Lemos J, 1991.** Modelling of excavation, thermal loading and bentonite swelling pressure for a waste repository. In: High-level waste management: proceedings of the Second Annual International Conference, Las Vegas, Nevada, 28 April–3 May 1991. New York: American Society of Civil Engineers, pp 1375–1381.
- Svensson U, 1991.** Groundwater flow at Äspö and changes due to the excavation of the laboratory. SKB HRL Progress report 25-91-03, Svensk Kärnbränslehantering AB.
- Svensson U, 2010.** DarcyTools, Version 3.4. Verification, validation and demonstration. SKB R-10-71, Svensk Kärnbränslehantering AB.
- Svensson U, Ferry M, 2010.** DarcyTools, Version 3.4. User’s guide. SKB R-10-72, Svensk Kärnbränslehantering AB.
- Svensson U, Follin S, 2010.** Groundwater flow modelling of the excavation and operation phases – SR-Site Forsmark. SKB R-09-19, Svensk Kärnbränslehantering AB.
- Svensson U, Rhén I, 2010.** Groundwater flow modelling of the excavation and operation phases – Laxemar. SKB R-09-23, Svensk Kärnbränslehantering AB.
- Svensson U, Ferry M, Kuylenstierna H-O, 2010.** DarcyTools, Version 3.4. Concepts, methods and equations. SKB R-07-38, Svensk Kärnbränslehantering AB.

- Tamisiea M E, Mitrovica J X, Milne G A, Davis J L, 2001.** Global geoid and sea level changes due to present-day ice mass fluctuations. *Journal of Geophysical Research*, 106, pp 30849–30863.
- Tamisiea M E, Mitrovica J X, Davis J L, Milne G A, 2003.** Long wavelength sea level and solid surface perturbations driven by polar ice mass variations: fingerprinting Greenland and Antarctic ice sheet flux. *Space Science Reviews*, 108, pp 81–93.
- Torudd J, 2010.** Long term radiological effects on plants, animals of a deep geological repository. SR-Site Biosphere. SKB TR-10-08, Svensk Kärnbränslehantering AB.
- Vahlund F, Hermansson H, 2006a.** Compulink. Implementing the COMP23 model in Simulink. SKB R-06-86, Svensk Kärnbränslehantering AB.
- Vahlund F, Hermansson H, 2006b.** A direct numerical approach to solving the transport equations for radionuclide transport in fractured rock. SKB R-04-50, Svensk Kärnbränslehantering AB.
- van der Vorst H A, 1992.** Bi-CGSTAB: a fast and smoothly converging variant of BI-CG for the solution of nonsymmetric linear systems. *SIAM Journal on Scientific and Statistical Computing*, 13, pp 631–644.
- Vidstrand P, Follin S, Zugec N, 2010a.** Groundwater flow modelling of periods with periglacial and glacial conditions – SR-Site Forsmark. SKB R-09-21, Svensk Kärnbränslehantering AB.
- Vidstrand P, Rhén I, Zugec N, 2010b.** Groundwater flow modelling of periods with periglacial and glacial climate conditions – Laxemar. SKB R-09-25, Svensk Kärnbränslehantering AB.
- Vikström M, Gustafsson L-G, 2006.** Modelling transport of water and solutes in future wetlands in Forsmark. SKB R-06-46, Svensk Kärnbränslehantering AB.
- Whitehouse P, Latychev K, Milne G A, Mitrovica J X, Kendall R, 2006.** Impact of 3-D Earth structure on Fennoscandian glacial isostatic adjustment: implications for space-geodetic estimates of present-day crustal deformations. *Geophysical Research Letters*, 33, L13502, doi:10.1029/2006GL026568.
- Xu T, Sonnenthal E, Spycher N, Pruess K, 2008.** TOUGHREACT User’s guide: a simulation program for non-isothermal multiphase reactive geochemical transport in variably saturated geologic media. LBNL-55460, Lawrence Berkeley National Laboratory, University of California.
- Åkesson M, Kristensson O, Börgesson L, Dueck A, 2010a.** THM modelling of buffer, backfill and other system components. Critical processes and scenarios. SKB TR-10-11, Svensk Kärnbränslehantering AB.
- Åkesson M, Börgesson L, Kristensson O, 2010b.** SR-Site Data report. THM modelling of buffer, backfill and other system components. SKB TR-10-44, Svensk Kärnbränslehantering AB.
- Åstrand P-G, Jones J, Broed R, Avila R, 2005.** Pandora technical description and user guide. Posiva Working Report 2005-64. Posiva Oy, Finland.