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Scenario development methodologies

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SCENARIO DEVELOPMENT METHODOLOGIES

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ABSTRACT

In the period 1981–1994, SKB has studied several methodologies to systemize and visualize all the features, events and processes (FEPs) that can influence a repository for radioactive waste in the future. All the work performed is based on the terminology and basic findings in the joint SKI/SKB work on scenario development presented in the SKB Technical Report 89-35.

The methodologies studied are a) Event tree analysis, b) Influence diagrams and c) Rock Engineering Systems (RES) matrices. Each one of the methodologies is explained in this report as well as examples of applications.

One chapter is devoted to a comparison between the two most promising methodologies, namely: Influence diagrams and the RES methodology.

In conclusion a combination of parts of the Influence diagram and the RES methodology is likely to be a promising approach.

SAMMANFATTNING

Under 1989–1994 har SKB studerat flera olika metoder för att systematisera information om alla egenskaper, händelser och processer (FEPs) vilka i framtiden kan påverka ett förvar för radioaktivt avfall. Arbetena baseras på den studie om scenarioutveckling som SKI och SKB gemensamt genomförde i slutet av 80-talet och som rapporterades i SKB Tekniska rapport 89-35.

De metoder som studerats är a) Händelseträd, b) Influensdiagram och c) Rock Engineering Systems (RES). Vardera metoden finns förklarad i denna rapport och utförda exempel på tillämpningar finns redovisade.

Ett kapitel har ägnats åt en jämförelse mellan de två mest lovande metoderna, nämligen Influensdiagrammen och RES-metoden.

Slutsatsen av detta arbete är att en metod, där delar från Influensdiagrammetoden och RES-metoden gemensamt används, bedöms lovande för att ta fram erforderligt underlag till scenariovalen i säkerhetsanalyserna.

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1 INTRODUCTION AND BACKGROUND

In the Joint SKI/SKB scenario development project /1-1/ it was stated that, in principle, the safety analysis of a radioactive waste repository involves the consideration of all possible relevant Features, Events, and Processes, FEPs, that could, directly or indirectly, influence the release and transport of radionuclides from the repository. Each identified FEP has to be analysed not only with regard to its cause, its probability of occurrence and its consequences, but also with regard to its eventual interactions with other FEPs. Such interactions often affect the probabilities and consequences associated with a given FEP.

In order to handle properly the complex amount of information involved in the safety analysis of a repository, a thoroughly worked out performance assessment methodology is needed. An important part of such a methodology consists of a scenario development procedure.

The basic objective for scenario development is to make sure that the relevant possible future evolution of the repository is properly considered. One of the most important aspects of scenario development is that it should aid in identifying critical issues.

Even if a scenario development strategy will never produce a complete set of scenarios, one must strive for completeness. In this context, it is extremely important to document all steps in the development. A transparent documentation makes possible an extensive review and updating of the relevant scenarios. Such a reviewing process, open to broad groups in society, is probably the best means of assuring reasonable completeness and building a general consensus on what are the critical issues for the safe disposal of radioactive waste.

In the SKI/SKB work, the scenario development methodology developed by the Waste Management Systems Division of Sandia National Laboratories, Albuquerque, USA, was used. The main objective of the Sandia method is to combine FEPs into scenarios and to produce, by means of an objective and consistent procedure, a set of scenarios that is important in a potential disposal site analysis. The Sandia methodology consists of the following steps:

- An initial comprehensive identification of those FEPs that are considered to be important to the long-term isolation of radioactive waste in a repository.

- Classification of FEPs into a scheme is needed in order to make the list as complete as possible.

- A screening of these FEPs based on well-defined criteria.

- The formation of scenarios by taking specific combinations of those FEPs remaining after the screening process.

- An initial screening of these scenarios.

- The selection of a final set of scenarios for use in the evaluation of a potential disposal site.

In the SKI/SKB work, a new concept, the PROCESS SYSTEM (PS) was established. The reason for establishing the PS was that the third step in the Sandia methodology – Screening of FEPs – was found to be complicated and time-consuming. The PS is defined as: "the organized assembly of all phenomena (FEPs) required for description of barrier performance and radionuclide behaviour in a repository and its environment, and that can be predicted with at least some degree of determinism from a given set of external conditions". A scenario is then defined by a specific set of external conditions which will influence the FEPs in the PS.

A key to reaching the level of completeness that is possible with present knowledge is to create and visualize the PS in a systematic way. This report shows several approaches to how this can be done. After having run through and documented the construction of the PS, the expert judgement step, (that always is needed to select which scenarios should be analysed), will have a solid background.

2 EVENT OR FAULT TREE ANALYSIS

The normal event or fault tree structure has been used in a number of studies, as indicated in /2-1/. The structure of the visualization tool can be seen in Figure 2-1.

The fault tree structure has several advantages if the events and processes are well-known or could be estimated with a high degree of certainty (i.e. processes where massive data have been gathered to create good statistics). In this case, the probabilities for each branch can easily be estimated. If the consequences also are known, the total risk for each branch can be evaluated.

For long term processes in repositories for high level waste, the knowledge and precision needed to make an elaborate risk judgement with the above indicated method are not sufficient due to the small amount of data available. However, the knowledge and understanding of the processes involved are high. A tool to visualize the different parts of the PROCESS SYSTEM and how the different parts of the system are connected is needed.

A first attempt within the SKB scenario development work was to visualize

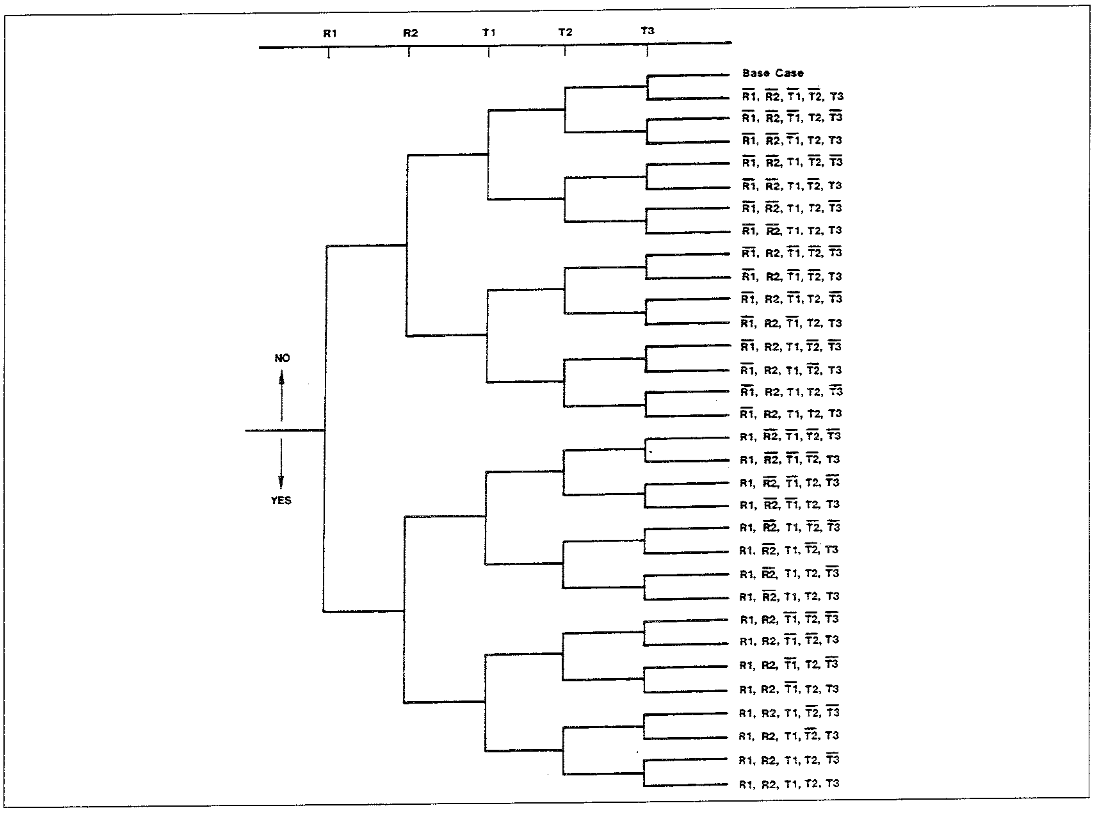


Figure 2-1. *The standard fault tree structure. Logic diagram showing the possible combinations of five FEPs (two release, R1 and R2, and three transport phenomena, T1–T3) from /2-2/.*

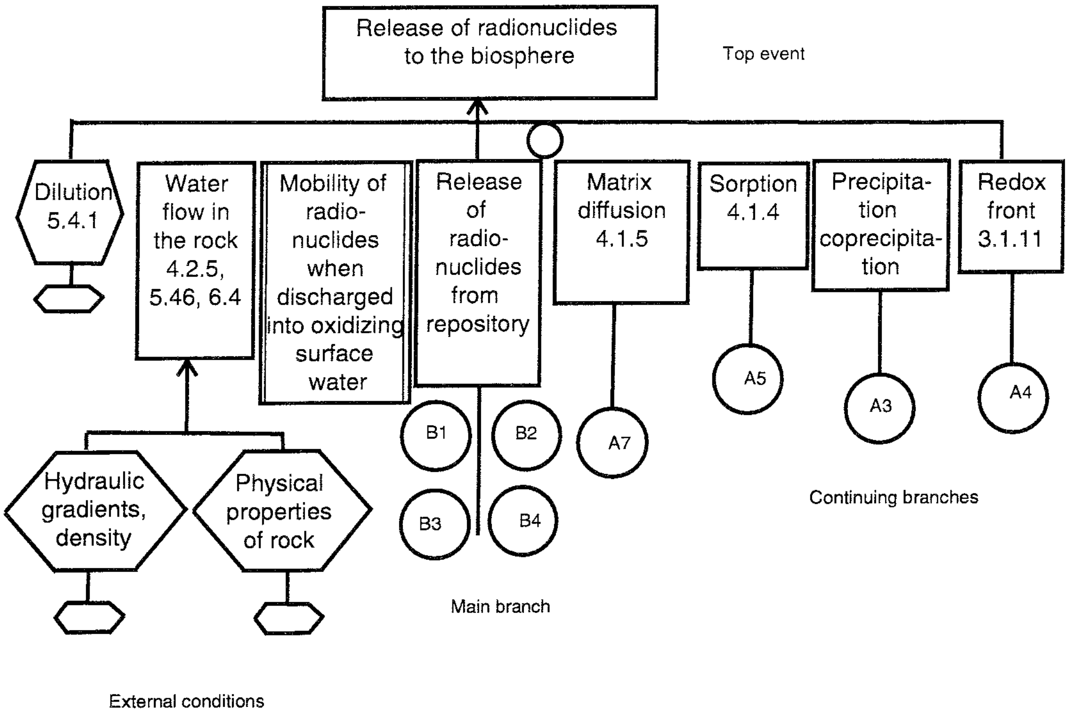


Figure 2-2. *Schematic illustration of the graphical description of the PROCESS SYSTEM in terms of a reversed event-tree. The numbers, i.e. 5.41, 4.2.5 etc, refers to the numbering of FEPs in the joint SKI/SKB scenario development project /1-1/.*

the PROCESS SYSTEM with a reversed event-tree structure /2-3/. A reversed event-tree diagram can be described as starting with a top event, e.g. the release of radionuclides to the biosphere, and then moving inward barrier by barrier to the initial source, namely the spent fuel. During the work, different preceding events and processes are added, which finally results in the top event, e.g. flow of water in fractured rock and sorption processes are shown to be essential processes affecting and preceding the top event. Thus, in the reversed event-tree diagrams, the different FEPs are assembled to visualize the cause and effect of different processes.

The structure of the reversed event-trees is schematically shown in Figure 2-2. The main branch in the tree consists of the release of radionuclides from the repository to the biosphere (which is further detailed in diagrams showing continuing branches). The other branches of the tree are built up by other phenomena which directly or indirectly affect the release of radionuclides from the repository to the biosphere. Each branch ends either with phenomena that are influenced by external conditions or with some kind of basic information. Hydraulic properties of the rock and hydraulic gradients are examples of phenomena which are affected by external conditions, for example land uplift. Examples of basic information are design of barriers and information on the fuel inventory.

3 INFLUENCE DIAGRAMS WITH LINKED DOCUMENTATION

3.1 GENERAL

One way to structure the Process System, (PS), is to construct an Influence Diagram of the PS where FEPs within PS are represented by boxes and interactions between FEPs are illustrated by lines between the boxes. A methodology based on Influence Diagrams with linked documentation has been developed by SKI in the Site-94 project /3-1/. A preliminary report on this work is found in /3-2/. The method fulfils the requirements that all systematic scenario methods have in common. These are:

- Systematic identification and review of Features, Events and Processes, FEPs, and interactions and combination of FEPs that can influence the performance of the repository concept.

- Documentation of decisions made in the development of scenarios as well as in subsequent assessments in order to ensure traceability of decisions.

- The results should be comprehensive and facilitate the identification of areas requiring further investigations or research.

The method thus developed by SKI has also been tested by SKB in the prestudy for the SFL 3-5 repository concept /3-3/, and involves the following main steps:

- construction of Basic Influence Diagram,

- development of Scenario Influence Diagrams from Basic Influence Diagram,

- formulation of scenarios and calculation cases.

These steps are further described in the following sections.

3.2 CONSTRUCTION OF BASIC INFLUENCE DIAGRAM

The first step is to construct a Basic Influence Diagram for the system to be studied in the assessment and at the same time initiate the documentation procedure. This implies the following actions:

- definition of the system,

- selection of FEPs relevant for the defined system,
- identification of influences between the FEPs.

All these actions need to be documented and compiled.

System definition

The Basic Influence Diagram should ideally contain all FEPs which are relevant for the system studied for any scenario. This requires a definition of the system and the following issues are important:

- waste form,
- engineered barrier design and materials,
- repository location and lay-out,
- natural barriers.

In addition to that, decisions must be taken on the geometrical extension of the system to be included in the Influence Diagram, i.e. the extension of the Process System. Ideally, the Process System, PS, should comprise all processes and be described in greatest possible detail, but this is of course not feasible. The aim of the assessment is to determine where the system boundary is set and also to what level of detail the system components should be described in the Influence Diagram.

At this stage, the components of the repository system, such as the different engineered barriers, are assigned to logical places in the Influence Diagram.

Selection of FEPs relevant to the defined system

When the system boundary and the system components to be studied are defined, FEPs that in some way may influence the performance in the short-term as well as in the long-term perspective are identified. The selection of FEPs can be made from existing FEP lists, e.g. the SKI/SKB list with documented descriptions /3-4/ or other compiled FEP lists /3-5/, /3-6/. The identification and selection of FEPs will also depend on the knowledge and experience of the person or the group of people who carries out the compilation of FEPs for the defined system. No screening of FEPs should be made at this stage.

The FEPs can now be sorted into two main groups: FEPs , belonging to the Process System, and FEPs, kept outside the system, i.e. External FEPs (EFEPs), or scenario initiating FEPs, see Figure 3-1. The construction of the Influence Diagram can now continue by representing all FEPs belonging to the Process System by a box containing the FEP-name in the diagram. If a FEP is relevant for several of the repository components in the PS, then this FEP should be represented by one box for each of the repository components. For example, if each barrier in the repository is defined as a repository component then the FEP "Diffusion" may be

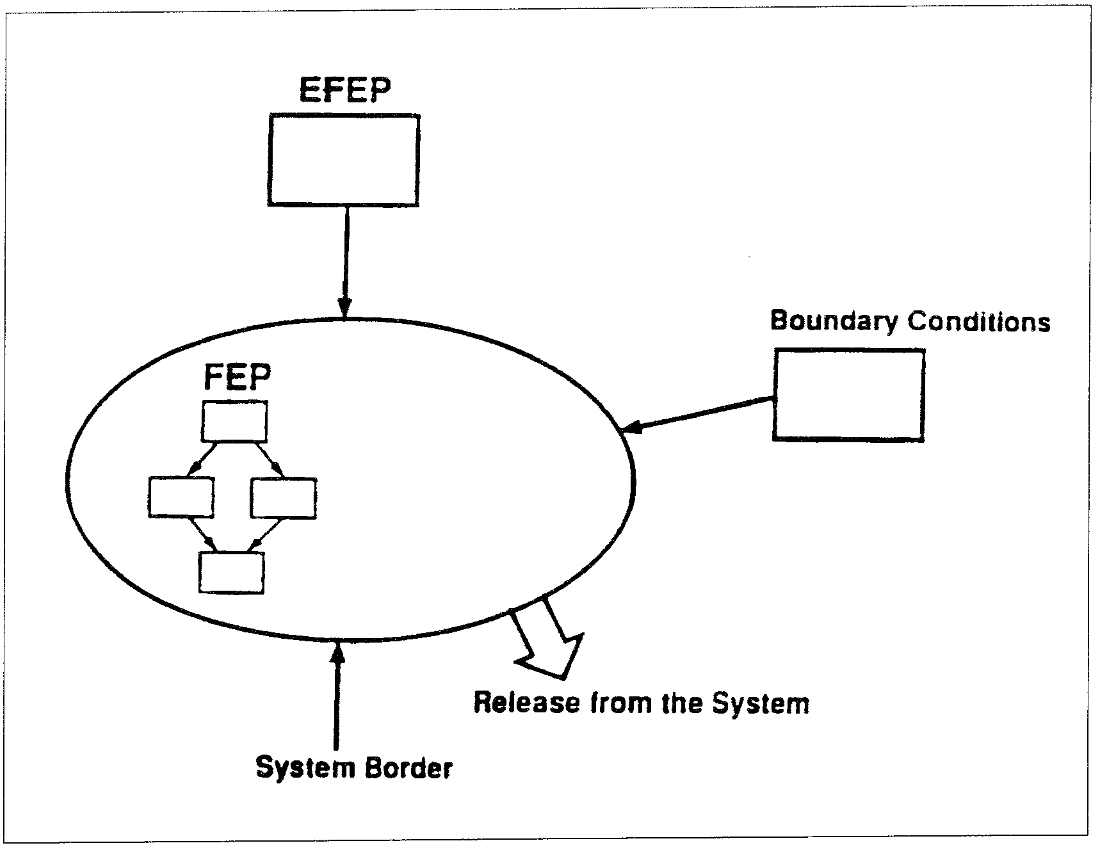


Figure 3-1. Schematic description of a defined system.

relevant for several of the repository components and a box named "Diffusion" could then appear at several places in the Influence Diagram.

Identification of Influences between selected FEPs

After all known FEPs have been compiled and introduced in the Influence Diagram, interactions between FEPs are identified and indicated in the diagram. This is done by drawing a line between the interacting FEPs, and with an arrow showing the direction of the influence. Each influence in the diagram is marked with a unique code. To facilitate the evaluation of the Influence Diagram, it is important that the interaction is described by an influence on the primary target FEP. There are no restrictions on the number of influences between two FEPs, since one FEP may influence another FEP in several different ways.

Documentation of FEPs and Influence descriptions

The FEPs are represented by a box and a name in the Influence Diagram. However, a more comprehensive description of the phenomenon is needed to clarify what actually is meant by the FEP name. It is also necessary to clearly define and document each identified influence between FEPs. A database with descriptions of all FEPs and interactions between FEPs is therefore prepared, and each FEP-box and each influence-arrow in the Influence Diagram is linked to its respective description/ definition in the document database.

3.3 DEVELOPMENT OF SCENARIO INFLUENCE DIAGRAMS

The Process System in the Basic Influence Diagram contains FEPs and influences which may affect the behaviour of the repository system, but at this stage no evaluation of the significance of the different FEPs and influences on the repository performance has been made. Since the significance of FEPs and influences depends on the initial conditions of the Process System and how the Process System is affected by the surroundings, the next step is to define these entities, i.e. to define the premises of the scenarios to be evaluated. Once this is done, the Influence Diagram is reviewed and the significance of each influence is assessed for the selected scenario premises and documented in a protocol linked to the influence. This results in an Influence Diagram for this specific scenario. By removing influences and FEPs from the Scenario Influence Diagram, reduced Influence Diagrams for the scenario at different significance levels can be prepared.

To assess the significance of influences, a pre-defined scale of significance is used. By an appropriate choice of the number of significance levels to be used and a clear definition of the requirements behind each level, it is possible to identify those influences and FEPs that, by "expert judgement", are believed to be so important for the behaviour of the system that the confidence in the performance assessment is lost if they are not considered. This significance level represents the required minimum level of complexity in the system description. Furthermore, it is possible to identify those influences and FEPs that at various degrees may increase the confidence in the performance assessment if included, but at the cost of a more and more complex system description. The identification of influences and FEPs of different importance is facilitated by the use of colour coding or different line types and fillings in the Influence Diagram for the different significance levels.

The development of Influence Diagrams is an iterative process. During the review it may be found that two FEPs can be combined into one FEP without information being lost, or that a FEP must be split into more than one FEP to better describe how the FEPs interact. In addition, new influences between FEPs will likely be identified. To facilitate the evaluation and improvement of the Influence Diagrams, the premises for a Reference Scenario are defined, and an Influence Diagram for the Reference Scenario is developed from the Basic Influence Diagram. Influence Diagrams for other scenarios can hereafter be developed with the Influence Diagram for the Reference Scenario as a base.

Development of Influence Diagrams for a Reference Scenario

The definition of a Reference Scenario should be as complete as possible with respect to the processes involved. However, simplifications must be made to reduce the complexity involved in describing expected performance and future evolution of the repository system. Examples of such simplifications are assumptions with respect to the initial state of the engineered barriers, e.g. properties according to design criteria or expected malfunction of barriers. In addition, assumptions regarding the impact of External FEPs on the Process System should be simple, e.g. assuming constant conditions at the Process System boundary, even though it is known that in a long-term perspective they will change with time.

The next step is to review the Influence Diagram and to evaluate the significance of each influence in the diagram for the defined Reference Scenario. Discovery of missing influences or FEPs or other modifications which would improve the Influence Diagram should immediately be implemented. Judgements of significance of interactions between FEPs should be made for each influence on the primary target FEP in the Influence Diagram without considering FEPs and influences further downstream.

The review and evaluation of the Scenario Influence Diagrams are best made by a group of people with a general overview, combined with experts in specific areas. It is possible to judge the significance of influences by using a significance scale (e.g. important, uncertain, negligible) or by using numbers indicating significance levels (e.g. 1 to 10).

The results of the evaluation of the Influence Diagram should be documented in protocols linked to each influence. The protocol should contain the judged significance, explanations of decisions, references to literature and identification of the group of expertise responsible for the evaluation. The existence of this documentation enables and facilitates future re-evaluations and updating of the studied system.

Reduced Influence Diagrams for the Reference Scenario can now be prepared at different significance levels by removing influences and FEPs. A significance level is defined and all influences assessed to be of lower significance than the defined level are removed from the Influence Diagram. A FEP can only be removed if all its influences on other FEPs are below the defined significance level or if all influences from other FEPs are below the defined significance level.

The procedure is schematically illustrated in Figure 3-2 for a three-level significance scale, "negligible", "uncertain" and "important", with "uncertain" as the significance level for which a reduced Influence Diagram is prepared. This means that all influences assessed to be negligible are removed, i.e. the influence on FEP B and the influence of FEP B on FEP C. Since the only cause of FEP B is assessed to be negligible, the occurrence of this FEP is negligible and can be removed. The consequence of removing FEP B is that also FEP D and the impact of FEP D on other FEPs can be removed since no influence is left to activate FEP D.

Development of Influence Diagrams for other scenarios

The development of Influence Diagrams for other scenarios can be made by using the **unreduced** Influence Diagram for the Reference Scenario as a base. The procedure is as follows:

The External FEP or combination of External FEPs describing the scenario to be studied is selected, and the primary target FEPs in the Influence

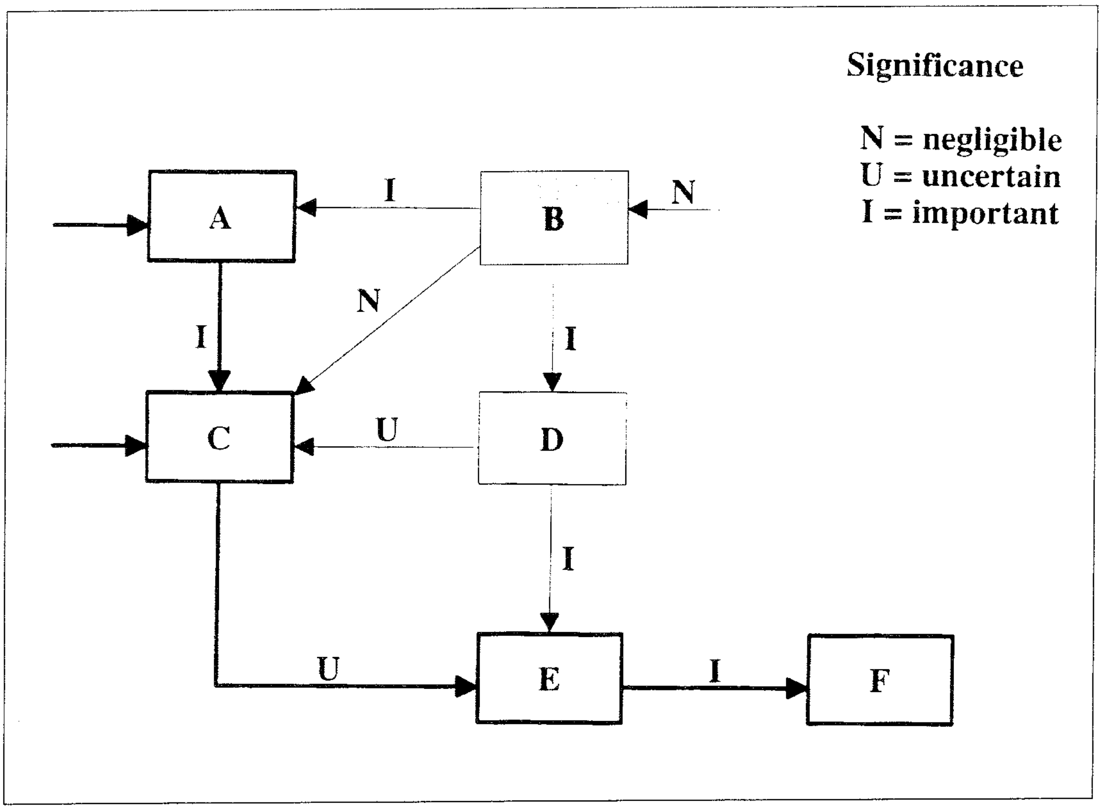


Figure 3-2. Schematic description of the preparation of a reduced Influence Diagram.

Diagram for the Reference Scenario perturbed by these External FEPs are identified. Then the significance of influences down-stream from the primary target FEPs is re-evaluated with respect to the potential disturbances caused by the effect of the External FEP. If the significance of an influence is assessed to be the same as in the Reference Scenario, further evaluation of influences and FEPs downstream along this route is not needed, unless the nature of the influence is different from that in the Reference Scenario. In this way, an Influence Diagram for the selected scenario is developed where the difference between the selected scenario and the Reference Scenario is given by a few paths in the diagram, as depicted in Figure 3-3.

In the same way as for the Reference Scenario the evaluation of other scenarios should be documented in protocols linked to each influence. Reduced Influence Diagrams can be prepared for selected External FEPs and/or combination of FEPs at different significance levels by removing influences and FEPs.

If it is found that modifications of the Influence Diagram are required to properly describe the selected scenario, e.g. FEPs and influences need to be re-defined or additional FEPs and influences are needed, then the Influence Diagram and the linked documentation should be revised, both for the selected scenario and for the Reference Scenario. This also includes a re-evaluation of the significance of modified influences in the Reference Scenario Influence Diagram.

The selection of scenarios is a difficult task since there is a large number of External FEPs and combination of External FEPs that can affect the

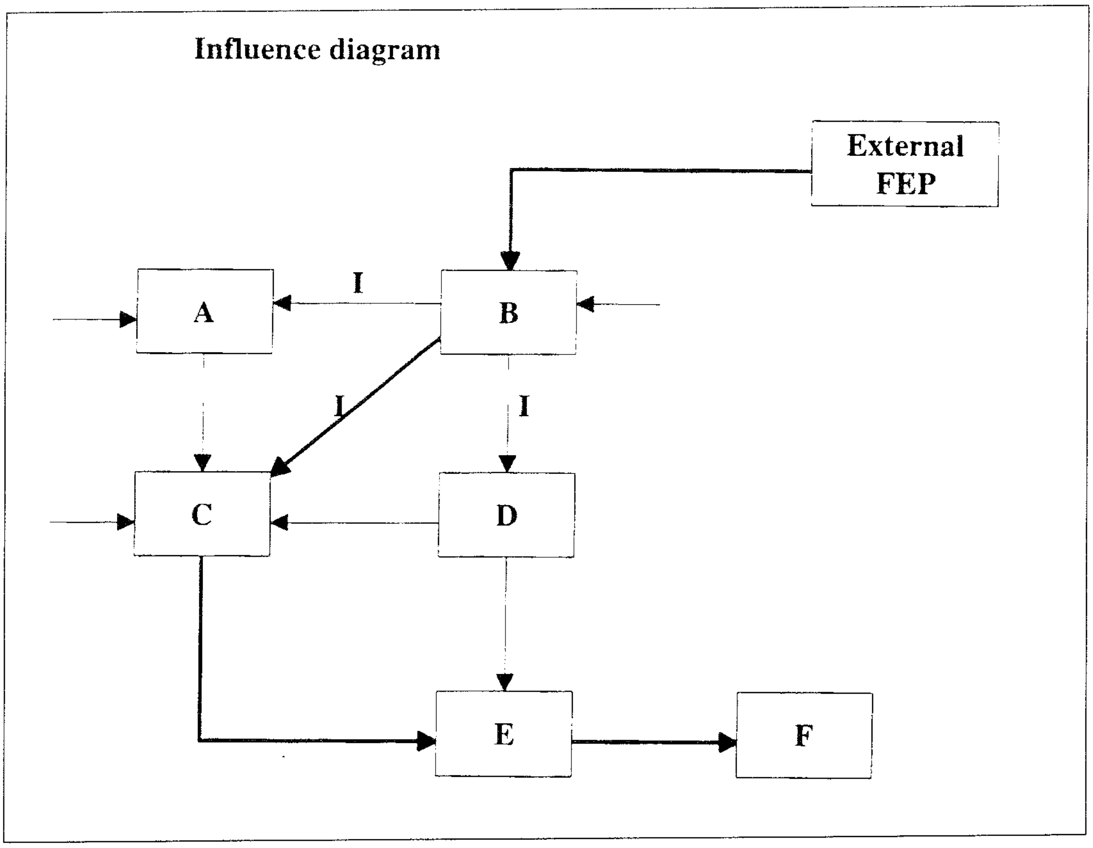


Figure 3-3. *Schematic description of the evaluation of the Influence Diagram for an External FEP.The External FEP might change the properties of the system and thereby the significance of the influences between the FEPs.*

Process System. To obtain a first structure of the External FEPs, a classification of the FEPs based on their origin could be made, e.g. Human induced phenomena, Natural phenomena and events, Waste and repository induced effects. In addition, External FEPs with the same impact FEP in the Process System may be lumped together.

An estimate of the most probable time of occurrence of the External FEP and its duration could also be helpful, as well as the identification of impossible/improbable combinations of External FEPs.

It is believed that the number of scenarios to be evaluated will remain large, unless a judgement of the most probable/critical External FEP or combination of External FEPs is made *a priori*. Alternatively, the most critical pathway through the Process System could be identified without specifying how this pathway is activated, i.e. totally disregarding External FEPs. It should be pointed out that one can never guarantee that the description of the Process System is complete. However, the uncertainty in the description of the Process System will decrease as the number of reviews and evaluations of the Process System increases. This suggests that at least a couple of scenarios defined by External FEPs should be evaluated prior to identifying a critical pathway through the Process System.

3.4 FORMULATION OF SCENARIOS AND CALCULATION CASES

The reduced Influence Diagrams can be used to formulate scenarios and calculation cases needed to analyse the selected scenarios. Different models and calculation cases will be required to study different parts and aspects of the Process System, e.g. temperature, hydrology, degradation of barriers etc. This implies that not all FEPs and influences can be studied in the same model or at the same time, but must be separated into groups of FEPs and influences. These studies must be performed in a consistent way since the results of these studies form the basis for the estimation of contaminant transport, which is the ultimate goal of the whole exercise.

The translation of the information in the Influence Diagram to scenario descriptions and calculation cases will expose areas where conceptual understanding, models and data are presently lacking.

Also at this stage, the documentation is essential. For this purpose, the protocols linked to the Influence Diagrams can be used. The documentation should include a description of how influences and FEPs have been considered in the models and the assessment calculations, as well as the results of these calculations and associated uncertainties. This documentation will be valuable in forthcoming studies.

The outcome of the performed studies and calculations will increase the understanding of the behaviour of the system. The Influence Diagrams should therefore be revisited and updated in line with the increased knowledge of the significance of interactions between FEPs.

4 THE “ROCK ENGINEERING SYSTEMS” (RES) APPROACH

4.1 GENERAL

In 1992, a new methodology for approaching rock engineering problems was presented. This is the “Rock Engineering Systems” (RES) approach /4-1/. The basis of the RES approach is that, for all rock engineering projects, one should start with a top-down approach in order to ensure that all aspects of the problem are being covered. One starts with the overall objective and then establishes which variables and interactions between variables comprise the mechanism pathways for all the factors. In this way, the problem is ‘broken down’ to establish its constituent parts. The method is intrinsically objective-based, and thus proceeds always bearing the objective in mind.

The basic device used in the RES approach is the interaction matrix, in which the main variables or parameters are identified and listed along the leading diagonal of a square matrix. The interactions between the parameters occur in the off-diagonal terms. This is illustrated in Figure 4-1 together with the clockwise convention for the influence direction.

In Figure 4-2, there is an example with two parameters, ‘Water flow’ and ‘Backfill’, and their interactions. The two parameters have been placed in the shaded boxes on the leading diagonal and then their interactions considered in the top right and bottom left boxes. The point about the methodology being objective-based is that we wish to consider all the parameters that might influence our prime objective in radioactive waste disposal and therefore extend this small 2 x 2 matrix to an *n*x*n* matrix with the *n* main parameters and all the individual interactions. As the number of parameters becomes larger, so does the number of interactions. In

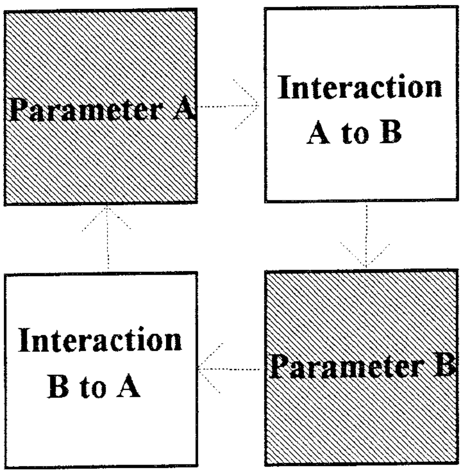


Figure 4-1. *Principle of the interaction matrix.*

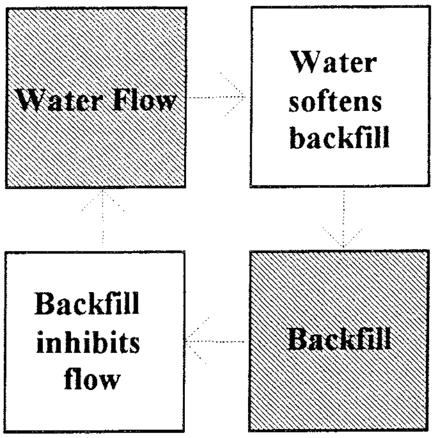


Figure 4-2. Example of two variables and their interactions.

Figures 4-1 and 4-2, there are two parameters and hence two interactions. In a 12 x 12 matrix, there are 144 components which, after subtracting the 12 parameter terms on the leading diagonal, gives 132 interactions.

An important aspect of the interaction matrix, which is well illustrated in Figure 4-2, is that such interaction matrices will generally not be symmetrical: the influence of variable A on variable B will not usually be the same as the influence of variable B on variable A; for example, the influence of water flow on the backfill is not the same as the influence of the backfill on the water flow. So, generally, all the interactions will be different. The idea is that it would be very difficult to ensure that all of the links between the *n* variables in a problem had been identified without some structure like the interaction matrix to support the analysis.

In Figure 4-3, a 4 x 4 interaction matrix is shown. This matrix has four variables, i.e. four leading diagonal terms, and 4 x 4 - 4 = 12 interactions, or twelve off-diagonal terms. Assume that we are interested in how variable D affects variable B. This will occur through the direct off-diagonal interaction DB, indicated by the cross-hatching in Figure 4-3. However, such interaction or influence can also occur indirectly through the other variables in the matrix. One such influence pathway, (D, A, C, B), is

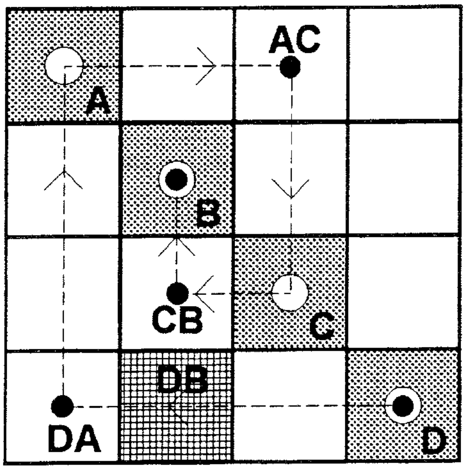


Figure 4-3. Principle of a pathway through the interaction matrix.

indicated though the 4 x 4 interaction matrix. Variable D affects variable B through the three interactions DA, AC and CB. It is the consideration of all such pathways that completes the RES analysis.

Thus, the RES methodology is comprised of:

- statement of the project objective,
- consideration of the necessary variables for the leading diagonal terms,
- establishment of all the interactions to fill the matrix,
- study of individual pathways through the matrix,
- study of the 'matrix evolution' as all the interactions take place.

The RES methodology can be as a 'soft' or 'hard' systems approach. In the 'soft' systems approach, the nature of the problem is established via the procedure described and statements are made about the relative importance of variables and interactions by assigning numerical values to the interactions through coding procedures. Also, the main mechanism network can be established. In the 'hard' systems approach, the leading diagonal terms are the physical variables, or state variables, of the system being modelled. The interactions are physically identified and quantified, and then the Fully-Coupled Model (FCM) is used to evaluate numerically the changes to the state variables according to any initial and subsequent conditions.

4.2 THE USE OF RES TO STRUCTURE AND COMPLETE THE FEPs

To study radioactive waste disposal by the RES technique, we consider the disposal objective i.e. isolation of the waste, and the associated criteria. Above we have seen the first step in the RES methodology, namely the construction of the interaction matrix where the main variables relevant to the objective are listed along the leading diagonal (top left to bottom right of the matrix) and then the interactions are considered in the off-diagonal boxes. The next step of the RES approach is to consider the terms in the leading diagonal boxes.

After consideration of all the FEPs, nine leading diagonal terms were chosen for the initial analysis:

1. Rock type/quality
2. Discontinuities
3. Rock stress
4. Construction
5. Backfill
6. Canister
7. Waste
8. Heat and
9. Water flow/migration/gas.

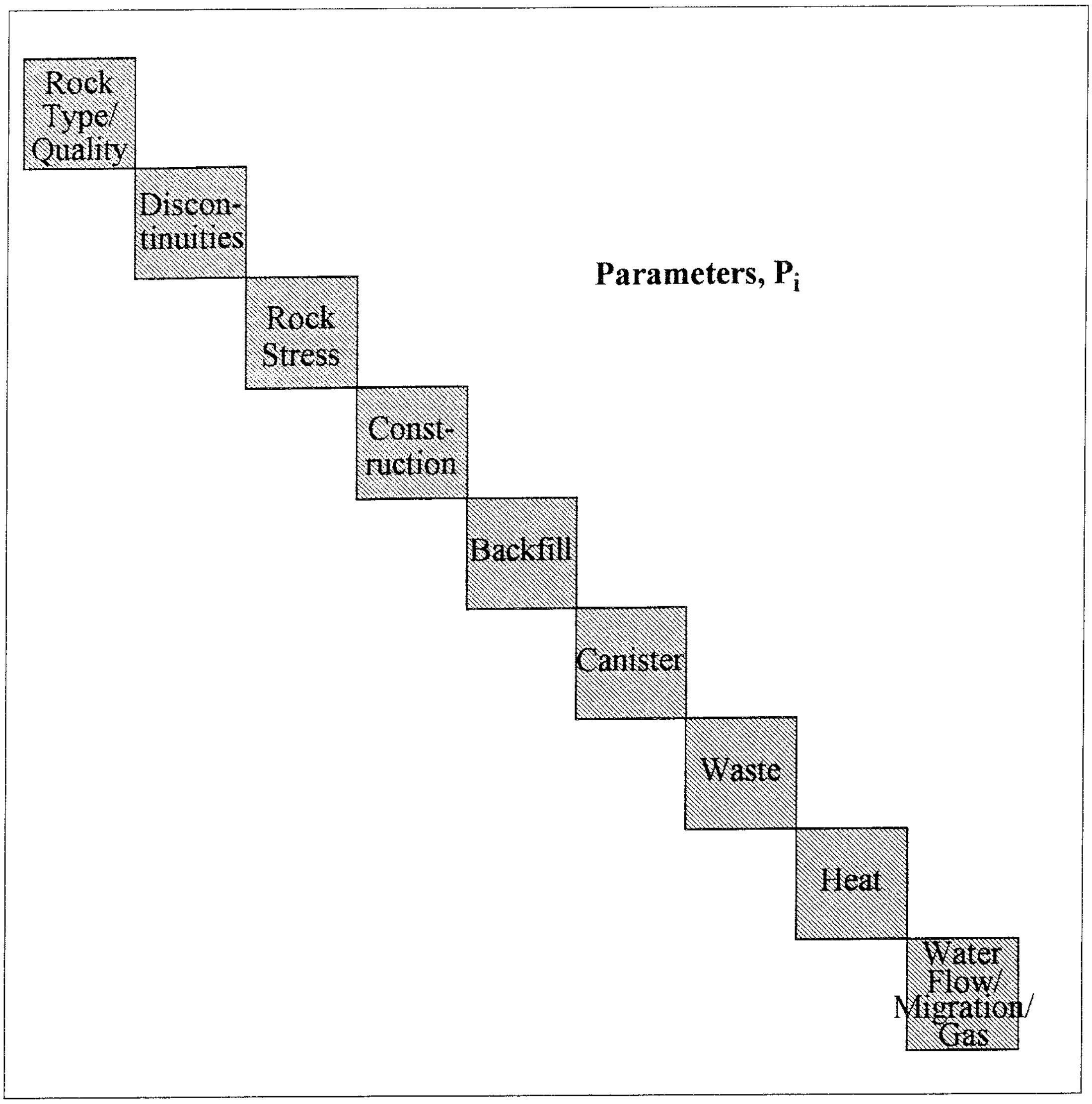


Figure 4-4. *Choosing the leading diagonal of the interaction matrix – the nine variables used in this study.*

The first three relate to the three most important aspects of the host rock environment; the next four relate to the engineered repository together with its contents, and the last two relate to the 'driving mechanisms'. It is emphasized that any number of variables can be chosen and the list above shown in Figure 4-4 can easily be extended to sub-divide any of the terms or to include, for example, wider environmental issues. Also, it should be noted that, at this stage, the order of the variables is not important because the matrix can be subsequently restructured so that the variables are in any required order. The analysis is not affected by the order of these leading diagonal terms.

The database of FEPs already exists /4-2, 4-3/ and so we can identify the position of all existing FEPs in the interaction matrix. Moreover, we can establish whether the FEPs fill the interaction matrix or whether more FEPs are required to fill in all the off-diagonal terms in the matrix. Identification and characterization of the FEPs are via one (or potentially more) of six different aspects of the matrix:

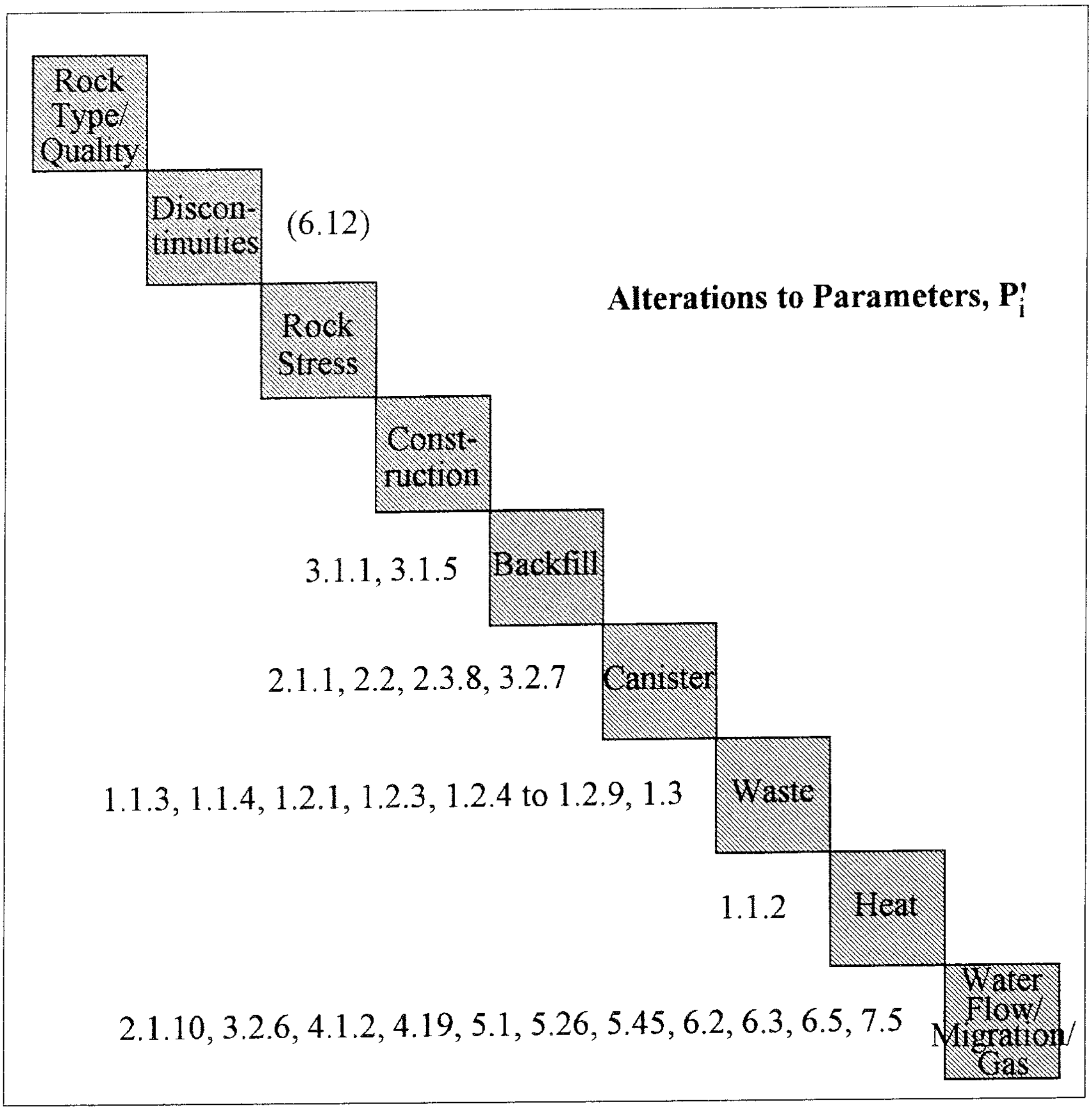


Figure 4-5. *FEPs that are alterations to variables P_i. Numbers refer to the numbers of FEPs in the joint SKI/SKB scenario development project /1-1/.*

1. Variables, P_i
2. Alterations to Variables, $P_i{}'$
3. Interactions, I_{ij}
4. Alterations to Interactions, $I_{ij}{}'$
5. Pathways through the Matrix, M
6. Evolution of the whole Matrix, M '

A FEP, as a Feature, Event or Process, can be a variable in itself, although those related to a single variable are best considered as alterations to variables. Or it could be an interaction between two variables, or indeed an alteration to that interaction. Finally, a FEP could be a pathway through the matrix (involving two or more variables) or evolution of the whole matrix through the cumulative effect of many consecutive and concurrent pathways.

In Figure 4-5, we have shown FEPs identified to be alterations within the leading diagonal terms themselves. Note that these occur within the near-

Rock Type/ Quality					2.1.8			4.1.4 4.1.5	3
	Discon- tinuities							4.1.4 4.2.3 6.4	3
		Rock Stress							0
4.2.2.1	4.2.2.1 4.2.8 4.2.9		Const- ruction					4.18 5.14	6
4.2.2.1	3.2.1.1 4.2.2.1		3.2.1.1	Backfill	2.1.8 2.1.7 2.1.9			3.1.2, 3.1.3 3.1.4, 3.1.6 4.14, 4.18	13
					Canister	1.5		2.1.4	2
				3.1.10 3.1.13	2.1.3	Waste		5.44	4
2.3.1				3.2.5	2.3.1		Heat	3.2.10 4.1.7 4.2.4 6.13	7
3.1.11 4.1.1 6.6	6.6		3.1.7	3.2.4	2.1.5 2.1.6.1 2.1.6.2		4.2.4	Water Flow/ Migration	10
6	6	0	2	4	9	1	1	19	TOTALS 48

Figure 4-6. *FEPs that are interactions* $\mathbf{I}_{ij}$.

field, because this is where the fundamental perturbation is occurring. For example, 3.1.1 is degradation of the bentonite by chemical reactions. This could be a 'within-bentonite' problem, in which case it is an alteration to a variable or it could be related to groundwater chemistry – in which case it would be an interaction between water flow and backfill.

Next, in Figure 4-6, we show FEPs identified as binary interactions, i.e. interactions between two variables on the leading diagonal (if more than two variables are involved, the FEP is a pathway). For example, 3.2.1.1 is swelling of bentonite into tunnels and cracks, so it can occur as an interaction between backfill and construction, and between backfill and discontinuities.

In Figure 4-7, we provide some indication of how FEPs can be considered as pathways. For example, 4.2.8 is enhanced rock fracturing: construction causes new fractures, which in turn affect the rock stress, which in turn affects water flow (which is through the fractures). Studying how the FEP is a pathway through the matrix – or can initiate a pathway through the matrix – is of great assistance in clarifying the nature of the FEP.

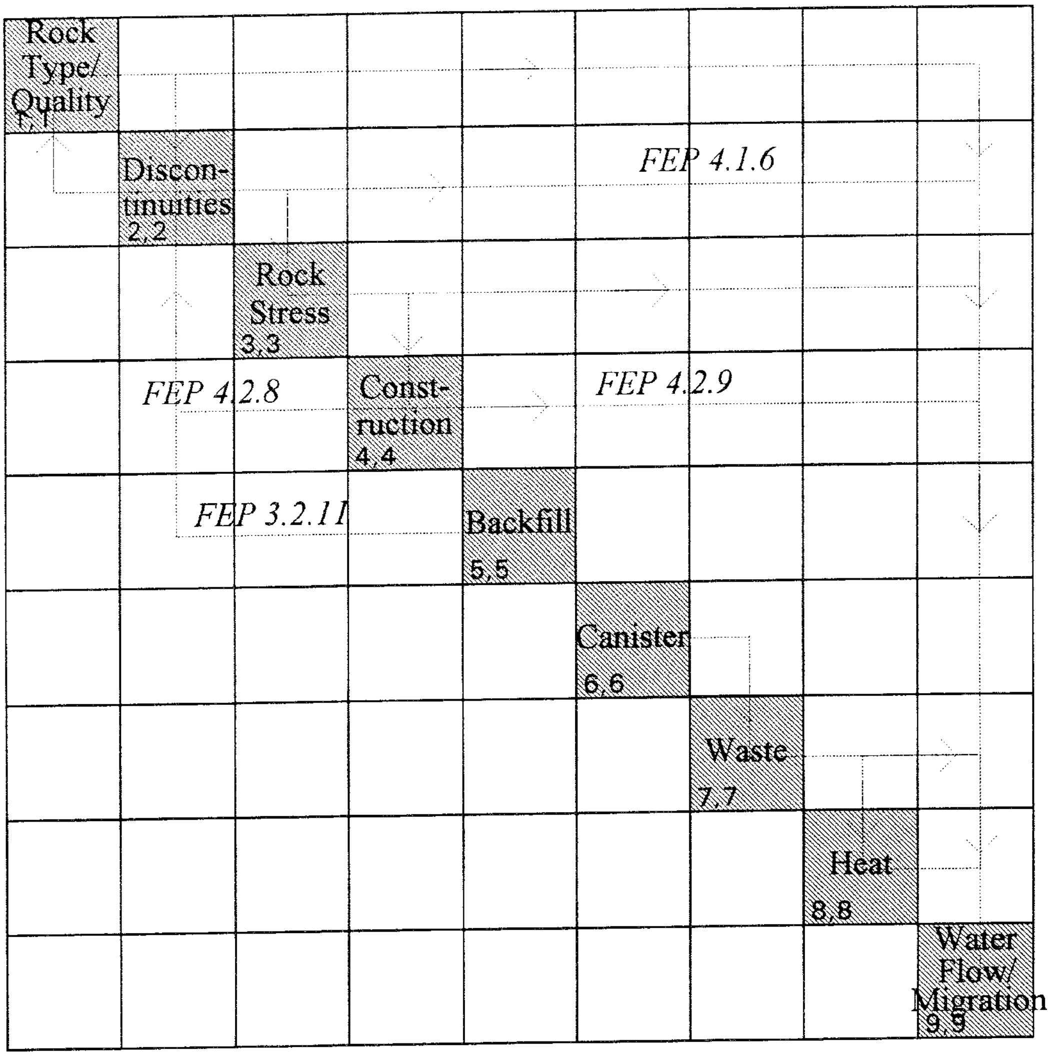


Figure 4-7. FEPs as pathways, M, through the interaction matrix (note this diagram does not include all the pathway FEPs).

FEP 3.2.11:	5,5 – 2,2 – 1,1 – 9,9	Backfill material deficiencies
FEP 4.1.6:	1,1 – 2,2 – 9,9	Reconcentration
FEP 4.2.8:	4,4 – 2,2 – 3,3 – 9,9	Enhanced rock fracturing
FEP 4.2.9:	1,1 – 2,2 – 3,3 – 4,4 – 9,9	Creeping of rock mass and several other pathway FEPs

In Figure 4-7, some FEPs that are involved in the evolution of the whole matrix are identified. For example, FEP 4.2.5 is change of groundwater flow. There are many potential pathways involved with this FEP and so it is really the evolution of the matrix and the associated evolution of the leading diagonal parameters that need to be considered for these FEPs e.g. 4.2.7 – thermo-hydro-mechanical effects, 7.5 – isotopic dilution and even 7.9 – loss of records. The total matrix evolution is indicated by Figure 4-8.

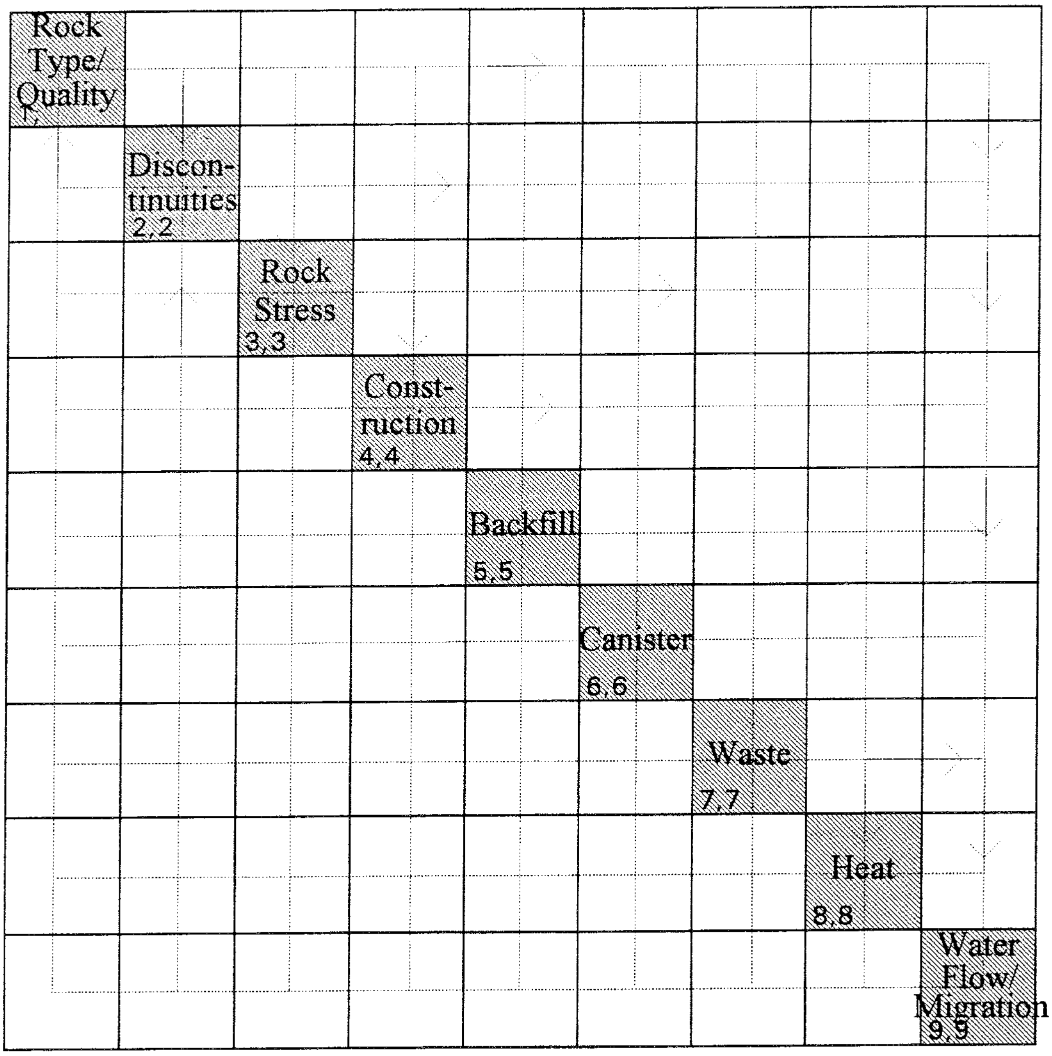


Figure 4-8. *FEPs as evolution of the whole interaction matrix, M ' (Note: In the general interaction matrix, all the leading diagonal terms are connected to each other by both feedforward loops and feedback loops via the off-diagonal terms.).*

4.3 ESTABLISHING THE MECHANISM NETWORK

The next step in the 'soft' RES approach is to consider coding the off-diagonal terms to provide an indication of their significance, given the project objective. This is indicated in Figure 4-9 where the interaction matrix is shown coded according to the 'Expert Semi-Quantitative' method of integer coding from 4 for a critical interaction to 0 for essentially no interaction.

The codes are shown below:

4 – 'Critical' Interaction

3 – Strong Interaction

2 – Medium Interaction

1 – Weak Interaction

0 – 'No' Interaction

Rock Type/ Quality	2	3	2	1	0	0	0	2	10
0	Discon-tinuities	4	3	0	0	0	0	4	11
2	3	Rock Stress	3	0	0	0	0	4	12
2	3	4	Construction	0	0	0	1	2	12
1	2	2	0	Backfill	1	0	1	3	10
0	0	0	0	1	Canister	1	1	4	7
0	0	0	0	1	1	Waste	4	4	10
2	2	3	0	3	3	2	Heat	4	19
2	4	3	3	3	3	1	3	Water Flow/ Migration	22
9	16	19	11	9	8	4	10	27	TOTALS 113

Figure 4-9. Coding interactions in the matrix by the 'Expert Semi-Quantitative'-method.

To establish how significant a leading diagonal variable is within the interaction matrix concept described, the coding values along the row and column through each parameter are summed. The way in which **a particular variable affects all the others** is through the interactions along **the matrix row** through the variable. The way in which **a variable is affected by all other variables** is by the interactions in **the column** through that variable. The sum of the row values is termed the 'Cause', *C*; the sum of the column values is termed the 'Effect', *E*. Study of these Cause-Effect co-ordinates for each leading diagonal variable clarifies the structure of the problem and the significance of the variables.

The totals for the individual rows and columns are given in the shaded boxes in Figure 4-9; these provide the *C-E* co-ordinates for each variable. For example, Heat has a cumulative row value of 19 points in terms of the coding method and how heat affects the other variables. The complementary column count through Heat is 10. This means, when comparing 19 with 10, that Heat is affecting the system more than the system is affecting

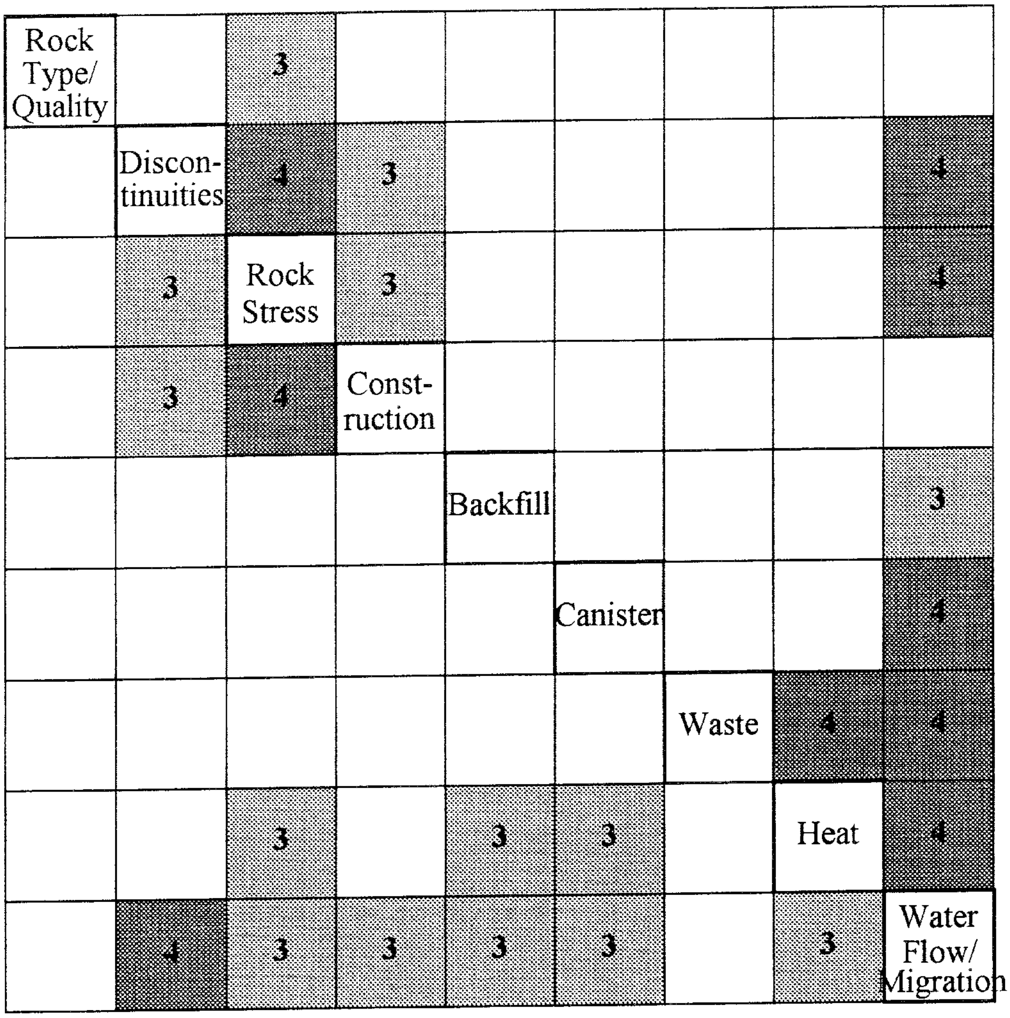
Rock Type/ Quality	8.1.1	8.1.2	8.1.3	8.1.4	SKB	8.1.5	8.1.6	SKB
8.2.1	Discon-tinuities	8.2.2	8.2.3	8.2.4	8.2.5	8.2.6	8.2.7	SKB
8.3.1	8.3.2	Rock Stress	8.3.3	8.3.4	8.3.5	8.3.6	8.3.7	8.3.8
SKB	SKB	8.4.1	Const-ruction	8.4.2	8.4.3	8.4.4	8.4.5	SKB
SKB	SKB	8.5.1	SKB	Backfill	SKB	8.5.2	8.5.3	SKB
8.6.1	8.6.2	8.6.3	8.6.4	8.6.5	Canister	SKB	8.6.6	SKB
8.7.1	8.7.2	8.7.3	8.7.4	SKB	SKB	Waste	8.7.5	SKB
SKB	8.8.1	8.8.2	8.8.3	SKB	SKB	8.8.4	Heat	SKB
SKB	SKB	8.9.1	SKB	SKB	SKB	8.9.1	SKB	Water Flow/ Migration

Figure 4-10. *RES-identified FEPs that are interactions.*

Heat. Also, because the sum of the numbers is relatively large, Heat is clearly a strongly interactive variable.

To match the FEP approach with the RES approach, it was necessary to create new FEPs to fill in the missing boxes in the interaction matrix in Figures 4-5 and 4-6, i.e. to add the missing parameter changes (P_i') and interactions (I_{ij}) that are required in order to have a fully-coupled model. Thus, 50 new FEPs were added: some of the FEPs had already been established by SKB but had been screened out; some are completely new FEPs. There are 4 additional variable change FEPs as shown in Figure 4-8. There are 46 additional interaction FEPs as shown in Figure 4-10.

The most significant additions were the 16 new FEPs associated with rock stress. This parameter has a substantial effect in the modelling, both in the construction and migration modelling aspects. In construction, the rock stress can establish cavern orientation and shape, and is always affected by construction; in modelling, the rock does not have a fixed permeability because the permeability (as fracture flow) is affected by the rock stress – as it is by other factors.



Rock Type/ Quality		3						
	Discon- tinuities	4	3					4
	3	Rock Stress	3					4
	3	4	Const- ruction					
				Backfill				3
					Canister			4
						Waste	4	4
		3		3	3		Heat	4
	4	3	3	3	3		3	Water Flow/ Migration

Figure 4-11. *Interaction matrix showing only the 3s and 4s in the ESQ coding.*

The diagram in Figure 4-10 shows those RES-identified FEPs which are:

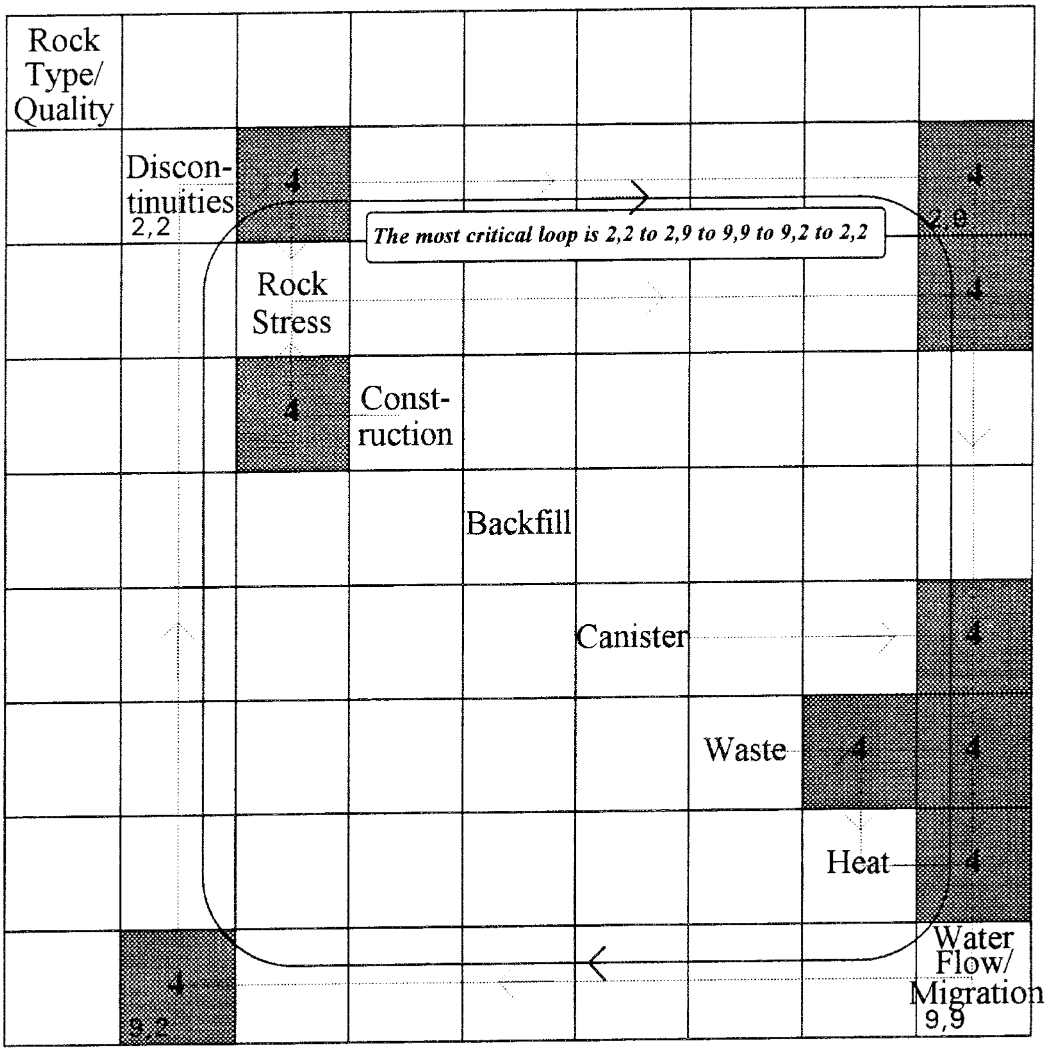
- **Interactions, I_{ij}**

(as referred to the leading diagonal of the interaction matrix).

The entry SKB means SKB-identified FEPs in the process system are in that position.

The next step is to consider the general principles by which the interaction matrix and the coding can be used to generate the identification and understanding of pathways. To begin, in Figure 4-11, we show just those boxes in Figure 4-9 that have been coded as 4, Critical interaction, or 3, Strong interaction. Note that these immediately indicate a distinction between the near-field and the far-field.

To form a binary loop, i.e. a loop between two variables, both related off-diagonal terms have to be highlighted, so that the loop can operate. For the interactions coded as 'Critical' with number 4, only one binary loop exists, as shown in Figure 4-12. This is the Discontinuities-Water loop. All the other 4s are pathway 4s in which the variable is visited once only; but boxes 2,2 and 9,9 can be looped around and visited many times.



The most critical loop is 2,2 to 2,9 to 9,9 to 9,2 to 2,2

Figure 4-12. *The primary loop through the interactions coded as 4.*

Now, considering the boxes coded 3 and 4 in Figure 4-9, we reconfigure the interaction matrix to produce the loops shown in Figure 4-13. Note that we have put Host Rock at one end, as the surrounding medium, and waste at the other end, as the 'generator'. Loops do not exist through these two outside variables (given the sensitivity of approach via the coding method).

Water flow at the centre of the diagram links the near-field with the far-field. The loops in the near-field and in the far-field are of a different type. In the near-field, the loops through Heat, Backfill and Canister all connect with Water Flow. Thus one cannot loop through, say, Heat and Backfill directly. In the far-field, however, there are twice as many loops and all variables loop with each other, so that compound loops can be formed, e.g. the loop Discontinuities to Rock Stress to Construction to Water Flow to Construction to Rock Stress to Discontinuities – and this can be operating at the same time as the single loop Discontinuities to Rock Stress to Discontinuities.

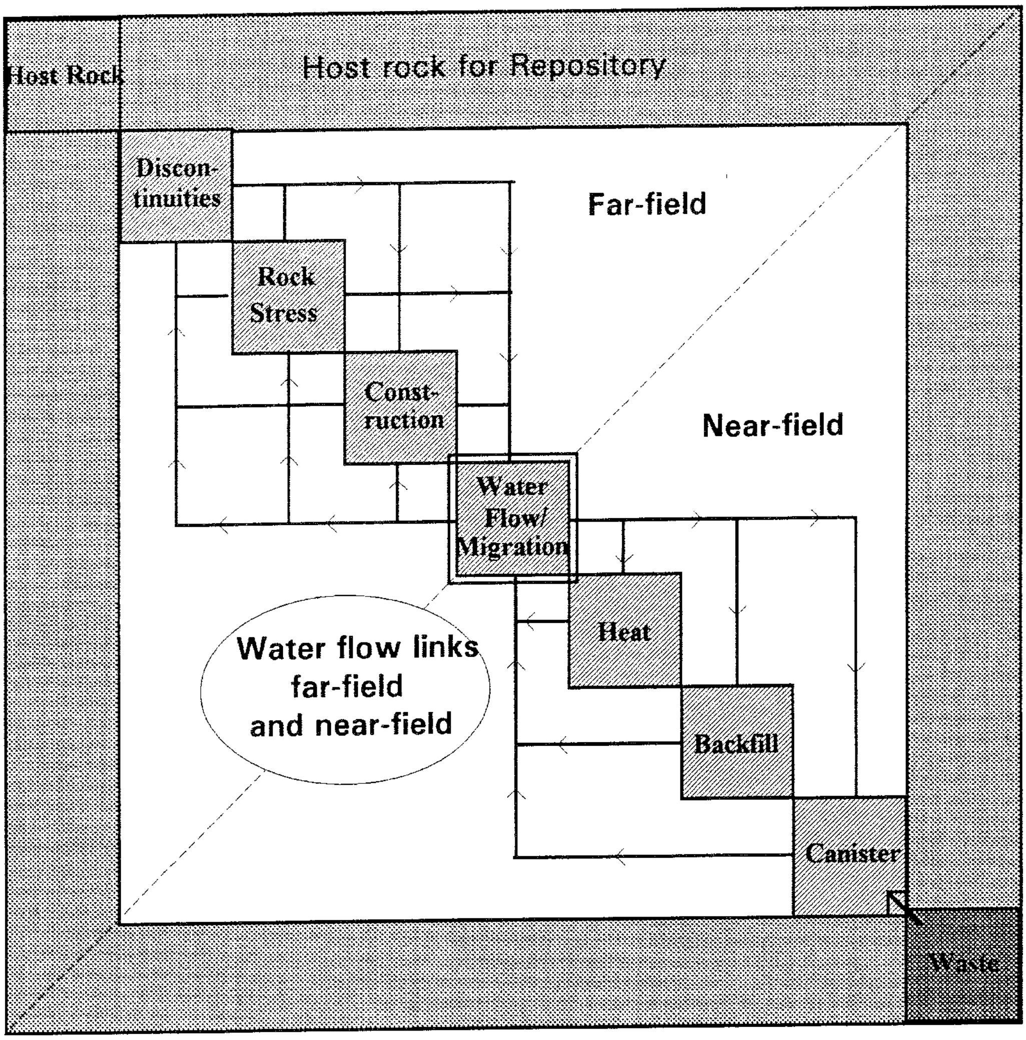


Figure 4-13. Reconfiguration of the basic interaction matrix to indicate the main loops.

This 'soft' RES approach has thus indicated the structure of the problem and the main mechanism pathways. The use of the 'hard' RES approach, or Fully-Coupled Model (FCM), would be the next step – where all the state variables in the interaction matrix have compatible units, are linked by explicit equations as each interaction term, and their evolution is established by considering the cumulative effect of all pathways using a recursion algorithm /4-4/.

5 APPLICATION EXAMPLES USING THE DIFFERENT METHODS

5.1 APPLICATION OF INFLUENCE DIAGRAMS ON THE REPOSITORY CONCEPT FOR LONG-LIVED LOW- AND INTERMEDIATE LEVEL WASTE

The methodology developed by SKI /3-1/ has been used by SKB for the development of Influence Diagrams describing the function of a waste repository for long-lived low and intermediate level waste (SFL 3-5) which is intended to be located adjacent to the waste repository for high level radioactive waste (SFL 2) /5.1-1/. The system to be studied was defined as the near-field and an Influence Diagram has been developed for a selected Reference Scenario. The Influence Diagram has been evaluated and significance levels have been assigned to the identified influences. Based on the significance of influences and FEPs, a reduced diagram has been prepared which was used to define calculation cases to be analysed in the prestudy. It was also used to identify areas which need to be investigated further in order to make a full performance assessment of the repository concept.

In the following sections the steps involved in the development of a reduced Influence Diagram forming the basis for the studied calculation cases are presented. As described in Chapter 3, these steps are:

- construction of a Basic Influence Diagram,
- development of an Influence Diagram for a Reference Scenario,
- development of a reduced Influence Diagram for the Reference Scenario.

5.1.1 Construction of Basic Influence Diagram

System definition

The system studied was restricted to the SFL 3-5 repository near-field. The near-field comprises the engineered barrier system and the nearby rock disturbed by the excavation and presence of the repository. The SFL 3-5 facility is assumed to be isolated from SFL 2 and no interactions are considered in the prestudy.

The three repository parts are planned to have barrier systems of different sophistication because the waste, as well as the waste packaging, will be significantly different between the different repository parts SFL 3, 4 and 5. Therefore, the Influence Diagram was divided into four main regions, one for each repository part, SFL 3, 4 and 5, and one for the near-field rock. The repository parts are assumed to be isolated from each other by tunnel plugs. The repository parts are all connected to the near-field rock and

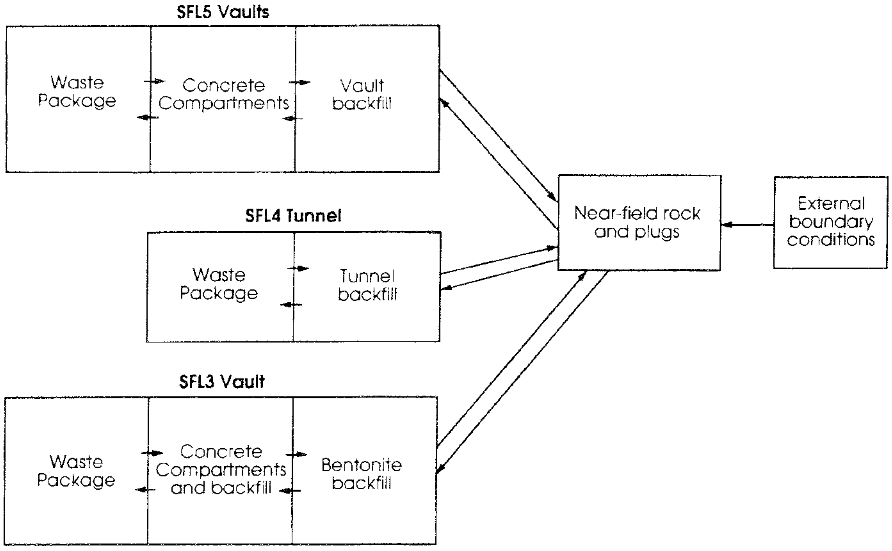


Figure 5.1-1. Schematic lay-out of the Influence Diagram for SFL 3-5.

cannot interact with each other directly. Interactions only occur via adjacent near-field rock or the plugs. Interaction with the surrounding far-field rock and the environment is defined by external boundary conditions influencing the near-field rock. The regions representing the repository parts were further divided into sub-regions representing the different barriers as illustrated in Figure 5.1-1.

Selection and documentation of FEPs relevant to the defined system

Existing FEPs lists and general know how regarding the repository system, see Chapter 3, formed the basis for selection of FEPs introduced in the Influence Diagrams. The selection of FEPs was based on the materials that can be found in the different repository parts and the possible processes and mechanisms that can influence their performance and, thereby, the release of radiotoxic and chemotoxic elements from the repository near-field.

In the repository, the main materials to be found are concrete, steel, sand and bentonite. A summary of the FEPs identified to potentially influence the performance of the engineered barriers and near-field rock and, thereby, the contaminant release is presented in Table 5.1-1.

The identified FEPs were assigned to different areas in the same way within each system component in the Influence Diagram. Since the ultimate goal was to estimate the release of radionuclides and chemotoxic elements from the different system components, barriers, transport and retardation phenomena were placed at the bottom and FEPs influencing barrier conditions at the top of the diagram. The physical and chemical conditions in the barriers constituted the link between the two groups of FEPs, see Figure 5.1-2.

Table 5.1-1. *Summary of FEPs considered for SFL 3-5 repository near-field.*

FEPs in Influence Diagram

Alkali-silica and portlandite-silica reations
Anion exclusion
Cave in
Cement/concrete leaching

Chemical alteration of bentonite backfill
Chemical properties
Chloride attack on cement/concrete
Colloid generation
Corrosion

Corrosion of reinforcement
Creeping of rock mass
Degradation of detector and control rod components
Degradation of organics
Degradation of rock reinforcement
Degradation of vault seals
Diffusion
Dilution of bentonite backfill
Disperson
Dissolution and release from miscellaneous waste
Dissolution and release of surface contamination
Electrochemical gradients

Erosion of backfill
Erosion of bentonite backfill
Ettringite formation
External boundary conditions
Faulting

Gas flow and transport

Gas flow in vault backfill

Gas flow in bentonite backfill

Gas flow in cement/concrete
Gas flow through steel packaging
Gas generation/source
Groundwater flow
Internal pressure
Matrix diffusion
Mechanical impact

Microbial activity
Physical properties
Precipitation of calcite/brucite
Precipitation/dissolution of corrosion products
Properties and conditons in otherpackages
Radiation effects on concrete
Radioactive decay of mobile nuclides
Radiolysis
Radionuclide inventory and radioactive decay
Reconcentration
Recrystallisation cement/concrete
Release from detector and control rod components
Release from metal waste
Repository excavation
Resaturation of bentonite backfill
Resaturation of cement/concrete
Resaturation of near-field rock
Resaturation of vault backfill

Sedimentation of bentonite backfill

Sorption
Sorption/coprecipitation with corrosion products
Stress field
Swelling of bentonite backfill
Temperature
Total release from waste
Transport and release of waste components from concrete compartments
Transport and release of waste components from near-field rock
Transport and release of waste components from repository vaults
Transport and release of waste components from waste package
Waster chemistry
Water flow in bentonite backfill
Water flow in cement/concrete
Water flow in vault backfill
Water flow through steel packagin
Weathering of flow paths

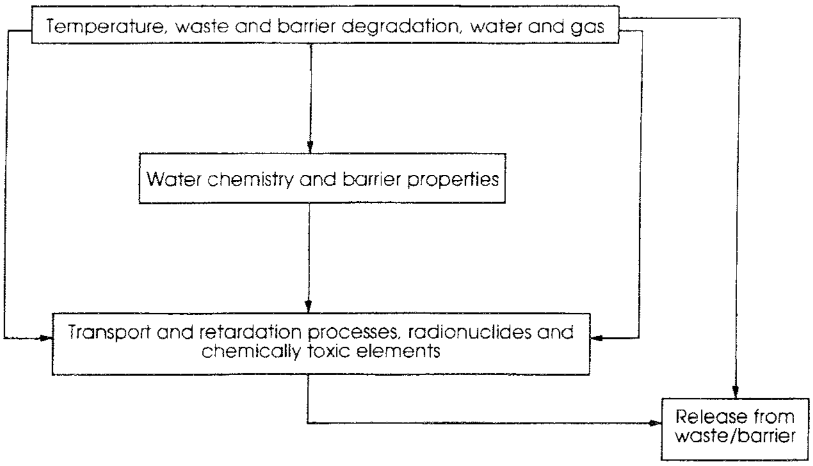


Figure 5.1-2. *Schematic lay-out of how FEPs are assigned to different areas in the Influence Diagram for SFL 3-5.*

In the Influence Diagram, the FEPs are defined by a name only, e.g. "Sorption". To make it clear what actually is meant by a FEP, a more comprehensive description is needed. Therefore a document was prepared for each FEP. This document contains the FEP name used in the Influence Diagram, a description of the FEP, possible cause and effects of the FEP and references to literature. These documents are stored in a database which is coupled to the Influence Diagram.

The same FEP may be relevant for several of the barriers in the system studied. This should be clear from the Influence Diagram, but frequently it is not necessary to have several descriptions of the same FEP. In general, the same FEP description is applicable independent of where in the system the phenomena occurs. In such cases all boxes in the Influence Diagram representing the same FEP are coupled to the same FEP description in the database. An example of a FEP documentation is given in Figure 5.1-3 for the FEP "Sorption". All FEP descriptions presently stored in the database for SFL 3-5 are available in the Annex to the report "Testing of Influence Diagrams as a Tool for Scenario Development by Application on the SFL 3-5 Repository Concept" /5.1-1/.

Identification and documentation of influences between selected FEPs

The next step is to identify interactions between the FEPs and indicate these in the Influence Diagram. This is done by drawing a line between the interacting FEPs and with an arrow showing the direction of the influence. Each influence on the diagram is marked with a unique code.

All identified influences must be clearly defined. Therefore each influence in the Influence Diagram is coupled to a document containing the influence code, the names of the FEPs between which the interaction occurs, a

FEP: **Sorption**

Description:
Sorption is the collective term of adsorption of molecules. ions, colloids, on outer or inner surfaces or solids. The forces responsible for sorption range from “physical” interactions (v d Waals’ forces) to the formation of “chemical” bonds. Sorption retards the transient diffusion and the advective transport or radionuclides and chemically toxic elements in the engineered barriers as well as in the near-field and far-field rock. The effect is well established and included in the migration models. Sorption is element specific and depends both on radionuclide speciation (valency state, hydrolysis, complexation) and the solid phase composition and surface characteristics. At true thermodynamic equilibrium these two sets of conditions are linked together.

Sorption could be reversible or irreversible. If sorption is reversible the sorbed species will be desorbed and mobilized if the concentration of the species in the water decreases. Species which are irreversible sorbed will to a large extent remain fixed to the solid surface even if the concentration in the water decreases.

There is an upper limit of the sorption capacity which depends on the specific surface of the materials. If the sorption mechanism is ion-exchange the ion-exchange capacity is also important for the sorption capacity. Saturation of sorption sites may have to be considered, and non-linear effects also.

Cause

Effect:

Significance:

Modelling aspects:
In most transport calculations sorption is accounted for by the simplistic method of letting the retardation be determined by constant distribution coefficients (K_d). This approach is sufficient only when truly conservative K_ds are chosen. More elaborate and thermodynamically convincing models for sorption are available (surface complexation etc), but the amount of useful data is as yet very scarce. It should also be recognized that along a transport trajectory the chemical conditions might change significantly on a scale less than one mm. Other issues of importance for proper modelling or sorption are the possibility of inclusion of radionuclides in fracture minerals, and the release of trapped (or sorbed) nuclides in connection with mineral dissolution. Phenomenologically it is difficult to distinguish between matrix diffusion on the microsale, surface sorption kinetics and weathering effects on mineral surfaces.

Others:

References:
“Sorption” = FEP 4.1.4 in SKI/SKB Scenario Development Project. SKB Technical Report 89-35.

“Saturation of sorption sites” = FEP 3.1.2 in SKI/SKB Scenario Development Project. SKB Technical Report 89-35.

***Figure 5.1-3**. Example of a FEP description.*

Identification no: 5PE59

Influence:

Water Chemistry, waste package – Sorption, package

Specification:

Influence of water chemistry (competing species, content of complexing agents, ions competing for complexing agents, etc) in waste package on the magnitude of sorption on concrete in waste package of radionuclides and chemotoxic elements released form the waste. The concentration of the same elements originating form other sources than the waste as well as stable isotopes or radioactive species should also be considered.

Significance:

Reference Scenario: Important ProjGrp-27.8

Modelling aspects:

Others:

References:

ProjGrp-27.8: F Karlsson + T Eng + M Johansson, SKB
L-O Höglund + K Skagius + M Wiborgh, Kemakta, B Allard + M Norden, ULi, I Engkvist, Chalmers,K Broden, Studsvik, August 27, 1993.

Figure 5.1-4. Example of an influence description.

specification of the interaction and references to literature if available. An example of an influence documentation is given in Figure 5.1-4 for the influence "Water chemistry – Sorption".

5.1.2 Development of Influence Diagram for Reference Scenario

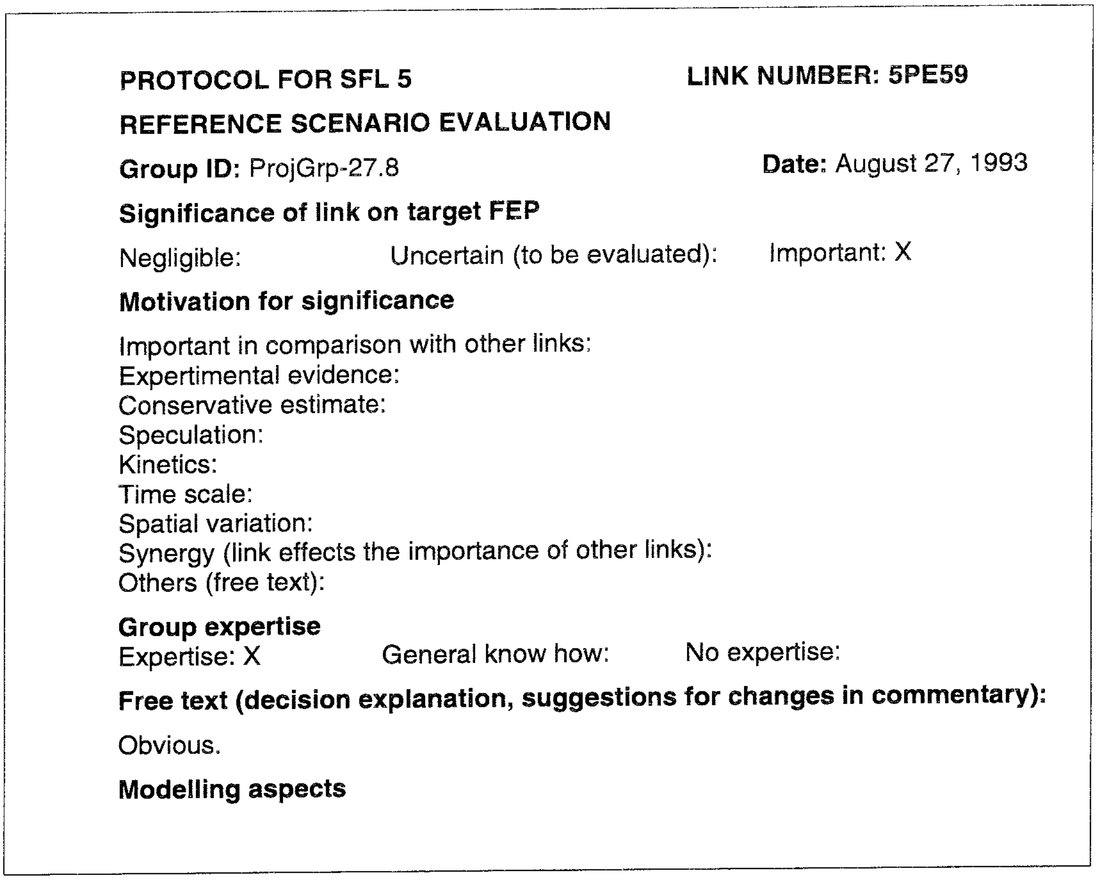
The evaluation of an Influence Diagram for a defined scenario is time consuming since there are a large number of FEPs and influences that should be reviewed and judged. By defining a simple Reference Scenario and making a complete evaluation of the Influence Diagram for the Reference Scenario, time can be saved since evaluation of additional, more complex, scenarios can be restricted to parts of the Influence Diagram that differ from the Reference Scenario diagram.

Reference Scenario premises

The premises for the selected Reference Scenario are as follows:

- the repository is closed and the properties of the barriers are in accordance with design criteria,

- the hydrological, hydrochemical, rock mechanical and thermal conditions at the Process System boundary, i.e. at the interface between near-field and far-field rock, are representative for typical Swedish bedrock and constant with time.



PROTOCOL FOR SFL 5 **LINK NUMBER: 5PE59**

REFERENCE SCENARIO EVALUATION

Group ID: ProjGrp-27.8 **Date:** August 27, 1993

Significance of link on target FEP

Negligible: Uncertain (to be evaluated): Important: X

Motivation for significance

Important in comparison with other links:
Expertimental evidence:
Conservative estimate:
Speculation:
Kinetics:
Time scale:
Spatial variation:
Synergy (link effects the importance of other links):
Others (free text):

Group expertise
Expertise: X General know how: No expertise:

Free text (decision explanation, suggestions for changes in commentary):

Obvious.

Modelling aspects

Figure 5.1-5. *Example of an influence protocol.*

Evaluation of significance

Once the premises for the Reference Scenario were defined, the Basic Influence Diagram was reviewed and the significance of each influence for the conditions specified in the Reference Scenario was assessed. Ideally, the review of the diagram should be carried out by a number of people with expertise in different disciplines in order to cover all aspects of the long-term performance of an underground repository. This was not possible to achieve within this study. However, the review was carried out by at least two persons, and part of the diagram was reviewed by the full Project Group involved in the prestudy.

A three-level significance scale was used. Influences judged to be insignificant for the target FEP were labelled “negligible”, influences which were assessed to be significant for the target FEP were labelled “important”, and influences which presently could not be judged either as negligible or important were labelled “uncertain”.

The assessed significance, together with the reasons behind the assessment, were documented in a protocol coupled to the influence in the Influence Diagram. A motivation for the significance is especially important for those influences judged to be “negligible”, since they will not be considered in the subsequent evaluation of the defined scenario. In the protocol ideas on how to consider the influence in modelling can be documented. In addition, the people involved in the review of the Influence Diagram and their degree of expertise in the topic were documented in the protocol.

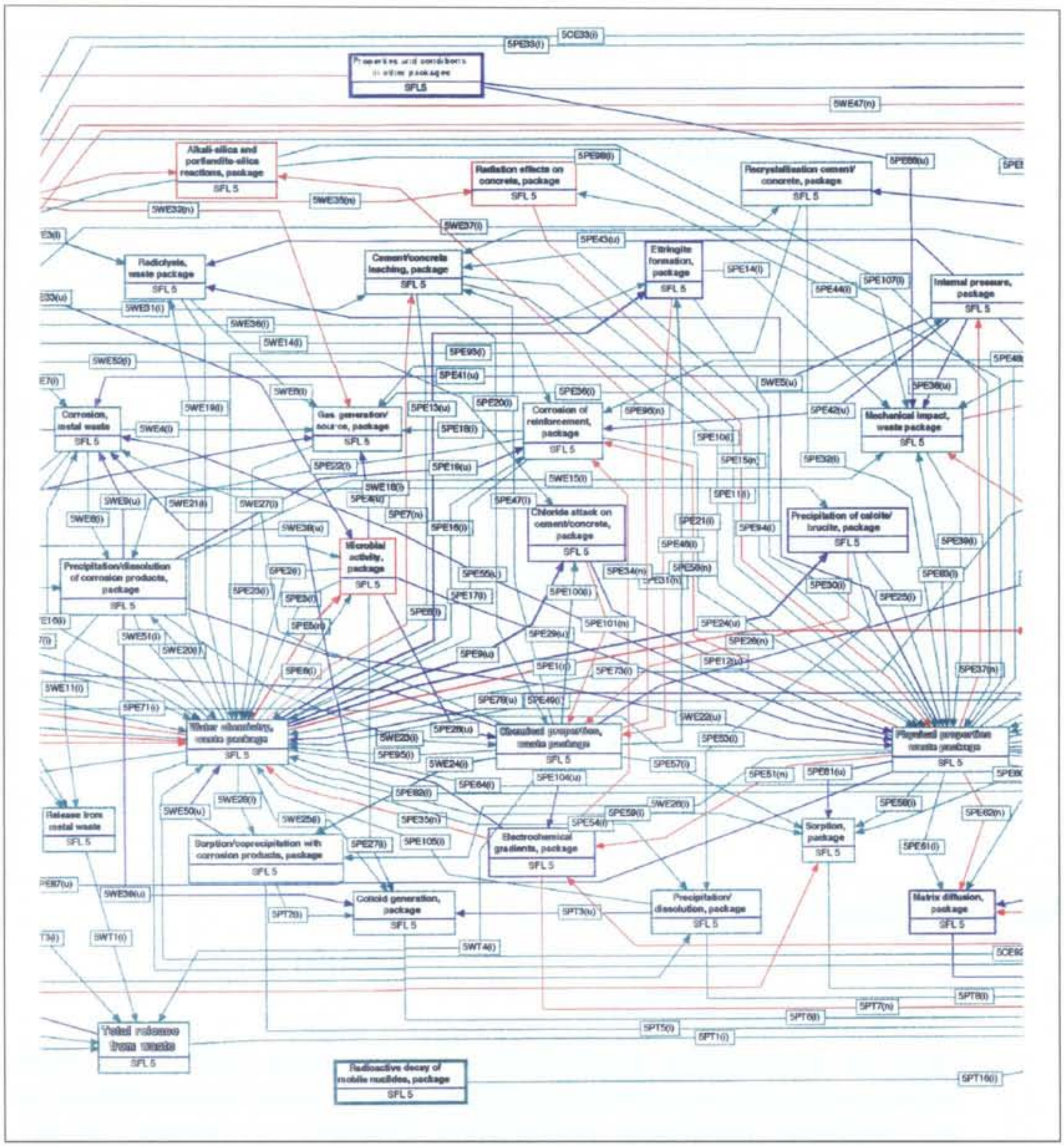


Figure 5.1-6. *Part of the Influence Diagram for the Reference Scenario. Bold links indicate influences which are required to activate the target FEP (on/off links on target FEPs).*

The influence protocol for the influence defined in Figure 5.1-4 is shown in Figure 5.1-5. Prior to the significance assessment, some keywords were defined with the aim to facilitate the documentation. However, it was found that in most cases it was easier and quicker to use one or several sentences to explain the decisions made.

During the review of the Influence Diagram a number of modifications which would improve the diagram were identified. These modifications were implemented by updating the Influence Diagram and the documentation coupled to the diagram.

Influence Diagrams for Reference Scenario

When the significance of all influences in the diagram was assessed for the Reference Scenario premises, a first version of the Influence Diagram for the Reference Scenario was completed. As an example, a small part of the Influence Diagram is shown in Figure 5.1-6. The diagram is large and

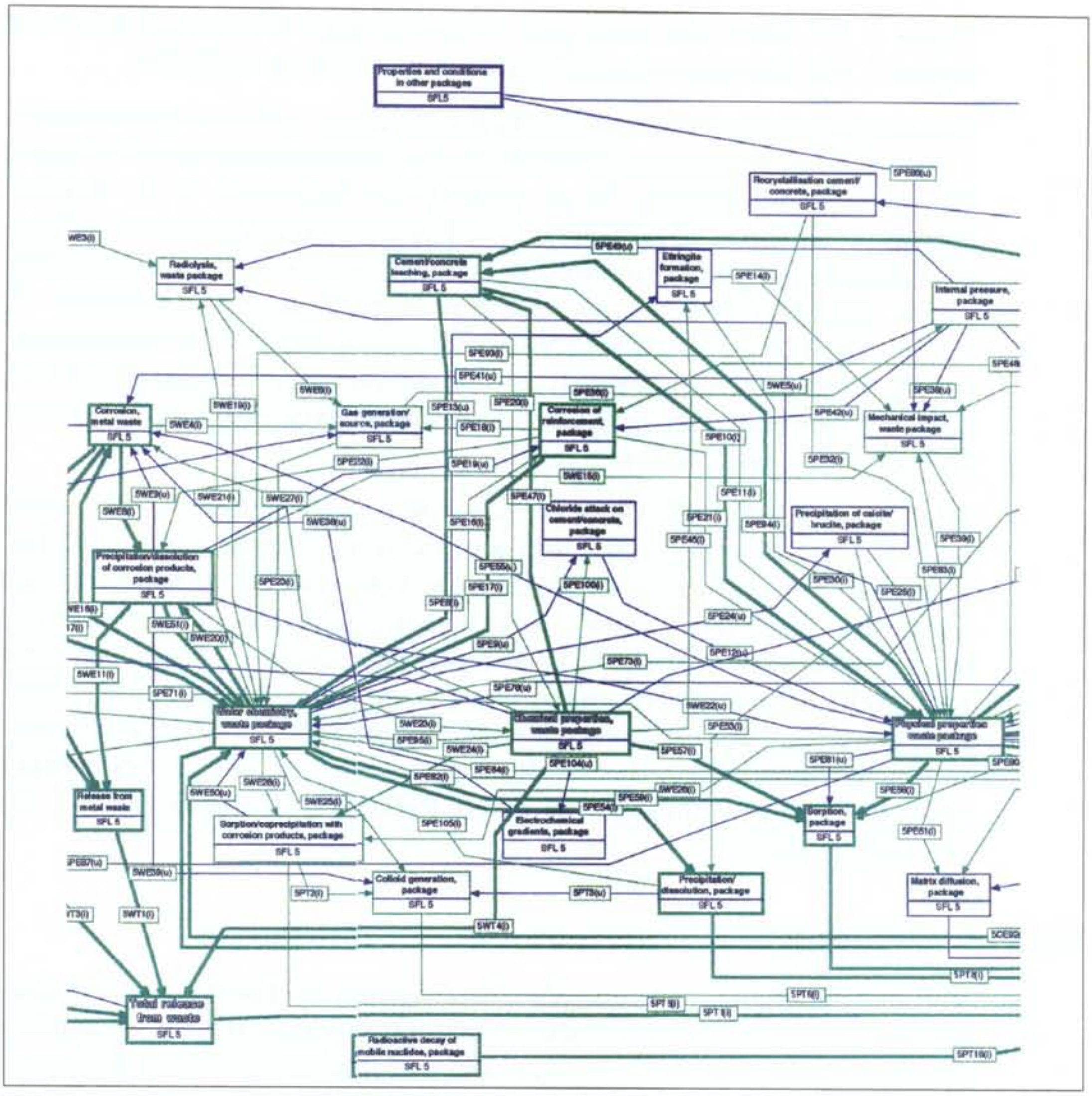


Figure 5.1-7. Part of the reduced Influence Diagram for the Reference Scenario. Processes and mechanisms considered in the Reference Case are shown in bold.

looks complicated due to the large number of FEPs and influences identified. This reflects to some extent the level of detail in the description of the system which aims to include all possible dependencies between FEPs. However, some influences are more important than others in the sense that they are required to activate the target FEP. The assessed significance of such an influence will then primarily determine the significance of the target FEP. This type of on/off influence is represented by bold links in the unreduced Influence Diagram.

The diagram would be less complex if a smaller number of FEPs and influences could be used to describe the system. One way to achieve this would be to broaden the definitions of FEPs and influences, but it has to be done carefully in order not to lose information in the description of the system. No such attempts have been made within this study.

The next step was to reduce the Influence Diagram to a selected significance level. Because of the coarse significance scale used, it seemed at this stage appropriate to remove only influences assessed to be negligible.

Figure 5.1-7 shows the same part of the Influence Diagram as shown in Figure 5.1-6 after removing influences assessed to be negligible.

The entire Reference Scenario Influence Diagram contains approximately 1 300 influences, and about 900 influences remain in the reduced Influence Diagram. Approximately 30 per cent of the influences in the reduced diagram were assessed as "uncertain". The quite large number of influences still remaining in the reduced diagram could seem a bit disappointing, but it should be pointed out that this is partly due to limitations in disciplines covered by the people involved in the significance assessment. A larger and more appropriately composed assessment group would probably have provided arguments for assessing a larger number of influences as negligible already at this stage.

The reduced Influence Diagram was used to formulate the Reference Scenario and identify calculation and modelling needs for quantitative estimates of the release of radionuclides and chemotoxic elements from the repository. Since this work and subsequent calculations were carried out as a part of a prestudy of the SFL 3-5 repository concept, it was not possible to consider all phenomena and influences remaining in the reduced Influence Diagram. Therefore a Reference Case for the Reference Scenario was formulated and analysed. The Reference Case as well as phenomena remaining to be addressed for a full Reference Scenario analysis are described in /5.1-1/.

5.1.3 Concluding remarks

The general impression after this first attempt is that the methodology seems promising. It has been shown that it is possible to carry through the different steps in the methodology, and that it has resulted in a Reference Scenario for SFL 3-5 and a Reference Case to be quantitatively analysed for the Reference Scenario. In addition to this, the developed Reference Scenario Influence Diagram highlights the present uncertainties in the behaviour of the SFL 3-5 disposal system (engineered barriers and near-field rock) for the Reference Scenario. This is valuable input to the planning of forthcoming studies and investigations of the SFL 3-5 concept.

One very important achievement from the study is the data base with documents and protocols describing the Process System and the decisions behind the development of the Reference Scenario. This allows easy checking of decisions and facilitates future re-evaluations. An additional advantage in this sense is that the documentation is coupled to the Influence Diagram which makes the documentation easily accessible.

The construction of the basic Influence Diagram and the review and evaluation of the diagram for the Reference Scenario premises required large efforts and were time-consuming. However, the time and effort needed for evaluation of the Influence Diagram for other scenario premises will be much less, since the work can be restricted to the parts of the Influence Diagram where the behaviour of the Process System differs compared to the Reference Scenario.

Finally, it must be remembered that the present Influence Diagram for the Reference Scenario reflects the view of the people involved in the judgement of influence significance and their present knowledge of the system. However, scenario development is a continuous process and the Influence Diagram, or other types of graphical system descriptions, with its documentation system should therefore be re-evaluated and up-dated as the knowledge of the system increases.

5.2 APPLICATION OF THE RES METHODOLOGY TO ANALYSIS OF A LARGE ROCK PERTUBATION

5.2.1 General

In this Section, we apply the RES methodology described in Chapter 4 to analysis of the influence of a 'large rock perturbation' imposed on the repository. Firstly, however, we present the way in which the methodology is applied in principle to scenario analysis.

In the scenario application, we are concerned with processes that can influence the repository, and these processes will be of various types. Thus, it is advantageous to consider the partitions within the total interaction matrix used for the analysis. The general idea of thematic sub-matrix components is shown in Figure 5.2-1.

We could also compile the complete interaction matrix from the thematic sub-matrices based on the leading diagonal terms chosen by the various

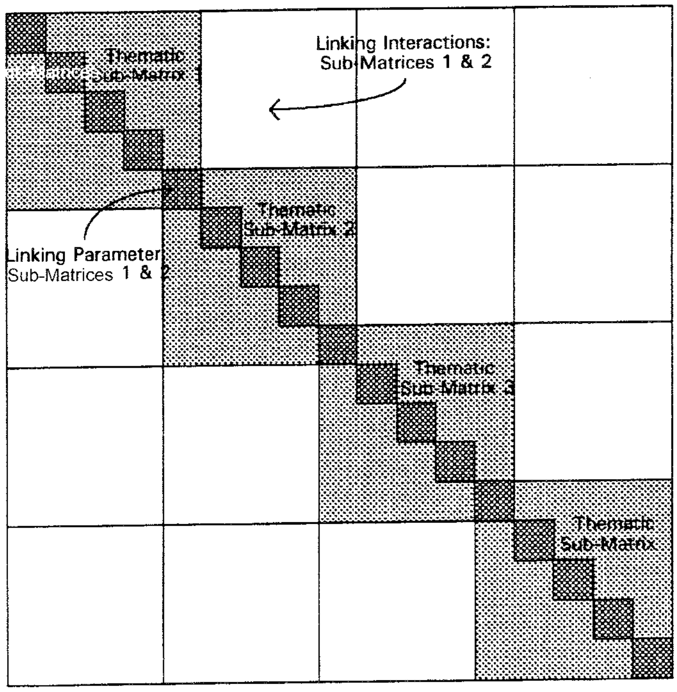
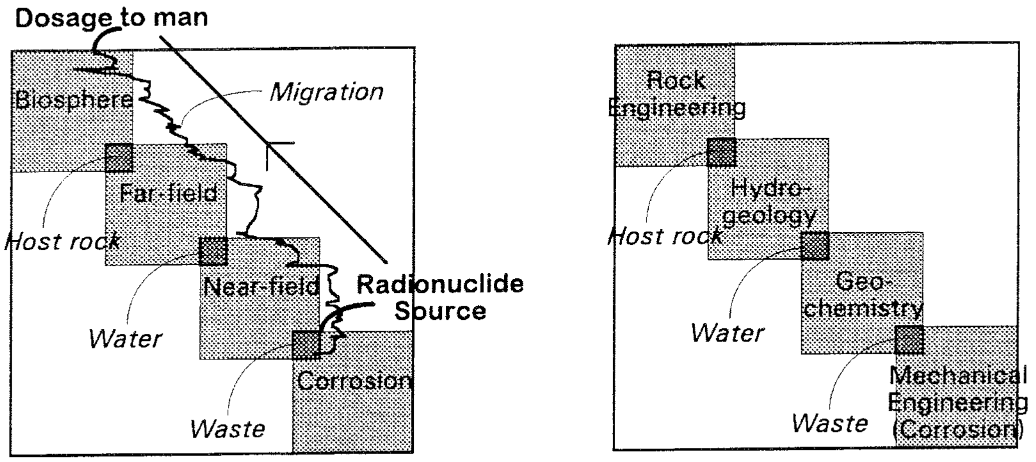


Figure 5.2-1. Concept of partitioning the total matrix into thematic sub-matrices.



a) path-dependent sub-matrices b) subject/discipline sub-matrices

Figure 5.2-2. *Main interaction matrix partitioned into thematic sub-matrices.*

experts in the appropriate fields. This is beneficial since it encourages direct liaison between specialists and groups of specialists because of the need to establish the interaction boxes in Figure 5.2-1, (white). These could be, for example, the links between the variables in geochemistry as one sub-matrix and far-field geology as another sub-matrix. The partitioning also highlights the need to utilize compatible parameters, so that the functional relations both within sub-matrices and between sub-matrices can be explicitly expressed.

The themes in the sub-matrices can also be developed according to different approaches to the waste disposal analysis. In Figure 5.2-2a), we indicate sub-matrices associated with the migration paths; in Figure 5.2-2b), the sub-matrices are subject/discipline dependent.

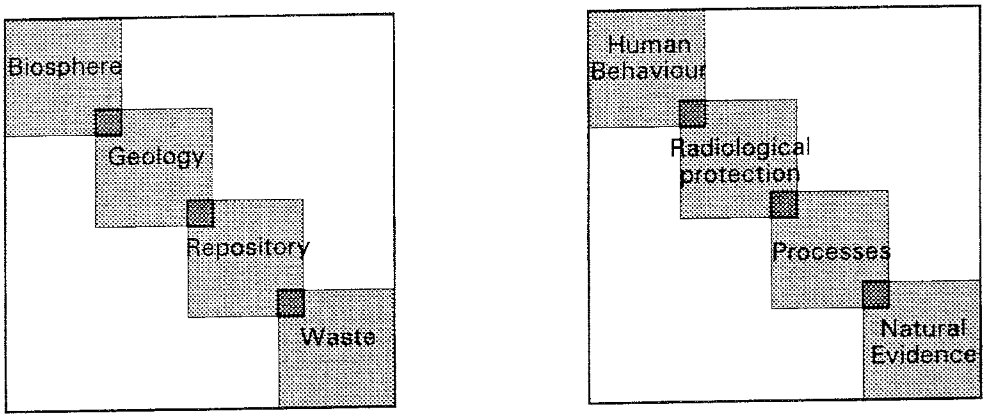
The locational or subject phases can be considered within the interaction matrix and its sub-matrices, as illustrated in Figure 5.2-2. Alternatively, we could be studying directly the disposal system sub-matrices or studying the interactions between biosphere and geosphere components. These are both illustrated in Figure 5.2-3.

However, for the analysis presented here we will use the matrix and network developed in Chapter 4.

We recall that a single **scenario** is specified as "one possible set of events and processes and providing a broad brush description of their characteristics and sequencing". In other words, it is an "alternative future" – which can be obtained by different initial conditions and perturbations (natural or engineered) in the matrix. In the RES methodology we use three basic system concepts when considering scenarios:

A) the natural rock system with all its parameters, interactions and natural perturbations which has already been operating for millions of years and will continue to do so;

B) the construction of a repository, emplacement of waste and closure which will introduce man-made engineered perturbations – the short



a) disposal system sub-matrices

b) biosphere and geosphere sub-matrices

Figure 5.2-3. *Sub-matrices developed from considerations in the NEA scenario development document /5.2-1/.*

and long term consequences of which can be established by consideration of all the mechanism pathways through the interaction matrix and which are considered as the evolution of the matrix and the changes which occur to the values of the leading diagonal terms and off-diagonal terms, i.e the trajectories of the state variables and modifications of the linking mechanisms; and

C) following closure, different outcomes result from 'additional perturbations', whether these be natural or engineered.

These circumstances leading to different system states are shown in Figure 5.2-4. In the System A states, the natural rock mass is in a continual state of flux as mechanisms continue to operate and new natural perturbations

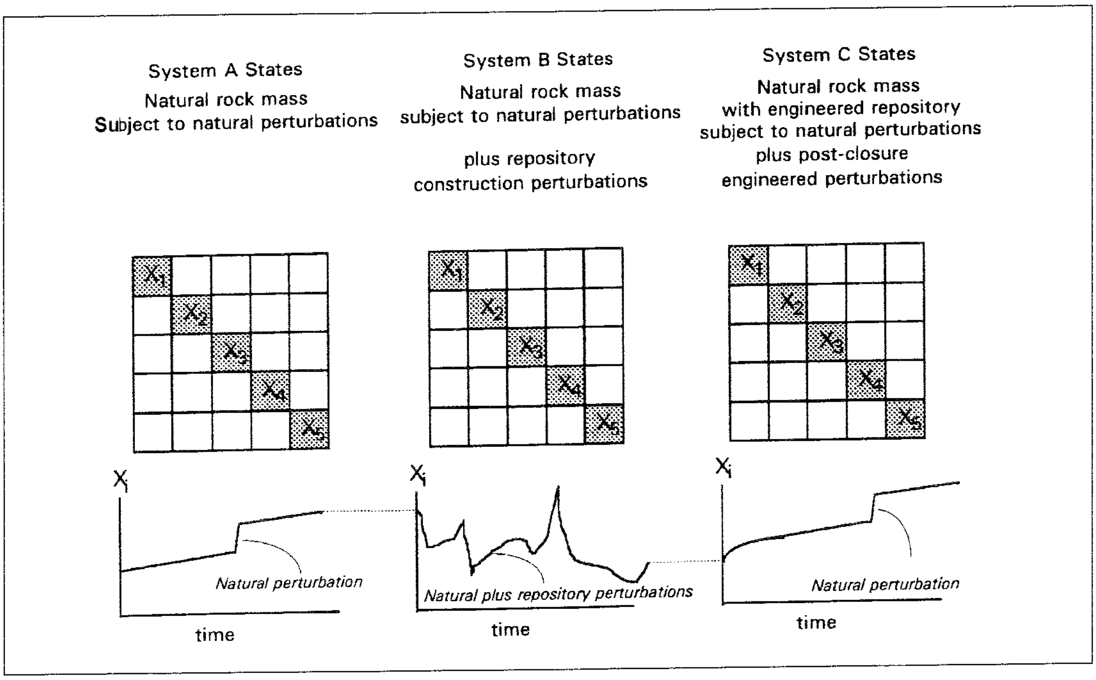


Figure 5.2-4. *The three generic system states. A) natural pre-repository conditions, B) repository construction, waste emplacement and closure operations, and C) post-closure conditions, and the concept of the associated state variables, x_i, evolution with time.*

are introduced. Note that the jump in the x_i state variable curve in Figure 5.2-4 could either result as a natural internal consequence of the matrix evolution, e.g. water flow occurs in a new fracture as the groundwater pressure increases, or as a result of an external perturbation, e.g. a flood on the ground surface. In the System B states, System A continues to operate but there is a suite of repository construction, waste emplacement and closure perturbations overlain on the system. In the System C states, the host rock now contains a repository, the matrix continues to be in a state of flux with repository-modified conditions, and to be subject to natural perturbations.

Thus, we have the following system states from which associated scenarios can be developed.

SYSTEM A STATES:

The natural rock mass subject to

i) continuing internal mechanisms, and

ii) non-repository associated external perturbations.

Note: perturbations can be natural sudden changes of state due to internal mechanisms, e.g. an earthquake, or be external perturbations, e.g. glacial loading. Also, there could be non-repository associated engineered perturbations, e.g. mining activities .

System A States, A_i

The natural rock mass is dynamically evolving with time as a result of internal mechanisms and non-repository associated external perturbations. It is possible that bifurcations in overall behaviour can occur and that the rock mass can be significantly affected by external perturbations. This leads to the possibility of different System A states before repository construction, or States A_i where $i = 1$ to l. The A_i states are all the possibilities that can develop and we assume that one particular A_i state is operating when repository construction begins. Any specific A_i state could be a scenario from a considered perturbation.

SYSTEM B STATES:

The natural rock mass is subject to

i) continuing internal mechanisms,

ii) continually changing repository-modified conditions, and

iii) non-repository associated external perturbations.

Note: perturbations can still occur as natural sudden changes of state due to internal mechanisms, and these will be enhanced, unaffected or inhibited as a result of repository-induced changes. We assume that the possibility of external perturbations remain the same.

System B States, A_iB_j

The host rock mass is in a state, A_i, as a result of the matrix operation leading up to the start of engineering operations. The repository is then constructed, waste is emplaced and closure is effected. These are all considered as part of the repository engineering, but are actually three sequential System B states. Depending on how the repository is constructed and the continuing non-repository associated perturbations, another set of system states is possible: A_iB_j where $j = 1$ to m. We assume that following repository closure the state is one specific A_iB_j. Again, one or more of these could be a scenario developed from initial conditions and introduced events.

SYSTEM C STATES:

The natural rock mass is now hosting a closed repository and subject to

i) continuing internal mechanisms, some modified by repository-induced conditions and perturbations,

ii) non-repository associated external perturbations.

Note: we are now back to conditions similar to System A except that the repository-induced conditions operate.

System C States, $A_iB_jC_k$

After repository engineering, the system state is one of the A_iB_j system states. The natural rock mass with the contained repository continues to dynamically evolve as a result of (modified) internal mechanisms and non-repository associated external perturbations. This leads to potential system states $A_iB_jC_k$ where $k = 1$ to n, and leads to one specific $A_iB_jC_k$ state. Any of these could be a scenario if we chose to define the particular conditions and events leading to it.

The concept of a **scenario** in the rock engineering system context has now been significantly clarified. Clearly, we could have more than the A, B and C phases and make other modifications but the concept of scenario as a specific evolved system state resulting from a defined set of events is clear. The system will potentially evolve to the $l\text{x}m\text{x}n$ $A_iB_jC_k$ states, one or more of which could be scenarios defined by initiating conditions and events.

In Figure 5.2-5, we illustrate the evolution of the scenarios from the initial state, through the generic system states, A, B and C, to the final states with a specific end state, one of the $l\text{x}m\text{x}n$ $A_iB_jC_k$ potential states. In Figure 5.2-5, there is an initial state shown at the left. From this state, depending on conditions, various states are possible, shown by the column of A_i states. Assume this is the A_i state indicated by the heavy line. From this specific A_i state, various A_iB_j states are possible and we assume that the specific state A_i is reached as by the heavy line. Finally, from this specific A_iB_j state, various A_i B_jC_k system states are possible, leading to a specific system state $A_iB_jC_k$ shown at the right of Figure 5.2-5.

The perturbations can either be internally generated through the natural matrix evolution (as state changes) or be externally imposed. Various scenarios can be identified from a defined set of initial conditions and events or perturbations. This methodology is considered to be robust as it simply incorporates the potential for any system changes as a result of both internal and external factors – leading to the suite of states $A_iB_jC_k$, some of which will be scenarios.

5.2.2 The 'Large Rock Movement' Perturbation Case Example

The perturbation example is a post-closure 'large rock movement' perturbation. It is assumed that this perturbation is a significant extra rock movement – in the sense that it would not be considered as part of the natural evolution of the interaction matrix. It is an imposed natural perturbation. The way in which the scenario associated with the perturbation is considered through the diagram in Figure 5.2-6 which follows the earlier diagram in Figure 5.2-5.

In the scenario context, we are at a specific system state A_iB_j and are considering how the large rock movement perturbation will affect the subsequent system states, i.e. to which different C_k state the system will evolve as the related scenario.

Firstly, we need to consider how the large rock movement perturbation will directly affect other parameters through the binary interactions in the

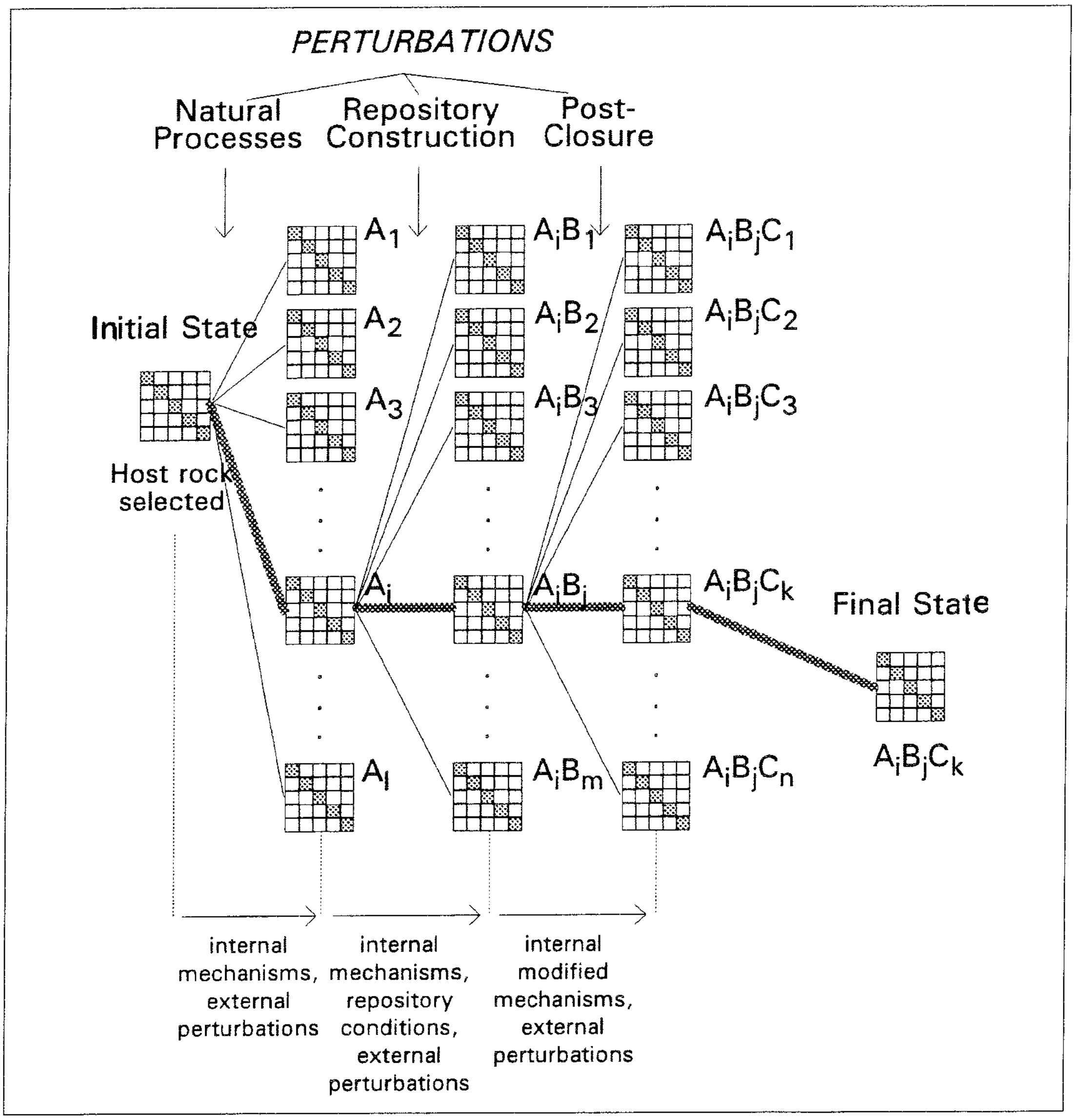


Figure 5.2-5. Perturbations causing alterations to the system and hence the evolution of potential system states, $A_iB_jC_k$. One or more of these evolution pathways can be a defined scenario.

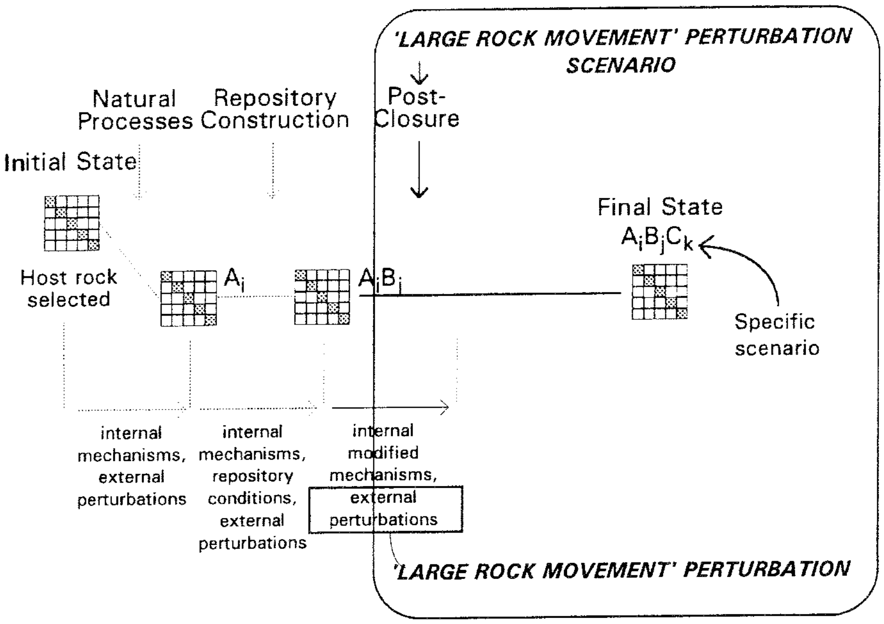


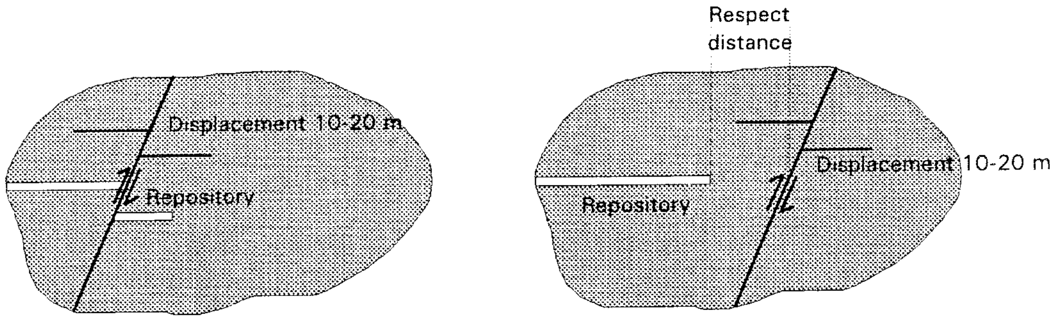
Figure 5.2-6. *Introduction of a 'large rock movement' perturbation after repository closure.*

interaction matrix; and to do this, we need to understand the physical expression of the perturbation. Following the studies that have been reported on movement along discontinuities /5.2-2/ we will concentrate on displacements in the order of 10–20 m, as illustrated in Figure 5.2-7.

The large rock movement perturbation is most likely to be a naturally occurring phenomenon of the type described on page App. 1b 16 of the SKB Report 94-11 by Höglund, Winberg and Brandberg /5.2-3/ and as supported by evidence and discussion reported in SKB Reports 89-31 by Bäckbom and Stanfors /5.2-4/, 93-11 edited by Stanfors and Ericsson /5.2-5/, 93-13 by Muir Wood /5.2-6/, 93-14 by Boulton and Payne /5.2-7/and 93-44 by Leijon /5.2-8/.

In SKB Report 94-11, the authors note with respect to Item 4.2.6 Faulting that "Faulting may occur due to sudden changes in the rock stress situation, e.g. an earthquake (FEP 5.15), or through slow movements (creep) induced by e.g. orogenic events or loading and unloading due to glaciation (FEP 5.42), or due to global plate movements. The result of the release of stress may be the formation of a fracture, and if movement occurs along the fracture, a fault. A more likely event is movement along already existing fractures and faults." The authors go on to point out that the main effect of a fault will be the adverse effect on the water flow regime and that the creation of a **new** fault or fracture zone within the repository rock block is of higher significance – given that it would not have been included in the analysis as a component of the *a priori* geometry.

A new fracture may not only be created by natural processes but by the construction of the repository and emplacement of the waste. Shen and Stephansson have studied the influence of thermal loading and buffer material swelling pressure in SKI TRs 90:3 and 90:12 /5.2-9 and 5.2-10/. They conclude that temperature effects could cause displacements of up to



a) Through repository b) Adjacent to repository

Figure 5.2-7. Large rock movement perturbation.

4 mm on pre-existing discontinuities. Although this displacement is small compared to 10–20 m, it could have severe effects on the groundwater flow and hence migration.

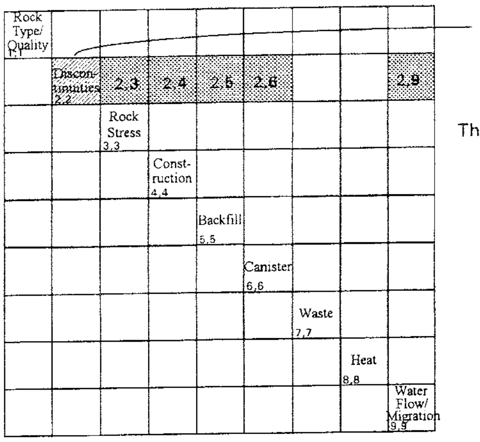
In Figure 5.2-7, we have shown the two cases of a large rock movement ocurring a) through the repository and b) adjacent to the repository. Naturally, Case a) is potentially far more severe because, as pointed out in SKB Arbetsrapport 94-11, this could involve damage to engineered barriers and even breach a canister – thus prejudicing the integrity of all four primary barriers simultaneously, i.e. mechanical displacements through the fuel, the canister, the clay, and the rock. In Case b), the main effect will be the alteration to the water conducting fracture network and the possible creation of a super-conductor.

The RES approach considers the main variables and all the interactions, together with concurrent and consecutive mechanism pathways and the consequential evolution of the whole system. Thus, a natural question arises as to the starting point in considering the large rock movement perturbation. As pointed out in the Kemakta report, SKB Arbetsrapport 94-11 /5.2-3/, such a displacement perturbation is most likely to have been initiated by changes in the *in situ* stress regime. So it might be useful to consider the initiating factor as a natural stress field perturbation, see System C states in Figure 5.2-4, which leads to a large rock movement perturbation. The stress field perturbation then causes a suite of interactions through the matrix, and the large rock movement perturbation causes another suite of interactions – both of which can be systematically studied through the matrix structure. However, it is likely that the stress changes will be gradual and that the consequential large rock perturbation is a sudden system state change, as the strain energy in the rock is released into surface energy effects along the pre-existing discontinuity (e.g. an earthquake). Hence, we will consider the large rock movement perturbation directly.

The perturbation can be considered in two stages:

firstly, through the direct binary interactions of the interaction matrix structure – the ‘first kick’; and

secondly, through the fully-coupled model as the perturbation diffuses through the matrix interactions – the ‘second kick’



The large rock movement perturbation is introduced via Box 2,2: Discontinuities

The perturbation has direct binary effects - as indicated by the shaded off-diagonal boxes

These interactions are listed in the table in the text

Figure 5.2-8. *Introduction of the 'large rock movement' perturbation via the second leading diagonal term of the interaction matrix, 'Discontinuities'.*

Table 5.2-1. *Binary Effect of a Large Rock Movement Perturbation Introduced Via Box 2,2 (Discontinuities) of the Basic Interaction Matrix (BIM).*

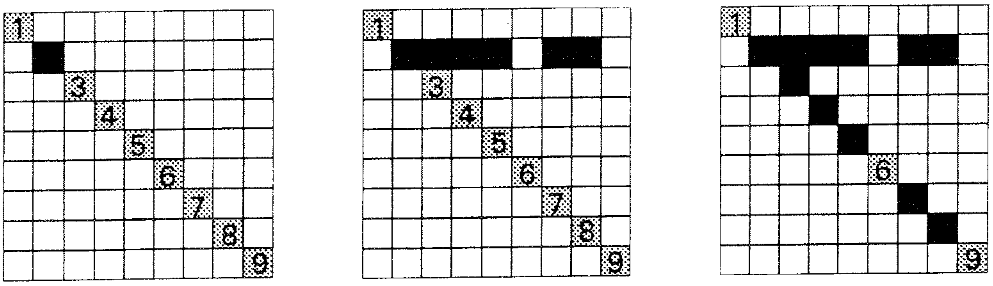
Interaction Box 2,1	Effect on Host Rock	No significant effect
Interaction Box 2,3	**Effect on Rock Stress**	**Stress magnitudes/orientations changed**
Interaction Box 2,4	**Effect on Construction**	**Integrity of repository compromised**
Interaction Box 2,5	**Effect on Backfill**	**Integrity of backfill compromised**
Interaction Box 2,6	**Effect on Canister**	**Integrity of canister compromised**
Interaction Box 2,7	Effect on Waste	No significant effect
Interaction Box 2,8	Effect on Heat	No significant effect
Interaction Box 2,9	**Effect on Water Flow**	**Water flow parameters altered**

To study the direct binary interactions, we use the basic binary interaction matrix to study the direct effects of the perturbation. The large rock movement perturbation has been introduced in Figure 5.2-8, via the second leading diagonal term of the interaction matrix: Discontinuities.

The interactions shaded in Figure 5.2-8 above are listed in Table 5.2-1 together with interactions with no significant effect. Note that these are the significant binary direct relations following the structure of the interaction matrix developed in Chapter 4.

It is part of the RES methodology to start with any variable order and then reorder the variables according to the interaction intensities and interpretations (e.g. a row and column through a P_i may be empty and then it is better to move that variable to the end of the diagonal). Recalling that we changed the order of the leading diagonal variables in Chapter 4 (from that in Figure 4-4 to that in Figure 4-13) to clarify the mechanism network, we will use the revised order of variables in the diagrams ahead. The reordered variables are as follows:

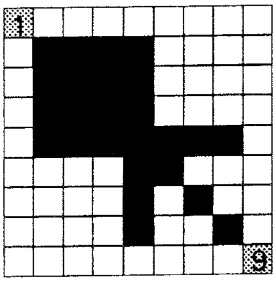
1. Host Rock
2. Discontinuities
3. Rock Stress
4. Construction
5. Water Flow
6. Heat
7. Backfill
8. Canister
9. Waste



a) Perturbation initiated

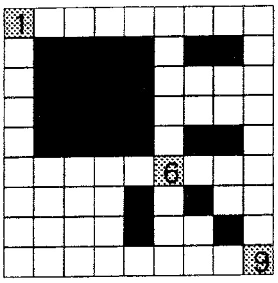
b) Interactions activated

c) Other parameters affected



The significant interactions
were identified in Chapter 4
as those shown to the left.
Thus diagrams c) and d)
are overlain to produce the
activated network in e).

d) Main interactions (last Fig. in Chp. 4)



Increase in Network Connectivity:
Interactions 2,7 and 2,8

Decrease in Network Connectivity:
Variable 6 plus Interactions 5,6 and 6,5

e) Perturbation network

Figure 5.2-9. *Establishing the primary interaction network through which the large rock movement perturbation travels in the development of the scenario.*

The way in which a perturbation to the second leading diagonal term, Discontinuities, propagates through the matrix can be seen in the suite of diagrams in Figure 5.2-9.

In Figure 5.2-9a, the large rock movement is introduced into the second leading diagonal box as a major perturbation to a discontinuity, indicated by the black box. This perturbation then initiates the interactions in the off-diagonal boxes (2,3), (2,4), (2,5), (2,7) and (2,8) which are shown in Figure 5.2-9b. These interactions alter the values of the leading diagonal parameters 3, 4, 5, 7 and 8, as shown in Figure 5.2-9c.

To consider what happens next, it is necessary to recall the last Figure in Chapter 4 which shows the main interaction network, as represented in the iconic form in Figure 5.2-9d. Thus, by combining Figures 5.2-9c and d, we can establish the overall effect of the large rock movement perturbation as its individual effects travel through the relevant interaction network. The process of taking the interactions and associated activated leading diagonal variables in Figure 5.2-9c and the relevant part of the main network in Figure 5.2-9d results in the network shown iconically in Figure 5.2-9e.

Considering the scenario network in Figure 5.2-9e as compared to the main network in Figure 5.2-9d, we note that there has been an increase in significant network connectivity because of the extra interactions 2,7 and 2,8 (the discontinuity now additionally affecting the backfill and the canister) and a decrease in the short-term network connectivity through the loss of parameter 6, Heat, and associated interactions 5,6 and 6,5 (because the large rock movement perturbation does not affect the Heat variable).

We are now in a position to be able to identify the FEPs, key matrix pathways and consequential matrix evolution for the scenario as the result of the large rock movement perturbation, i.e. the evolution of the C_k scenario given that the perturbation was introduced into a known system state represented by system state A_iB_j. The next step is to develop the methodology in Figure 5.2-9 explicitly for the two perturbation cases of a) through the repository and b) adjacent to the repository, and using the 'Expert Semi-Quantitative' method of interaction coding.

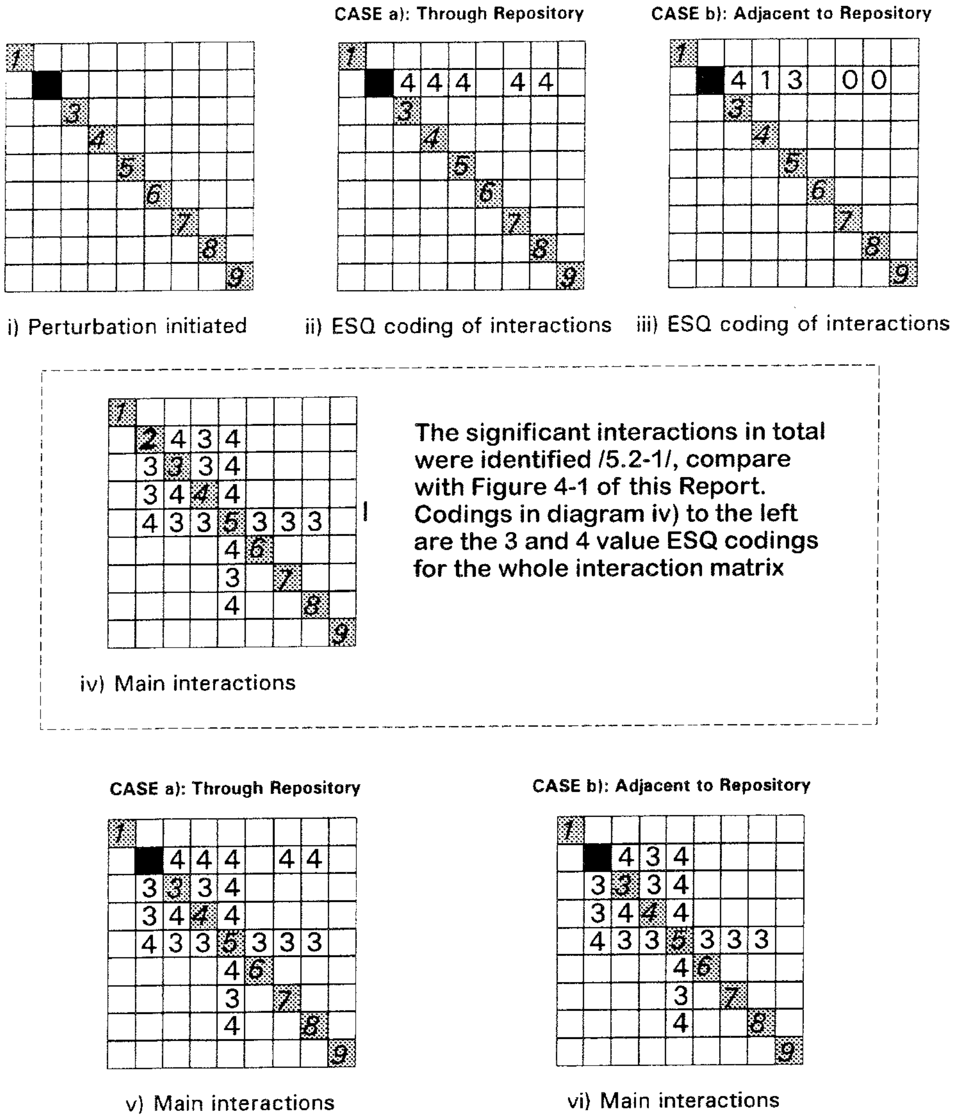
In Figure 5.2-10 we have generated the main interaction matrix scenario network for the large rock movement perturbation with the two cases of a 'through repository' perturbation and an 'adjacent to repository' perturbation. This has been done separately for the two cases by using the 'Expert Semi-Quantitative' (ESQ) method of coding to establish the critical ineractive mechanisms in each case. Recall that the order of leading diagonal variables is still the reordered one.

The perturbation is initiated via Variable 2, Discontinuities, in Figure 5.2-10 i). The activated mechanisms are ESQ-coded in Figures 5.2-10 ii) and iii) for the two perturbation locations. We recall that the ESQ method of coding is as follows:

0 - No interaction
1 - Weak interaction
2 - Medium interaction
3 - Strong Interaction
4 -'Critical' interaction

Note that from a comparison of the two Figures, 5.2-10 ii) and 5.2-10 iii), the mechanisms associated with the through-repository perturbation are much more significant than those for the adjacent-to-repository perturbation. This is because the through-repository perturbation potentially severely compromises the repository structure, the water flow, the backfill and the canister.

In Figure 5.2-10 iv), the most significant interactions are listed for the complete interaction matrix. An empty matrix box in Figure 5.2-10 iv) means that the coding is below a value of 3. Next, we compare the coding of the mechanisms initiated by the perturbation (for the through-repository and adjacent-to-repository cases in Figures 5.2-10 ii) and iii)) with those for the general matrix shown in Figure 5.2-10 iv) and, by always taking the higher coding value, produce the ESQ-coded matrices in Figures 5.2-10 v) and 5.2-10 vi). It should be noted that this has had an effect in the



The significant interactions in total were identified /5.2-1/, compare with Figure 4-1 of this Report. Codings in diagram iv) to the left are the 3 and 4 value ESQ codings for the whole interaction matrix

Figure 5.2-10. *Development of modified 'Expert Semi-Quantitative' coding of main interaction matrix network in the context of a large rock movement perturbation scenario for the cases a) through the repository and b) adjacent to the repository (cf Figures 5.2-4, 5 and 9).*

'through-repository' case (Figure 5.2-10 v) versus Figure 5.2-10 iv)) but no effect in the 'adjacent-to-repository' case (Figure 5.2-10 vi) versus Figure 5.2-10 iv)).

We can now identify the dominant network paths by following the boxes coded as 4 in each case, with the perturbation initiation in leading diagonal Box 2. Pathways forming loops are emboldened.

The pathways have been listed as for example 24, then 243, then 2435, i.e. separately, in order to clarify pathway bifurcations, e.g. 24, then 243, then 2435. However, it happens in this pathway example that there are few bifurcations.

Thus, we have identified the five dominant effects of the 'through-repository' large rock perturbation, these being the loop pathways (emboldened) in Table 5.2-2 below and as reproduced in Table 5.2-3 below.

Table 5.2-2. *Dominant Pathways for Case a): 'Through-Repository'Large Rock Movement Perturbation*

Pathway	*1st Parameter Affected*	*2nd Parameter Affected*	*3rd Parameter Affected*	*4th Parameter Affected*
Pathway 23	Rock Stress			
Pathway 235	Rock Stress	Water Flow		
Pathway 2352	**Rock Stress**	**Water Flow**	**Discontinuities**	
Pathway 24	Repository			
Pathway 243	Repository	Rock Stress		
Pathway 2435	Repository	Rock Stress	Water Flow	
Pathway 24352	**Repository**	**Rock Stress**	**Water Flow**	**Discontinuities**
Pathway 245	Repository	Water Flow		
Pathway 2452	**Repository**	**Water Flow**	**Discontinuities**	
Pathway 25	Water Flow			
Pathway 252	**Water Flow**	**Discontinuities**		
Pathway 27	Backfill			
Pathway 28	Canister			
Pathway 285	Canister	Water Flow		
Pathway 2852	**Canister**	**Water Flow**	**Discontinuities**	

Table 5.2-3. *The Five Loop Pathways for Case a): 'Through-Repository' Large Rock Movement Perturbation*

Pathway 2352	**Rock Stress**	**Water Flow**	**Discontinuities**	
Pathway 24352	**Repository**	**Rock Stress**	**Water Flow**	**Discontinuities**
Pathway 2452	**Repository**	**Water Flow**	**Discontinuities**	
Pathway 252	**Water Flow**	**Discontinuities**		
Pathway 2852	**Canister**	**Water Flow**	**Discontinuities**	

The large rock movement perturbation affects the rock stress conditions leading to enhanced water flow leading to further opening of discontinuities. Damage to the repository alters the rock stress, changing the water flow and opening the discontinuities. Concurrently, the perturbation damaging the repository structure, leads directly to enhanced water flow and then further opening of discontinuities. More directly, the water flow is affected by the perturbation which directly affects the discontinuities. Moreover, the canister is breached, again affecting local water flow and subsequent damage to discontinuities.

The diagrams in Figure 5.2-11 illustrate the physical reality of the first of the pathway mechanisms in Table 5.2-3: Pathway 2352.

The next sequence of diagrams, Figures 5.2-12–15, illustrates the matrix pathways, FEPs and physical representation for the other four loops in Table 5.2-3.

Thus, the pathways in Table 5.2-2, and especially the loops listed in Table 5.2-3 and illustrated in Figures 5.2-12–15, are the main pathways in the development of the associated Scenario C_k.

We have been able to isolate the main network pathways rapidly through the coding process. It should be remembered, however, that all the secondary pathways associated with the 3 values in Figure 5.2-10 v will also be simultaneously operating, not to mention all the tertiary pathways associ-

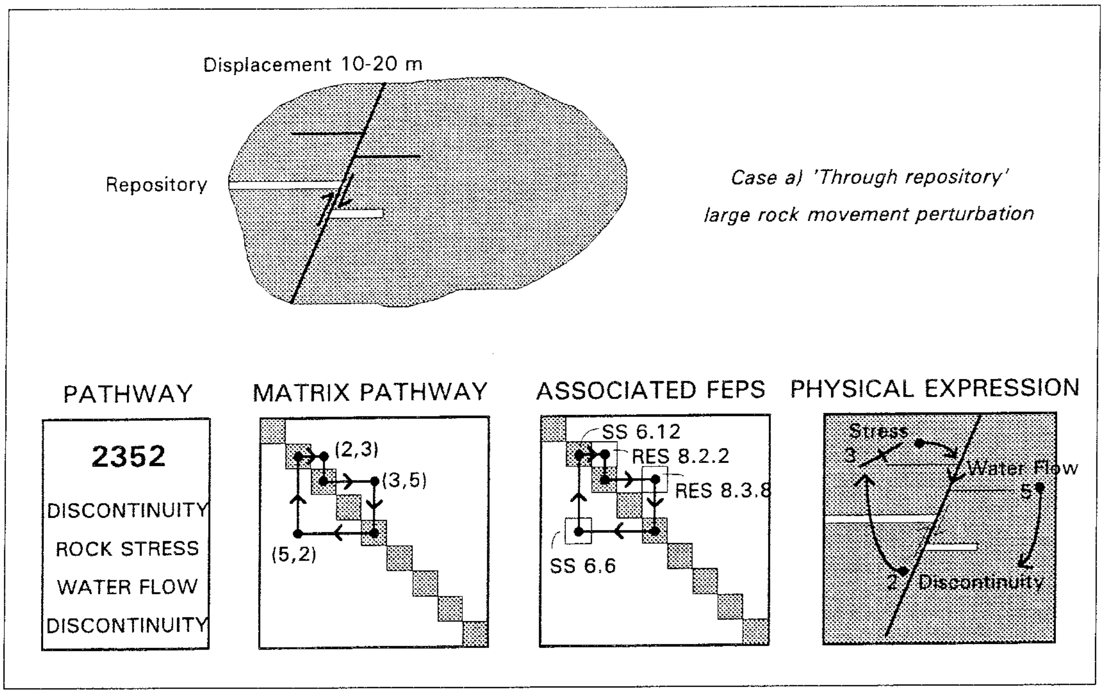


Figure 5.2-11. Illustration of one dominant mechanism loop pathway identified: Pathway 2352 (the SS numbers refer to the SKI/SKB FEPs; the RES numbers refer to the RES FEPs).

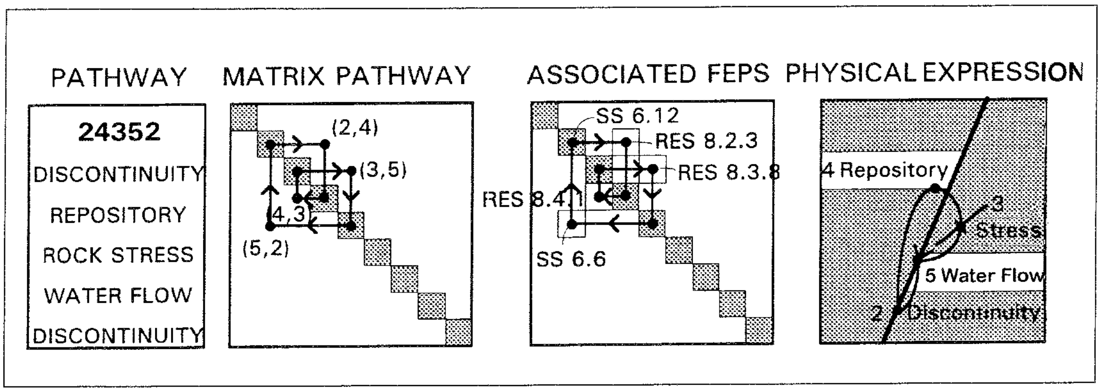


Figure 5.2-12. Mechanism loop pathway 24352.

ated with boxes coded as 1 and 2. To establish the complete evolution of the matrix taking into account all the interactions, it is necessary to use the fully-coupled model. What we have done here is to isolate the primary mechanism pathways governing the complete matrix behaviour. Let us now compare the 'through-repository' perturbation with the 'adjacent-to-repository' perturbation for the large rock movement scenario, see Table 5.2-4.

In this case, we have the two loops where the perturbation affects the stress field which affects the water flow which opens the discontinuities further, and the perturbation has a direct effect on the water flow which adversely affects the discontinuities. Even so, the effects will not be as severe as for the 'through-repository' case. The two loop pathways are illustrated in Figures 5.2-16 and 17.

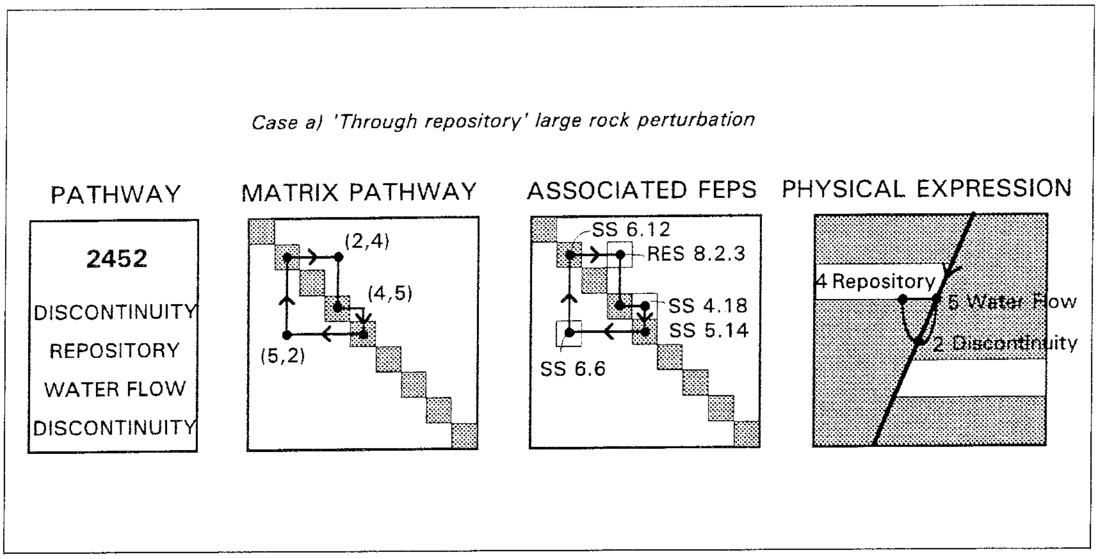


Figure 5.2-13. Mechanism loop pathway 2452.

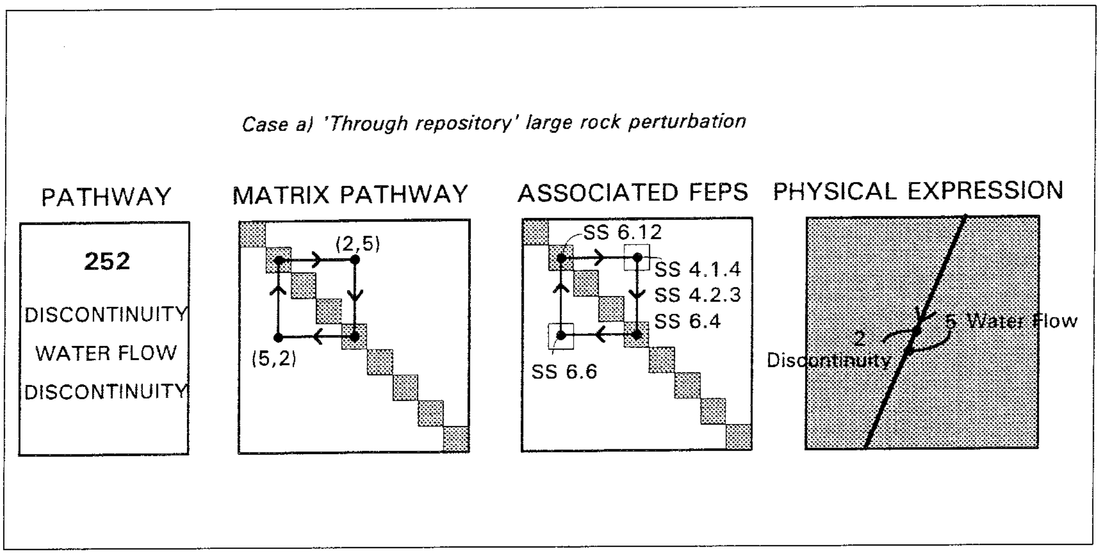


Figure 5.2-14. Mechanism loop pathway 252.

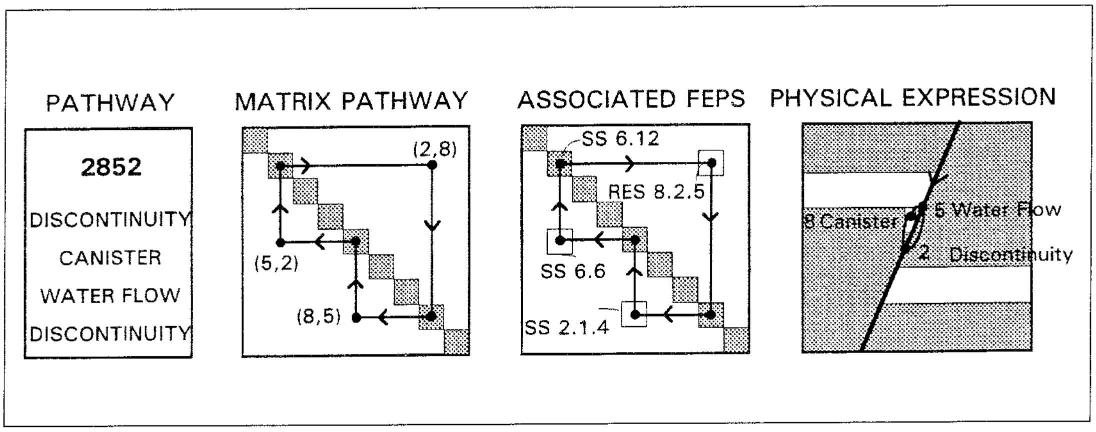


Figure 5.2-15. Mechanism loop pathway 2852.

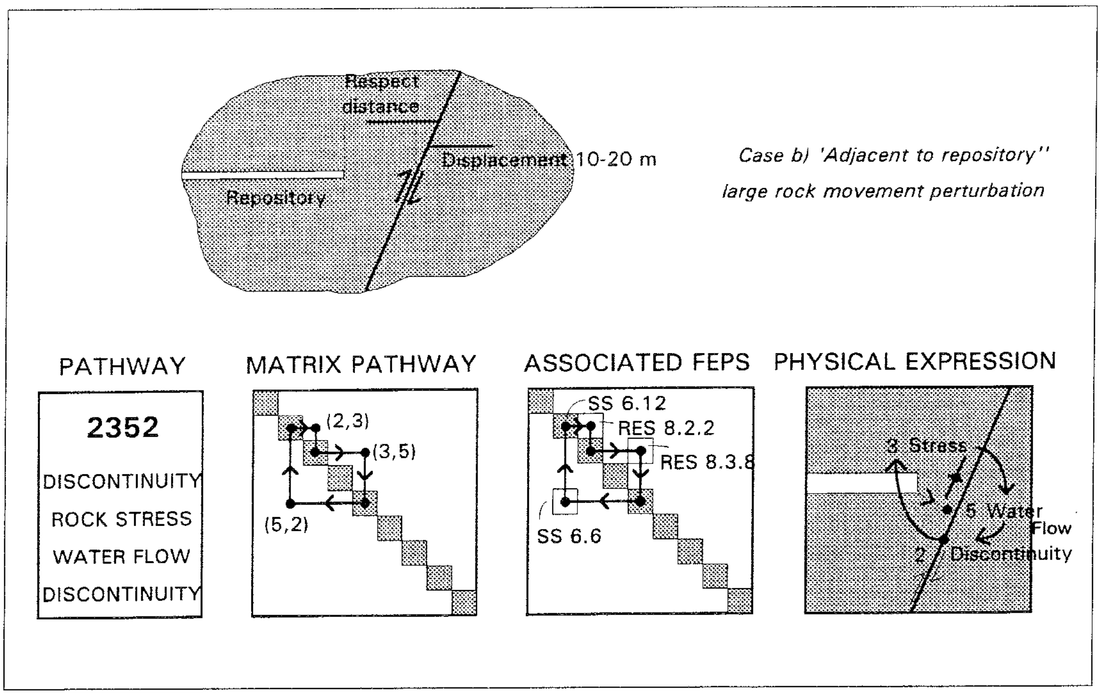


Figure 5.2-16. *Mechanism loop pathway 2352.*

Table 5.2-4. *Dominant Pathways for 'Adjacent-to-Repository' Large Rock Movement Perturbation*

Pathway	*1st Parameter Affected*	*2nd Parameter Affected*	*3rd Parameter Affected*	*4th Parameter Affected*
Pathway 23	Rock Stress			
Pathway 235	Rock Stress	Water Flow		
Pathway 2352	**Rock Stress**	**Water Flow**	**Discontinuities**	
Pathway 25	Water Flow			
Pathway 252	**Water Flow**	**Discontinuities**		

It is very instructive to note the similarities and differences between Figures 5.2-12 and 5.2-16 (for Pathway 2352 in both 'through repository' and 'adjacent to repository' cases) and Figures 5.2-14 and 5.2-17 (for the same two cases). For Pathway 2352, the overall mechanism is physically different: in the 'through repository' case, increased water flow in the perturbed discontinuity will be the dominant effect; in the 'adjacent to repository' case, the water flow between the repository and the perturbed discontinuity will be the dominant effect. In the 'adjacent to repository' case, the main effect is that the stress redistribution could enhance the permeability between the repository and the discontinuity, thus increasing potential water flow between the two.

As we expect from the character of the 'through-repository' perturbation and the 'adjacent-to-repository' pertubation, the 'through-repository' perturbation is more severe, activating more mechanism pathways. Although we have only studied the pathways linking the ESQ-coded critical mecha-

Case b) 'Adjacent to repository' large rock perturbation

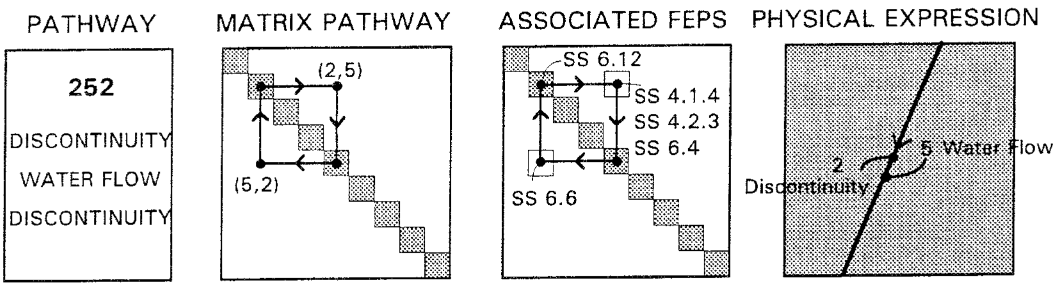


Figure 5.2-17. Mechanism loop pathway 252.

nisms, it is likely that the same result would be obtained for the total effect – because of the higher number of critical interactions in the 'through-repository' perturbated matrix.

5.3 RES - PROCESS SYSTEM APPROACH

The total repository system can be divided into several subsystems which are analysed in the safety assessment. In many international programmes, the total repository system is divided into the near-field, the far-field and the biosphere. During 1994, SKB has made some first attempts to apply the "soft" part of the RES-methodology to each of these subsystems as shown in Figure 5.3-1.

As can be seen in this figure, the near-field component has been analyzed in even greater detail by creating a RES matrix also for the buffer/backfill part. A special analysis of interactions between diagonal elements (variables) in different system parts should be performed to ensure the best possible completeness. However, in most cases the interactions are sparse and the boxes will therefore be empty.

Several working groups have been established to perform the compilation of the subsystem matrices. For the biosphere part, the IAEA BIOMOVS Project in cooperation with SKB, formed a special working group to create the RES-matrix.

The work has been focussed on creating the matrices with documentation of the discussions for each interaction box. The next step has been to check with existing FEPs-lists for the system component being assessed to identify possible gaps in the analysis. The most important interactions and pathways through the subsystem have then been identified and judged on a semi-quantitative scale.

The result of the above mentioned work can be seen in Figure 5.3-2 regarding the near-field, Figure 5.3-3 for the buffer/backfill, Figure 5.3-4 for the far-field and Figure 5.3-5 for the biosphere. The Figures are presented without any detailed explanations as some first examples of the

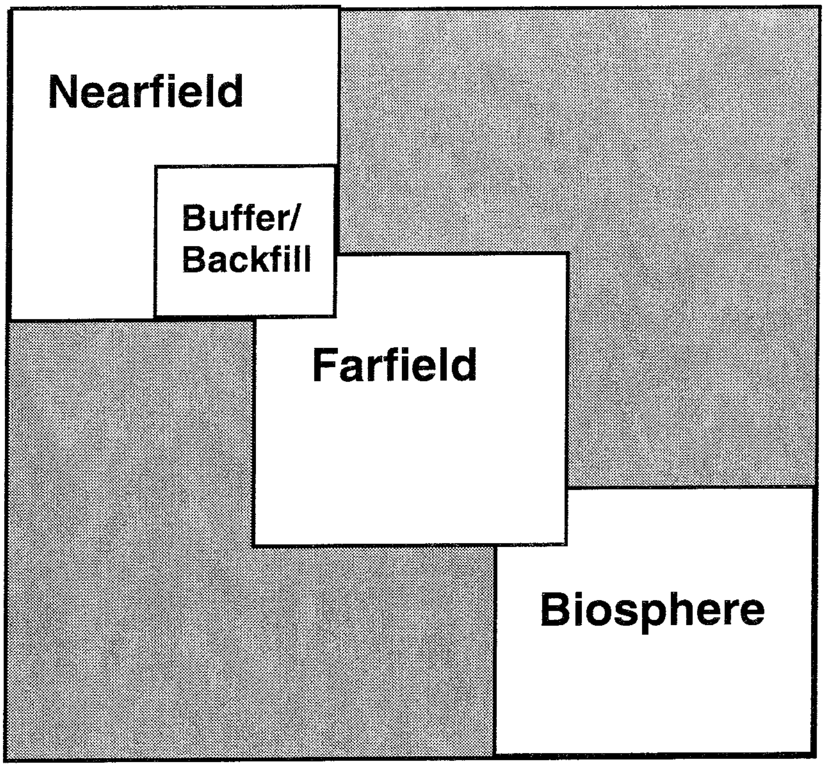


Figure 5.3-1. The RES-matrices applied for visualizing the total repository system.

type of work now underway at SKB. This work will be reported in more detail in the SKB report series.

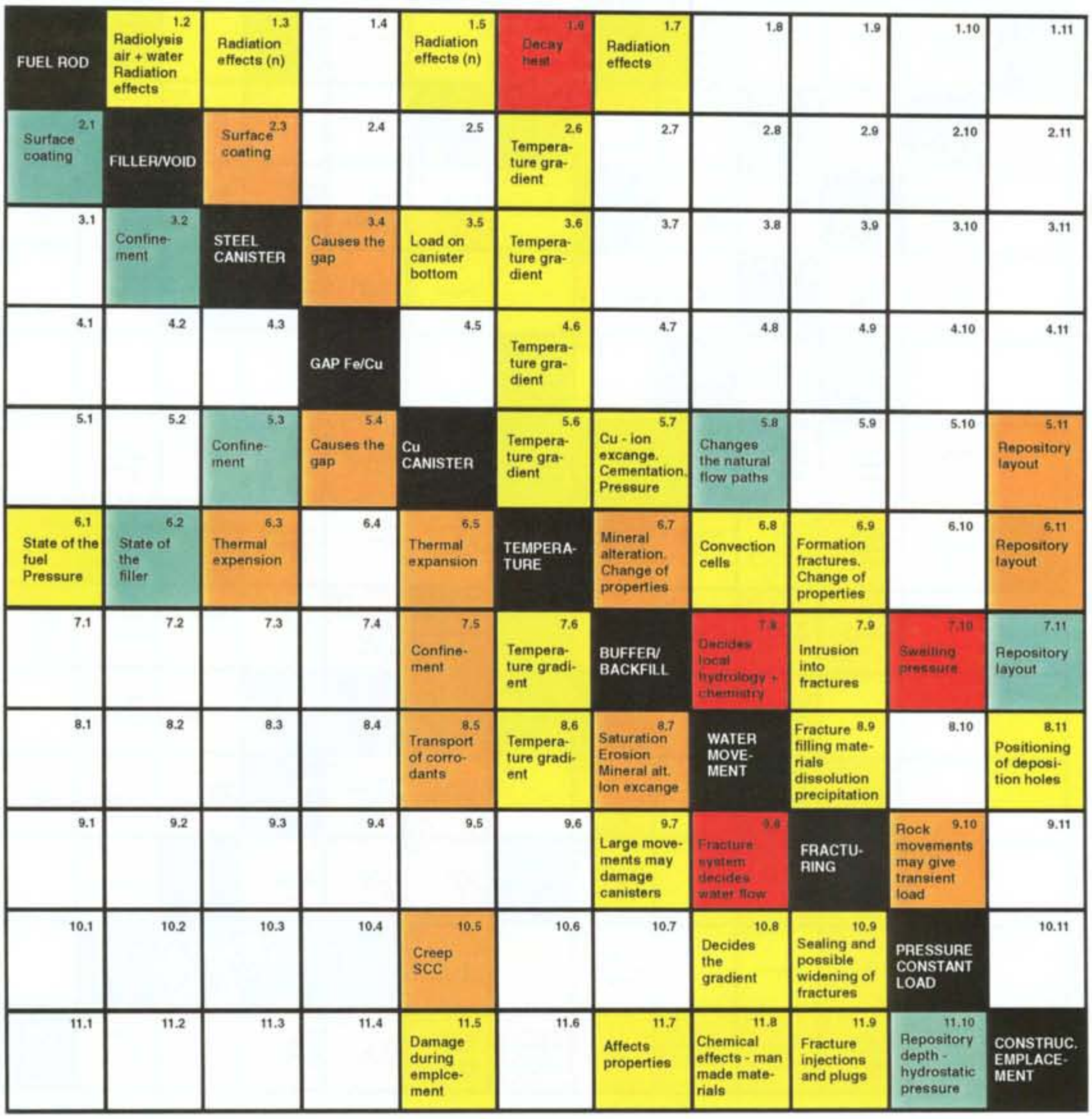
The work undertaken so far is a test to explore the feasibility of the RES methodology. All the above mentioned working groups have so far expressed their satisfaction with the methodology. When systematically going through the matrix, an overview of the system and the linking betweeen processes are visualized and the conceptualization of the system and its behaviour at the same time is discussed and documented. The weakness is that, to date, no strategy has been established on how to document the different steps in the procedure. Each group has its own way of presenting the result. To ensure that the work in different working groups will have the same quality and that the review of the work can be achieved in a practical and comparable way, such a documentation strategy will be needed.

🟥 Interaction which should be part of the model chain

🟧 Important interaction - can give effects on other parameters, should be well documented

🟨 Interaction present - influences on other parts of the process system in a limited way and under special curcumstances

🟩 Interaction present - influences on other parts of the process system can be neglected



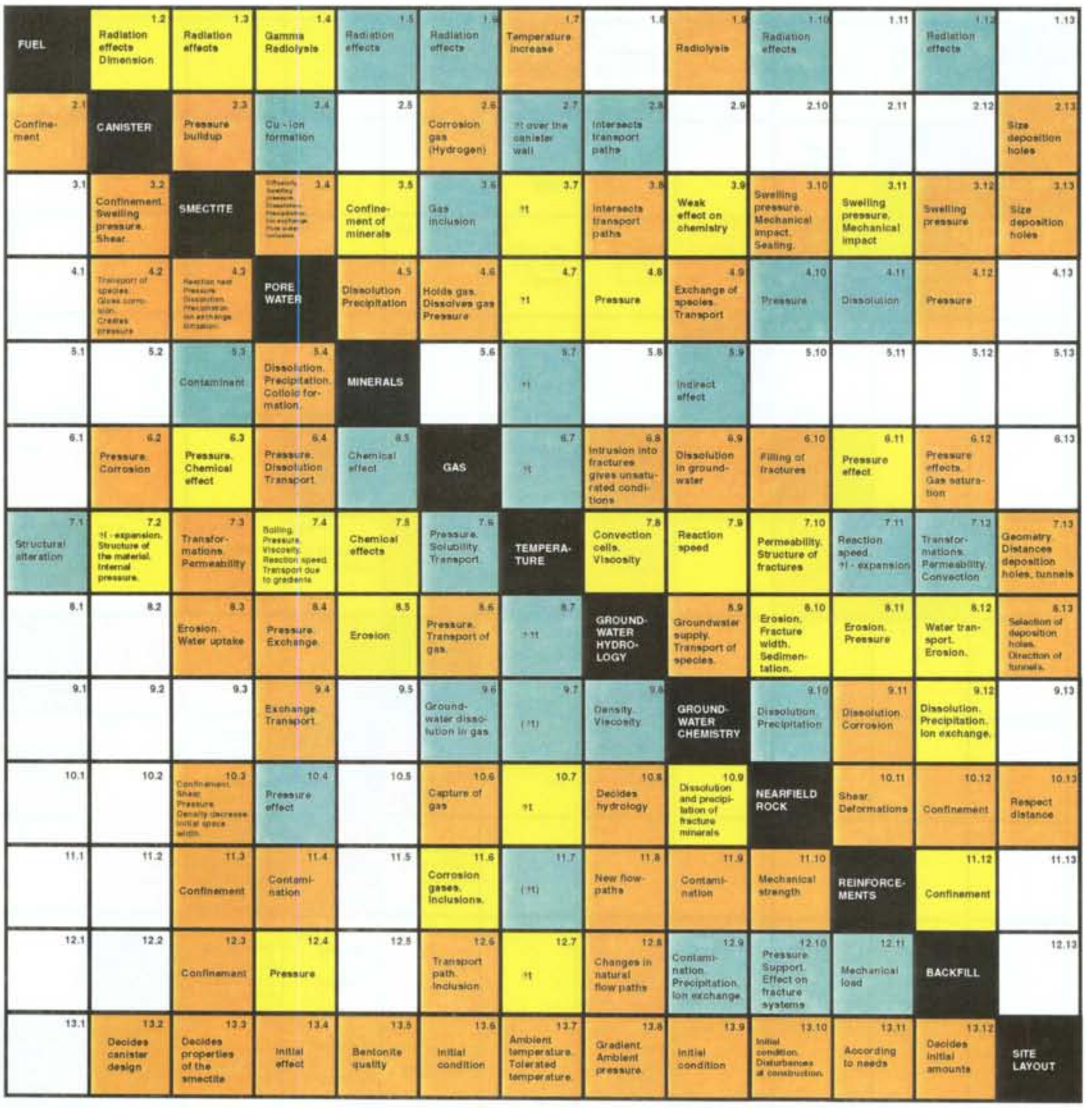
FUEL ROD	🟨 1.2 Radiolysis air + water Radiation effects	🟨 1.3 Radiation effects (n)	1.4	🟨 1.5 Radiation effects (n)	🟥 1.6 Decay heat	🟨 1.7 Radiation effects	1.8	1.9	1.10	1.11
🟩 2.1 Surface coating	**FILLER/VOID**	🟧 2.3 Surface coating	2.4	2.5	🟨 2.6 Temperature gradient	2.7	2.8	2.9	2.10	2.11
3.1	🟩 3.2 Confinement	**STEEL CANISTER**	🟧 3.4 Causes the gap	🟨 3.5 Load on canister bottom	🟨 3.6 Temperature gradient	3.7	3.8	3.9	3.10	3.11
4.1	4.2	4.3	**GAP Fe/Cu**	4.5	🟨 4.6 Temperature gradient	4.7	4.8	4.9	4.10	4.11
5.1	5.2	🟩 5.3 Confinement	🟧 5.4 Causes the gap	**Cu CANISTER**	🟨 5.6 Temperature gradient	🟨 5.7 Cu - ion excange. Cementation. Pressure	🟩 5.8 Changes the natural flow paths	5.9	5.10	🟧 5.11 Repository layout
🟨 6.1 State of the fuel Pressure	🟩 6.2 State of the filler	🟧 6.3 Thermal expension	6.4	🟧 6.5 Thermal expansion	**TEMPERATURE**	🟧 6.7 Mineral alteration. Change of properties	🟨 6.8 Convection cells	🟨 6.9 Formation fractures. Change of properties	6.10	🟧 6.11 Repository layout
7.1	7.2	7.3	7.4	🟧 7.5 Confinement	🟨 7.6 Temperature gradient	**BUFFER/ BACKFILL**	🟥 7.8 Decides local hydrology + chemistry	🟨 7.9 Intrusion into fractures	🟥 7.10 Swelling pressure	🟩 7.11 Repository layout
8.1	8.2	8.3	8.4	🟧 8.5 Transport of corrodants	🟨 8.6 Temperature gradient	🟧 8.7 Saturation Erosion Mineral alt. Ion excange	**WATER MOVEMENT**	🟨 8.9 Fracture filling materials dissolution precipitation	8.10	🟨 8.11 Positioning of deposition holes
9.1	9.2	9.3	9.4	9.5	9.6	🟨 9.7 Large movements may damage canisters	🟥 9.8 Fracture system decides water flow	**FRACTURING**	🟧 9.10 Rock movements may give transient load	9.11
10.1	10.2	10.3	10.4	🟧 10.5 Creep SCC	10.6	10.7	🟨 10.8 Decides the gradient	🟨 10.9 Sealing and possible widening of fractures	**PRESSURE CONSTANT LOAD**	10.11
11.1	11.2	11.3	11.4	🟨 11.5 Damage during emplcement	11.6	🟨 11.7 Affects properties	🟨 11.8 Chemical effects - man made materials	🟨 11.9 Fracture injections and plugs	🟩 11.10 Repository depth - hydrostatic pressure	**CONSTRUC. EMPLACEMENT**

Figure 5.3-2. *A first attempt regarding the RES-matrix for the near-field (intact copper canister). The work has been reported in SKB Technical Report 94-14 /5.3-1/.*

🟧 Important interaction - can give effects on other parameters, should be well documented

🟨 Interaction present - influences on other parts of the process system in a limited way and under special circumstances

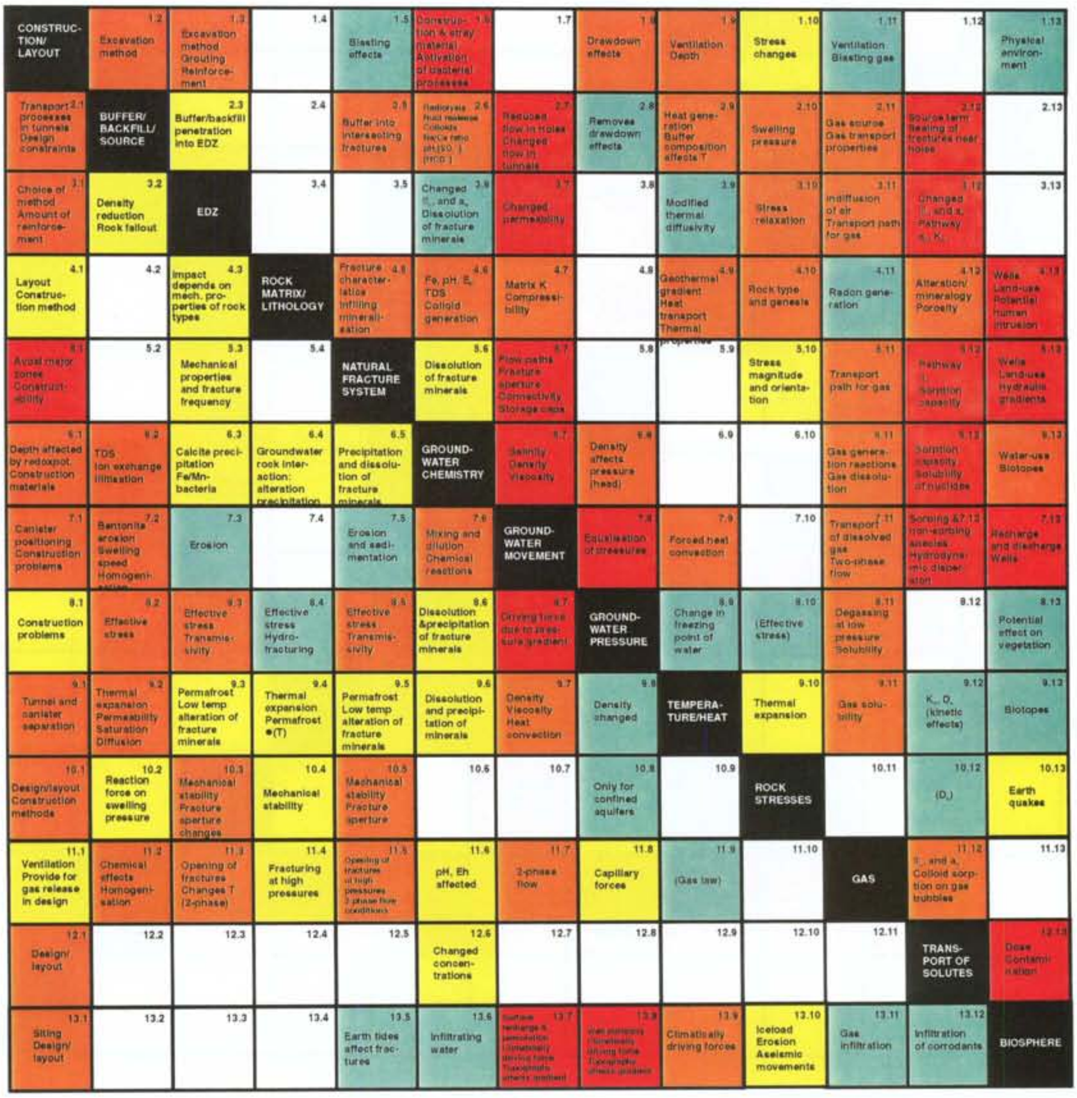
🟦 Interaction present - influences on other parts of the process system can be neglected



FUEL	🟨 1.2 Radiation effects Dimension	🟨 1.3 Radiation effects	🟨 1.4 Gamma Radiolysis	🟦 1.5 Radiation effects	🟦 1.6 Radiation effects	🟧 1.7 Temperature increase	1.8	🟧 1.9 Radiolysis	🟦 1.10 Radiation effects	1.11	🟦 1.12 Radiation effects	1.13
🟧 2.1 Confinement	**CANISTER**	🟧 2.3 Pressure buildup	🟦 2.4 Cu - ion formation	2.5	🟧 2.6 Corrosion gas (Hydrogen)	🟦 2.7 ?t over the canister wall	🟦 2.8 Intersects transport paths	2.9	2.10	2.11	2.12	🟧 2.13 Size deposition holes
3.1	🟧 3.2 Confinement. Swelling pressure. Shear.	**SMECTITE**	🟧 3.4 Diffusivity. Swelling pressure. Dissolution. Precipitation. Ion exchange. Pore water inclusions	🟨 3.5 Confinement of minerals	🟦 3.6 Gas inclusion	🟨 3.7 ?t	🟧 3.8 Intersects transport paths	🟨 3.9 Weak effect on chemistry	🟧 3.10 Swelling pressure. Mechanical impact. Sealing.	🟨 3.11 Swelling pressure. Mechanical impact	🟧 3.12 Swelling pressure	🟧 3.13 Size deposition holes
4.1	🟧 4.2 Transport of species. Gives corrosion. Creates pressure	🟧 4.3 Reaction heat. Pressure. Dissolution. Precipitation. Ion exchange. Diffusion.	**PORE WATER**	🟧 4.5 Dissolution Precipitation	🟧 4.6 Holds gas. Dissolves gas Pressure	🟨 4.7 ?t	🟨 4.8 Pressure	🟧 4.9 Exchange of species. Transport	🟦 4.10 Pressure	🟦 4.11 Dissolution	🟧 4.12 Pressure	4.13
5.1	5.2	🟦 5.3 Contaminant	🟧 5.4 Dissolution. Precipitation. Colloid formation.	**MINERALS**	5.6	🟦 5.7 ?t	5.8	🟦 5.9 Indirect effect	5.10	5.11	5.12	5.13
6.1	🟧 6.2 Pressure. Corrosion	🟨 6.3 Pressure. Chemical effect	🟧 6.4 Pressure. Dissolution Transport.	🟦 6.5 Chemical effect	**GAS**	🟦 6.7 ?t	🟧 6.8 Intrusion into fractures gives unsaturated conditions	🟧 6.9 Dissolution in groundwater	🟧 6.10 Filling of fractures	🟨 6.11 Pressure effect	🟧 6.12 Pressure effects. Gas saturation	6.13
🟦 7.1 Structural alteration	🟨 7.2 ?t - expansion. Structure of the material. Internal pressure.	🟧 7.3 Transformations Permeability	🟨 7.4 Boiling. Pressure. Viscosity. Reaction speed. Transport due to gradients	🟨 7.5 Chemical effects	🟦 7.6 Pressure. Solubility Transport	**TEMPERATURE**	🟨 7.8 Convection cells. Viscosity	🟨 7.9 Reaction speed	🟨 7.10 Permeability. Structure of fractures	🟦 7.11 Reaction speed ?t - expansion	🟦 7.12 Transformations. Permeability. Convection	🟧 7.13 Geometry. Distances deposition holes, tunnels
8.1	8.2	🟧 8.3 Erosion. Water uptake	🟧 8.4 Pressure. Exchange.	🟨 8.5 Erosion	🟧 8.6 Pressure. Transport of gas.	🟦 8.7 ??t	**GROUNDWATER HYDROLOGY**	🟧 8.9 Groundwater supply. Transport of species.	🟨 8.10 Erosion. Fracture width. Sedimentation.	🟨 8.11 Erosion. Pressure	🟨 8.12 Water transport. Erosion.	🟧 8.13 Selection of deposition holes. Direction of tunnels.
9.1	9.2	9.3	🟧 9.4 Exchange. Transport.	9.5	🟦 9.6 Groundwater dissolution in gas	🟦 9.7 (?t)	🟦 9.8 Density. Viscosity	**GROUNDWATER CHEMISTRY**	🟦 9.10 Dissolution Precipitation	🟧 9.11 Dissolution. Corrosion	🟨 9.12 Dissolution. Precipitation. Ion exchange.	9.13
10.1	10.2	🟧 10.3 Confinement. Shear. Pressure. Density decrease. Initial space width.	🟦 10.4 Pressure effect	10.5	🟧 10.6 Capture of gas	🟨 10.7 ?t	🟧 10.8 Decides hydrology	🟨 10.9 Dissolution and precipitation of fracture minerals	**NEARFIELD ROCK**	🟧 10.11 Shear Deformations	🟧 10.12 Confinement	🟧 10.13 Respect distance
11.1	11.2	🟧 11.3 Confinement	🟧 11.4 Contamination	11.5	🟨 11.6 Corrosion gases. Inclusions.	🟦 11.7 (?t)	🟧 11.8 New flowpaths	🟧 11.9 Contamination	🟧 11.10 Mechanical strength	**REINFORCEMENTS**	🟨 11.12 Confinement	11.13
12.1	12.2	🟧 12.3 Confinement	🟨 12.4 Pressure	12.5	🟧 12.6 Transport path. Inclusion	🟨 12.7 ?t	🟧 12.8 Changes in natural flow paths	🟦 12.9 Contamination. Precipitation. Ion exchange.	🟦 12.10 Pressure. Support. Effect on fracture systems	🟦 12.11 Mechanical load	**BACKFILL**	12.13
13.1	🟧 13.2 Decides canister design	🟧 13.3 Decides properties of the smectite	🟧 13.4 Initial effect	🟧 13.5 Bentonite quality	🟧 13.6 Initial condition	🟧 13.7 Ambient temperature. Tolerated temperature.	🟧 13.8 Gradient. Ambient pressure.	🟧 13.9 Initial condition	🟧 13.10 Initial condition. Disturbances at construction.	🟧 13.11 According to needs	🟧 13.12 Decides initial amounts	**SITE LAYOUT**

Figure 5.3-3. *A first attempt regarding the RES-matrix for the buffer/backfill. Please note that the colour marking is slightly different from the other RES-matrices since the buffer/backfill is a sub-system and does not have a model-chain of the same order. The orange boxes hence represent both red and orange boxes in other RES-matrices.*

- 🟥 Interaction which should be part of the model chain, i e assessment modelling of radionuclide transport
- 🟧 Important interaction - can give effects on other parameters, should be well documented
- 🟨 Interaction present - influences on other parts of the process system in a limited way and/or under special circumstances
- 🟦 Interaction present - influences on other parts of the process system can be neglected



CONSTRUCTION/ LAYOUT	1.2 🟧 Excavation method	1.3 🟧 Excavation method Grouting Reinforcement	1.4	1.5 🟦 Blasting effects	1.6 🟥 Construction & stray material Activation of bacterial processes	1.7	1.8 🟧 Drawdown effects	1.9 🟧 Ventilation Depth	1.10 🟨 Stress changes	1.11 🟦 Ventilation Blasting gas	1.12	1.13 🟦 Physical environment
2.1 🟧 Transport processes in tunnels Design constraints	**BUFFER/ BACKFILL/ SOURCE**	2.3 🟨 Buffer/backfill penetration into EDZ	2.4	2.5 🟧 Buffer into intersecting fractures	2.6 🟧 Radiolysis Fluid release Colloids Na/Ca ratio pH [SO [illegible]] [HCO [illegible]]	2.7 🟥 Reduced flow in holes Changed flow in tunnels	2.8 🟦 Removes drawdown effects	2.9 🟧 Heat generation Buffer composition affects T	2.10 🟧 Swelling pressure	2.11 🟧 Gas source Gas transport properties	2.12 🟥 Source term Sealing of fractures near holes	2.13
3.1 🟧 Choice of method Amount of reinforcement	3.2 🟨 Density reduction Rock fallout	**EDZ**	3.4	3.5	3.6 🟦 Changed K_d and a_w Dissolution of fracture minerals	3.7 🟥 Changed permeability	3.8	3.9 🟦 Modified thermal diffusivity	3.10 🟧 Stress relaxation	3.11 🟧 Indiffusion of air Transport path for gas	3.12 🟥 Changed K_d and a_w Pathway a_w, K	3.13
4.1 🟨 Layout Construction method	4.2	4.3 🟨 Impact depends on mech. properties of rock types	**ROCK MATRIX/ LITHOLOGY**	4.5 🟧 Fracture characteristics infilling mineralisation	4.6 🟧 Fe, pH, E_h TDS Colloid generation	4.7 🟧 Matrix K Compressibility	4.8	4.9 🟧 Geothermal gradient Heat transport Thermal properties	4.10 🟧 Rock type and genesis	4.11 🟦 Radon generation	4.12 🟧 Alteration/ mineralogy Porosity	4.13 🟥 Wells Land-use Potential human intrusion
5.1 🟥 Avoid major zones Constructability	5.2	5.3 🟨 Mechanical properties and fracture frequency	5.4	**NATURAL FRACTURE SYSTEM**	5.6 🟨 Dissolution of fracture minerals	5.7 🟥 Flow paths Fracture aperture Connectivity Storage capacity	5.8	5.9	5.10 🟨 Stress magnitude and orientation	5.11 🟧 Transport path for gas	5.12 🟥 Pathway a_w Sorption capacity	5.13 🟥 Wells Land-use Hydraulic gradients
6.1 🟧 Depth affected by redoxpot. Construction materials	6.2 🟧 TDS Ion exchange Illitisation	6.3 🟨 Calcite precipitation Fe/Mn-bacteria	6.4 🟨 Groundwater rock interaction: alteration precipitation	6.5 🟨 Precipitation and dissolution of fracture minerals	**GROUND-WATER CHEMISTRY**	6.7 🟥 Salinity Density Viscosity	6.8 🟧 Density affects pressure (head)	6.9	6.10	6.11 🟧 Gas generation reactions Gas dissolution	6.12 🟥 Sorption capacity Solubility of nuclides	6.13 🟧 Water-use Biotopes
7.1 🟧 Canister positioning Construction problems	7.2 🟧 Bentonite erosion Swelling speed Homogenisation	7.3 🟦 Erosion	7.4	7.5 🟦 Erosion and sedimentation	7.6 🟧 Mixing and dilution Chemical reactions	**GROUND-WATER MOVEMENT**	7.8 🟥 Equalisation of pressures	7.9 🟧 Forced heat convection	7.10	7.11 🟧 Transport of dissolved gas Two-phase flow	7.12 🟥 Sorbing & non-sorbing species Hydrodynamic dispersion	7.13 🟥 Recharge and discharge Wells
8.1 🟨 Construction problems	8.2 🟧 Effective stress	8.3 🟧 Effective stress Transmissivity	8.4 🟦 Effective stress Hydro-fracturing	8.5 🟧 Effective stress Transmissivity	8.6 🟨 Dissolution &precipitation of fracture minerals	8.7 🟥 Driving force due to pressure gradient	**GROUND-WATER PRESSURE**	8.9 🟦 Change in freezing point of water	8.10 🟦 (Effective stress)	8.11 🟧 Degassing at low pressure Solubility	8.12	8.13 🟦 Potential effect on vegetation
9.1 🟧 Tunnel and canister separation	9.2 🟧 Thermal expansion Permeability Saturation Diffusion	9.3 🟨 Permafrost Low temp alteration of fracture minerals	9.4 🟨 Thermal expansion Permafrost ●(T)	9.5 🟨 Permafrost Low temp alteration of fracture minerals	9.6 🟨 Dissolution and precipitation of minerals	9.7 🟧 Density Viscosity Heat convection	9.8 🟦 Density changed	**TEMPERATURE/HEAT**	9.10 🟨 Thermal expansion	9.11 🟧 Gas solubility	9.12 🟦 K_d, D_e (kinetic effects)	9.13 🟦 Biotopes
10.1 🟧 Design/layout Construction methods	10.2 🟨 Reaction force on swelling pressure	10.3 🟧 Mechanical stability Fracture aperture changes	10.4 🟨 Mechanical stability	10.5 🟧 Mechanical stability Fracture aperture	10.6	10.7	10.8 🟦 Only for confined aquifers	10.9	**ROCK STRESSES**	10.11	10.12 🟦 (D_e)	10.13 🟨 Earth quakes
11.1 🟨 Ventilation Provide for gas release in design	11.2 🟧 Chemical effects Homogenisation	11.3 🟧 Opening of fractures Changes T (2-phase)	11.4 🟨 Fracturing at high pressures	11.5 🟧 Opening of fractures at high pressures 2-phase flow conditions	11.6 🟨 pH, Eh affected	11.7 🟧 2-phase flow	11.8 🟨 Capillary forces	11.9 🟦 (Gas law)	11.10	**GAS**	11.12 🟧 K_d and a_w Colloid sorption on gas bubbles	11.13
12.1 🟧 Design/ layout	12.2	12.3	12.4	12.5	12.6 🟨 Changed concentrations	12.7	12.8	12.9	12.10	12.11	**TRANS-PORT OF SOLUTES**	12.13 🟥 Dose Contamination
13.1 🟧 Siting Design/ layout	13.2	13.3	13.4	13.5 🟦 Earth tides affect fractures	13.6 🟦 Infiltrating water	13.7 🟥 Surface recharge & percolation Climatically driving force Topographic [illegible] gradient	13.8 🟥 [illegible] Climatically driving force Topographic [illegible] gradient	13.9 🟧 Climatically driving forces	13.10 🟨 Iceload Erosion Aseismic movements	13.11 🟦 Gas infiltration	13.12 🟦 Infiltration of corrodants	**BIOSPHERE**

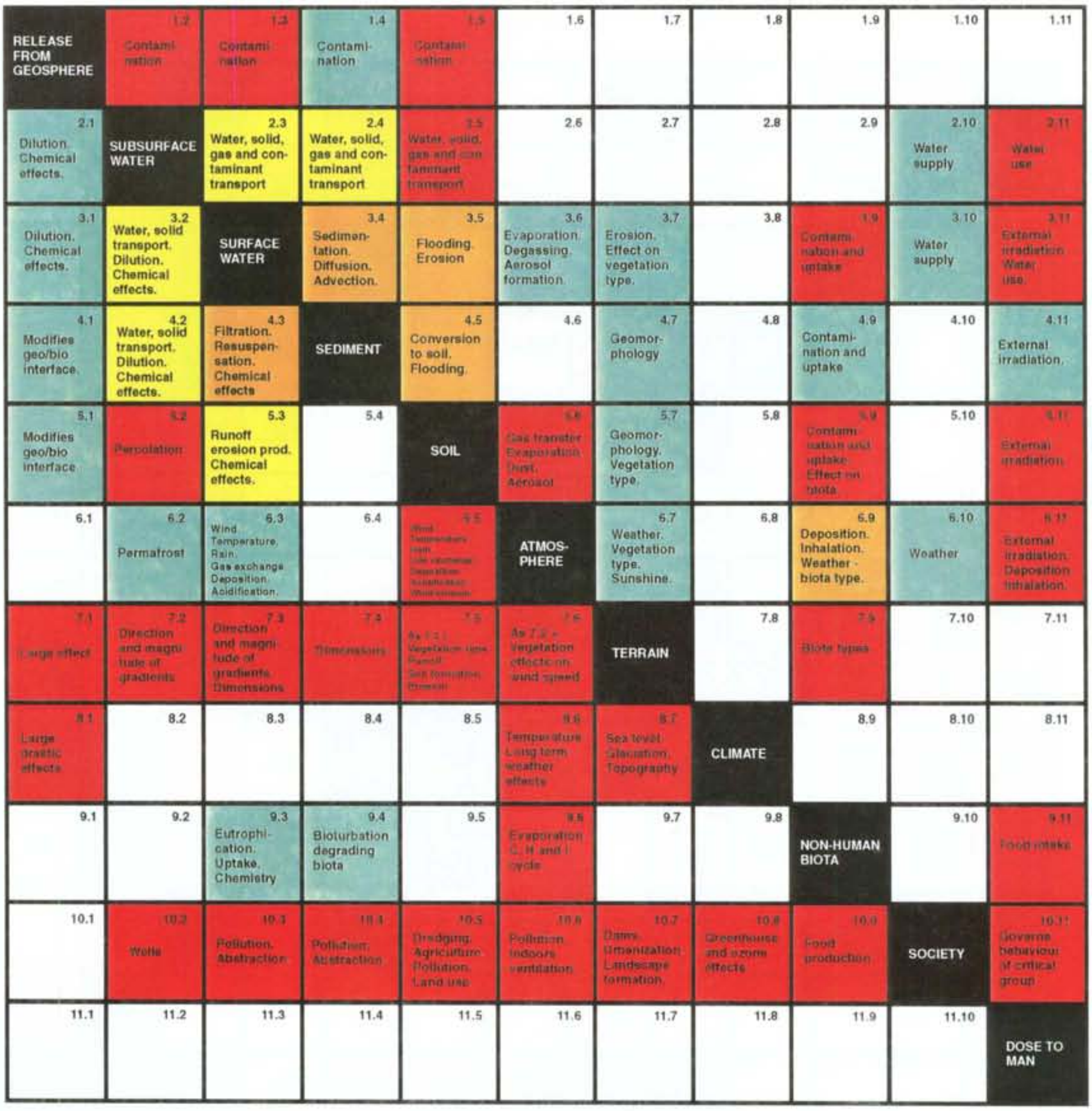
Figure 5.3-4. *A first attempt regarding the RES-matrix for the far-field.*

🟥 Interaction which should be part of the model chain

🟧 Important interaction - can give effects on other parameters, should be well documented

🟨 Interaction present - influences on other parts of the process systemin a limited way and under special curcumstances

🟦 Interaction present - influences on other parts of the process systemcan be neglected



RELEASE FROM GEOSPHERE	🟥 1.2 Contamination	🟥 1.3 Contamination	🟦 1.4 Contamination	🟥 1.5 Contamination	1.6	1.7	1.8	1.9	1.10	1.11
🟦 2.1 Dilution. Chemical effects.	SUBSURFACE WATER	🟨 2.3 Water, solid, gas and contaminant transport	🟨 2.4 Water, solid, gas and contaminant transport	🟥 2.5 Water, solid, gas and contaminant transport	2.6	2.7	2.8	2.9	🟦 2.10 Water supply	🟥 2.11 Water use
🟦 3.1 Dilution. Chemical effects.	🟨 3.2 Water, solid transport. Dilution. Chemical effects.	SURFACE WATER	🟧 3.4 Sedimentation. Diffusion. Advection.	🟧 3.5 Flooding. Erosion	🟦 3.6 Evaporation. Degassing. Aerosol formation.	🟦 3.7 Erosion. Effect on vegetation type.	3.8	🟥 3.9 Contamination and uptake	🟦 3.10 Water supply	🟥 3.11 External irradiation. Water use.
🟦 4.1 Modifies geo/bio interface.	🟨 4.2 Water, solid transport. Dilution. Chemical effects.	🟧 4.3 Filtration. Resuspensation. Chemical effects	SEDIMENT	🟧 4.5 Conversion to soil. Flooding.	4.6	🟦 4.7 Geomorphology	4.8	🟦 4.9 Contamination and uptake	4.10	🟦 4.11 External irradiation.
🟦 5.1 Modifies geo/bio interface	🟥 5.2 Percolation	🟨 5.3 Runoff erosion prod. Chemical effects.	5.4	SOIL	🟥 5.6 Gas transfer. Evaporation. Dust. Aerosol	🟦 5.7 Geomorphology. Vegetation type.	5.8	🟥 5.9 Contamination and uptake. Effect on biota	5.10	🟥 5.11 External irradiation.
6.1	🟦 6.2 Permafrost	🟦 6.3 Wind. Temperature. Rain. Gas exchange. Deposition. Acidification.	5.4	🟥 6.5 Wind. Temperature. Rain. [illegible] Deposition. Acidification. Wind erosion.	ATMOSPHERE	🟦 6.7 Weather. Vegetation type. Sunshine.	6.8	🟧 6.9 Deposition. Inhalation. Weather - biota type.	🟦 6.10 Weather	🟥 6.11 External irradiation. Deposition. Inhalation.
🟥 7.1 Large effect	🟥 7.2 Direction and magnitude of gradients	🟥 7.3 Direction and magnitude of gradients. Dimensions	🟥 7.4 Dimensions	🟥 7.5 As 7.2. Vegetation type. Rainfall. Soil formation. Erosion.	🟥 7.6 As 7.2 + Vegetation effects on wind speed	TERRAIN	7.8	🟥 7.9 Biota types	7.10	7.11
🟥 8.1 Large drastic effects	8.2	8.3	8.4	8.5	🟥 8.6 Temperature. Long term weather effects	🟥 8.7 Sea level. Glaciation. Topography	CLIMATE	8.9	8.10	8.11
9.1	9.2	🟦 9.3 Eutrophication. Uptake. Chemistry	🟦 9.4 Bioturbation degrading biota	9.5	🟥 9.6 Evaporation. C, H and I cycle	9.7	9.8	NON-HUMAN BIOTA	9.10	🟥 9.11 Food intake
10.1	🟥 10.2 Wells	🟥 10.3 Pollution. Abstraction	🟥 10.4 Pollution. Abstraction	🟥 10.5 Dredging. Agriculture. Pollution. Land use	🟥 10.6 Pollution indoors ventilation	🟥 10.7 Dams. Urbanization. Landscape formation.	🟥 10.8 Greenhouse and ozone effects	🟥 10.9 Food production	SOCIETY	🟥 10.11 Governs behaviour of critical group
11.1	11.2	11.3	11.4	11.5	11.6	11.7	11.8	11.9	11.10	DOSE TO MAN

Figure 5.3-5. A first attempt regarding the RES-matrix for the biosphere. This work was conducted as a co-operative study between the BIOMOVS group and the SKB and the work has been presented in SKB Arbetsrapport 94-51 /5.3-2/.

6 COMPARISON BETWEEN THE DIFFERENT APPROACHES

6.1 GENERAL

In this report, different scenario methodologies tested by SKB are described. In this Chapter, the methodology based on Influence Diagrams with coupled documentation, see Chapter 3, is compared with the RES methodology, see Chapter 4. It should be pointed out that this is not a complete comparison, but just a first attempt to identify similarities and differences between the methods.

The Influence Diagram method and the RES method have the same primary aim, namely, to describe the behaviour of a defined system for different scenario initiating FEPs. In both methods, this is achieved by using graphics to structure the system, thereby showing how different FEPs acting within the system will affect the release of radionuclides from the system for a certain scenario initiating FEP. In addition, both methods use "expert judgements" with semi-quantitative coding to assess the relative importance of interactions in the system studied. Thus, it is possible to reduce the complexity of the system and in the scenario analysis focus on aspects that are of primary importance for the overall performance of the repository. Furthermore, documentation of FEPs and interaction mechanisms and the importance of these for the selected scenario initiating FEP, as well as the reasons behind the judged importance, are important parts of both methods. In the Influence Diagram method, documentation of FEPs and influence descriptions, as well as of all decisions in the scenario development process, are compiled in a database electronically linked to the Influence Diagrams. In the newer RES method, the need for documentation is identified, but a system for this documentation is not yet developed other than for classifying FEPs.

Of course, there are also differences between the two methodologies. The most obvious one concerns the graphical lay-out: the RES methodology uses a matrix form; whereas the Influence Diagram methodology uses nodes and arrows. Other differences concern the strategy behind the construction of the Influence Diagram and Interaction Matrix and how these are used to develop and describe scenarios. The question is whether these differences also mean that the information compiled in the Influence Diagram, with its coupled documentation and resultant representation of the behaviour of the system for a specific scenario initiating FEP, will differ from the information given in a RES matrix and its documentation.

The essence of the RES methodology is that the state variables of the disposal system are developed and then the interactions between these variables are assessed. Such variables are preferably the physical variables of the system and could be 'temperature', 'rock stress', 'water flow' etc. These state variables may or may not be FEPs. All the existing FEPs are identified with reference to the state variables, their interactions, and all associated mechanism pathways. It may be necessary to create new FEPs to complete the RES model structure.

The RES approach can then be a 'soft' or 'hard' systems approach, or both. The 'soft' RES approach is to code all interactions between variables in order to establish the structure of the problem (according to the objective) and then to establish the most important mechanism pathways. The 'hard' RES approach is to utilize the fully-coupled model to assess numerically the simultaneous operation of all mechanisms in the system. Scenarios can be studied by both approaches.

The essence of the Influence Diagram method is the development of a network of interaction chains or flowpaths which can be used to describe the evolution of the barrier components and radionuclide transport in the system. This is done by representing FEPs, existing FEPs and FEPs identified during the development process, by boxes in the appropriate barrier regions of the diagram. Some of the FEPs represent the main parameters or physical variables of the system, e.g. 'water flow', 'temperature', 'rock stress' etc. Interactions between FEPs are identified and represented by arrows linking pairs of FEPs and showing the direction of the influence. All FEPs are described and all influences specified and the documentation is compiled in a database associated with the diagram.

By assessing the importance of all interactions for a defined set of scenario premises Influence Diagrams at different importance levels are developed. These diagrams express the mechanisms that should be considered in the performance assessment for a certain importance level and are thus an indicator of the conceptual uncertainty in the system description. However, the Influence Diagram is not intended to be a fully-coupled model to be directly used for quantitative analyses of the system behaviour.

6.2 COMPARISON OF COMPONENTS AND LAY-OUT OF THE GRAPHICAL DESCRIPTION

In the RES methodology, the main variables and alteration to these are represented by the leading diagonal elements in a square matrix. Interactions between the main variables are represented by the off-diagonal elements. The location of the FEPs in the matrix follows from their identification as either main variables, alteration to main variables or interactions between main variables or alteration to interactions, or pathways through the matrix, or indeed evolution of the whole matrix.

In the Influence Diagram, different regions of the diagram are used to represent the safety features of the system, e.g. the different repository barriers. Within each region, nodes and arrows are used to describe FEPs and the interplay between them. Some of the nodes within each region represent FEPs that describe the main variables of the barrier, e.g. "Chemical properties", "Physical properties", "Water chemistry", "Water flow", "Gas flow and transport", "Temperature" and "Contaminant release". These FEP nodes then correspond to the leading diagonal elements in a RES matrix. In the Influence Diagram, these main variable FEPs are repeated for each safety feature or barrier, see Chapter 3, while in the RES matrices described in Chapter 4 one diagonal element is in some cases used to represent a certain main parameter FEP in all parts of the repository system.

In the Influence Diagram, the nodes representing the above exemplified main parameter FEPs are linked either directly by an arrow representing an interaction or a chain containing arrows and nodes, i.e. interactions and FEPs. These different types of links are schematically shown in Figure 6-1 as well as their corresponding locations in a RES matrix. The influence arrows are indicated by dashed lines in the matrix just for comparison reasons.

Influence **a** illustrates a direct interaction between the main parameter FEPs **1** and **2** in the Influence Diagram. The corresponding location for influence **a** in a RES matrix would be in the upper off-diagonal element between the diagonal elements **1** and **2**. An example of this type of link could be: the impact of magnitude, direction and distribution of flow through a barrier on the contaminant release from the barrier.

In the Influence Diagram, the FEPs noted **A**, **B** and **C** are involved in interaction chains between more than one pair of main parameter FEPs. The main parameter FEP **1** interacts with the main parameter FEP **3** via influence **b**, FEP **A** and influence **c**. This interaction chain could be described in a matrix by placing FEP **A** in the upper off-diagonal element connecting the diagonal elements **1** and **3**. Influence **b** defines which of the main parameters represented by diagonal element **1** that affect FEP **A**, and influence **c** specifies which of the parameters represented by diagonal element **3** that will be affected by FEP **A**. Thus, influences **b** and **c** define the location of FEP **A** in a RES matrix, and this interaction chain could therefore be translated from the Influence Diagram form to a RES matrix as long as the documentation associated with FEP **A** in this position of the matrix contains the specifications of influences **b** and **c**.

FEP **A** in the Influence Diagram is also involved in an interaction chain connecting the main parameter FEPs **1** and **4** through influences **b** and **d**. This interaction chain could be described in a RES matrix by placing FEP **A** in the upper off-diagonal element connecting the diagonal elements **1** and **4**. As in the previous example, the position in the matrix corresponds to the influence arrows in the diagram, and the information about this interaction chain will be the same in the RES matrix as in the Influence Diagram as long as influences **b** and **d** are specified in the documentation.

In the Influence Diagram, a third interaction chain involving FEP **A** is the route from the main parameter FEP **1** to FEP **A** via influence **b** and back to the main parameter FEP **1** via influence **e**. In this type of interaction, FEP **A** is comparable to an "Alteration to parameter" FEP in a RES matrix, and thereby associated with the diagonal element **1**. Neither the FEP nor the influences are displayed in the interaction matrix. This requires that the documentation coupled to the diagonal element **1** contains a description of the FEP and specification of the influences, but could still be a drawback

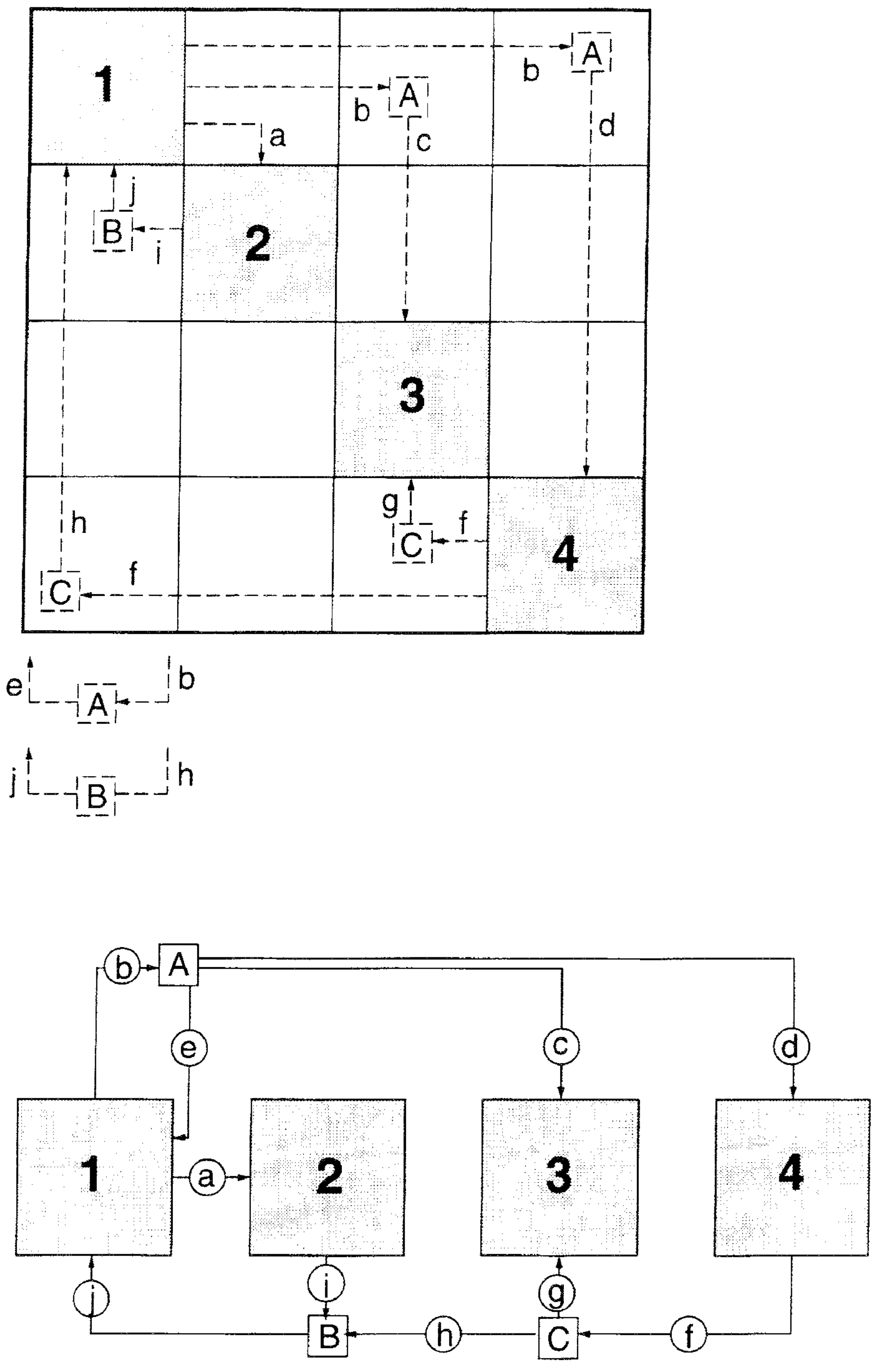


__Figure 6-1.__ Interactions and interaction chains between main parameter FEPs in an Influence Diagram (lower) and their corresponding locations in a RES matrix (upper).

in the identification and description of the impact of a scenario initiating FEP.

To clarify the above described types of interaction chains involving FEP **A,** an example from the bentonite backfill in the Influence Diagram for SFL 3 is selected. FEP **A** could be "Microbial activity", and the main parameter FEPs and diagonal elements **1**, **3** and **4** could be "Water chemistry", " Gas flow and transport" and "Barrier properties", respectively. Microbes, dissolved nutrients and organic carbon, pH and dissolved poisonous elements in the water will determine the occurrence and extent of microbial activity in the bentonite backfill (influence **b**). The potential impact of microbial activity on "Gas flow and transport" (main parameter FEP **3**) is gas generation (influence **c**). Creation of biofilms (influence **d**) could affect "Barrier properties" (main parameter **4**) and microbial activity may change pH, redox and the concentration of corrosive and complexing agents in the water (influence **e**) thereby affecting "Water chemistry" (main parameter FEP **1**).

Figure 6-1 illustrates an additional type of interaction chain which could be found in the Influence Diagram, namely that the interaction chain between two main parameter FEPs containing two FEPs. The main parameter FEP **4** will interact with the main parameter FEP **1** through influence **f**, FEP **C**, influence **h**, FEP **B** and influence **j**. There is no direct translation of such an interaction chain to the interaction matrix form. One possible solution could be to classify FEP **B** as being an "Alteration to main parameter **1**". The interaction chain could then be described in the matrix by locating FEP **C** in the lower off-diagonal element connecting the diagonal elements **4** and **1**. However, this would require that the off-diagonal elements represents not only binary interactions between main parameters, but also binary interactions between main parameters and alteration to parameters.

One example of an interaction chain involving two FEPs is the interaction between "Groundwater flow" and "Bentonite backfill properties". The magnitude, direction and distribution of groundwater flow in the near-field rock (influence **f**) will affect "Resaturation" (FEP **C**) of the bentonite backfill. Resaturation will in turn initiate "Swelling" of the backfill (influence **h** and FEP **B**) and the degree of swelling will affect the hydraulic properties of the backfill (influence **j** to main parameter FEP **1**). In a matrix this could be descibed as proposed above by locating "Resaturation" in the off-diagonal element connecting "Groundwater flow" and "Bentonite backfill properties" and classifying "Swelling" as an alteration to "Bentonite backfill properties". In this case, "Resaturation" acts as an interaction between a main parameter and an alteration to a parameter. However, a more stringent description of this interaction chain in the Influence Diagram would probably have been from "Groundwater flow" to "Resaturation", as above, but then from "Resaturation" to "Bentonite backfill properties", since saturation degree could be defined as a main parameter of the backfill. This saturation degree would then impact "Swelling", which in turn would affect the hydraulic properties of the backfill. The location of the FEPs in the matrix would be the same, but in this case "Resaturation" is an interaction between two main parameters.

As has been shown above, a translation of the Influence Diagram into a RES matrix is possible provided that only those FEPs that represent physical variables of the system are defined as leading diagonal elements in the matrix. The Influence Diagram can be directly converted into a matrix form by defining all FEPs in the system as diagonal elements and all influences between FEPs as off-diagonal elements /6-1/. However, this is not a matrix which fulfils the requirements of a RES matrix.

6.3 COMPARISON OF STRATEGY

Both the Influence Diagram method and the RES method involve the structuring of FEPs for a repository system in such a way that all interactions and combinations between FEPs relevant for the long-term behaviour of the system can be determined. In both methods, FEPs relevant for the system are selected from existing FEPs lists and new FEPs are created when necessary to complete the description of the system. However, there are some differences in the approach of the two methodologies.

One difference concerns the development of the structured description of the system. In the RES methodology, the main variables of the system are selected and placed along the leading diagonal in a square matrix. FEPs are classified and located in the matrix according to their relation to the main variables. In the Influence Diagram methodology, the system is divided into regions representing the barrier system. FEPs are introduced as boxes in each region where they could occur and ordered so that those affecting barrier performance are separated from those affecting radionuclide transport by FEPs describing the chemical, physical and mechanical properties or conditions within the barrier. Interactions between FEPs are then identified and represented by arrows linking pairs of FEPs and showing the direction of the influence. All FEPs are described and all influences specified in documents coupled to the diagram.

Without comparing the result in terms of information gathered in the RES matrix and Influence Diagram, respectively, the RES method seems more straight-forward in the construction phase since it focuses on the physical variables of the system and how FEPs are affecting these. In addition, a RES matrix representation of the system is probably easier to assimilate than an Influence diagram.

A comparison of the information contained in a RES matrix and Influence Diagram based on the applications described in Chapter 5 favours the Influence Diagram approach because this analysis is FEPs driven. If a direct model using physical variables is to be developed, the RES methodology is favoured. To be comparable with the Influence Diagram method in this sense, the documentation behind the development of a RES matrix must be extended. In addition, a higher resolution of the matrix is probably needed, as indicated by the examples in the previous sub-section.

Another difference in strategy concerns the development of scenarios. The first step in the methodology based on Influence Diagrams is to build a basic or general version of the Influence Diagram for a defined system. This general version should contain all possible FEPs inside the system boundary and all possible interactions between these FEPs which might be envisaged regardless of circumstances. Therefore unscreened FEPs lists form the basis for the construction of the general version of the diagram. Scenario Influence Diagrams are then developed from the general version by assessing the importance of the influences for a certain set of boundary conditions or when perturbed by a scenario initiating FEP. Scenario Influence Diagrams at different importance levels can then be produced by removing influences of lower importance and subsequently FEPs which no longer have any impact on system behaviour. Thus, screening of FEPs is part of the systematic methodology and the documentation coupled to the system provides the arguments behind the screening.

The RES methodology, as applied so far, does not involve the construction of a general Interaction Matrix which includes all possible interactions between physical parameters regardless of circumstances. The RES methodology rather concentrates on the important processes and mechanisms during the build-up of the matrix and comparisons with available FEPs lists are done at a later stage in the methodology. In the application of the RES methodology to a large rock movement perturbation (see Chapter 5) the screened SKI/SKB FEPs list was considered and new RES FEPs were also taken into account to provide a comprehensive description of the system. In the application to canister failure, bentonite and biosphere the RES-matrix was constructed for a reference failure scenario. In these cases so far no documentation is available on comparisons with available FEPs lists.

In the context of imposing a scenario initiating FEP onto the system and the possibility of describing how the effects of the scenario initiating FEP propagate through the system, the Influence Diagram methodology and the RES methodology seem to be quite similar. With both methods it is also possible to illustrate time sequences. In both a RES matrix and an Influence Diagram this is done by highlighting flowpaths through the matrix and diagram, respectively.

6.4 CONCLUDING REMARKS

This first brief comparison between the Influence Diagram methodology and the RES methodology indicates that, although different in the development approach, a translation of the resulting system description between the two seems to be possible. The RES methodology approach appears to be more straight forward since it foccuses on the physical variables of the system and how FEPs are related to these. However, the documentation procedure has to be improved to match the Influence Diagram methodology, both in terms of the specification of the interactions in the matrix and how the matrix actually is used to select the mechanisms that should be considered in different scenarios.

The comparison has also revealed that the resolution of the RES matrices used in the applications described in this report is too low to handle all the information contained in the Influence Diagram. Chosing the number of diagonal elements in the matrix depends on the purpose of the study, but is also a question of balancing the overview of the system against the completeness of the system. A larger number of diagonal elements will increase the possibility of identifying all relevant interactions in the system at the cost of losing the overview of the system and vice versa. The best solution to this problem is probably to describe a system with both a high resolution and a low resolution matrix in which the high resolution variables are expansions of the low resolution variables.

The advantage with the Influence Diagram methodology is that it uses the FEPs directly and a great deal of supporting documentation has been collated and computerized. The advantage with the RES methodology is that it uses the physical state variables of the disposal system and a matrix structure to represent all mechanisms and FEPs. Both approaches use expert judgements to screen mechanisms and identify the important mechanisms pathways. Both approaches are practical, documentable, and quality assurable with associated protocols – and the supporting documentation for the Influence Diagrams is already extensive. The RES approach has the potential to use the fully-coupled model to numerically evaluate all mechanisms operating simultaneously. Moreover, both approaches are well-suited to identifying the disposal-sub-systems. This can be done by considering a cluster of FEPs in the Influence Diagram methodology and a cluster of related state variables in the RES matrix.

7 CONCLUSIONS

The overall conclusions from the comparison of the three methodologies mentioned in this report are that:

a) detailed work going through all currently known Features, Events and Processes (FEPs) is of great value for the understanding of the repository system,

b) a visualization tool to obtain an overview of relevant linkages between the processes in the repository system is also of great value,

c) thorough documentation of all steps in a scenario development methodology is necessary to record all judgements made and to allow the possibility for future revisions,

d) a documentation strategy is needed to ensure that all steps in the methodologies are treated at a compatible level of detail,

e) an expert judgement will always be needed for selecting the final set of scenarios, which should be assessed to demonstrate the safety of the repository system. A systematic scenario development methodology will give the necessary background and motives for the selection of the scenarios.

The specific conclusions drawn from work with each methodology are the following:

1) The event tree or "fault tree" methodology is the least favourable method for visualization when dealing with systems of great complexity.

2) The Influence Diagram Methodology is feasible although somewhat complicated to use for visualization of a repository system. The system can be divided into smaller parts which can be separately assessed. Prioritization of important subsystems can be done with the aid of this methodology e.g. by emphasizing important influence arrows by colour codings and/or by reducing the complexity of the presentation by deleting unimportant influences. However, the structure of the total diagram is very complex for a new reader and the understanding of important pathways and how disturbances will propagate through the system can be hard to follow. The documentation system within the methodology is very good with elaborate databases for all FEPs and influences.

3) The RES methodology is also feasible to use for visualization of a repository system. When constructing the matrix a top-down approach is used which utilizes the expertise in the working group in a stimulating manner. The resulting matrix is relatively easy to understand even for new readers with limited knowledge. The repository system can be divided in subsets each represented by its own matrix. Prioritization of

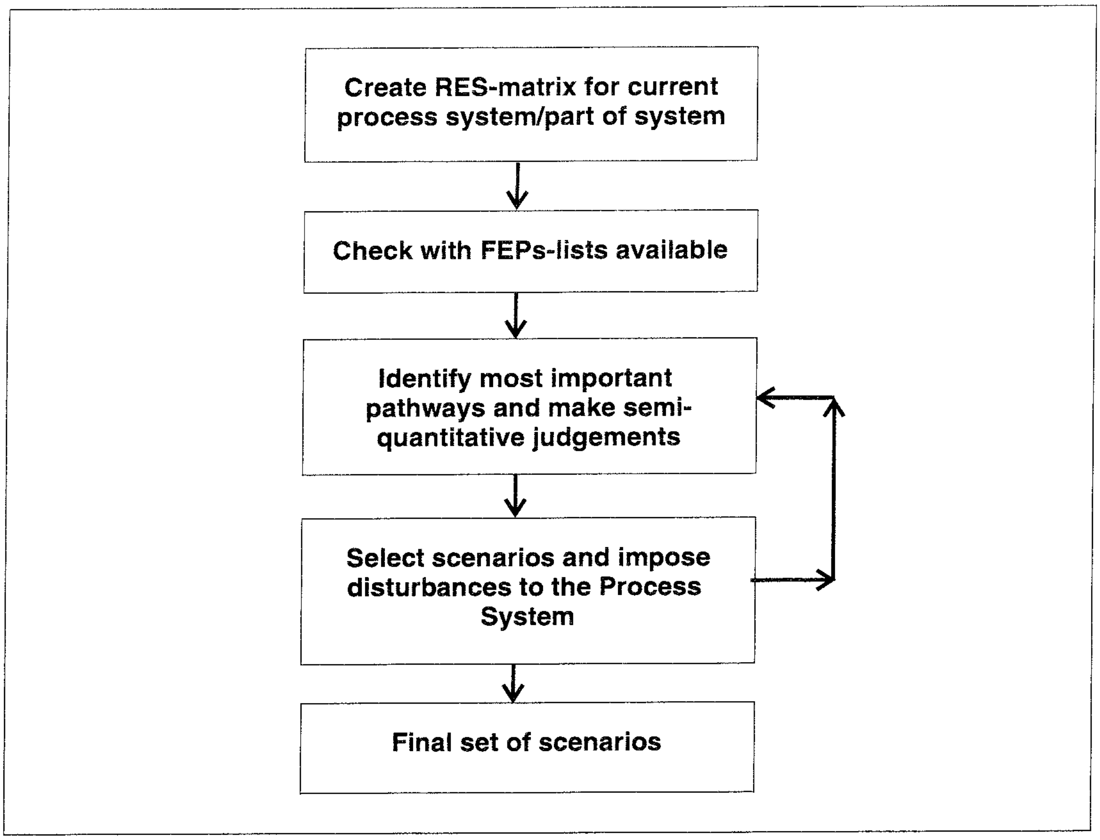


Figure 7-1. *Proposed steps in a scenario development methodology. Comprehensive documentation of each step will be of vital importance.*

the interactions can easily be indicated with semiquantitative systems or colour codings in the presentations. The level of detail in each interaction box can sometimes be insufficient for scientific use and must then be elaborated on in written documents. The documentation strategy needs to be developed.

The overall conclusion is the that a scenario development methodology with the best parts from the Influence Diagram Methodology and the RES Methodology would be of great value. Such a methodology could include the steps indicated in Figure 7-1.

SKB will continue with scenario methodology development proposed above to ensure that sufficient background material is available when selecting scenarios for future safety assessments.

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[2] Section for Solid Earth Physics, Department of Geophysics, Uppsala University, Sweden
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[1] Department of Geology, Chalmers University of Technology/Göteborg University
[2] Terralogica AB
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3 CTH
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[2] Chalmers University of Technology, Gothenburg, Sweden
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