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# Final disposal of spent nuclear fuel – Standard programme for site investigations

Compiled by
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Swedish Geological
April 1983

SVENSK KÄRNBRÄNSLEFÖRSÖRJNING AB / AVDELNING KBS

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# FINAL DISPOSAL OF SPENT NUCLEAR FUEL - STANDARD PROGRAMME FOR SITE INVESTIGATIONS

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A list of other reports published in this series during 1983 is attached at the end of this report. Information on KBS technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17) and 1982 (TR 82-28) is available through SKBF/KBS.

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SUMMARY

Like many other contries with similar geological conditions, Sweden plans to dispose of its long-lived radioactive nuclear waste by depositing it in final repositories located deep down in the crystalline bedrock.

In order to be able to demonstrate that a given rock formation is suited for waste storage, it is necessary to have knowledge concerning its properties, particularly those that determine groundwater conditions and chemistry within the area. Also of importance are data that shed light on rock mechanics in the area and the occurrence of valuable minerals.

The SKBF/KBS programme includes plans to carry out geological studies of 10-15 areas in different parts of the country during the 1980s. A "standard programme" for these studies is described in the following. The standard programme is intended to serve as a basis for planning of the work and revisions or modifications that may be found to be appropriate in view of local conditions or experience.

# 2 OVERVIEW

## 2.1 General working frames

The investigations that are required for a repository for high-level waste or other nuclear fuel can be arranged in a natural sequence of phases.

The first of these phases comprises those investigations that are conducted for the most part from the ground surface and that are intended to determine whether the fundamental premises exist for a safe final storage of nuclear waste within the study area.

If such premises do exist, the first phase is followed by a second one intended to yield a body of data to serve as a basis for the overall planning of the design of the repository underground. The second phase therefore consists primarily of investigations down at the intended storage depth, conducted with increasing detail as the work progresses.

A third study phase will precede the detailed design of the repository.

The outlines of a standard programme for the first of the study phases are described in the following. The different stages are illustrated in figure 1.

## 2.2 Choice of study area

The first study phase consists of a sequence of stages. The first of these stages concerns the choice of the study area.

The first stage begins with an introductory study of regional conditions with the aid of available geological, geophysical and topographical maps, satellite and aerial photographs, well data on file, landowner-supplied information etc. These studies lead to the selection of a small number of areas that are judged to be promising and are therefore subjected to general field reconnaissance.

After the permission of the landowners has been obtained for further investigatory work and drilling, this stage is concluded with the drilling of an initial deep borehole within selected areas. The purpose of the hole is to verify that the area can actually offer favourable rock conditions at great depth before proceeding to subsequent, more time-consuming and costly investigations.

## 2.3 Surface investigations

This stage consists largely of detailed geological and geophysical studies for the purpose of defining the hydrogeological boundaries and main characteristics of the area and obtaining data to be used as a basis for planning the subsequent depth investigations.

An attempt is made to distinguish from the surface the large existing sections of sound rock and to locate any zones of disturbance that might conceivably affect groundwater movement and the available volume for a repository.

These surface investigations generally cover a central study area of about 4 $km^2$, with some excursions to provide a picture of the wider geological and geophysical field contexts.

## 2.4 Preparatory depth investigations

The surface investigations are followed up and tested to a depth of about 100-200 metres. Special attention is given to the nature of the surface-indicated zones of disturbance, their downward direction and possible interrelationships. This is done by means of a series of hammer- and diamond drilled boreholes and investigations conducted in these holes.

Similar investigations in selected parts of the major zones of disturbance, judged to constitute the hydraulic boundaries of the study area, can also be included in this phase. Pumping in boreholes running through such zones and measurement of the lowering of the groundwater level in surrounding observation holes provide a measure of the water flow rate in both the zone of disturbance and surrounding sections of sound rock.

Interpretation of the results from this stage provides an initial more detailed picture of the probable location of the zones of disturbance at greater depth and of the extent of sound rock between these zones. Based on the information obtained in this manner, the following depth investigation stage is planned.

## 2.5 Depth investigations

The purpose of this stage is to investigate the distribution and characteristics of both sound rock and zones of disturbance at greater depth. This is done in a number of core boreholes running down to and past the intended repository depth. These boreholes permit sampling of the rock and the zones of disturbance as well as geophysical and hydraulic measurements. Special pumpings also provide samples of the groundwater from well-defined sections for determination of the chemical conditions surrounding a possible future repository.

## 2.6 Compilation and evaluation of data

The collected observation data are compiled and evaluated. The primary goal is a general picture of the area, including the location and extent of any zones of disturbance as well as volumes of sound rock.

On the basis of the results of measurements performed, the different hydrogeological units can be assigned representative hydraulic values. The collected data constitutes a basis for a qualitative appraisal of groundwater movements within the area and around a hypothetical repository located within it.

## 2.7 Supplementary investigations

While the compilation and evaluation work is being conducted, certain investigations are still being carried out in the field. These include test pumpings and measurements of groundwater heads. The compilation work can also reveal gaps in existing data that require supplementary investigations.

It should be said that the division into stages reported above is schematic and that the detailed execution of the investigations will depend on local conditions.

The activities included in the different stages are presented below. A more detailed outline is provided in table form in appendix 1.

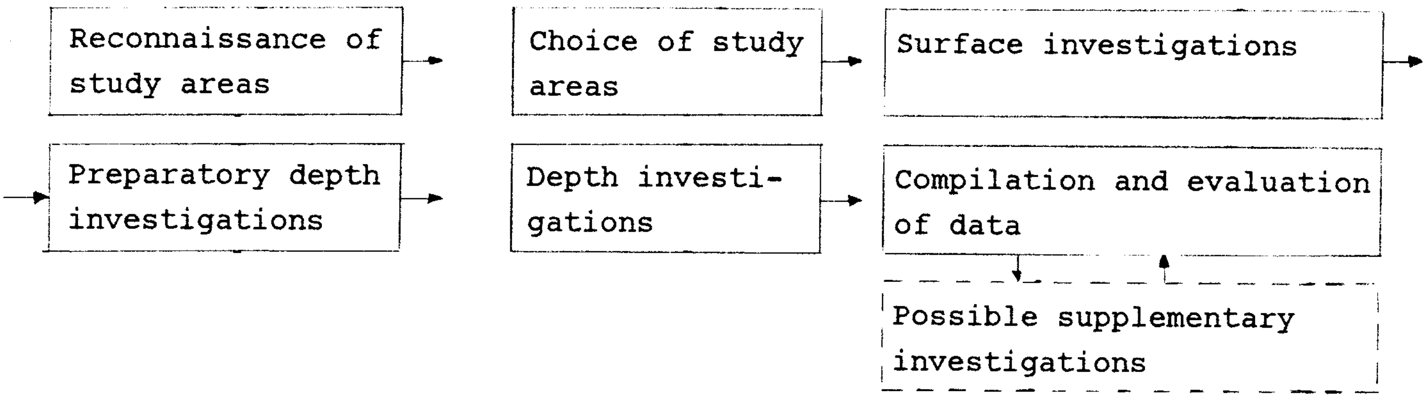


Figure 1

# 3 STAGE 1: RECONNAISSANCE FOR STUDY AREAS

This stage includes geological reconnaissance work and drilling of a deep reconnaissance hole.

## 3.1 Geological reconnaissance

Through map and literature studies, contacts with persons who have experience from civil engineering projects in various types of bedrock and studies of the water capacity of wells drilled in rock, a number of rock formations are selected for reconnaissance studies. The selection is based on the following criteria:

- flat bedrock topography
- large distance between major fracture zones
- uniform composition and structure of rock mass
- low seismic activity
- low water flow rate in rock mass (well survey)
- absence of ore deposits or other exploitable mineral deposits
- landowner structure
- accessibility

After data have been compiled from a large number of areas, several areas are selected for further studies.

The landowners are contacted, and on those areas where permission to pursue further investigations is obtained, detailed aerial studies and field reconnaissance are planned. Geology, tectonics, degree of exposure etc. are studied in this phase.

In some cases, geophysical and gravimetric aerial measurements have already been carried out within the areas in question. These data are subjected to interpretation aimed at clarifying the regional fault pattern, fault processes, existence of water-bearing crush zones, rock species boundaries and intrusions of foreign rock species.

After field reconnaissance and general geophysical (VLF) studies, a decision is made as to whether reconnaissance drilling is to be done.

## 3.2 Reconnaissance drilling

In order to obtain information on the distribution of rock species and tectonics at depth, a deep (about 1 000 m) vertical borehole with a diameter of 56 mm is drilled at an early stage of the study. The hole is set out on the basis of the results of the general field study and interpretation of aerial photographs and aerial geophysical maps.

In order to obtain further data on the nature of the bedrock, geophysical measurements are made in the borehole and on the drill core, which is also mapped. These investigations are described in section 5.4 "Geophysical borehole measurements" and 5.2 "Core mapping".

Hydraulic measurements with water injection tests in 25-metre sections are also carried out in the borehole. See also section 5.5 "Hydrogeological investigations".

The results of the geophysical reconnaissance work, including reconnaissance drilling, then serve as a basis for the selection of areas for further investigations.

# 4 STAGE 2: SURFACE INVESTIGATIONS

This stage includes geological surface mapping, geophysical ground measurements and establishment of a drilling programme.

## 4.1 Geological surface mapping

The geological mapping starts with a general regional mapping around the area. The work necessary in this phase of the investigation is dependent to a large extent on the quality of existing geological maps.

Contact is made with geologists with experience from the area. With their assistance, a general picture of the distribution of rock species and rock structures in the area is assembled.

After this initial work, the geological and tectonic mapping work is concentrated on the actual study area, with a size of about 4-6 $km^2$. There, detailed surface mapping of rock species, intrusions, fracture zones, axes of folding, schistosity, fracture frequency, fracture length, fracture fill etc. is carried out.

A scale of 1:5 000 and level curves with an equidistance of 1-2 m are used for the detailed mapping work. The results are reported on a scale of 1:10 000.

## 4.2 Geophysical ground measurements

In order to obtain information on the properties of the rock at greater depth and in soil-covered areas, geophysical investigations are conducted on the ground surface. The geophysical measurements record various physical properties of the rock. The data is used to locate fracture and crush zones that can contain water, rock species boundaries and the presence of any mineralizations.

The measurements are carried out in the form of both a dense surface measurement over the study area (4-6 km$^2$) and individual profiles within a larger area.

Measurements are made using the following methods:

Magnetic measurements: Indicate the presence of fracture and crush zones and the extent of rock species with different magnetic properties.

Electrical resistivity measurements: Indicate the presence of water-bearing fracture zones as well as black shales and certain ore deposits (e.g. compact sulphide ores).

Induced polarization (IP): Indicates the presence of electrically conductive minerals, even at low concentrations, e.g. graphite and sulphides. Used in this context to distinguish mineralizations and crush zones.

Electromagnetic measurements (slingram and VLF): Indicate the presence of water-bearing fracture and crush zones as well as shales and certain ore deposits. Used, among other things, to estimate the dip of fracture and crush zones.

Seismic measurements: Indicate the presence of fracture and crush zones. The measurement also yields a measure of the soil depth.

The measurement results are reported in the form of maps on a scale of 1:5 000.

## 4.3 Evaluation

On the basis of the results obtained from the geological surface mapping and the geophysical ground measurements, a compilation and evaluation is carried out.

This evaluation then provides a basis for decisions concerning further depth investigations within the area (stage 3) and establishment of a drilling programme with proposed locations of hammer- and coredrilled boreholes.

# 5 STAGE 3: DEPTH INVESTIGATIONS

This stage includes the drilling work planned in stage 2 and the geological, geophysical and hydrogeological measurements in the boreholes. The stage 3 work also includes a compilation of the observation data collected from the area and an evaluation intended to provide a geological, tectonic and hydrological picture of the area.

## 5.1 Drilling work

### 5.1.1 Hammer drilling

Hammer drilling is carried out in order to confirm the existence of presumed fracture zones located by the geological and geophysical investigations. The drillings also provide an idea of the dip and width of the fracture zones as well as any water inflow into the boreholes.

The hammer-drilled boreholes can be used for water sampling and, when there is ample water inflow, as flushing water wells for the core drillings.

The boreholes are drilled with a diameter of 115-110 mm and to a depth of between 100 and 200 m. The slope of the holes can vary between $50^{\circ}$ and $90^{\circ}$.

The following parameters are measured in connection with the drilling work:

- drilling rate
- water flow rate at different levels
- level of groundwater table
- gamma radiation and point resistance in order to obtain a picture of fracture frequency in the borehole
- slope and depth of the borehole

### 5.1.2 Core drilling

The geological depth investigations within each area are carried out in a number of core boreholes. In the "standard case", the number is assumed to be 7.

Setting-out of the boreholes is based on the geological picture obtained during stage 2 and from the hammer-drilled boreholes. The core boreholes are located so that they can be expected to provide information down to 500-700 m on the location and extent of major fracture zones and representative properties of the undisturbed rock mass.

In core drilling, recovery of the drill cores with emptying the core barrel, takes place at a maximum rate of 6 m per recovery. The core boreholes have a diameter of 56 mm, while the diameter of the drill cores is 42 mm or 45 mm.

The cores are registered by recovery number and documented in the field with a drilling record. In addition, flushing water pressure and flushing water consumption are measured. The flushing water is marked in order to permit the proportion of flushing water in the groundwater to be measured in connection with later sampling for chemical analyses.

## 5.2 Core mapping

In order to obtain an idea of the geological conditions at depth, the recovered drill cores are mapped.

Core mapping covers the following points:

- o rock species distribution
- o orientation and character of fractures
- o fracture filler minerals and chemical analysis of these
- o sampling for determination of chemistry and mineral content of representative rock species
- o photographic documentation

The presence of fractures, their character, orientation etc. is recorded in a core log record. Rock species distribution and other information from the drill core is presented in a text section.

## 5.3 Gas lift pumping

In connection with core drilling, flushing water must be continuously pumped down into the borehole under high pressure (up to 20 $kg/cm^2$) in order to cool the drill bit. The flushing water can have a different chemical composition than the groundwater in the rock formation penetrated by the drilling. In order to permit the quantity of flushing water in the groundwater to be calculated in connection with water chemistry analyses, the flushing water has been marked with $I^-$.

In order to reduce the difference between the flushing water and the groundwater, the flushing water is taken from a well drilled in the rock, if possible, one of the hammer-drilled boreholes mentioned in section 5.1.1. If the flushing water is much too turbid, it is filtered mechanically before use.

Another problem connected with core drilling is that drill cuttings are forced into fractures, adhere to the borehole wall and remain in the borehole water for a long time in suspended form.

Flushing-out and cleaning of the borehole is done with nitrogen gas pumped through a hose to the bottom of the hole.

As a result of pumping, some of the foreign water, including particles, is evacuated from the borehole and nearby parts of fractures in contact with the boreholes.

## 5.4 Geophysical borehole measurements

The geophysical borehole measurements provide information on the resistivity of rock, the presence and character of fractures, certain chemical properties of the borehole liquid, groundwater flow along the borehole and the presence of electrically conductive and radioactive minerals. The location of each borehole is also measured.

The measurements yield data on the bedrock adjacent to the borehole and provide support for the description of the geological structure of the area, its hydrogeological conditions and its chemistry.

Measurements are performed by means of the following methods:

| | |
|---|---|
| Curvature measurement: | Location of the borehole |
| Gammalog: | Background radioactivity |
| Geohm: | Small fissures |
| Resistivity: | Zones of high water content |
| Spontaneous protential (SP): | Sulphide minerals, water flow |
| Temperature: | Temperature of the borehole liquid, water flow in the borehole |

IP: Presence of sulphide minerals

To provide further support for the description of the properties of the bedrock, the following properties of the drill core are also measured:

- o Density, porosity, resistivity
- o IP effect, susceptibity and
- o remanent magnetization

## 5.5 Hydrogeological investigations

The hydrogeological investigations of the deep-drilled core boreholes within the study area are aimed primarily at determining the following hydraulic parameters: hydraulic conductivity of the rock mass, groundwater head and, in certain zones, kinematic porosity. These parameters provide a point of departure for the subsequent description of the local and regional groundwater conditions within the areas. With knowledge of these hydraulic parameters, the flow velocity of the groundwater and the rate and direction of the groundwater flow through the rock mass can be calculated.

### 5.5.1 Determination of hydraulic conductivity

Hydraulic conductivity is a measure of the permeability of a medium to water. The concept of hydraulic conductivity encompasses both the material properties of the rock and the properties of the water.

The bedrock that will be studied within the potential repository site investigations consists of crystalline bedrock. From the hydraulic point of view, a crystalline rock formation can be regarded as an impervious rock mass penetrated by fractures running in different directions. Only the fractures are groundwater-bearing to any appreciable extent.

Hydraulic conductivity can be determined in a number of ways. The area studies have been preceded by extensive method studies resulting in the choice of transient water injection tests at constant pressure in sections of the boreholes as a method.

### 5.5.2 Determination of groundwater pressure conditions

A map on a scale of 1:5 000 showing the groundwater levels is drawn up for each area. The map provides a basis for the hydraulic gradients included in the computation model for groundwater flow. Groundwater levels are measured in boreholes and, in some cases, wells. In certain boreholes, the deeper parts are sealed off in order to prevent disturbances from deeper heads.

In order to check the model computations, groundwater head is also measured at different depths in the core boreholes. This is done in connection with the hydraulic conductivity measurements, i.e. in the same test sections and with the same instruments. In order to get simultaneous measurements of the heads, a separate measurement is also carried out in approximately 5 sections in 2-3 core boreholes within each area.

### 5.5.3 Determination of kinematic porosity

Kinematic porosity, i.e. the porosity of the bedrock to the mobile groundwater, is determined within each area only in connection with test pumpings in major fracture zones (see 5.5.4). Otherwise, data obtained from other studies is used for model computations.

### 5.5.4 Interference tests

The purpose of the interference tests is to provide a measure of certain highly conductive parts of the bedrock, e.g. crush zones that surround the central study area and that can control the groundwater flow to a great extent. The zones can therefore constitute the boundary conditions for the hydrological model computations. The tests are carried out in the form of test pumping from a central hole surrounded by approximately 4 observation holes.

The interference tests are used mainly in relatively shallow holes.

## 5.6 Hydrochemical investigations

The purpose of the hydrochemical investigations is to document the chemical-physical composition of the groundwater within the study area. The data are utilized in other parts of the KBS programme for calculating corrosion, sorption etc.

After evaluation of the core mapping and the hydraulic measurements at least two core boreholes are selected for sampling. Water is collected in each core borehole from 3-4 different levels sealed off by packers. Before the start of pumping, the borehole will be gas-lift pumped several times.

Water samples can also be taken from hammer-drilled boreholes utilized for pumping.

Water from the core boreholes will be analyzed with respect to: main components, redox equilibria, corrosive properties, solubility for uranium, complex formation for radionuclides, chemical equilibria with certain radionuclides, radioactive background levels and datings.

## 5.7 Evaluation and model work

### 5.7.1 Purpose and scope

The purpose of evaluation and model work is to describe, qualitatively and quantitatively:

- the groundwater conditions within the study area
- the flow times and flow paths of the groundwater from different possible repository sites within each study area
- long-term changes
- basic mineralogical and groundwater chemistry data

The work procedure and scope can be described as a summary account of:

- o geological-tectonic conditions
- o surface hydrology and meteorology data
- o hydraulic conductivity conditions
- o groundwater pressure conditions
- o mineralogical and groundwater chemistry conditions

The summary account leads to a descriptive model of the studied area. This model serves as a basis for numerical model computations that yield quantitative values on groundwater conditions.

The evaluation also includes a description of the methods used for the various investigations.

### 5.7.2 Investigation methods

The investigation methods used are described with respect to:

- o theoretical background
- o applicability
- o measuring accuracy
- o reproducibility
- o sources of error

In cases where different methods have been used to investigate the same property, both agreements and deviations are reported. It is important that different methods be used during both the planning phase and the investigation phase (field measurements) in order to shed light on important properties and conditions. The background for the choice of methods, location of boreholes etc. shall also be reported.

### 5.7.3 Descriptive model

The hydrology, geology and tectonics of the different areas are described. (The results of the groundwater chemistry investigations are compiled by the Swedish Water and Air pollution Research Institute, IVL.) The descriptions are based on the results of the investigations. Special emphasis is placed on distingushing and characterizing different hydraulic units in the bedrock. The groundwater head in the upper parts of the bedrock is illustrated schematically, and data from measurements and tests carried out in the deeper parts of the bedrock are reported and evaluated.

The descriptive model for each area must embrace such a large area that it can be utilizied directly for numerical and analytical model computations. The results of the descriptive model shall show where, geometrically, a repository can be located within a given area.

### 5.7.4 Numerical model computations

The descriptive models serve as a basis for the numerical computations, which are performed by Kemakta. The hydrothermal model was developed by Dr. Roger Thunvik (KBS TR) and the nuclide migration model by Prof. Ivars Neretnieks (KBS TR) both a the Royal Institute of Technology (KTH) in Stockholm.

In essence, the procedure for the hydrothermal model involves setting out an element grid for each area adapted to existing hydraulic units (fracture and crush zone), boundary conditions and repository locations, and postulating for each hydraulic unit different values for hydraulic conductivity, porosity and their dependence on depth. The results of the model computations shall show:

- o water flow rate at postulated repository site
- o flow times from repository to ground surface
- o geographical location of expected outflow.

The model computations are carried out for the most part on two scales. A regional model is developed . This model includes the study area. Using the boundary conditions from the regional model, a more detailed model covering the study area is also computed.

It is important that the model computation can be carried out with different combinations of parameters within intervals of variation obtained from processing of the results of the field studies. This permits sensitivity analysis of groundwater flow and transit times. Certain limited analytical computations are also carried out to supplement the numerical model computations.

### 5.7.5 Literature studies and comparisons with other investigations

Evaluation of the suitability of different areas for waste disposal also requires comparisons with investigations and results within the same field performed outside of Sweden. The literature is continuously reviewed, with the nuclide migration model includes the effects of dispersion, sorption, channeling and matrix diffusion playing an important role through its exchange of information with other countries and organizations. The results of literature studies will be made available at the same time as the computation results from the project so that comparisons can be made for inclusion in the final report.

### 5.7.6 Report summary

The report summary describes methods, results etc. in abbreviated form with references to publications where detailed results etc. can be found. The results are presented in the form of tables, diagrams etc. and, in certain cases, comparisons between different areas as well. The report summary shall be simple, clear and concise.

# 6 RESOURCE REQUIREMENTS

## 6.1 Stage 1

This stage involves the selection of approximately four potential sites for further investigation and drilling of four 1 000 m reconnaissance holes, one at each site inclucding measurements in the boreholes.

The resource requirements for this work are estimated to be as follows:

### Geology

3 geologists for 12 months
2 geologist's assistants for 6 months

### Geophysics

1 geophysicist for 12 months
4 measuring technicians for 5 months

### Hydrogeology

1 hydrogeologist for 12 months
3 measuring technicians for 6 months

### Reconnaissance drilling

1 core drilling machine for 2.5 months (single shift)

## 6.2 Stage 2

This stage involves geological surface mapping, geophysical ground measurements and establishment of a drilling programme.

The resource requirements are estimated to be as follows:

### Geological surface mapping

2 geologists for 6 months
3 geologist's assistants for 2.5 months

### Geophysical ground measurements

1 geophysicist for 2 months
5 measuring technicians for 4.5 months

### Evaluation

3 geologists/geophysicists for 2 months

## 6.3 Stage 3

This stage involves the drilling programme planned in stage 2 within the potetential site and the geological, geophysical, hydrogeological and hydrochemical measurements in the boreholes. The work in this stage also includes compilation and evaluation of the observation data collected from the area and concluding model work.

The resource requirement is estimated to be as follows:

Drilling work

1 hammer-drilling machine for 2.5 months
2-3 core drilling machines for 4 months (single shift)

Core mapping

2 geologists for 4 months
1 measuring technician for 4 months

Gas lift pumping

2 measuring technicians for 2 months

Geophysical borehole measurements

1 geophysicists for 7 months
2 measuring technicians for 5 months

Hydrogeological investigations

5 hydrogeologists for 7 months
8 measuring technicians for 6 months

Hydrochemical investigations

1 hydrogeologist for 5 months
2 measuring technicians for 5 months

Evaluation and model work

1 geologist/geophysicist/hydrogeologist for a total of
9 months
Model computation consultant

STANDARD PROGRAMME FOR SITE SELECTION INVESTIGATIONS DETAILED OUTLINE

APPENDIX 1

| Type of investigation | Investigation phase | Investigation method | Expected results etc. |
|---|---|---|---|
| 1. Reconnaissance | 1.1 Geology<br>1.1.1 Map and literature studies | Collection of basic geological information from geological maps, literature studies and interviews with geologists active within the region | Indicates large contiguous areas with rock species considered to be of interest in the light of literature studies |
| | | Study of topographical maps | Gives an indication of major fracture zones and the topography of the area in general. A flat topography is striven for |
| | 1.1.2 Interpretation of aerial photographs | Interpretation of stereoscopic aerial photographs | Indictates fracture zones, degree of exposure in the area etc. |
| | 1.1.3 Questions of landownership | Studies of economic maps | Indicate large areas with only a few landowners |
| | 1.2 Hydrology<br>1.2.1 Well data | Studies of well data from SGU's well files | Provide an idea of areas/rock species with low water capacities |

| | | | |
|---|---|---|---|
| 1.3 | Geophysics | | |
| 1.3.1 | Aerial geophysics | General review of existing geophysical aerial maps | Provides an idea of the tectonics of the area |
| 1.3.2 | Ground geophysics | Measurement of individual profiles using magnetometer, slingram, VLF and seismic instruments | Provides information on existence of fracture zones and general information on rock species composition and soil cover within the area |
| 1.4 | Reconnaissance in the field | General studies of bedrock and tectonics | |
| 1.5 | Evaluation | Compilation and analysis of area data | Selection of typical areas for detail investigations |
| | | Setting-out of reconnaissance boreholes | Typical area size about 5 $km^2$ |
| 1.6 | Reconnaissance drilling begins | Core drilling ø 56 mm approx. 800 m | |

| Type of investigation | Investigation phase | Investigation method | Expected results etc. |
|---|---|---|---|
| 2. Detail investigation: Ground surface | 2.1 Geology<br>2.1.1 Geological detail mapping | Bedrock mapping of all outcrops within the study area and general mapping of surrounding areas | Provides an idea of the composition and variation of the bedrock |
| | 2.1.2 Tectonic detail mapping | Mapping of the tectonics of the area | Provides data on fractures, fracture frequency, strike and dip of rock species, axes of folding etc.<br><br>Production of fracture zone map |
| | 2.1.3 Core mapping of reconnaissance boreholes | Mapping with regard to rock species distribution, fracture frequency etc. | Supplements surface investigations by providing an idea of rock species variation and degree of fracturing at greater depth |
| | 2.2 Geophysics<br>2.2.1 Regional geophysics | Interpretation of electrical, magnetic and radiometric measurements from the air and, in some cases, regional gravimeter measurements | Aimed at revealing the regional fault pattern, fault processes, presence of water-bearing crush zones, rock species boundaries and intrusions of e.g. diabase |

| | | | |
|---|---|---|---|
| | | Petrophysical measurements of rock specimens and in situ | |
| | | Measurement of individual profiles with magnetometer, slingram and VLF | |
| 2.2.2 | Ground geo-physics | Dense measurement (line spacing 40 m, point spac-ing 20 m) with magnetometer, slingram and IP instruments | Provides a detailed picture of fracture sets and geo-logical structures. Also permits min-eralized zones to to be distinguished from fracture zones |
| | | Petrophysical measurements on specimens from the dense measurement area | |
| 2.3 | Evaluation and estab-lishment of drilling programme | Compilation of results of geo-logical and geo-physical detail investigations | Results in pro-posal for location of hammer-drilled boreholes and core boreholes |

| Type of investigation | Investigation phase | Investigation method | Expected results etc. |
|---|---|---|---|
| 3. Detail investigation: Depth | 3.1 Drillings | | |
| | 3.1.1 Hammer drilling | A number of hammer-drilled boreholes, ø 115 mm, are drilled to a depth of about 100 m | Provides supplementary information on fracture zones and rock species boundaries for more accurate determination of direction and slope of core boreholes<br><br>Can supply core drilling machines with cooling water and be used for hydraulic tests and water sampling |
| | 3.1.2 Core drilling | 6-7 core boreholes ø 56 mm are drilled for depth investigations to a depth of between 400 m and 800 m | Drill core with diameter of ø 42 mm |
| | 3.2 Mapping of drill cores | Geological and tectonic mapping of drill cores including photo documentation | Provides information on rock species distribution and fracture frequency etc. at depth |

| | | |
|---|---|---|
| 3.3 Sampling of drill cores | | |
| 3.3.1 Petrophysical sampling | Sampling for measurement of:<br>Density<br>Porosity<br>Resistivity<br>IP effect<br>Susceptibility etc. | Supplements and refines interpretation of aerial, ground and borehole geophysical measurements |
| 3.3.2 Rock mechanics sampling | Sampling for measurement of:<br>Strength<br>Thermal conductivity etc. | Provides information on strength, thermal properties etc. of the rock |
| 3.4 Gas lift pumping | Flushing-out of core borehole with the aid of nitrogen gas | Done in order to clean the borehole of drill cuttings and thereby increase the rate of water turnover in the borehole |
| 3.5 Geophysical measurements | | |
| 3.5.1 Borehole logging | Borehole logging is performed in all boreholes using the following methods:<br>Curvature measurement<br>Gamma radiation<br>Point resistance<br>Resistivity<br>Differential-resistance | Sheds light on the following:<br>Nature and composition of the bedrock<br>Presence and character of fractures<br>Movements and composition of groundwater |

| | | | |
|---|---|---|---|
| | | Spontaneous potential<br>Temperature<br>Salinity<br>Density<br>Caliper<br>Induced polarization<br>(1-2 holes/area)<br>Geochemical log<br>(under development)<br>(TV log) | Direction and variation in diameter of borehole |
| 3.5.2 | Special geophysical borehole investigations (under development) | Between-hole measurements | Reveal extent and location of fracture zones between boreholes |
| 3.6<br>3.6.1 | Hydrology<br>Hydraulic tests | Water injection between packers in different borehole sections | Provides a measure of the hydraulic conductivity of the bedrock. Performed approximately in long sections and with greater detai in selected shorte sections |
| | | Test pumping | Provides a measure of the hydraulic conductivity of the bedrock. Performed in selected fracture zones |

| | | | |
|---|---|---|---|
| 3.6.2 | Piezometric measurements | Measurement of groundwater head in different bore-hole sections | Provides ground-water levels for model computations and for checking computations |
| 3.6.3 | Sampling of groundwater | Collection of water samples from isolated fracture levels in the boreholes | Provides an idea of the chemical-physical composition of the ground-water |
| | | Analyses of chemical-physical composition and age ($C^{14}$, helium, tritium, U/TH) of the groundwater | |
| 3.7 | Evaluation | Compilation of field measure-ments and evalua-tion, description and model compu-tation of hydro-logical condi-tions in the area | The results of the descriptive models show where the repository can be located within the study area |
| | | | The results of the model computa-tions show the water flow rate through the postulated re-pository, flow times from the repository to the ground surface and geographic location of the outflow. |

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