A PRELIMINARY STUDY OF A FINAL REPOSITORY FOR LOW-LEVEL WASTE IN CRYSTALLINE ROCK AT SHALLOW DEPTH.
THE ALMA PROJECT.

O. Degerman
The National Council for Radioactive Waste

BACKGROUND

The final disposal of high-level waste (HLW) by means of permanent storage poses many problems, most of which stem from the long period of time required for certain nuclides to decay to a harmless level. For many reasons, too lengthy to go into in detail here, it is, however, advantageous if the final decision on the method to be used for this final storage can be postponed an additional decade or two. The situation is somewhat different for low-level waste, although similar problems exist. In the first place, the activity content of low-level waste is considerably lower (the total activity content of waste from 30 years of operation at 10 000 MW corresponds to the activity content of one ton of reprocessed fuel), and in the second place, most of the waste will have decayed to a harmless level within a few hundred years. Another factor is that the temporary storage facilities at the power stations do not normally have a capacity for more than 5 to 10 years of waste production. This means that an expansion of storage capacity will be necessary at most Swedish nuclear power stations during the latter half of the 1980s. Since, furthermore, experience is urgently needed as a basis for planning the more difficult method of disposing of the high-level waste, it is important that a suitable storage form for the low-level waste be found as soon as possible.

Two organizations are currently working in this area in Sweden. Three years ago, the power station operators formed a working group known as KBS (Kärnbränslesäkerhet - the Nuclear Fuel Safety Project). The purpose of the power station operators in forming this organization was to convince the Swedish Government of the feasibility of storing spent nuclear fuel or waste from reprocessing in an absolutely safe manner for biological life for all future time. A year ago, KBS was also put to work on the treatment and storage of low-level waste, but the problem of high-level waste has so far overshadowed the problem of low-level waste. The National Council for Radioactive Waste (PRAV) is a four-year-old organization that was formed under the Ministry of Industry to take charge of all necessary research and development for the management of waste from the Swedish nuclear plants. The transportation and storage of low-level waste has been under study by PRAV for two and a half years, for the most part with the collaboration of universities, consultants and corporations in Sweden. In order to prevent duplication of the work and to permit available resources to be concentrated on the most urgent areas, intimate contacts have been maintained between KBS, PRAV and the nuclear power utilities during this work.

The purpose of this report is to provide an overview of the work that has been carried out to date under PRAV's auspices aimed at finding a satisfactory method for the terminal disposal of low-level waste in Sweden. The results of the preliminary study will then form a basis for deciding on which areas continued planning efforts for the final storage of low-level waste should be concentrated.

The goal is that such a repository should be ready to receive waste by no later, than 1990.

PREMISES FOR THE STUDY

The geological conditions necessary for such a repository are limited in Sweden to crystalline rocks, since there are few large formations of sedimentary soils or rocks in the areas of low population density. During 1979, our work has been concentrated primarily on:

- Designing and sizing a suitable transportation system.

- The size and configuration of the rock cavern in which the facility will be housed. Different basic solutions have been discussed and cost comparisons have been made.

- The design and function of various man-made barriers between the waste and the rock.

- Leakage to the rock (diffusion), taking into consideration possible cracks in the barriers.

- Dilution conditions in the rock and in possible wells near the repository.

- Risks to the environment, where dispersion via one or more wells in the immediate vicinity of the repository or through the repository has been analyzed.

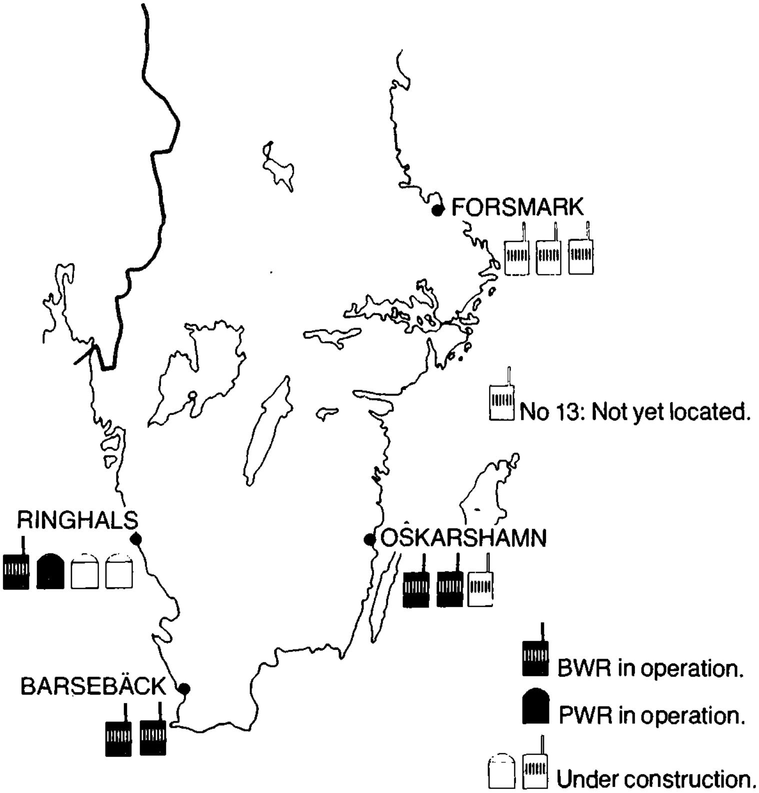
The layout work has also taken into consideration the proposed transportation system as well as convenient handling of the waste packages in the repository.

We hope that the results of this work will provide us with guidelines for the continued project work and indications as to where efforts should be concentrated in order to obtain a better and cheaper design.

Among the premises for the project work is that low-level waste from 13 nuclear power units (of approx. 10 000 MW) and from 30 years of operation are to be stored in the repository (see Fig. 1). If spent fuel from Swedish nuclear power units is reprocessed in the future, provisions must be made to permit an expansion of the repository for the low-level waste which must be then stored. This waste has not yet been specified, nor have decommissioning waste or core components been studied in detail as yet. However, the layout of the rock caverns and the man-made barriers have been designed on the premise that the facilities shall be capable of receiving all types of low-level waste, regardless of activity content and quantities. Economic and safety analyses can then result in an optimum combination of various studied alternatives in a manner which best meets the requirements imposed for different categories of waste. A depth of between 50 and 300 m below the surface of the ground has been discussed for the repository. It has been assumed that the repository will be located near an area with other nuclear activity, but other local conditions have not been taken into consideration.

The total quantity of waste is about 125 000 m^3 (see Table I). Of this total, solidified ion exchange resins constitute about 75%. This volume includes the concrete or bitumen which is currently added to solidify the waste at the nuclear power plants. In calculating the waste quantities, 0.1% fuel damages have been assumed. It has been estimated that a third of the waste packages will emit a surface dose rate in excess of 200 mrem/h. Approximately 200 000 packages will be transported

Figure 1



The Swedish nuclear power program decided in 1975.

TABLE I. ALMA REACTOR WASTE FROM 250.000 MWYe

Type of package	Volume	Number of package	Total volume m^3
Concrete blocks	1,73 m^3	36.000	63.000
Bitumen drums	200 l	66.000	20.000
Concrete tanks	9,6 m^3	1.300	12.000
Drums with ashes	200 l	19.000	6.000
Remainings	mostly 200 l drums	70.000	23.000
Total		193.000	124.000

to the final repository, unless some of the waste can be considered to be inactive or so short-lived that storage at the power plants is sufficient. The calculation of the total activity content shows that a maximum of 100,000 Ci will be deposited in Alma, not including core components and reprocessing waste (see Fig. 2).

New treatment methods for the low-level waste are currently being studied by PRAV. If these methods are employed, the previously specified waste volumes will be greatly reduced, which in turn can influence the evaluation of the design of the final repository.

TRANSPORTATION

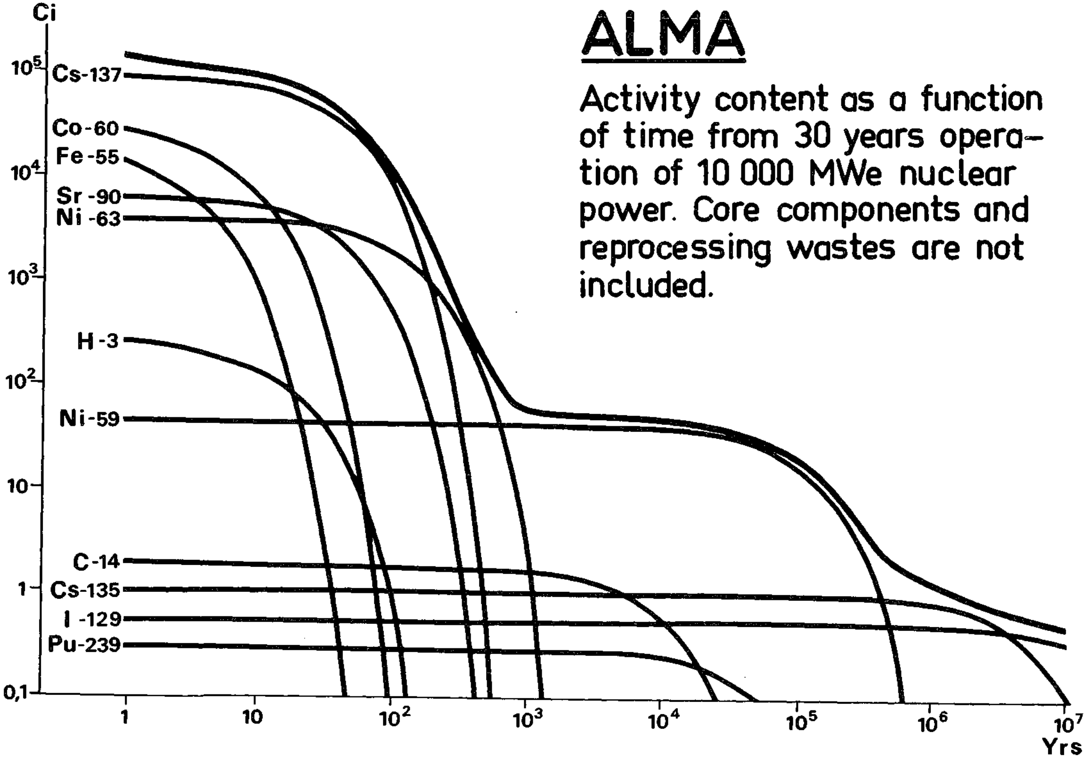
A transportation system has been designed by PRAV for transporting the waste from the power stations to the final repository. The waste is moved in transport containers of steel or concrete, depending upon the radiation shielding required (see Fig. 3). The up-to-100-tons heavy containers will be transported by sea in a ship specially designed for waste and spent fuel, and will be transferred between the power station and the ship and between the ship and the repository by means of hydraulic lift cars. The probability of shipwrecks where the cargo can be damaged is low, and the activity that would be released in such an event gives rise to low individual and collective doses.

LAYOUT OF ROCK CAVERNS

As already mentioned, our design studies of the final repository have dealt mainly with different designs of the cavities in the rock and the barriers placed between the waste and the rock. The three main alternatives that have been dealt with are:

- Horizontal rock vaults with a cross-sectional area of 500-600 m^2 (see Fig. 4).
- Vertical cylindrical caverns (silos) with a diameter of 30 m and a height of 60 m (see Fig. 5).

Figure 2

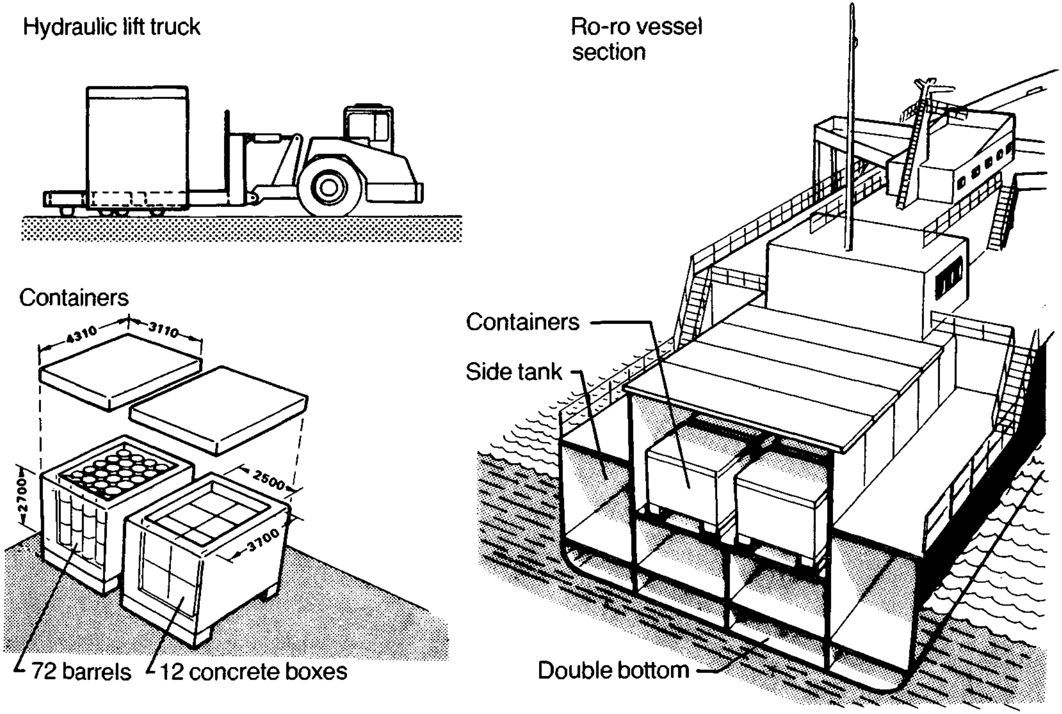


ALMA

Activity content as a function of time from 30 years operation of 10 000 MWe nuclear power. Core components and reprocessing wastes are not included.

Figure 3

ALMA Transportation system.



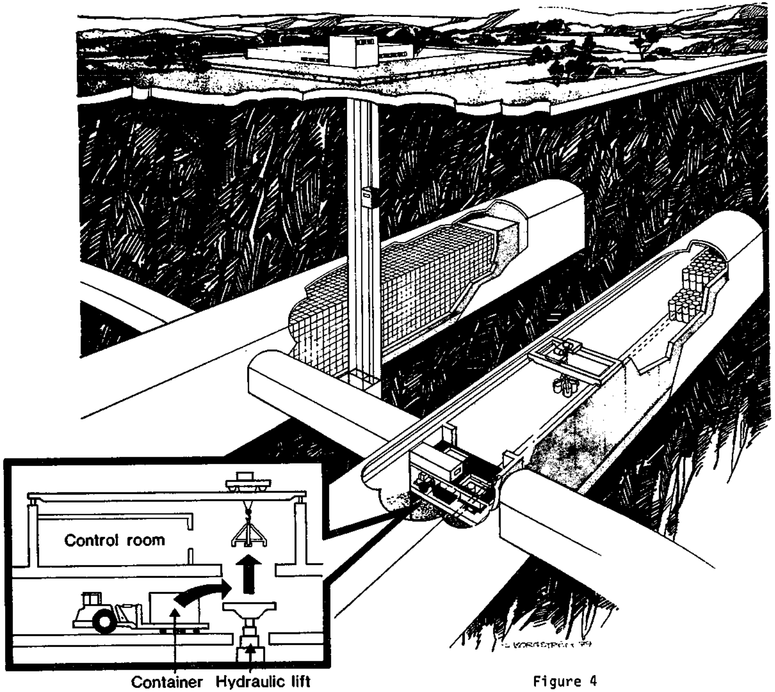
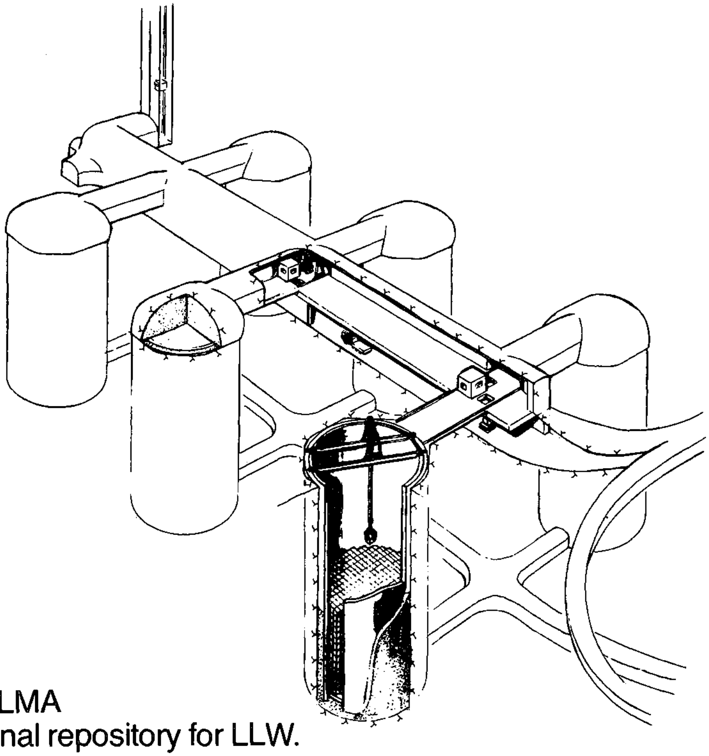


Figure 4

ALMA **Final repository for low- and medium level waste**

Figure 5



ALMA
Final repository for LLW.
Alt. 2 "silo".

AH Bergstrand/80

- A series of parallel tunnels with a cross-sectional area of about 100 m^2 (see Fig. 6).

The following factors are analyzed in the study:

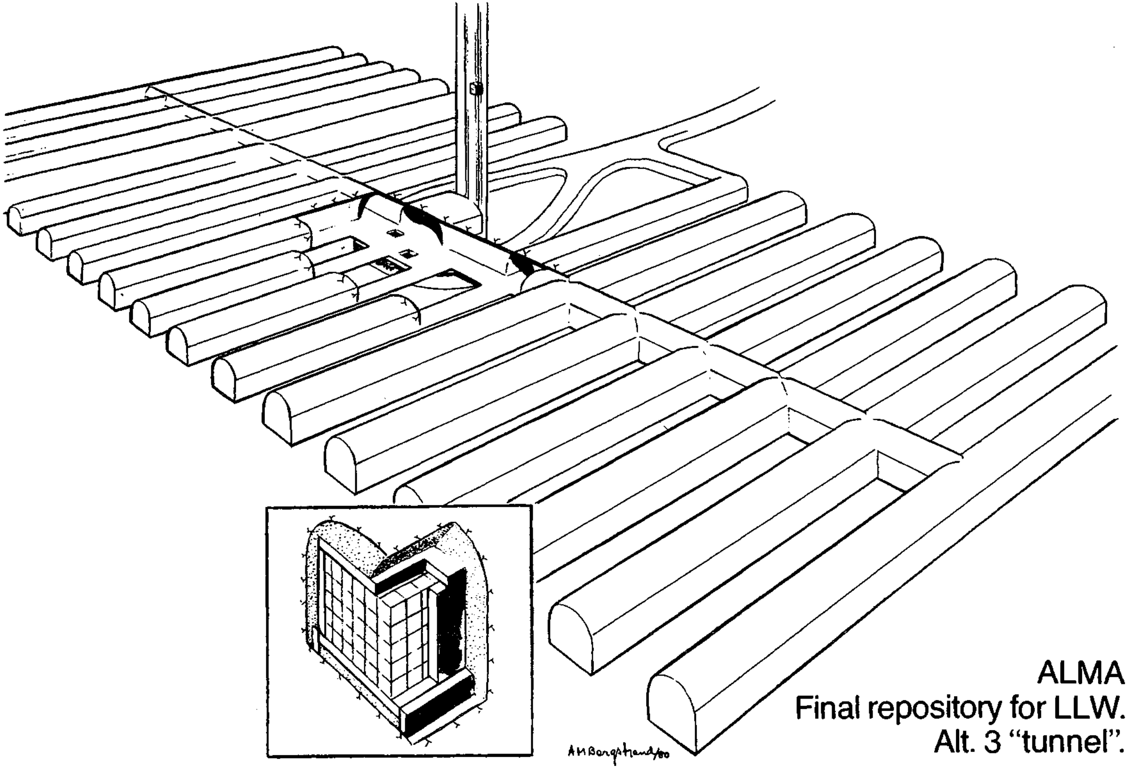
- requirements of rock and barrier material
- desirable material properties
- execution, work methods
- materials handling and operating conditions (main features)
- service and auxiliary systems (main features)
- cost comparisons
- timetable.

Some of the most important aspects of layout and choice of materials in the constructions are discussed in the following.

The concrete works are of decisive importance for the design of the rock vaults. Especially the small tunnels which have higher costs per volume available for waste deposition than the large rock vaults. However, they make lower demands on the quality of the rock and can be blasted out progressively, as needed. With our premises the first alternative gives the lowest total costs, but if, in the second alternative (silos), the diameter can be enlarged with 3 m, the costs will be equivalent for both alternatives (see Table II).

Materials handling and operating conditions also influence the choice of layout. It is assumed that all materials handling in the large rock vaults will be remote-controlled via overhead cranes, while the tunnel alternative is best suited for handling with a forklift truck or rail-mounted bridge crane. In the large rock vaults, the best solution has been found to be that of filling up remaining space with concrete or soil material after one or a few layers of waste material have been deposited. In most cases, this must be done before the repository is closed and thereby subjected to the high water pressures exerted by the groundwater. This backfilling operation can be done by remote control or from a radiation-shielded vehicle.

Figure 6



ALMA
Final repository for LLW.
Alt. 3 “tunnel”.

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Table II

ALMA - REPOSITORY COST

50 m below surface   Price January 1979

	Alt I Rock vaults SEK	Alt II Silos SEK	Alt III Tunnels SEK
Construction costs			
- Excavation	$55\cdot10^6$	$65\cdot10^6$	$62\cdot10^6$
- Concrete work	$62\cdot10^6$	$63\cdot10^6$	$112\cdot10^6$
- Moraine/betonite barrier	$5\cdot10^6$	$2\cdot10^6$	$6\cdot10^6$
- Misc	$61\cdot10^6$	$60\cdot10^6$	$55\cdot10^6$
Sum	$183\cdot10^6$	$190\cdot10^6$	$235\cdot10^6$
Closure cost	$82\cdot10^6$	$100\cdot10^6$	$120\cdot10^6$
TOTAL	$265\cdot10^6$	$290\cdot10^6$	$355\cdot10^6$

\$ 1 = 4,15 SEK

REDUCTION OF TOTAL COST IF A BARRIER IS EXCLUDED

	Alt I	Alt II	Alt III
Concrete barrier excluded	20 %	20 %	40 %
Moraine/betonite barrier excluded	30 %	30 %	40 %
Both barriers excluded	40 %	40 %	50 %

Repository cost \$ 500 per m^3 waste

Repository cost \$ $3\cdot10^{-5}$ per kWh

Transportation and operation cost are of the same order.

The layout of the facility is also of some importance for the dispersal of radioactivity to the rock following closure. This influence has been judged to be relatively small. The tunnel alternative is the one with the greatest extent and therefore leads to a greater dispersal of radioactivity, which should result in more favorable dilution conditions in the groundwater. On the negative side, it is more difficult to obtain good barriers in the tunnel alternative. This alternative is therefore preferable only when the activity level of the waste is low and where extra tunnel volumes have been created for excavation of the rock vaults.

MAN-MADE BARRIERS

Since the low-level waste imposes widely varying demands on isolation from the environment, the study considers alternative barriers:

- No extra man-made barrier (just the rock).
- Backfilling with concrete between waste and rock.
- Backfilling with a mixture of moraine and 5-10% bentonite.
- 50-70 cm of concrete nearest the waste and a 1-1.5 m layer of moraine-bentonite mixture outside of this.

Moraine without the addition of expensive bentonite has been discussed, but in view of the risk of subsidence and cracking, this alternative has not been dealt with further.

The main characteristics which barriers should possess are:

- low permeability
- durability
- strength
- good sorption properties
- cheap and easily available materials.

The materials which have been given the most attention in the study are concrete, moraine and clay (specially bentonite). Other materials such as asphalt, plastic and metals have been judged to have insufficient durability or to be too expensive.

Concrete is considered to have excellent sorption properties and, where good quality is available, low permeability as well, with values less than 10^{-9} cm/s. However, the sorption properties of concrete have not been thoroughly studied. We have therefore started laboratory tests at the Chalmers University of Technology in Gothenburg. It is known that concrete can reach an age of several thousand years, and in the highly favorably environment in question (low oxygen content, slow diffusion), it is reasonable to assume a life of many thousands of years. However, concrete can crack for many reasons and its imperviousness be jeopardized. At high humidity and uniform temperature, however, the risk of cracking is minimal, and with suitable reinforcement, crack width can be kept to <0.1 mm. Through cracks can be avoided entirely. Cracking occurs mainly during the curing phase, so that suitable sealing measures can generally be adopted prior to closure of the repository.

In most of our alternatives, concrete structures also funtion as radiation shields during operating time. The concrete walls also provide support for the stacking of the waste material and can serve as form work for back-pouring around the waste. The concrete structures in the final repository are not expected to be subjected to large stresses, so no special strength requirements need be imposed on the concrete.

The most ambitious barrier alternatives include both concrete and soil materials. By being mixed with bentonite, soil material can be given properties so that it prevents cracks in the material entirely. The bentonite swells in the presence of water and exerts a swelling pressure that counteracts any subsidence due to insufficiently compacted material. The bentonite content should therefore be increased in those portions of the barrier where compacting cannot be executed with good results. Moraine is a common soil type in Sweden and is widely used as a sealant in earth dams.

With suitable grading and the addition of bentonite, permeability values as low as $<10^{-10}$ cm/s can be expected. With these low flow rates prevailing through the repository, diffusion is the principle transport mechanism for the radioactive nuclides through the barriers. A barrier of the moraine-bentonite mixture will remain intact even if minor displacement fractures occur in the rock around the repository in the event of, for example, earthquakes. However, the bentonite content should be kept as low as possible, partly because bentonite is a relatively expensive soil material and partly because compactibility is reduced and porosity increased at higher bentonite contents (8-10%).

Our design study makes no claims to be complete, but rather is intended to provide a basis for the coming risk analysis and for a decision as to what we should concentrate our continued efforts on. Owing to public concern about radioactivity, it may be necessary to make a final repository for low-level waste far safer than purely rational or economical considerations would motivate. Providing that the costs of such extra safety are moderate, the public relations gain can be worth the price. Preliminary assessments have shown that \$ 500 /m^3 waste or \$ $3 \cdot 10^{-5}$ /kWh can be realistically achieved, even with the most advanced designs covered by our study. (Only construction costs.)

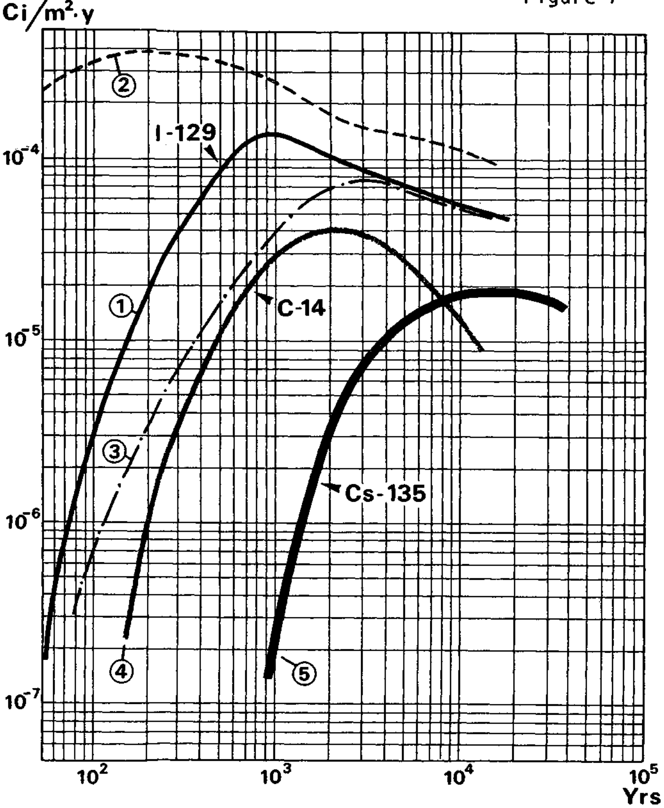
We have not taken a stand on the depth of the repository, but increasing this depth from 100 m to 300 m would increase construction costs by 30-40%.

Depending on local conditions, repository depth, etc., it is judged that a final repository for low-level waste could be operative in Sweden five to six years after a decision is made to construct it.

ACTIVITY LEAKAGE FROM THE ROCK CAVERNS

The quantities of radioactivity that can leak out of a repository such as the one sketched above are very small. Diffusion calculations that also take into account decay and sorption have been carried out in order to ascertain which nuclides dominate and when and how much activity can escape from the repository. Diffusion constants and maximum quantity of activity leakage per unit time are given in Table III. Parameter studies show that possible cracks in the concrete barrier have little effect on the final results (see Fig. 7). The table shows

Figure 7



ALMA

Diffusion/m · year as a function of time

Assumption: 1 Ci/m³ for each nuclide

① —— I-129, no crack, homogeneous rock

② - - - I-129, 0,5 mm crack, homogeneous rock

③ —·— I-129, 0,1 mm crack/m in rock only

④ —— C-14, no crack, homogeneous rock

⑤ ▬▬ Cs-135, no crack, homogeneous rock

Table III

Final repository for low level waste, 250 000 MWyear

Maximum flow of different nuclides to the rock

Man-made barrier of 0,7 m concrete + 1,5 m moraine-bentonite

Nuclide	Diffusion constant, m /y in concrete	Diffusion constant, m /y in moraine – bentonite	Maximum total activity content C_2	Maximum flow to the rock Ci/m² and Year	Maximum flow to the rock Ci / Year
H – 3	7×10^{-4}	7×10^{-2}	260	3×10^{-12}	1×10^{-7}
C – 14	3×10^{-4}	3×10^{-2}	2,3	3×10^{-10}	1×10^{-5}
Ni – 59	4×10^{-9}	8×10^{-6}	46	1×10^{-22}	6×10^{-18}
Co – 60	4×10^{-9}	8×10^{-6}	27.000	1×10^{-80}	3×10^{-76}
Ni – 63	4×10^{-9}	8×10^{-6}	3.900	3×10^{-59}	1×10^{-54}
Sr – 90	7×10^{-6}	7×10^{-5}	6.100	5×10^{-33}	2×10^{-28}
I – 129	6×10^{-4}	6×10^{-2}	0,5	4×10^{-10}	2×10^{-5}
Cs – 135	3×10^{-4}	2×10^{-4}	1,0	2×10^{-10}	6×10^{-6}
Cs – 137	3×10^{-4}	2×10^{-4}	90.000	4×10^{-17}	1×10^{-12}
Pu – 239	* 4×10^{-9}	3×10^{-6}	0,3	3×10^{-27}	1×10^{-22}

* Conservative. A more realistic value is 10^{-12} m²/y.

that only non-interacting and long-lived nuclides are of any importance. Concentration maxima for activity leakage associated with these nuclides normally occur 1000-10,000 years after closure of the repository. Iodine-129, which also has high toxicity, is the nuclide that gives the largest dose burdens, despite the fact that the quantity of iodine-129 in the low-level waste is very low in relation to the total activity content.

DILUTION CONDITIONS IN THE BEDROCK

The radioactivity that passes through the man-made barriers in the final repository is further transported in the rock mainly through the groundwater. Preliminary analyses have shown that the greatest risks to biological life occur when water from wells drilled near or through the final repository is consumed.

A factor of great importance in this respect is the amount of water with which the radioactive nuclides are diluted.

In order to shed light on these questions, different factors that affect the dilution of the radioactivity have been analyzed, after which our well cases have been chosen for the coming risk analyses.

Dilution in the groundwater and the size of the well's influence area are affected by the following factors:

- The rock's hydraulic conductivity with existing inhomogeneities (crush or fracture zones).
- Topography and gradient conditions.
- The porosity of the rock (which is related within certain limits to the rock's hydraulic conductivity).
- Infiltration and precipitation.
- Well water pumping rate.
- Well depth and drawdown.
- Extent of waste repository and depth below surface.

- Sorption properties of rock and fracture filler material (although these have not been taken into account in calculating the dispersal of activity in the bedrock).

Naturally, with all of these parameters, an infinite number of well situations can be sketched. We have chosen to examine two cases that have been judged to give the highest dose burdens to human beings. In the first case, a well is drilled in the vicinity of the final repository so that all leaking activity is captured in the well. At the same time, the well is situated so that its capacity is the minimum possible. The well is drilled midway between the two storage chambers. In the second case, the well is drilled through one of the storage chambers. To give the highest doses the pumping rate is chosen to be as low as possible, suitable only for a small family (2-3 persons). It is assumed that the second case will not be permitted until 100 years after closure of the repository. The final repository has been located underneath the watershed, 75-105 m below the surface, in a relatively homogeneous rock slab sized 800-1000 m. The rock slab is surrounded by fracture or crush zones into which groundwater flows from the rock slab (see Fig. 8).

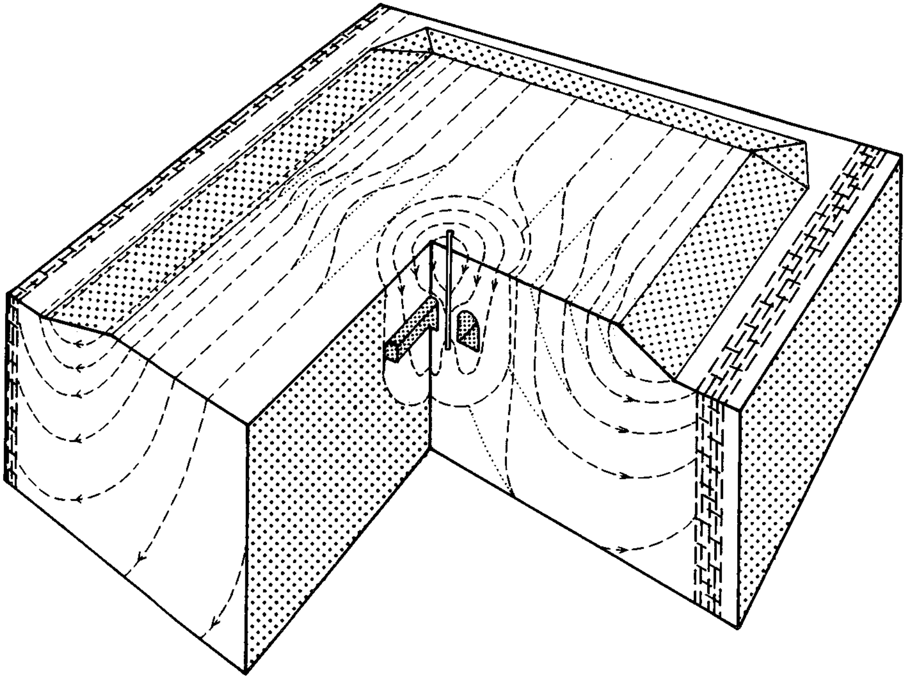
With the chosen premises, the well data can be calculated. Table IV gives the values for well depth, pumping capacity and radius of influence.

Table IV

ALMA well data chosen for the risk analyses.

	Well in the center between the two rock caverns	Family well through the repository
Well depth	100 m	130 m
Drawdown	80 m	12.5 m
Yield	$8 \cdot 10^{-5}$ m^3/s	$8 \cdot 10^{-5}$ m^3/s
Average Production	$5 \cdot 10^{-5}$ m^3/s	10^{-5} m^3/s
Hydraulic conductivity of the rock mass	10^{-8} m/s	10^{-8} m/s
Radius of influence by average production	~100 m	~50 m

Figure 8



Interference between the ground waterflow to a central well in a rock block (hill) and a natural (topographically induced) flow to the surrounding valleys (fracture zones).

The concentration of different radioactive substances in the well water can then be calculated.

The chosen data are very conservative. In the first case, given all other positions of the well, a higher pumping capacity (in order for all activity to come to the well), and either an increase or a decrease of pumping capacity or well depth, leads to a lower concentration of radioactive substances in the well.

Locating the final repository at a lower level leads to some increase in the pumping capacity necessary to capture all leaking activity, but this effect is relatively limited. However, the probability that a well will be contaminated with radioactivity from the repository is generally reduced with increasing repository depth. Most rock wells in Sweden are less than 60 m deep and the number of such wells more than 150 m is less than 3% (more than 200 m deep <0 5%).

ACTIVITY DISPERSION BY WELL WATER

All data in this section must be regarded as very preliminary. They may be changed in the final report, which will be completed in the spring of 1980.

The maximum concentration in the well water has been calculated with the well data presented earlier. They are compared with the ICRP MPC values (MPC = maximum permissible concentration) for drinking water. The maximum dose rates to individuals have been estimated as well. The preliminary results for the most important nuclides in the first well case are presented in Table V.

Table V

	Time to maximum in years	Maximum concentration in well, Ci/m^3	MPC$_W$ value 168h, critical organ Ci/m3	Maximum dose rate to the critical group, individual (Sv/y)
H-3	100	$7\cdot10^{-11}$	$3\cdot10^{-2}$	$4\cdot10^{-11}$
C-14	1000	$7\cdot10^{-9}$	$8\cdot10^{-3}$	$3\cdot10^{-8}$
I-129	1000	$1\cdot10^{-8}$	$4\cdot10^{-6}$	$2\cdot10^{-5}$=(2 mrem/y)
Cs-135	10000	$4\cdot10^{-9}$	$1\cdot10^{-3}$	$1\cdot10^{-7}$

The nuclide which gives the highest dose rate is I-129. However, new data on I-129 content in the waste reduces this dose rate by a factor of ten. Thus it is obvious that the individual doses to a critical group are insignificant.

The second case (intrusion) must be considered as very special, but has been treated in order to illustrate the possible effects if regulations against well drilling in the vicinity are limited. This scenario is very unlikely and the data chosen are most unfavorable.

The maximum concentration in the well water will be $1 \cdot 10^{-5}$ Ci/m^3. If water is consumed from a well through the repository 100 years after sealing and only 10^{-5} m^3/s (860 l/day) is pumped from the well, the dominant nuclide is Cs-137, and the concentration is still below the MPC$_w$ value, $2 \cdot 10^{-4}$ Ci/m^3.

The maximum individual dose rate is calculated to $3 \cdot 10^{-3}$ Sv/y (300 mrem/y) and will decrease gradually with time.

The conclusion is that a repository, constructed according to Fig. 4, gives very small radioactive doses to any individual in the future and there are still many possibilities to further reduce this risk. One way is to locate the repository under the sea; another is to choose a more permeable rock. The continued work in this field and a study of rock conditions at possible sites will give the most adequate layout for the final repository for our low-level waste.