Design Study of a Radioactive Waste Repository to be Mined in a Medium-Size Salt Dome

J. Hamstra and P.Th. Velzeboer
Netherlands Energy Research Foundation (ECN) and The University of Technology, Delft, Holland

ABSTRACT

Based on an assumed nuclear energy program of 1 Million MWe/year electricity production, a design study was made of a radioactive waste repository to be mined in a medium-size salt dome. Model calculations were made to establish the consequences of the decay heat production in the buried solidified high-level reprocessing waste with regard to temperature rises in the rock salt and the structural stability of the salt dome for two different burial configurations.

The results of these calculations reviewed resulting in a preference for both a vertically orientated high-level waste burial configuration and a burial sequence in which the cooling capacity of the mine ventilation is utilized.

The overall mine lay-out with respect to different categories of waste and the normal dry mining techniques to be used for this burial mining are treated as well as some special provisions required to achieve both a high standard of safety and a high-level of flexibility during the operational phase of this radioactive waste respository.

INTRODUCTION

As part of a research program on the ultimate disposal of waste from the nuclear fuel cycle, a study has been made on the use of salt formations for this purpose. All preparatory work for this study had to be based on data from literature and on calculations based on a salt dome model to establish the consequences of the decay heat and the structural stability of the salt dome for different burial configurations. The conceptual design study of a radioactive waste repository in a salt dome as presented in this report will be based on two major categories of design criteria, capacity and design requirements.

Capacity requirements—based on a hypothetical nuclear power construction and operation program and on estimations with regard to the quantities of solid radioactive waste of the different categories deriving from such a nuclear power program, as explained more fully in section 2; these capacity figures should be considered purely as calculation data and in no way be related to a Netherlands nuclear power program.

Quality requirements—primarily based on rather stringent safety requirements both for the long-term containment of the buried radioactive wastes and during the operational period of the waste repository, as explained more fully in section 3.

From these criteria, the decay heat developed in the solidified high-level reprocessing waste which creates a heat load in the rock salt surrounding the buried high-level reprocessing waste canisters proved to be a dominating design factor for the lay-out of the waste repository. Not only will there be limits to the temperature rise to be allowed in the rock salt directly surrounding the waste canisters, but the expansion movement in the rock salt mass and the overlying sediments as a consequence of rock salt temperature rise may have to be limited in order to maintain the structural stability of the salt dome and also the structural stability of the waste repository excavations during the operational period.

A preliminary approximation of possible expansion movements was made for a salt dome model and for two extremely different burial configurations arranged in that salt dome[1]. A summary of this study will be given in section 4. This first approach was followed by further rock salt temperature calculations for a variety of multi-layer burial configurations[2], all of which were based on the restricting assumption that only proven drilling techniques were to be used and that in rock salt the proven techniques do not allow drilling dry vertical disposal boreholes deeper than 55 m. A review of these multi-layer temperature calculations will be given in section 5.

The lay-out of the waste repository and more specifically the subdivision of the rock salt mass available for waste repository activities as developed in the conceptual design given in section 6 is mainly based on the outcome of these multi-layer temperature calculations. In this section attention is also paid to the problem of the unpredictable internal structure of a salt dome with regard to the presence of evaporites other than halite.

Section 7 deals with the construction of the main shafts and the dry mining techniques to be used for the mine roadways and the burial facilities for the different categories of waste. In section 8 attention will be paid to the burial sequence in which the high-level reprocessing waste canisters will be placed and the use that can be made in this respect of the cooling capacity of the mine ventilation. Finally in section 9 attention is focussed on the possibility of simplifying the disposal of high-level reprocessing waste in a salt dome, if techniques could be developed to drill dry vertical disposal boreholes from a depth of 600 m down to 900 or even 1,000 m.

CAPACITY REQUIREMENTS FOR A RADIOACTIVE WASTE REPOSITORY

The capacity requirements are subdivided into two categories of solid radioactive wastes; one that comprises all wastes in which no decay heat or a negligible amount of decay heat is developed and that thus can be disposed of in bulk, and the other category, comprising the solidified high-level reprocessing waste, that due to its decay heat requires a disperse disposal in relatively small units. In order not to underestimate the waste disposal problem the capacity requirements were primarily based on a nuclear power construction program resulting in a total of 25,000 MWe nuclear power capacity by the year 2015. To limit the problem, the operational period of each nuclear power plant was set at 40 years, assuming that within 40 years from now other ways of generating electricity will be available for replacing the present nuclear power. In doing so the different categories of solid radioactive waste deriving from the nuclear fuel cycle that will have to be disposed of were quantified on the basis of a total of 1 Million MWe-year nuclear power production.

For the solid radioactive wastes that can be disposed of in bulk, the capacity requirements were based on amounts of low-, medium- and high-level waste estimated to originate yearly from the nuclear power stations. In addition a yearly supply of low-level waste from hospitals and laboratories was assumed to continue during the period of operation of the waste repository. Finally the assumption was made that the radioactive waste rubble resulting from the ultimate dismantling and demolition of decommissioned nuclear power plants would also have to be disposed of in the repository.

For the category comprising the solidified high-level reprocessing waste, the assumptions were made, that the high-level waste from reprocessing one ton of spent fuel can be contained in 90 liters of solidified material and that the canisters received for disposal will each contain 50 liters of solidified material.

The total amounts of solid radioactive waste that thus will require disposal capacity can be summarized in round figures as follows.

Disposal in bulk

1 Million MWe-year nuclear power station operation

Low-level waste	100,000 m³	
Medium-level waste	25,000 m³	
High-level waste	15,000 m³	
	Sub total	140,000 m³
Dismantling of the nuclear power stations		80,000 m³
Hospitals and laboratories (100 year period)		50,000 m³
	Total supply for disposal in bulk	270,000 m³

HLW-disposal

1 Million MWe-year nuclear power station operation

Number of 50 liter canisters (20 cm diameter, 2 m length)	50,000

It was assumed that a certain yearly supply of low- and medium-level waste will exist already, derived from hospitals and laboratories and from two nuclear power stations already in operation. Figure 1 shows how the supply of bulk disposal wastes will increase gradually according to the assumed increase in nuclear power capacity until the year 2015. From then on each nuclear power station is assumed to be taken out of operation once it has operated for 40 years, resulting in a termination of nuclear power production by the year 2055. From then on a delay of at least 25 years is assumed to occur before the last nuclear power station will be dismantled and its radioactive rubble disposed of in the waste repository. It is worth noting that the maximum yearly supply of bulk waste is of the order of

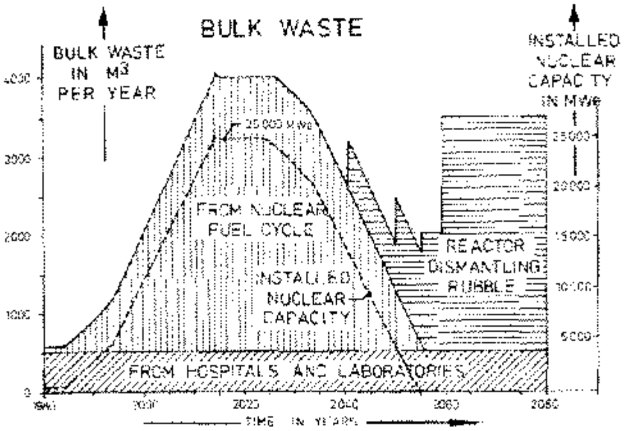

Figure 1. Estimate yearly supply of bulkwaste.

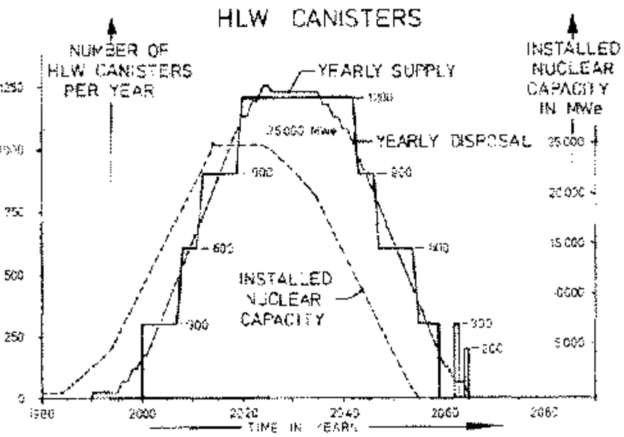

Figure 2. Estimate yearly supply of HLW-canisters.

4,000 m³ per year. It is also worth stressing the point that the waste repository will have to remain accessible for bulk disposal for a period of some 100 years. Consequently also the low- and medium-level waste supply from hospitals and laboratories are put into the estimate for that period of time.

The number of canisters with solidified high-level reprocessing waste offered for disposal will gradually increase from 25 per year in the year 1990 to a maximum of 1,250 canisters per year by the year 2025 and then decrease until the last canisters will be received by the year 2065.

An interim waterbasin storage on the mine site is assumed to be necessary for accumulating canisters such that a regular disposal frequency can be maintained notwithstanding irregularities in the supply of these canisters from the reprocessors. The disposal of canisters can thus start at 300 per year from the year 2000, then increase via 600 and 900 to a maximum of 1,200 per year during the period from 2020 until 2036. From then on the disposal rate will decrease until the last canister may be assumed to be disposed of by the year 2065. Fig. 2 shows in graph the estimated yearly supply and yearly disposal of the HLW-canisters.

QUALITY REQUIREMENTS FOR A RADIOACTIVE WASTE REPOSITORY

The prime quality requirements for a radioactive waste repository, all aiming at a high degree of radiologic safety, are: 1) to select carefully the salt dome to be designated for radioactive waste disposal purpose on its favorable geohydrologic and geologic properties; 2) to make a careful access to the inside of the salt dome and to carry out the waste repository mining operations such that these favorable properties are not disturbed permanently; 3) to accomplish the waste disposal operations in such a way that radiation dose rates for the workers in the mine and on the mine site will remain well within acceptable levels and no unacceptable increase in radiation level will occur in the environment surrounding that site; 4) to maintain a containment shield of rock salt of about 200 m thickness around the waste repository as undisturbed as possible: and 5) to seal carefully the waste repository and its shafts after decommissioning in such a way that this rock salt containment shield will keep its function for the long term.

Secondary quality requirements worth mentioning are: 1) to use only proven techniques and procedures for making the shafts, for mining the excavations and for disposing of the different categories of waste; 2) if new techniques are to be used, to test these experimentally and in-situ; and 3) to maintain a high degree of flexibility of disposal methods in order to be able to cope with qualitative and quantitative changes for the different categories of waste.

THERMAL LOADING OF A SALT DOME

The decay heat released from the solidified high-level reprocessing waste will create a heat load of the rock salt surrounding the buried HLW-canisters, which will result in a rise in rock salt temperature and in a consequent expansion movement in the rock salt structure. As a first approach to determine the thermal loading consequences for HLW-repository to be mined in a salt dome, the following input data were used for calculating temperature distributions in a salt dome model[1]:

As shown in Figure 3 the salt dome model was supposed to be cylindrical with a diameter of 1,500 m, to have its flat top rock salt situated at a depth of 250 m and to originate from a mother salt layer below 3,000 m and at least 300 m thick.

The initial heat source was chosen to be 30 MW at the moment of disposal and was assumed to decay with a half-life of 30 years to a minimum value of 0.25 MW. This heat source is based on the amount of solidified high-level waste derived from reprocessing of spent fuel that originates from 40 years of operation of 25 light-water reactors of 1,000 MWe capacity each and assuming a 10-year decay period preceding the disposal. This initial heat source was supposed to be spread over a total of 50,000 canisters, each

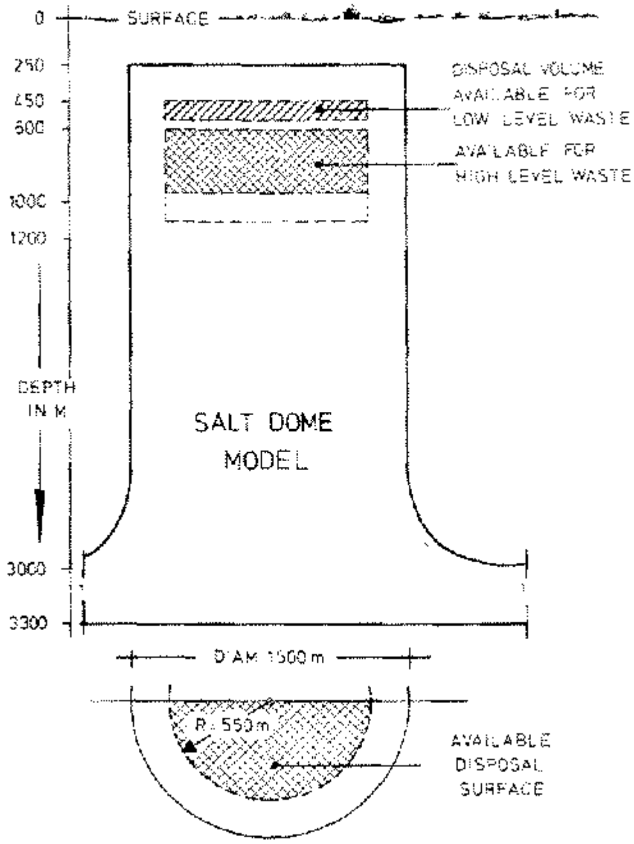

Figure 3. Salt dome model.

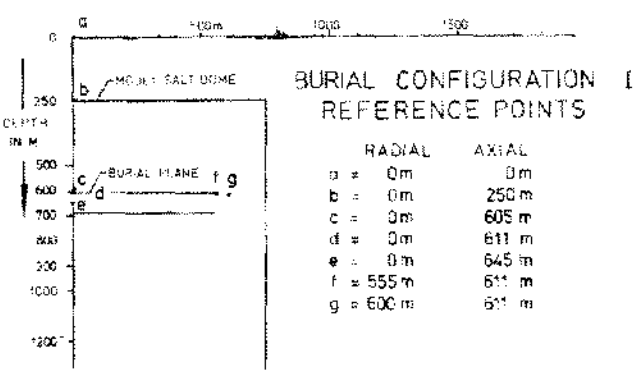

Figure 4. Burial configuration I.

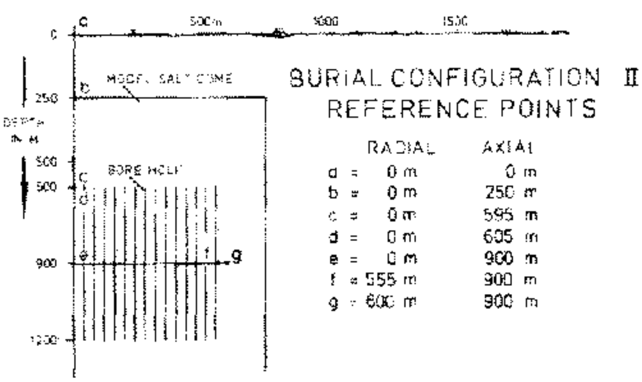

Figure 5. Burial configuration II.

containing 50 l of waste, having a diameter of 20 cm, requiring a disposal bore-hole length of 2 m and thus resulting in a linear heat source of 300 Watt per m. The 50,000 canisters were assumed to be buried in vertical bore-holes drilled within a containment shield of rock salt of at least 200 m thickness in any direction, from 600 m depth down to some 900 m, possibly 1,200 m, as a maximum attainable disposal depth.

These input data being set, the following two burial configurations were studied as being two purposely formulated extreme possibilities[2]:

Burial configuration I.—As shown in Figure 4, the 50,000 canisters were assumed to be concentrated in two horizontal circular burial areas with a radius of 550 m, situated at a depth of 608 m and 686 m respectively. Spaced at a pitch of about 10 m in a square pattern 8,333 disposal holes were assumed to be drilled in each area, each disposal hole of sufficient depth to house a stack of 3 HLW-canisters; and

Burial configuration II.—As shown in Figure 5, the 50,000 canisters were assumed to be spread over a maximum burial volume within a radius of 550 m, by drilling 167 disposal holes from a depth of 600 m down to a depth of 1,200 m, spaced at a pitch of about 75 m in a square pattern. The depth of these disposal holes is sufficient to house a stack of 300 canisters.

The transient temperature distributions in the rock salt surrounding the buried HLW-canisters were calculated using the computer program TROTYL based on the differential method. The material properties applied in the calculations were assumed to be temperature independent for the temperature increase envisaged. This assumption allows temperature rises which are calculated separately for two or more different heat sources to be superimposed. This feature allowed the simple incorporation of the geothermal gradient in the global temperature distributions, calculated for the specific reference points a up to g indicated in the Figures 4 and 5, and reproduced as rock salt temperature curves for Burial configuration I in Figure 6 and for Burial configuration II in Figure 7. When one compares the temperature curves for the different reference points and for the two burial configurations, the effect of the far greater rock salt mass in dissipating heat in Burial configuration II becomes evident. The maximum global rock salt temperatures are not only considerably lower, 70°C for configuration II against 108°C for configuration I, these maxima are also reached at a considerably later stage.

One of the preliminary conclusions to be drawn from these first figures is that the heat source of 30 MW initially

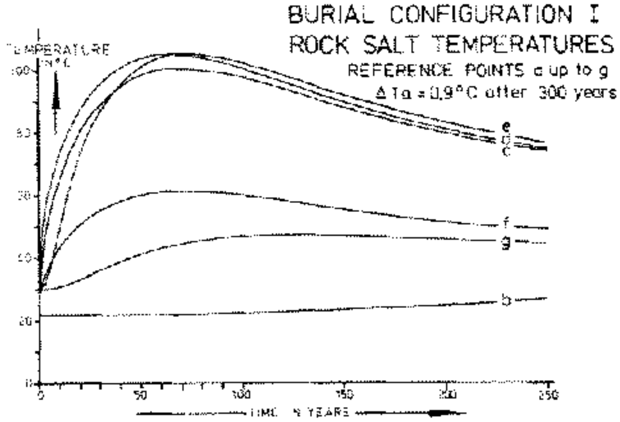

Figure 6. Burial configuration I, rock salt temperatures versus time for reference points.

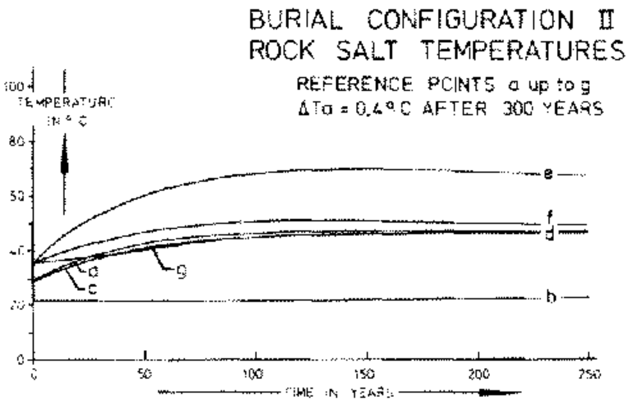

Figure 7. Burial configuration II, rock salt temperatures versus time for reference points.

does not look excessive, from the point of view of maximum rock salt temperatures, when accommodated in a rock salt structure of the size of the chosen salt dome model. The question then can be raised whether the structural stability of this salt dome model will not be affected unacceptably by the process of heat dissipation. For a first approximate answer to this question the rock salt and the overlying sediments were assumed to have a linear elastic mechanical response to the calculated temperature rises. This approximation leads to an overestimation because neither mining excavations nor possible salt creep were accounted for in this calculation.

The results are summarized in Figure 8 with vertical displacements of the top rock salt for the two burial configurations after 67, 145 and 300 years respectively. In Figure 9 the maximum displacements are given that may occur vertically on the centerline of the salt dome at top rock salt level and that may occur in the horizontal direction at the edge of the burial area for both configurations.

From these calculations one also can draw the conclusion, that from the geomechanical point of view, a heat source of 30 MW initially does not look excessive for the size of the chosen salt dome model. Figure 8 clearly indicates a favorable effect in the form of a decrease in vertical displacement as a result of the greater rock salt mass taking part in the process of heat dissipation for the case of Burial configuration II. In general, maximum displacements in the order of 0.5 to 1 cm per year and less than 50 cm in hundreds of years compare favorably with other rock movements due to mining operations. Even a doubling of these figures, that is a doubling of the initial heat source and HLW-canister storage capacity, does not look unacceptable from the structural stability point of view if a burial configuration can be found in which the maximum rock salt temperature itself also can be kept within acceptable limits. Within the limitation of only using proven drilling techniques and thus restricting the vertical depth of the disposal holes to 55 m, a solution was sought for approaching the favorable effects of Burial configuration II by making a multi-layer burial configuration.

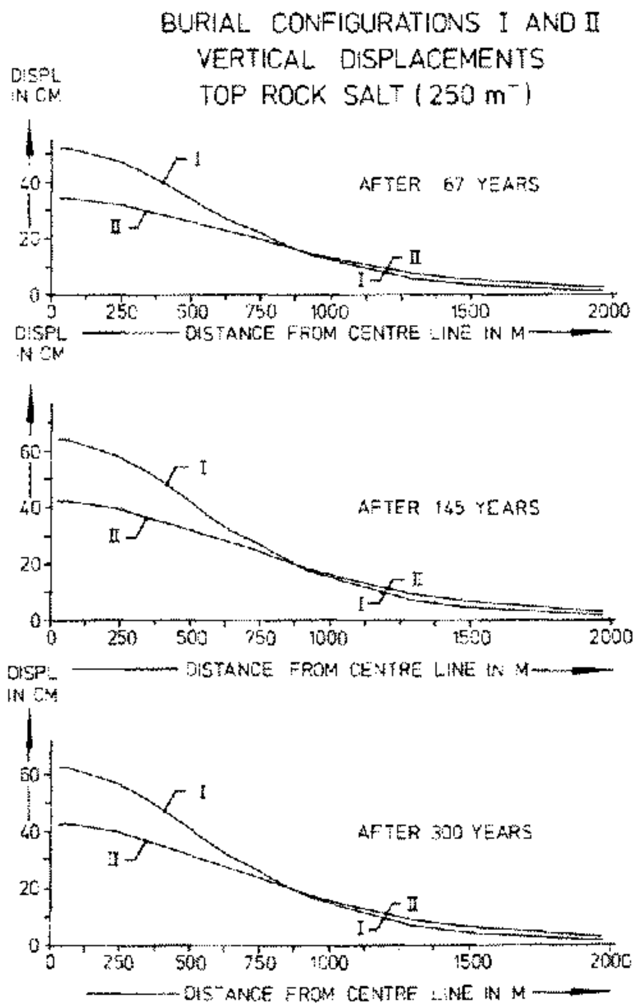

Figure 8. Burial configurations I and II, vertical displacements top rock salt.

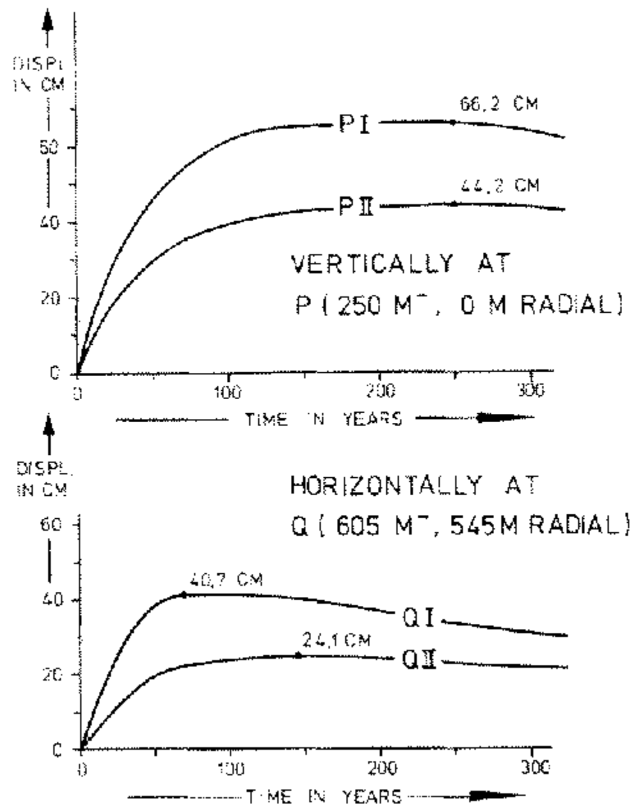

Figure 9. Burial configurations I and II, maximum displacements.

MULTI-LAYER BURIAL CONFIGURATIONS

As a result of the temperature calculations for the former two burial configurations, a unit cell model was developed to calculate local and global rock salt temperatures for five different two-layer burial configurations, shown in Figure 10 as the Burial configurations III A, B, C, D and E[2].

The effect of a decrease in maximum global temperatures, because of an increase in distance between the two burial layers, is evident when comparing the global rock salt temperature lines for these five two-layer burial configurations given in the Figures 11 to 15. The path of the radial temperature distribution in a unit cell of rock salt around each stack of HLW-canisters is given for a plane half-way between the stack of canisters in the upper burial layer of Burial configuration III-B (Fig. 16) and then the matching radial temperature distribution is given at roadway level (Fig. 17). It should be noted that all these temperature lines were calculated without taking into account the presence of the roadway excavations and the cooling capacity of the mine ventilation in these roadways.

The rise in rock salt temperatures at roadway level from about 40°C 5 years after burial of the HLW-canisters up to about 70°C 26 years after burial clearly indicates a limitation in time for the accessibility of the HLW-canister burial roadways.

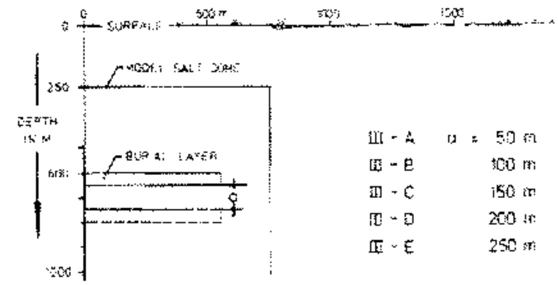

Figure 10. Burial configurations III, distance between burial layers.

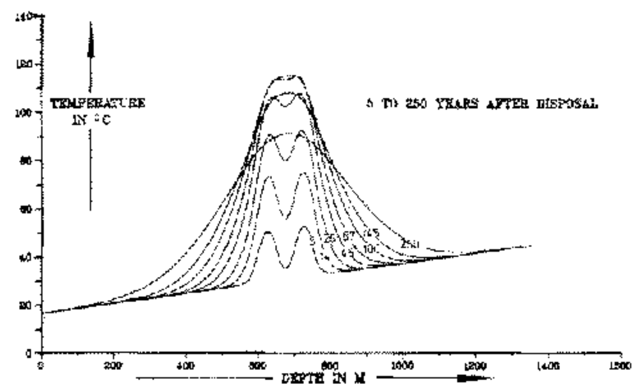

Figure 11. Configuration III-A, global temperatures.

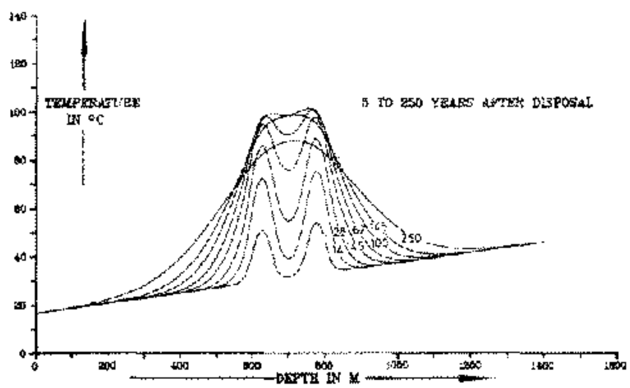

Figure 12. Configuration III-B, global temperatures.

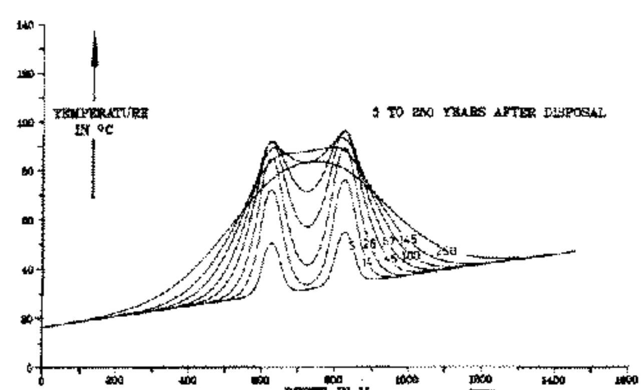

Figure 13. Configuration III-C, global temperatures.

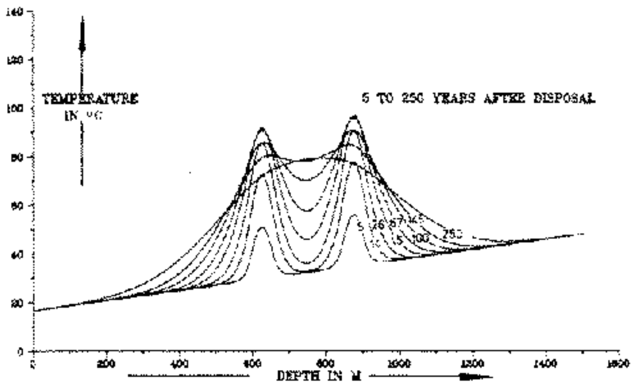

Figure 14. Configuration III-D, global temperatures.

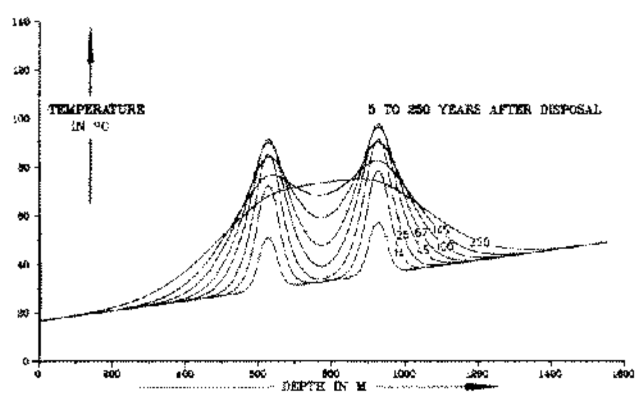

Figure 15. Configuration III-E, global temperatures.

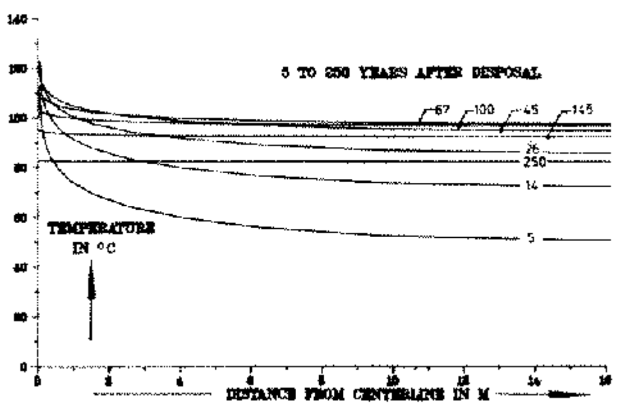

Figure 16. Configuration III-B, radial temperature distribution at a depth of 625 m.

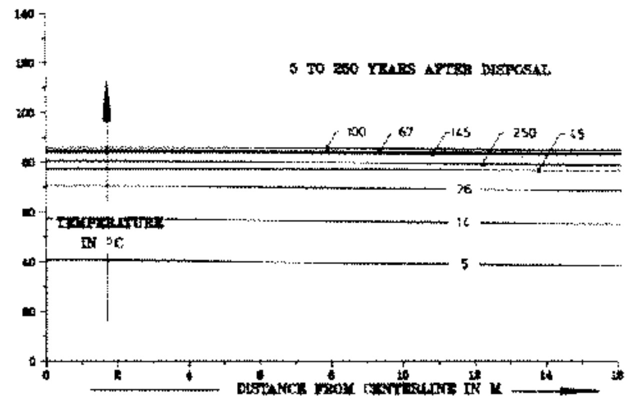

Figure 17. Configuration III-B, radial temperature distribution at a depth of 595 m.

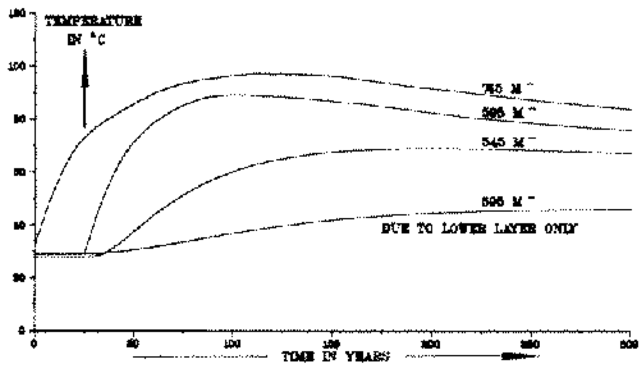

Figure 18. Configuration III-B, temperatures at roadway levels.

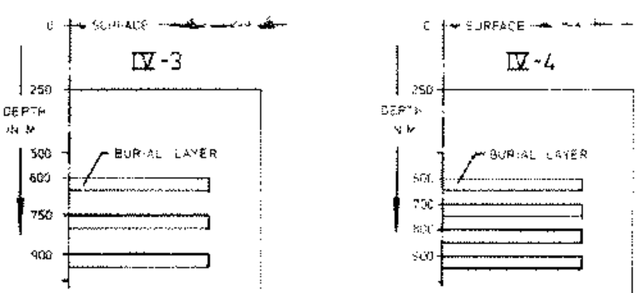

Figure 19. Burial configurations IV-3 and IV-4.

Figure 18 shows the temperature lines for the different mining levels for the Burial configuration III-B, the 745 m level for the deepest HLW-canister burial level to be used first, the 595 m level for the second HLW-canister burial level and the 545 m level at which mining activities will proceed during some 100 years for providing low-level waste disposal cavities. Specifically the temperature line for the deepest low-level waste disposal mining level on which work is assumed to continue long after the last HLW-canister will be buried again indicates that a possible better spreading of the HLW-canisters, i.e. an increase in number of HLW-canister burial levels, might be worth aiming at. Therefore temperature calculations were also made for a three-layer and a four-layer burial configuration as shown in Figure 19 and marked as Burial configurations IV-3 and IV-4[2]. It should be noted that for both these configurations the deepest mining level was assumed to be 900 m.

The results of the temperature calculations are summarized in global temperatures on the center line of the salt dome for Burial configurations IV-3 in Figure 20 and for Burial configuration IV-4 in Figure 21. The temperature lines for the different roadway levels are given for Burial

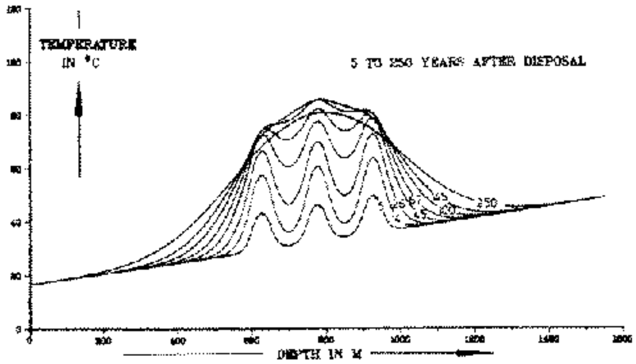

Figure 20. Configuration IV-3, global temperatures.

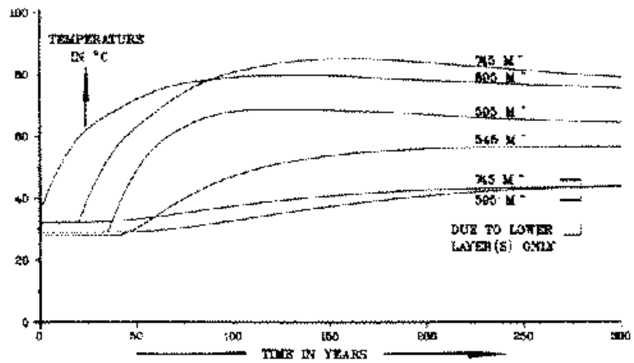

Figure 22. Configuration IV-3, temperatures at roadway levels.

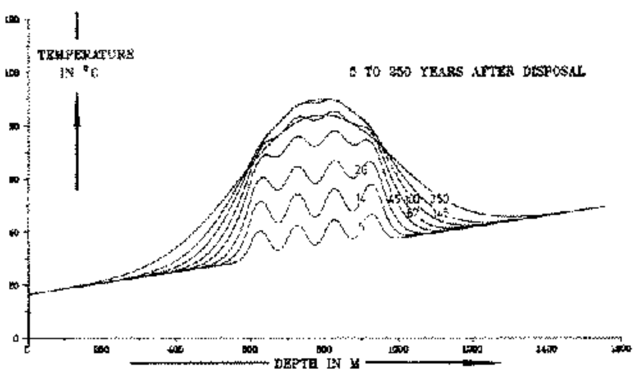

Figure 21. Configuration IV-4, global temperatures.

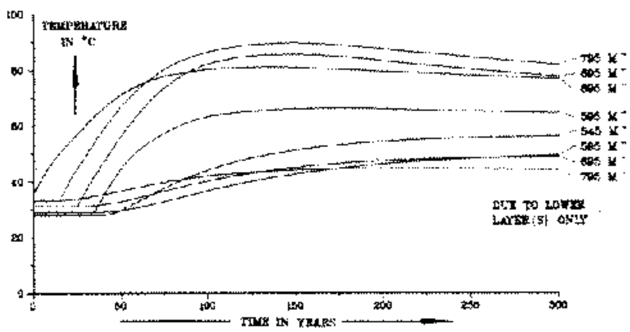

Figure 23. Configuration IV-4, temperatures at roadway levels.

configuration IV-3 in Figure 22 and for Burial configuration IV-4 in Figure 23. The very limited favorable effect of a further decrease in loading density per burial layer when one goes from a three to a four layer burial configuration, gave way to a preference for the Burial configuration IV-3 as the starting point for the conceptual design outlined in the next paragraph.

As shown in Figure 29 the nominal number of bore-holes resulting from the chosen bore-hole pattern and bore-hole pitch is some 16 to 20% in excess of the number of bore-holes required to dispose the total amount of 50,000 HLW-canisters. These spare bore-holes will allow for a certain flexibility in order to cope with unexpected presence in the burial area of appreciable carnallite ($KCl.MgCl_2.6H_2O$) or anhydrite ($CaSO_4$) layers. By not using potential bore-hole places in way of and bordering a carnallite layer, a local decrease in global host rock temperature can be created. At the same time the course of the roadways can be adapted to restrict the exposure of an unfavorable layer if this would be judged necessary.

There is however a far more effective possible way to lower the global host rock temperature, by increasing the time of intermediate storage for the HLW-canisters. As pointed out in section 2 an interim waterbasin storage on the mine site will be necessary to achieve a regular disposal frequency notwithstanding irregularities in the supply of the canisters to the site. Given this facility, an increase of the interim storage capacity can be realized at relative low costs. An increase in decay time from 10 years, as was assumed for all temperature calculations, to 25 years will result in a decrease in the initial heat source at the moment of burial from 600 Watt down to 425 Watt per canister. As there is a linear relation between the initial heat source and the maximum rise in global rock salt temperature, the maximum global rock salt temperature can be decreased accordingly if the time of intermediate storage would be increased. For the 600 m level this means a reduction in maximum global host rock temperatures of some 20°C.

Interim storage period can be increased without interference with the burial mining operations as can be seen in Figures 2 and 1. The assumed disposal sequence, which was based on a disposal as soon as practicable, can easily be delayed by some 15 years while the HLW-canister disposal would still be terminated before the bulk waste disposal would come to an end. The availability of at least a certain percentage of older HLW-canisters might give the disposal mining an additional degree of flexibility in case too many unexpected carnallite or anhydrite layers would be found to be present in the burial areas.

LAY-OUT OF THE MINE

In a most elementary way, the repository mine will consist of three main working levels, a top-level for dumping the low-, medium- and high-level wastes into vertical cylindrical bunkers, an intermediate-level for ventilation purposes and for salt-transport during construction of the waste disposal cavities from the top-level and one or more deeper levels for disposal of the high-level reprocessing waste, as is shown in Figure 25. As shown in Figures 26 and 27, the branch roads coming off the main transport arteries towards the disposal bunkers at the top-level (the 500 m level) are driven slightly offset from the corresponding roads on the intermediate level to enable a dustfree disposal of the low-, medium- and high-level wastes in the bunkers. As soon as a new bunker is completed, and prior to the disposal of wastes into that cavity, the connection at the intermediate level is sealed off, after which this level will serve only for ventilation purposes as far as this bunker is concerned.

In the pit bottom at the 500 m level the normal facilities, such as garage, storeroom and offices, are provided together with an explosives magasin and a dumping station for the salt. This dumping station is connected via a chute and bunker to a special salt loading arrangement, that will be further discussed below. In view of the disposal operations that will take place at this level, this will be an air intake-level.

To enable transport of the trackless material, a spiral incline will be driven between the three main levels. At the intermediate level, i.e. the 550 m level, the roads branching off the main arteries will serve a dual purpose, i.e. transport of salt during the construction phase of a disposal bunker and as an airreturn for the top-level. The filters provided in the air-outlet of each disposal bunker will ensure that only uncontaminated air will flow through this level.

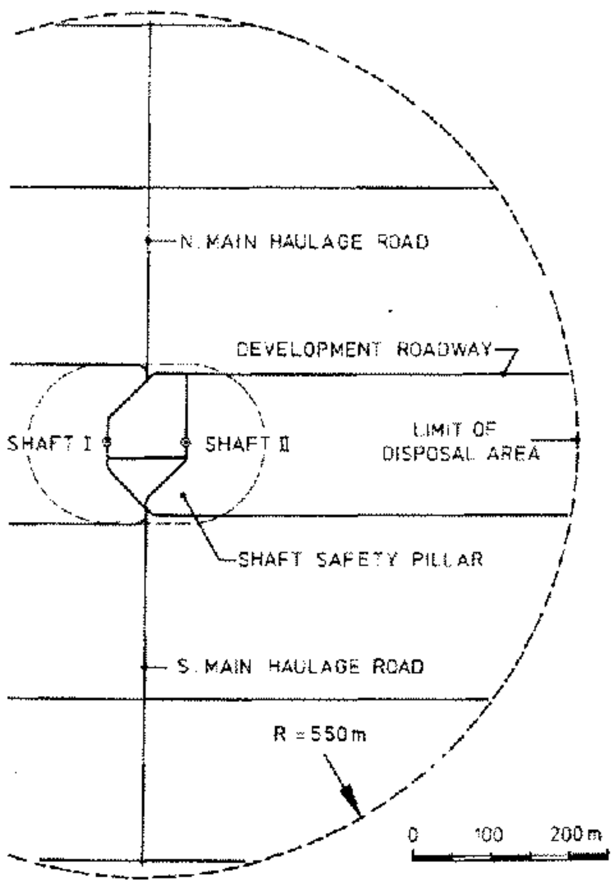

Figure 24. Lay-out of roadways on the −500 m level.

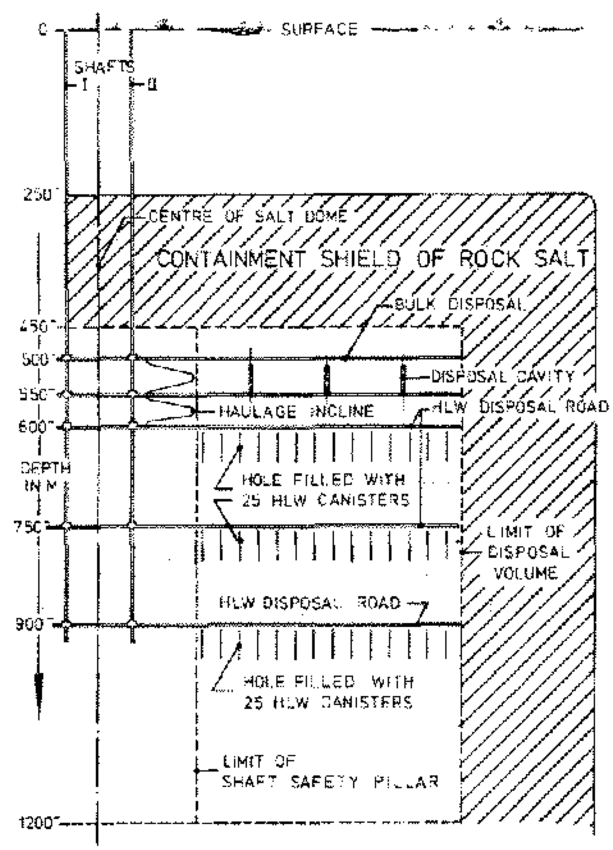

Figure 25. Schematic section through available disposal site.

Apart from acting as a haulage level with air return for the top level, the intermediate level will also serve as a return level for the top high-level waste disposal level. For this purpose large diameter holes will be drilled from the main artery roads at the 550 m level downwards into the branch roads on the 600 m level, as shown in Figure 31. When as shown in Figure 25 more than one HLW-level is needed, the additional deeper levels should each carry their own air return main artery roads, driven some distance above the HLW-level.

The deepest level, i.e. the 600 m level, will consist of the main artery roads with branch roads, branching off in a much closer pattern than those on the top-level. As shown

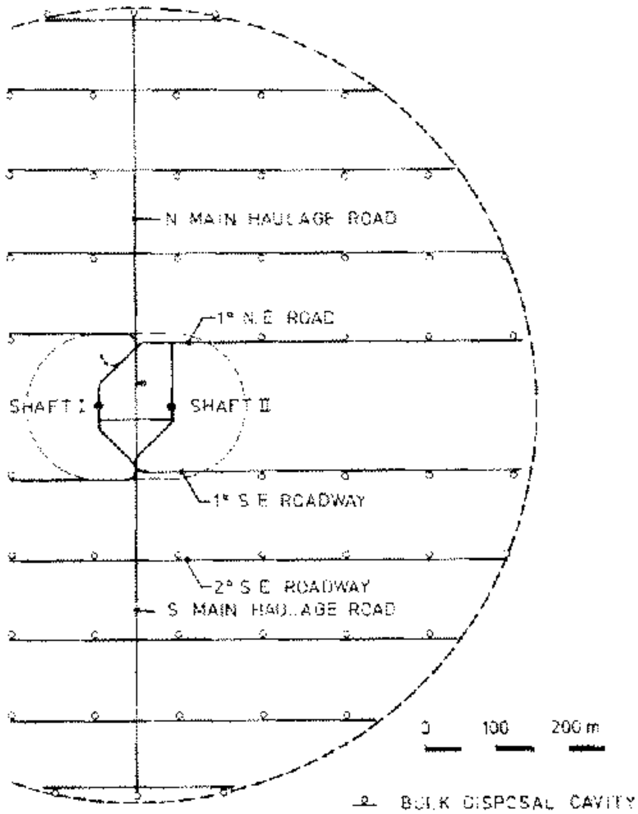

Figure 26. Schematic plan of bulk disposal area at −500 m level.

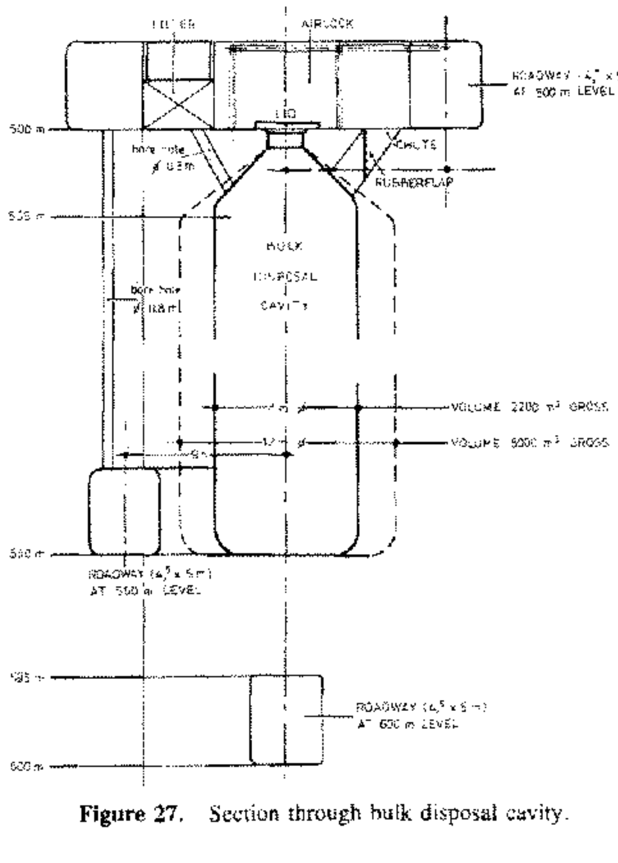

Figure 27. Section through bulk disposal cavity.

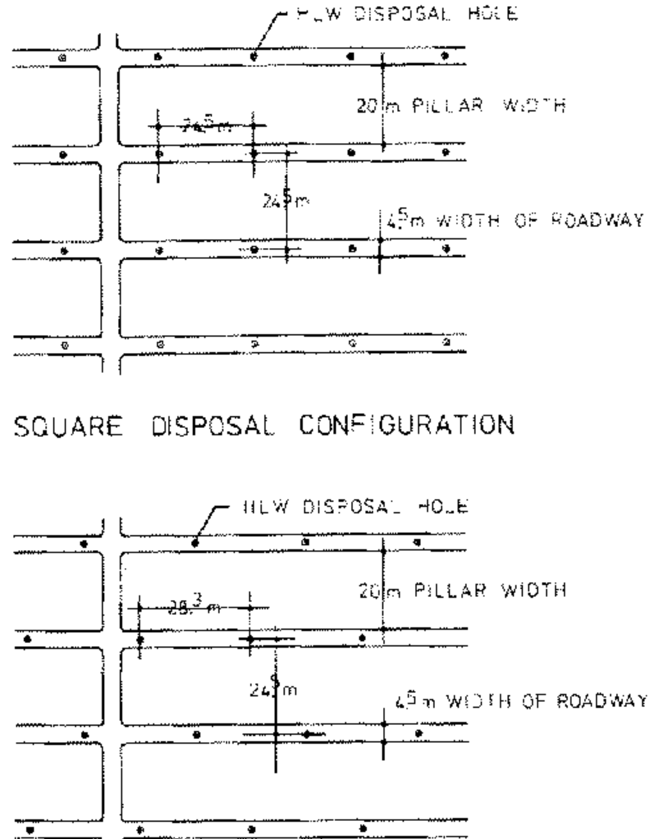

Figure 28. Square and hexagonal disposal configuration.

in Figure 29 it is in these branch roads that the vertical holes are to be drilled, which are to be filled with the HLW-canisters. To be able to work in "upstream" conditions, these branch roads are to be connected with each other at the border of the containment shield as shown in the Figures 31 and 32.

By preceding the disposal operation by one branch road, both driving and disposal can be completely separated from each other, albeit the transport container with the HLW-canisters will have to use the same main road as the rest of the transport.

This matter of combined haulage ways makes it absolutely essential that the transport container will not become contaminated at the outside thus assuring a safe use of the same cage and haulage roads as the men. After positioning the transport container above a disposal bore-hole, the HLW-canisters will be lowered into the bore-hole by remote control up to the required number. The remainder of the hole will be filled with crushed salt and plugged at the top to safeguard against radiation and accidental damage by transport as shown in Figure 30. When all the holes in one particular branch road will have been filled, the roadway itself can be refilled with industrial debris and salt, after which the ventilation bore-hole and border connection road

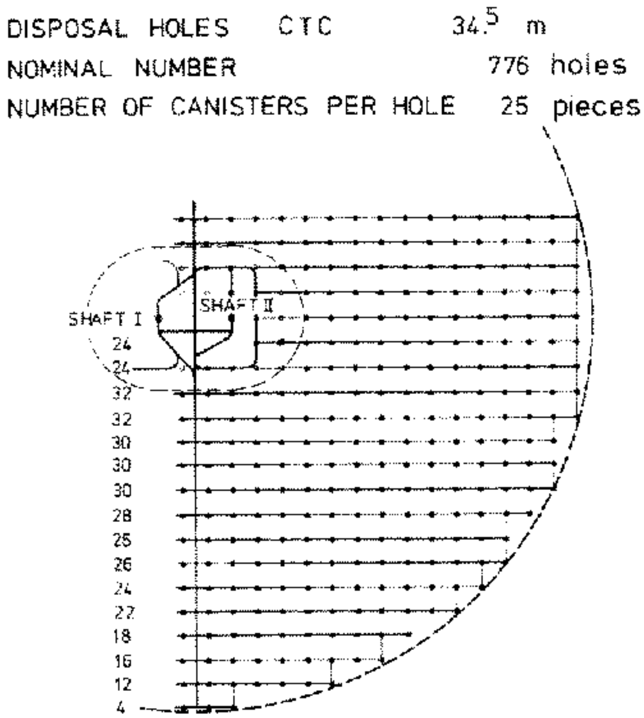

Figure 29. Schematic grouping of HLW-disposal level

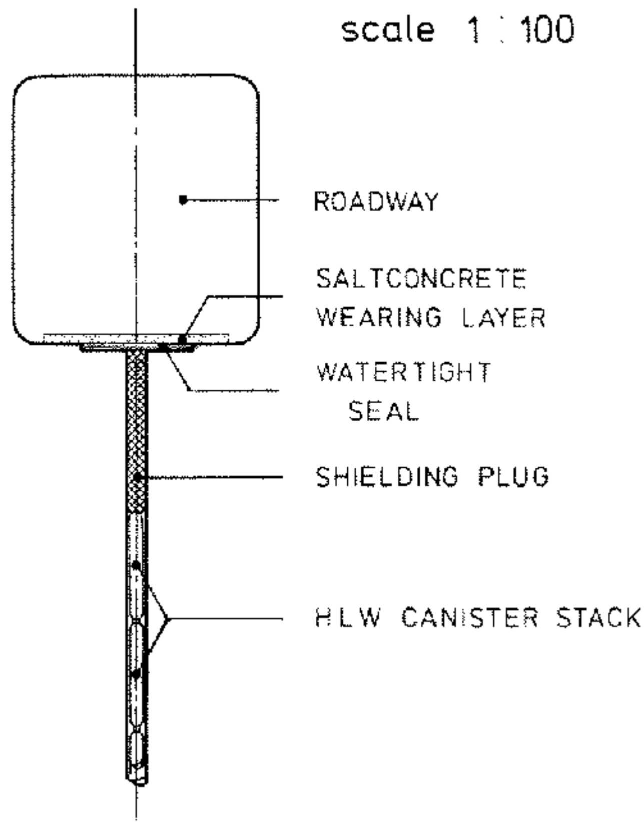

Figure 30. Section through HLW-disposal hole.

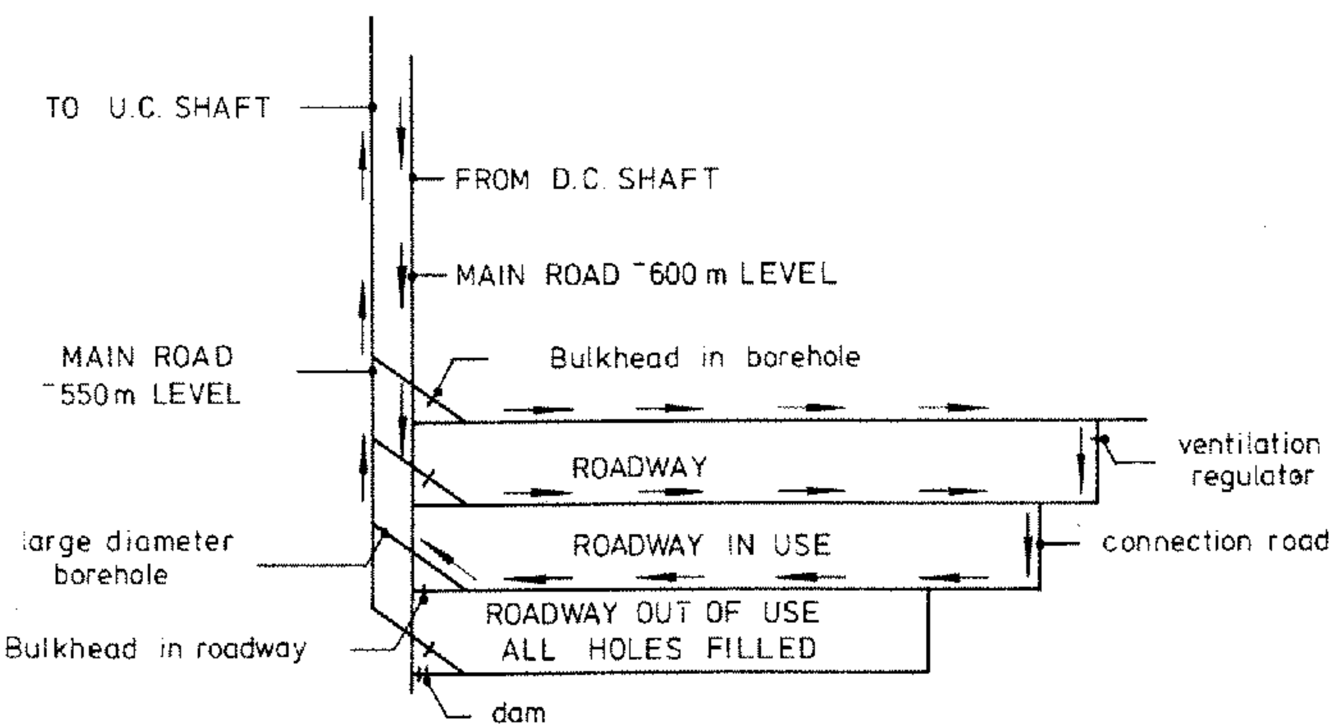

Figure 31. Ventilation scheme HLW-disposal level.

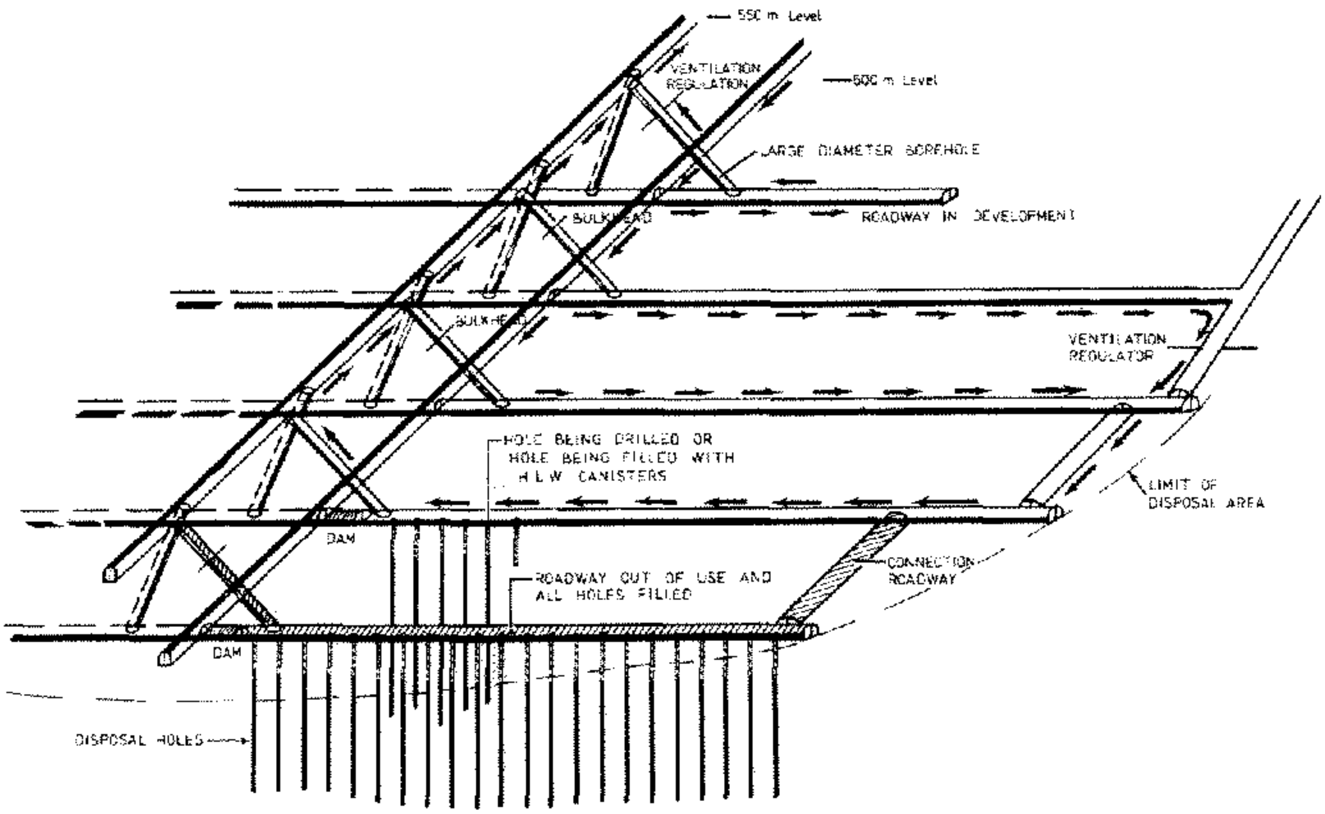

Figure 32. Ventilation scheme HLW-disposal roads.

are also filled so that the branch road will be totally disconnected from the mine ventilation system. It is thus envisaged that on completion the mine will exist of three or more levels, the disposal bunkers being filled with waste and salt, the disposal bore-holes being filled with heat-generating HLW-canisters and the roadways being filled with salt and possibly demolition rubble from the power stations.

These refilled roadways will be isolated from the shafts by means of watertight dams so as to eliminate to the highest possible degree the consequences of a flooding.

As it is assumed that the overall temperature of the salt dome will have to be kept below 100°C, except for a very small area directly around each HLW-disposal bore-hole. The effect of the temperature rise will have to be considered, both on the movements of the salt dome as a whole as well as on the stability of the mine structure in view of the decreased yield value of rock salt at higher temperatures. Although the study of these phenomena has not been finalized, calculations have been made, as discussed in section 4, which show that no unacceptable occurrences are expected.

DEVELOPMENT OF THE MINE

When constructing a salt mine the most important part is the construction of the shafts. The penetration of the subsurface of the salt dome seen in the light of the time required to guarantee the isolation of the radioactive wastes from the biosphere will require much more stringent conditions of planning and execution of work than would have normally been the case when developing a straight forward salt mine.

One of the first conditions will be to limit these penetrations to the barest minimum, so that only two drillholes for exploration purposes can be brought down, which will have to be drilled within the future shaft cross-section. This will put the burden of satisfactory reconnaissance of the salt dome squarely upon geophysical methods and shallow bore-holes, not reaching the salt dome itself.

Notwithstanding this, a double shaft mine will be required, mainly for safety, ventilation and transport considerations, so that only two exploratory bore-holes are envisaged before starting the construction of the mine. In bringing down the shaft, the overlying strata, which are considered to be water-logged, will have to be penetrated in such a way that a watertight shaft-lining can be guaranteed.

Also the penetration of the subsurface of the salt dome and the transition of the shaft-lining at some depth in the salt have to be considered in the light of the extended duties of this shaft, i.e. the requirements after abandoning the mine at the end of its duty. Two methods can be applied to bring the shafts down, i.e. the freezing method and the drilling method. It is assumed that both methods are known well enough so that a description thereof can be omitted. However, specific points need to be considered more thoroughly in view of these extended duties as referred to above.

In applying the freezing method, the freezing pipes will have to penetrate some depth into the salt dome, thus exposing the most critical part of the salt dome structure to penetrations and temporarily to a considerable lowering of temperature.

Against these disadvantages the big advantage exists that the transition from the tubing, which is to be applied as lining in the overlaying stata, to the concrete lining, which forms the lining in the salt part of the shaft, can be made under supervision and close inspection, so that any irregularities can be dealt with.

In applying the drilling method, the penetration of the salt dome top has to be done with the assistance of mud and it is in this respect that the possibility of unpleasant surprises exists, though the same problems arise, albeit on a lesser scale with the drillholes for the freezing pipes. The transition of the two shaft linings will generally be situated at the bottom of the drilled part of the shaft, so that for the actual anchoring of the tubing part no visual inspection is possible until after the construction has taken place. Therefore, close study of these two methods in relation to the penetration of the salt dome top, the transition point of the two linings and the anchoring of the tubing part is necessary to decide upon the eventual choice[3].

The lining in both methods will be basically the same, i.e. welded steel and concrete for the tubing part and mass concrete for the lining within the salt dome. The steel and concrete tubing which will form the lining from the surface down to well within the salt dome will be safeguarded against stratal movement and direct contact with the surrounding waterlogged strata by means of a mantle of bitumen. The insets at the different levels will be made in reinforced concrete and extend for a short length into the pit bottom, this length is sufficient to house the decking equipment and ultimately, to provide the space for the watertight dams when abandoning the mine.

It is not expected that substantial roof- and side-support will be required in pit bottoms and roadways, other than very localized, though special care will be taken to seal off any anhydrite banks. Special care will be taken to keep the strength of the surrounding salt at the highest possible level by driving the roadways without the use of explosives.

Where the use of explosives is absolutely essential, special care will have to be taken to minimize the effect upon the surrounding salt mass[4]. For ventilation purposes between the different levels it is expected that extensive use will be made of large diameter drillholes. As the behavior of the salt carnallite ($KCl.MgCl_2.6H_2O$) under the combined influence of stress and temperature requires special attention, it is envisaged to use only those parts of the salt dome for disposal purposes where the potassium content does not exceed a nominal value.

To plan the mine as a whole and to work out the disposal schedule, it is therefore essential to know the consistency of that part of the salt dome that is earmarked for the HLW-disposal purposes. Consequently, great importance is being attached to the timely reconnaissance of the interior of the dome by driving the roadways at the 500 m level. At the same time this will give the opportunity to ensure the consistency of the containment shield by means of geophysical observations. It is during this time of reconnaissance that the salt production will be at the highest and the maximum of ventilation air will be needed due to the driving, transporting and drilling equipment needed.

During the active life of the disposal mine a certain amount of salt will have to be transported on the different levels. To concentrate this salt on one particular loading station, a special level is driven, solely for salt loading and winding. This level will receive its salt from the other levels by means of a bunker and chute so that the windings of this salt is concentrated on this special level and can take place at such times that do not interfere with the disposal of the waste.

Finally at the end of the useful life of the mine, special precautions will be taken to prevent the flooding of the abandoned workings. Though it is not very likely, even in the case of flooding the mine after it has been abandoned, that excessive amounts of radioactive material will reach the biosphere, it is felt that every precaution should be taken to eliminate this flooding danger. To realize this all insets will be dammed by means of watertight stoppings in the reinforced concrete parts and the shafts will be filled completely and also sealed off watertight above the levels and in the transition zone salt-overburden. Finally, at the surface another watertight seal is put in place[5].

BURIAL SEQUENCE AND COOLING CAPACITY OF MINE VENTILATION

As shown in Figure 22 the rock salt temperatures at the successive roadway levels will be affected by the disposal of HLW-canisters at a deeper level. Contrary to normal mining practice, the disposal of the HLW-canisters is assumed to begin at the deepest burial level of 895 m depth, to be continued after 20 years on the 745 m level and to finish after 35 years on the 595 m level.

The rock salt temperature calculations are based on the assumption that the total amount of about 16,675 waste canisters will be disposed of instantly for each burial level. In reality it will take at least 15 to 20 years time to fill a burial level.

The burial sequence will start at the border of the burial plane from two opposite sides by filling the disposal boreholes per roadway and by retreating the excavation and drilling work from the outside backwards towards the centrally arranged shafts.

It was noted above that the mine ventilation will be arranged in such a way that the airflow in the HLW-disposal roadways will be directed from the roadway excavation and the bore-hole drilling towards the roadways in which the disposal bore-holes already are filled. In doing so the mine ventilation can contribute in removing heat from the rock salt surrounding the roadways up to its cooling capacity.

The question can be raised whether the cooling capacity of a normal mine ventilation could be worth taking into account when calculating maximum rock salt temperatures due to HLW-disposal. The following approximation can be made to answer this question. Assuming that the diameter of 5 m for both shafts will allow for a normal ventilation capacity of 10,000 m^3 air per minute and that the intake air arrives at the 600 m level with a global temperature of 25.3°C and an average relative humidity of 40% and setting the maximum mine air temperature at that level at 30°C, then the nominal cooling capacity for the mine ventilation can be calculated to be 1000 KW. Finally assuming that half the ventilation capacity will be used on the bulk disposal levels and half for the HLW-disposal, then each half of the HLW-disposal level under development can be provided with about 250 KW cooling capacity.

After a deduction of about 50 KW for cooling of mining equipment and such, about 200 KW will remain as a local cooling capacity to lower the temperature of the rock salt surrounding the roadways in which burial mining work is proceeding.

Compared to the initial total heat source of 5,000 KW, developed in the approximately 8,000 canisters that will be disposed of in one half of a HLW-disposal level, this 200 KW ventilation air cooling capacity is small. However, it will take quite some time before an appreciable amount of the decay heat developed in the buried HLW-canisters will be dissipated in all directions in the rock salt surrounding the canisters, such that a temperature gradient will be established from the buried canisters upwards towards the floor and the walls of the roadways that will support a heat flow greater than the available cooling capacity. As shown in Figure 20 it will take more than 10 years for the global rock salt temperature at the burial levels of Burial configuration IV-3 to reach a 60°C level, without taking into account the cooling capacity of the mine ventilation during that time period.

Long before that temperature level will be reached the roadways with filled disposal holes will have been refilled with crushed salt and the accessibility of these galaries will have come to an end. In this respect the cooling capacity of the mine ventilation can hardly be used effectively to remove decay heat from the buried canisters. The ventilation will therefore only be dimensioned to provide the required amounts of fresh air in the areas where the excavation and drilling is taking place and where diesel engines are operating.

POSSIBLE IMPROVEMENT DUE TO ACHIEVING DEEPER DISPOSAL BORE-HOLES

All preceding sections deal with a design study approach based on the restrictive assumption that the proven techniques in rock salt mining do not allow drilling dry vertical disposal bore-holes deeper than 55 m. With this restriction the favorable effects of a greater dispersal of the HLW-canisters over the available rock salt mass could only be approximated by developing three HLW-disposal mining levels.

These mining efforts would however be greatly reduced if all HLW-disposal could be realized by drilling deeper vertical disposal bore-holes from the 600 m level only.

Temperature distribution calculations were made for the Burial configurations V-A up to V-F in which, as shown in Figure 33, the bore-hole depth was increased in steps of 100 m from 100 m in Burial configurations V-A to 600 m in Burial configuration V-F. For comparison it should be noted that Burial configuration V-A is a worse variant of the Burial configuration III series, in which the distance between the two burial layers of 50 m depth became zero. On the other hand the Burial configuration V-F is fully comparable to Burial configuration II. The global temperatures calculated 5 to 250 years after disposal are shown for the Burial configurations V-A up to V-F in Figure 34 up to Figure 39 respectively.

When comparing the global temperature lines of the Burial Configurations III-A (Fig. 11) with V-A (Fig. 34), III-B (Fig. 12) with V-B (Fig. 35) and both III-C (Fig. 13) and III-D (Fig. 14) with V-C (Fig. 36) it is interesting to see the effect of the heat storage capacity of the rock salt between the two burial layers in the Burial configurations III, that results in lower maximum global temperatures halfway the respective burial layers.

The same effect can be seen when comparing the global temperature lines of Burial configuration IV-3 (Fig. 20) with those of the nearest comparable Burial configurations V-C (Fig. 36) and V-D (Fig. 37). The relatively higher maximum global temperature that will be developed in the horizon halfway the stack of HLW-canisters will decrease with increasing disposal bore-hole length from about 140°C for Burial configuration V-A through about 100°C for Burial configuration V-C to below 80°C for Burial configuration V-F.

Of more importance may be the rock salt temperatures at the HLW-disposal level which, as shown in Figure 40, will remain for the first 50 years, that is assumed to be the maximum period of accessibility for that level within about 100°C for Burial configuration V-A down to below 60°C for the Burial configurations V-C up to V-F.

The rock salt temperature development at the deepest of the two low-level waste disposal levels, above a HLW-disposal according to one of the Burial configurations V-A up

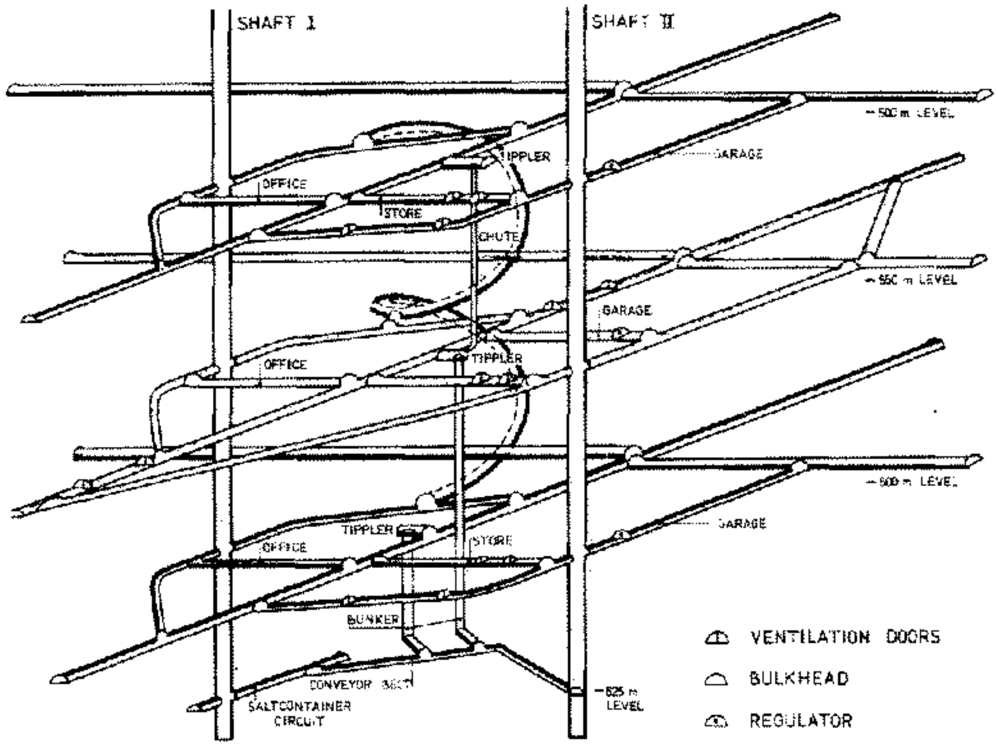

Figure 33. Pitbottom Lay-out.

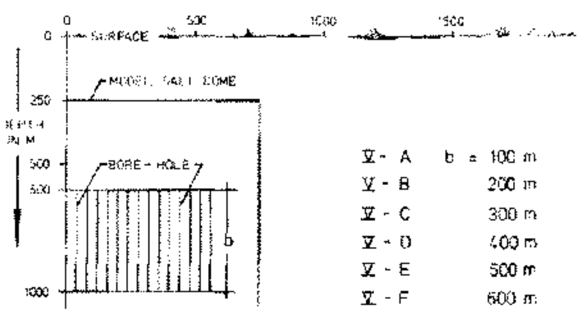

Figure 34. Burial configurations V, depth of bore-holes.

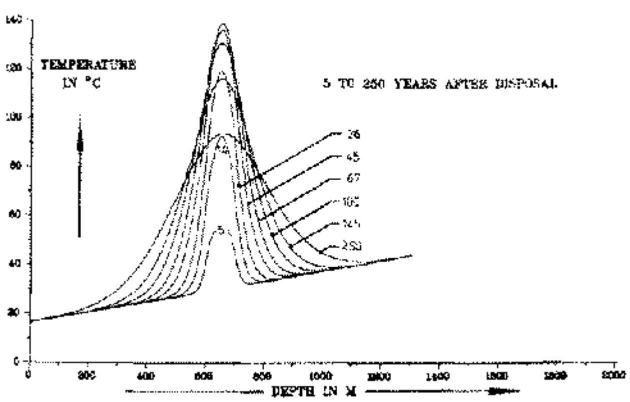

Figure 35. Configuration V-A, global temperatures.

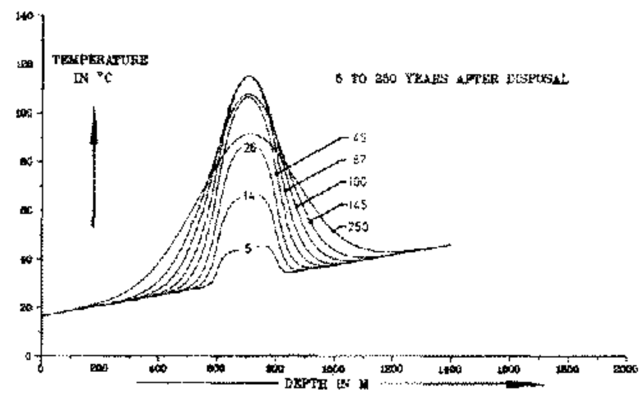

Figure 36. Configuration V-B, global temperatures.

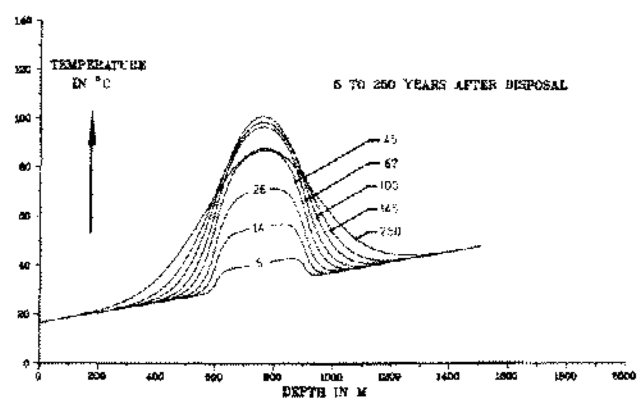

Figure 37. Configuration V-C, global temperatures.

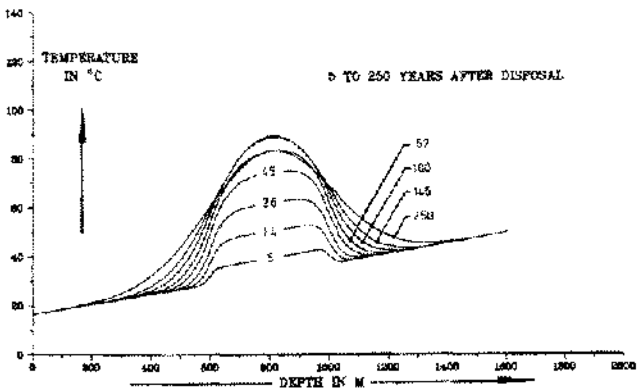

Figure 38. Configuration V-D, global temperatures.

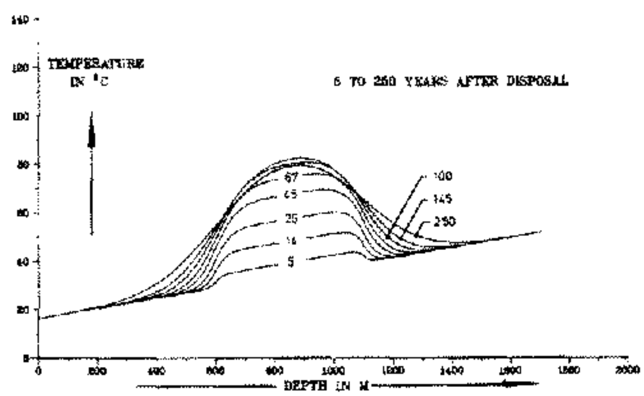

Figure 39. Configuration V-E, global temperatures.

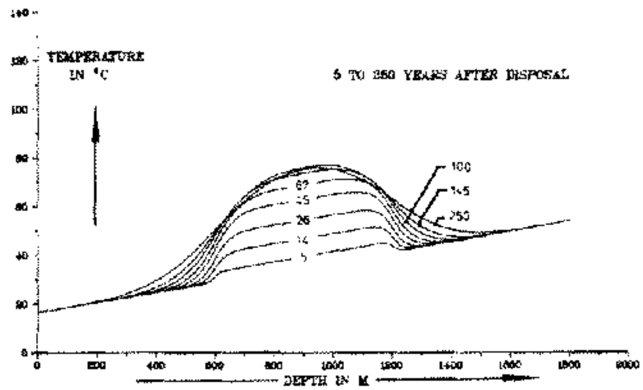

Figure 40. Configuration V-F, global temperatures.

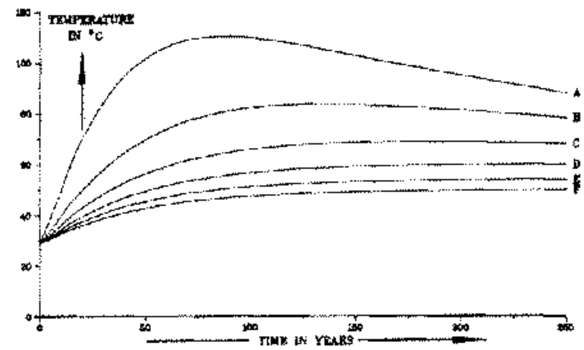

Figure 41. Configurations V-A through F, temperature versus time at a depth of 595 m.

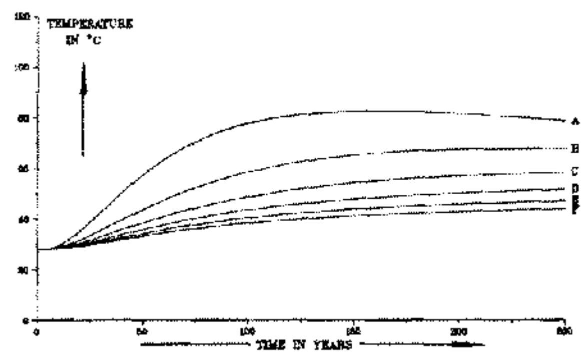

Figure 42. Configurations V-A through F, temperature versus time at a depth of 545 m.

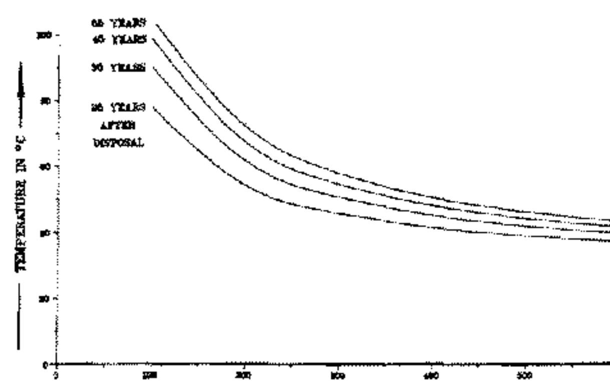

Figure 43. Configurations V-A through F, temperature at a depth of 595 m versus bore-hole length.

to V-F, is shown in Figure 41. As the low-level waste disposal may continue over a period of about 100 years, it is worth noting that even after such a long period of time a 60°C limit will not be reached with the Burial configurations V-B up to V-F.

To derive the effectiveness of each additional 50 m disposal bore-hole depth on a reduction in rock salt temperature at disposal level the outcome of the rock salt temperature calculations were plotted for different time periods against the disposal bore-hole length, as shown in Figure 42. The change in angle under which all four curves decline with increasing bore-hole depth is an indication that beyond a depth of about 300 m the effectiveness of each additional 50 m disposal bore-hole depth is less than 5°C and may not be worth the effort to realize it.

Summarizing that for bore-hole depths of 300 m or more the maximum global rock salt temperatures will remain below about 100°C (see Fig. 37) and the rock salt temperatures at disposal level will for the first 50 years remain below 60°C (see Fig. 41), the conclusion may be drawn that Burial configurations V-C is an attractive proposition to aim at as a replacement for Burial configuration IV-3. It requires, however, work to improve or provide drilling techniques for realizing dry vertical disposal bore-holes from 600 m depth down to 900 m depth. It is expected that sufficient interest can be raised for this work so that after some preliminary laboratory work, access can be realized to an existing salt mine in order to perform experimental drilling work at the required depths.

CONCLUSION

Based on certain capacity requirements for an assumed nuclear power construction and operation program and certain quality requirements aiming at a long-term containment of the radioactive waste to be buried in a salt dome, a waste repository can be realized by using proven techniques and procedures for making the shafts, for mining the excavations, for disposing the different categories of waste, for decommissioning the waste repository and for sealing the shafts. The design study demonstrates the feasibility of accommodating and operating, in a medium-size salt dome, a low- and medium-level waste disposal in bulk above a solidified high-level reprocessing waste disposal in bore-holes, drilled from three successive disposal mining levels deeper in the salt dome.

Rock salt temperature calculations indicate that an overall initial heat source of 30 MW, quantified on the basis of a total of 1 Million MWe-year nuclear power productions, can be accommodated in such a way that, based on the assumptions made with regard to the original rock salt temperatures and the heat source distribution, it will not result in surpassing very conservative design limits of:

- 60°C in the containment shield of about 200 m rock salt to be maintained undisturbed around the buried wastes,
- 100°C for the HLW-disposal area globally,
- 150°C locally directly around the disposal bore-holes, and
- 60°C at the mine gallery levels during the required period of accessibility, not taking into account the cooling capacity of the mine ventilation.

Additional temperature calculations indicate the possibility to simplify the conceptual design by restricting the HLW-disposal to one mining level only, if drilling techniques could be developed for realizing dry vertical disposal bore-holes from 600 m depth down to about 900 m depth.

ACKNOWLEDGEMENTS

This study was carried out under contract with the Commission of the European Communities (Contract No. 026-76-9 WAS N).

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