Disposal of Medium and Low-Level Radioactive Waste (MLW/LLW) in Leached Caverns

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ABSTRACT

This presentation describes the criteria for the layout of stable caverns in rock salt made by solution mining. Some examples of storage caverns in the Federal Republic of Germany are reported with regard to long-term stability, convergence rates and control methods used.

Five model caverns with a volume of 10 m³ each were leached from a drift in the Asse salt mine to check the deposition procedure of medium and low-level radioactive wastes (MLW/LLW) as pellets in a cement slurry in leached caverns. Construction, filling procedure and temperature measurements conducted during and after curing of the cement are presented.

Furthermore, the report gives an insight into an investigation regarding the construction of caverns with volumes of 75,000 m³ each. Possible discharge methods before filling with MLW/LLW and deposition methods are described, as well as time and cost of construction.

Experiments with the 10 m³ caverns and investigations of larger caverns have shown that this concept is technically feasible and has substantial advantages over other methods. Costs for such a repository for MLW/LLW are also relatively low.

INTRODUCTION

There are presently different concepts for the final disposal of medium and low-level radioactive waste (MLW/LLW) from nuclear reactors, medicine and research. In the opinion of most experts final disposal in salt formations is a safe method of isolating such a waste from the environment and the hydrologic cycle until the decay of the radionuclides has reached acceptable levels. Salt formations at an age of about 200 million years have no internal connection with the hydrologic cycle in nature. If MLW/LLW are disposed of with technical care they will be excluded from the biosphere and will not be of any hazard for the environment. Even final disposal of high-level radioactive waste is feasible in salt formations. However, this is not part of this presentation.

It is the basic idea of the concept described in the following to dispose of MLW/LLW in caverns in salt formations as pellets distributed homogenously in a cement slurry. Different techniques were investigated to transport this mixture of pellets and cement slurry from the surface into leached caverns through boreholes having minimal diameter, where it will then solidify to a quasi-monolithic block (Figure 1).

The investigations are part of a bigger project that includes research on final disposal in caverns in salt mined conventionally from drifts in a salt mine.

The following presentation is divided into two main parts:

1. The leaching of model caverns with volumes of several m³, the filling process with a mixture of pellets and cement slurry, the conducted measurements and the know-how acquired
2. The construction of a larger project for disposal of some 100,000 m³, construction of several caverns by solution mining, methods for displacing the brine from the caverns and data concerning time and cost of construction.

DIMENSION DESIGN OF STABLE CAVERNS IN SALT FORMATIONS

For centuries practical experience has been made with conventionally mined stable rooms in halite and potash.

This paper was written in connection with a project sponsored by the Ministry for Research and Technology under the project management of PWA-Karlsruhe (Dr. Kroebel/Kraemer) together with external partners.

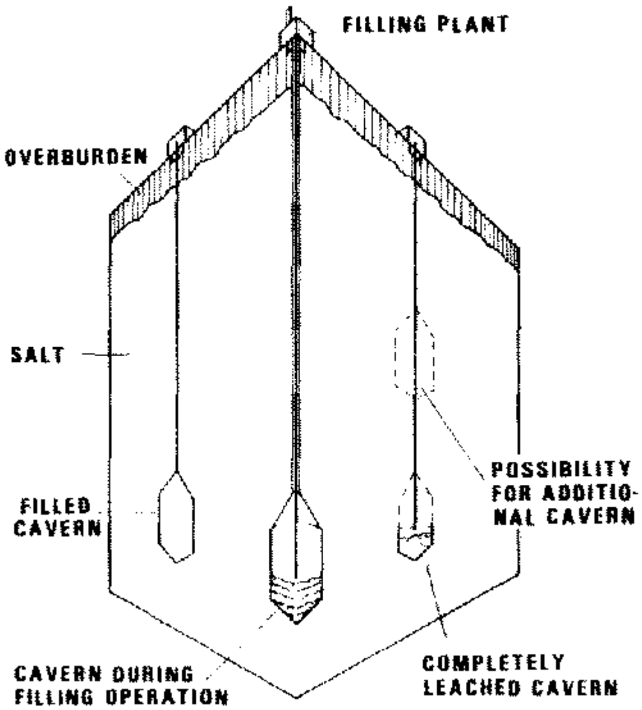

Figure 1. Disposal of MLW/LLW cavern field array

Open rooms have been mined up to depths of 1,200 m with a free area of some 1,000 m^2 which remained stable for decades. Construction of these open cavities depended on practical experience gained with the respective type of salt and to a minor degree on investigations with mechanical models. Extensive investigations over the last few decades due to the long-term use of caverns made by solution mining for storage of liquid and gaseous hydrocarbons have resulted in a better understanding of the rheologic properties of rocksalt. The goal was and is to find a constitutive law that can be used in finite element calculations for construction of long-term, stable, large-scale open cavities in salt.

These open cavities must be stable and closure must not exceed economically acceptable convergence rates. Currently, different constitutive laws are used worldwide for calculation and construction. To our knowledge, long-term experience (over some decades) is not yet available for caverns constructed and mined in such a way. However, present experience is positive with regard to solution mined caverns with volumes of 100,000 up to 500,000 m^3 at depths between 400 and 1800 m in the Federal Republic of Germany. About 100 caverns exist in the FRG and some have been in operation for more than 10 years. All are tight and stable under working conditions. Meanwhile, initial findings are available concerning actual convergence.

It has been shown that according to the rheological properties of the salt the convergence rates are extremely dependent on the depth, inner pressure, temperature and configuration of the caverns. At present there is no evidence of the detection of convergence rates in storage caverns in Northern Germany of more than 1% per year. Recently, necessary measurement methods had to be developed for exact determination of convergence and configuration in inaccessible caverns.

Convergence rates of caverns filled with liquid hydrocarbons are presently determined by discharge measurements combined with pressure and temperature measurements. Control of configuration is achieved by sonar measurement methods. However, this procedure makes it necessary to pull up the production string, which is both time-consuming and expensive. For this reason, convergence calculations using PVT measurements are employed for caverns used for storage of compressed natural gas or compressed air. The rates are measured during a filling or discharge cycle respectively, for this purpose, as well as pressure and temperature in the storage at the beginning and at the end of each cycle. This method requires very exact measurement devices. Nevertheless, the error in determining the storage volume is still more than 1%.

Configuration control is carried out with sufficient accuracy for natural gas storage facilities, using a modified sonar measurement method (Figure 2). The vertical sec-

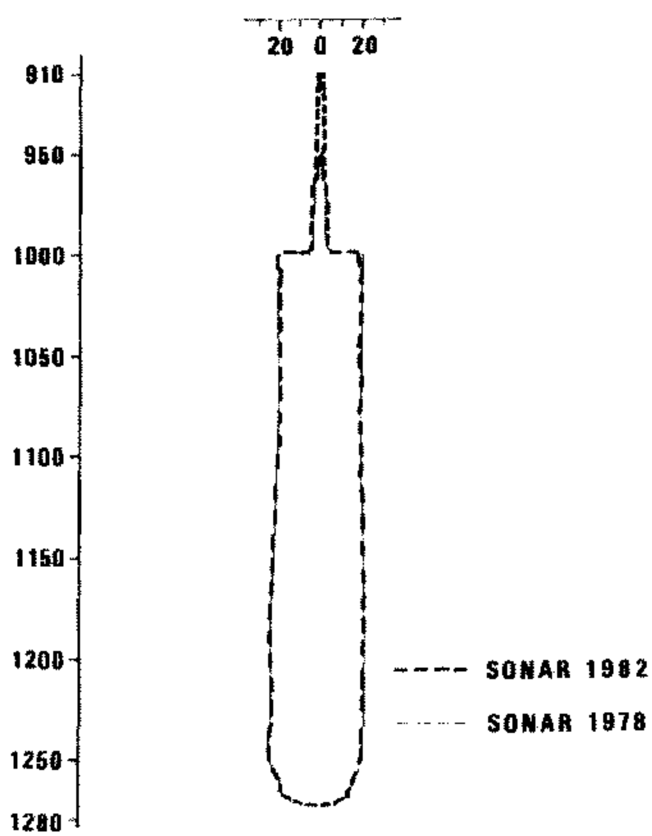

Figure 2. Disposal of MLW/LLW vertical section through a gas cavern

tion shows the configuration of a 400,000-m^3 cavern at the end of the leaching operation and after 4 years of gas storage operation. During this period the cavern was maintained with inner pressures between 25 and 160 bars. The shape of the cavern has not undergone any substantial changes within the limits of measurement accuracy, which means that neither peeling nor caving-in could be detected, and convergence rates remain lower than a quantifiable magnitude of several percent.

A laser method for cavern configuration control was developed for compressed air storage caverns because measurement by the sonar method used in natural gas storage did not produce sufficient resolution. A horizontal section of a compressed air storage cavern, indicating the initial configuration at the end of the leaching process and additionally the control measurements by laser log after 4 years of operation, is shown in Figure 3. During this period the cavern was subjected to about 1,000 pressure changes. Furthermore, it was kept under atmospheric pressure for more than one year.

It can be seen that the cavern withstood all these stresses without substantial deformation. Therefore, it can be concluded that caverns for deposition of MLW/LLW are reasonably stable and do not show unacceptable convergence rates during the filling process without inner pressure, if they are mined in suitable salt formations and adequate depths.

The size of the underground cavern for the storage concept of MLW/LLW is a compromise of diverging options such as:

1. Long-term use of surface facilities which are bound to the borehole location. Despite the possibility of using some components for subsequent facilities, an operational life in the order of 10 to 15 years would be desirable from an economical view
2. Smallest possible number of penetrations through the overburden into the saltdome. This produces greater safety, longer operational life and economical advantages during cavern construction. This requires cavern volumes of about 10^5 m^3
3. A sufficiently accurate statement with regard to stability of large open caverns without inner pressure at depths between 900 and 1,000 m. This requires cavern volumes of 10^5 m^3 or several superposed caverns.

The chosen single cavern volume of 75,000 m^3 guarantees the deposition of waste, conditioned according to the storage concept, equivalent to the production of a reprocessing plant for 5 years operation. For this particular purpose, this cavern volume represents an upper limit for the given conditions, according to today's knowledge of rock mechanics and the resulting stability statement. Therefore, it is obvious that the stability analyses ranked very high for this special storage project.

Principles of Stability Analyses

The stability analysis carried out for the caverns is divided into three parts equally complementing one another:

1. Analyses of experiences made with construction, operation and shut-down of comparable underground cavities
2. Preparation of models for calculation of approximate stresses in rock after mining of the cavity as

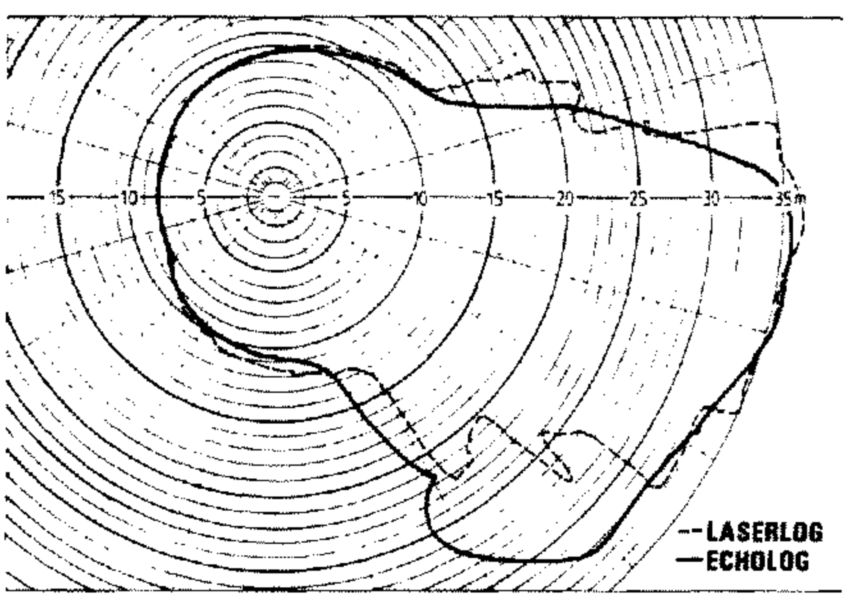

Figure 3. Disposal of MLW/LLW Caes Huntorf-Cavern NK 1 horizontal section echolog 1976 laserlog 1980

well as time-deformation behaviour during and after mining of the cavities applying, for example, finite element methods (FEM)
3. Verification of the model results by in situ measurements.

Preparation of the stability analyses and the reliability of the statements require updating of the analyses progressively, depending on the respective knowledge gained by geological investigations, rock mechanical laboratory tests and in situ observations. The general goal is the maintenance of the cavity, or, in a most common sense, the maintenance and care of the geological barrier.

Analyses of Experiences

Additional geomechanical findings from GSF investigations in the prototype cavern in the Asse II salt mine can be applied to the present problem. This prototype is one of the rare caverns in salt formations that can be explored in detail from a geomechanical point of view because of the availability of inspection and early installed instrumentation (Figure 4).

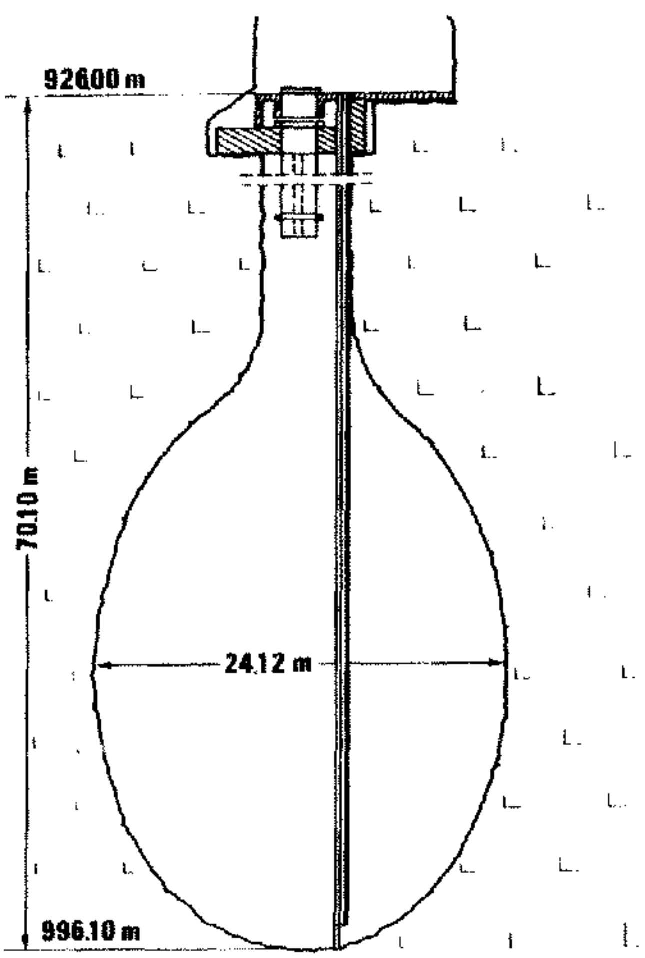

Figure 4. Disposal of MLW/LLW prototype cavern Asse

The geotechnical observations of the cavern and the shaft area for a period of more than 4 years now allow us to draw the following general conclusions:

1. Deformation around the cavern takes place at a decreasing rate with time
2. Stability of the cavern, as previously mentioned, is guaranteed
3. Deformation behaviour deduced from extensometer measurements is largely homogenous and can be proved by FEM-calculations.

The necessary calculated estimates for the deposition cavern were carried out by the Institute of Stability of the University of Braunschweig. Details of these calculations are not considered in this presentation. By contract with GSF, the Institute for Statics of the University of Braunschweig (Prof. Dr. Duddek) investigated two variants of cavities which fulfill both rock-mechanical and construction criteria.

Stability Statement of the System of Caverns

Construction of the borehole and the required 75,000-m^3 cavern for deposition of low and medium radioactive wastes is safely controllable from a technical view and the cavern has sufficient stability from a rock-mechanical viewpoint.

Shortly after disposal of the MLW/LLW in the cavern and solidification of the cement slurry, the totally filled cavern displays a behaviour nearly comparable to the mechanical conditions of the original rock of the surrounding salt mass. For this reason, and due to the short filling time, the long-term behaviour of the cavern is particularly favourable (Figures 5 and 6).

MODEL CAVERNS IN THE ASSE SALT MINE

Layout

Within the scope of the project, "Deposition and Solidification of MLW/LLW in Underground Cavities," promoted by the Federal Ministry of Research and Technology (BMFT), reliable material data must be provided concerning the interrelations between the MLW/LLW product and the salt formations. To achieve this, model caverns with a volume of 10 m^3 each should be constructed in an undisturbed rock region and filled with the product (the waste, within cement matrix). Furthermore the setting behaviour of this product in the salt, as well as the temperature development due to hydration heat resulting from the cement suspension, should be measured. These data will be used as input for calculations enabling subsequent conclusions from the tested model caverns regarding the temperature development in a large 75,000-m^3 cavern.

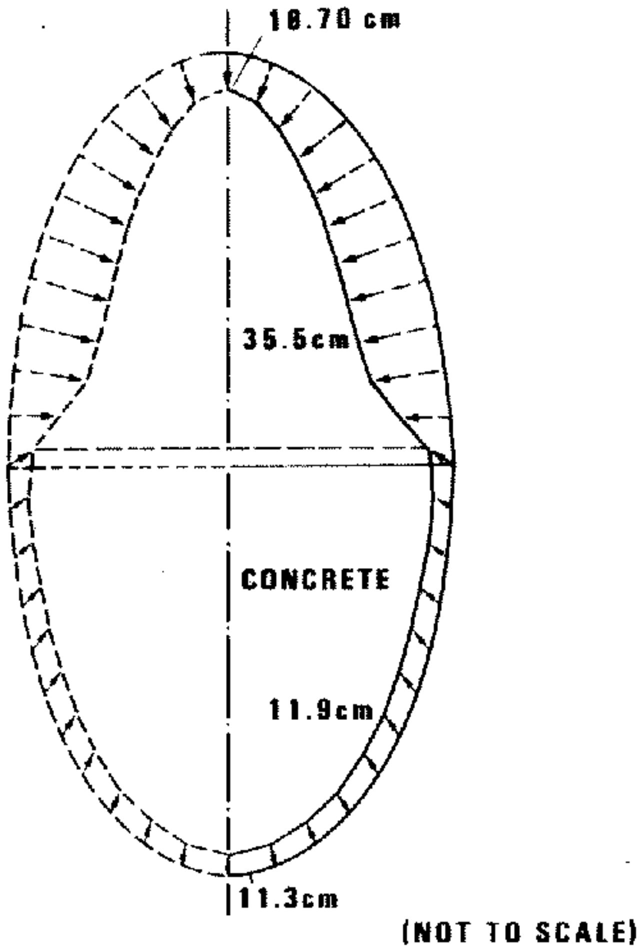

Figure 5. Disposal of MLW/LLW cavern wall displacement t=4 years after completion

In the Asse salt mine, an experimental mine of the Gesellschaft für Strahlen- und Umweltforschung mbH München (Company for Radiation and Environment Research Ltd. Munich) galleries were conventionally mined for establishment of the five model caverns. The galleries are located in older halite of the Stassfurt series (Z2) of the Upper Permian deposits. The length of the galleries is 123 m, the cross section is 4.5 times 3 m, which results roughly in 1700 m^3 solid rock extracted by drilling and blasting that was removed by front-end loader.

The necessary boreholes for the five caverns were drilled in these galleries. The distance between the center lines of two caverns was established as 20 m to eliminate temperature interactions. The range of depths of the model caverns was set to be 15–18 m below the gallery. In addition there is a pump sump of 1 m below the caverns. Parallel to this gallery at a depth of 800 m, another 60-m-long gallery was mined with the same cross section for deposition of the brine produced during the solution mining of the model caverns (Figure 7).

The boreholes for the solution mining of the caverns were 180 mm in diameter and had a depth of 19 m each. A pilot hole having a smaller diameter was drilled and stabilized drill pipes achieved an exact vertical position of the axis. Subsequently, the boreholes were enlarged up to the required diameter of 180 mm. The drilling was carried out by dry drilling methods, meaning that the drill cuttings were entrained by compressed air.

The insoluble or weakly soluble portions in different parts of the cavern ranged between 1.3% and 4%. These insoluble components of the rocksalt should sediment in the sump at the bottom of the cavern. For deposition of

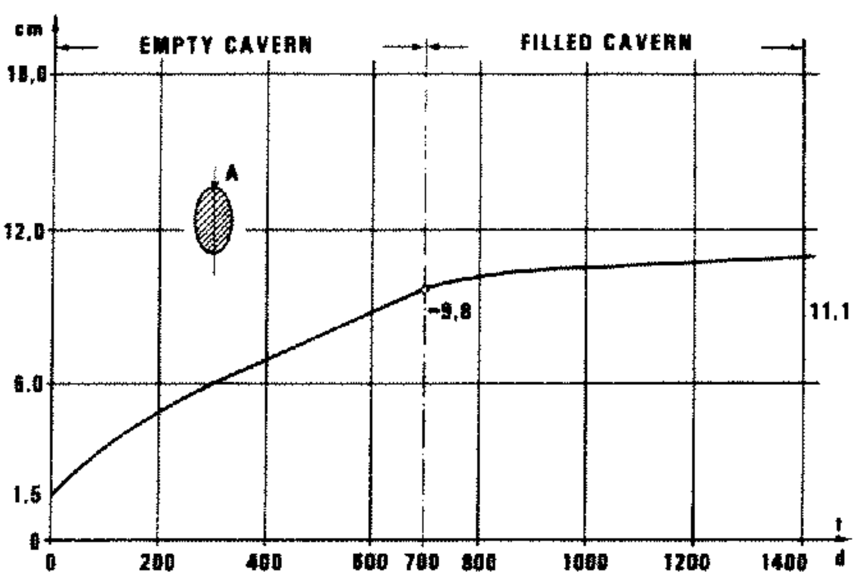

Figure 6. Disposal of MLW/LLW convergence: displacement of point a at cavern top (according to Duddek)

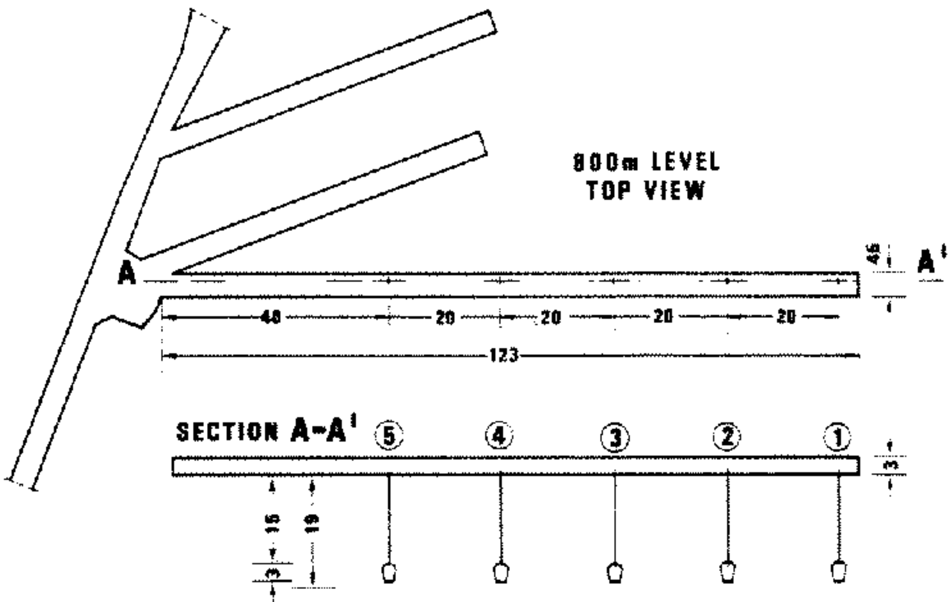

Figure 7. Disposal of MLW/LLW experimental model cavern array in Asse mine

the brine in the adjacent gallery a brine density of 1.20 was required by both mine management and mining authority. In this way undesirable leaching effects were not possible in this gallery. The total time needed for excavation of the gallery was 50 shifts. All mining work was carried out by the Institute of Underground Disposal, i.e., the Technical Department of this Institute.

The construction of 10-m^3 caverns from the boreholes takes place by solution mining with freshwater. This freshwater had to be transported from the surface to the 800-m level of the mine. For this purpose two containers were built which were installed on top of the hoisting cage of Shaft 2. At the surface the water was put into the containers and was then transported to the 750-m level. There the water was stored in a tank and later moved to the tank at the 800-m level by employing a drop pipe in blind shaft no. 4. The boreholes at the 800-m level were supplied with water from these tanks via pipes. (Fig. 8). Transport of 4-m^3 water from above ground into the containers at the 800-m level required a period of approximately 20 minutes. Design of the leaching work and execution were then undertaken by Kavernenbau-und Betriebs-GmbH (KBB).

By closing of stop cocks installed at the 800-m level tanks, the water can also flow in a by-pass along the tanks

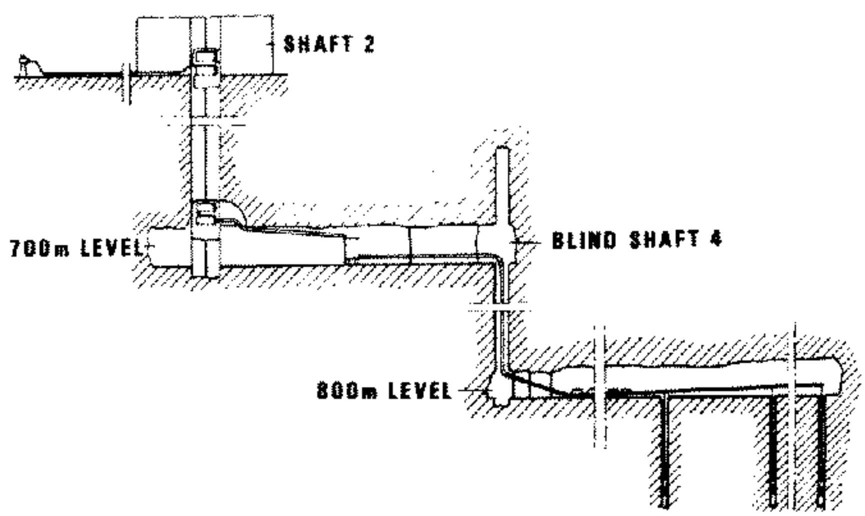

Figure 8. Disposal of MLW/LLW experimental model cavern water supply for leaching operation

directly into the boreholes. After filling of boreholes the three-way cock on top of the fill pipe is changed over to compressed air. With it the water supply is interrupted and compressed air can be blown by compressor into the borehole. At the bottom of the pipe the air escapes and rises in the brine. In this way turbulence is achieved in the water, leading to a uniform leaching of the cavern. After saturation the brine is pumped out of the cavern and transported by pipeline to the disposal gallery by submersible pumps.

Construction

The construction of 5 caverns starting at the 800-m level of the Asse mine was required. These caverns were to be set up 15–18 m below the gallery level. In each case a 180-mm ϕ uncased borehole was available as connection to the gallery.

The remaining data were pre-given as shown in Table 1. It was not possible to fulfil these requirements using a conventional leaching operation. The use of a blanket medium to limit the cavern height was not possible, due to the lack of a cemented casing and also for explosion protection reasons.

The demand for the production of an almost saturated brine represented a particular handicap, as this was to be disposed of in a gallery especially excavated for this purpose, and therefore the brine volume was to be limited as much as possible. In a normal leaching operation, with the small leaching face of only 3 m, this requirement immediately leads to the formation of a flower pot cavern configuration and therefore does not comply with the prescribed form.

For these reasons the following leaching method was developed and put into practice:

- Intermittent leaching
- Circulation of brine by injection of compressed air during saturation period
- Removal of brine by submersible pumps.

The technical equipment required is shown in Figures 9 and 10.

Above one pipe the borehole was, in each case, filled up to the upper leaching zone with freshwater. Filling was monitored by an optical sounder; during the saturation period air was injected at the lowest point, in order to achieve by circulation a constantly uniform concentration over the entire leaching area. This uniformity would ensure a regular increase in diameter.

TABLE 1

Respective cavern volume	approx. 10 m^3
Cavern shape	cylindrical
Depth location	15–18 m below 800 m level
Cavern height	approx. 3 m
Cavern diameter	approx. 2 m
Density of brine produced	min. 1,190 kg/m^3

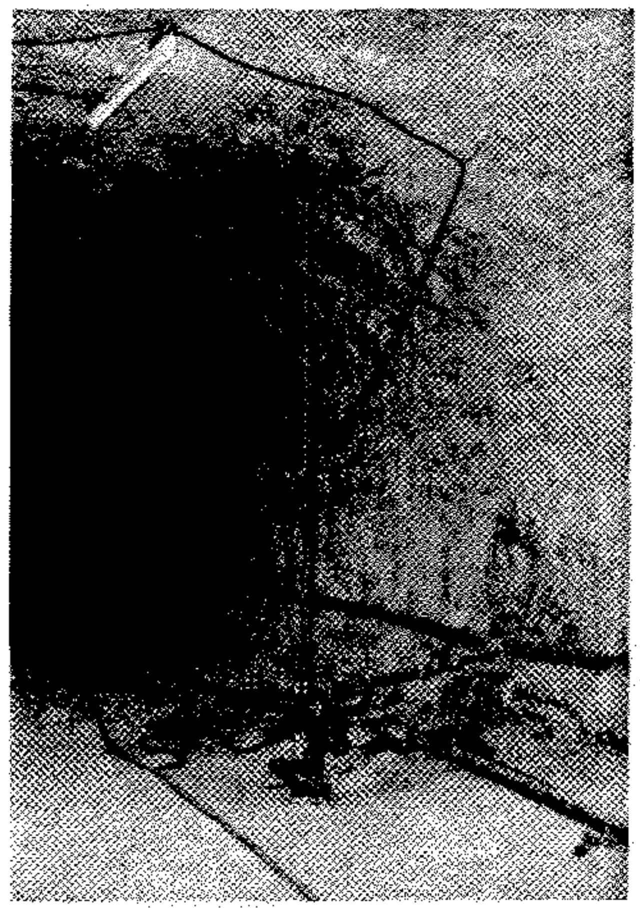

Figure 9.

After saturation the brine was pumped off and the cavern region refilled with freshwater. With an initial volume of 00.76 m^3 in the cavern region of the borehole, approximately 40 freshwater turnovers were necessary with the required brine concentration (approximately 300 kg/m^3) to achieve a total volume of 10 m^3. The necessary freshwater retention time, until it achieves the required saturation, is dependent on the water volume/salt surface ratio. The larger the cavern volume, the longer the retention time required until the desired concentration is achieved. For these caverns, the required retention time was fixed as in Table 2 on the basis of the salt dissolution velocity rate.

This resulted in a construction time having a maximum of 2 months. A brine volume of 400 m^3 produced a total cavern volume of approximately 50 m^3.

Monitoring

The actual cavern volume development was monitored by measurement of the freshwater volume at each refill.

Figure 10.

TABLE 2

1–10th turnover	2 × per day
11–25th turnover	1 × per day
26–40th turnover	1 × per 2 days

The volume distribution over the depth could also be determined by sounding the water level during fill. Cavern shape development can be seen in Figure 11. The final volume after 40 freshwater turnovers, the last 5 being only partial turnovers (intended to improve the cavern form), was 10.5 m^3. The development of concentration, cavern volume as well as freshwater volume, over the construction time is to be seen in Figure 12.

According to this study the brine produced had a minimal density of 1,190 kg/m^3 and maximum 1,205 kg/m^3; this means it was always more or less saturated. During the leaching process further chemical analyses of sodium, potassium, calcium, magnesium and chloride were carried out to provide early detection of salts other than halite being dissolved. If potassium layers had been found, the required cylindrical cavern form would no longer have

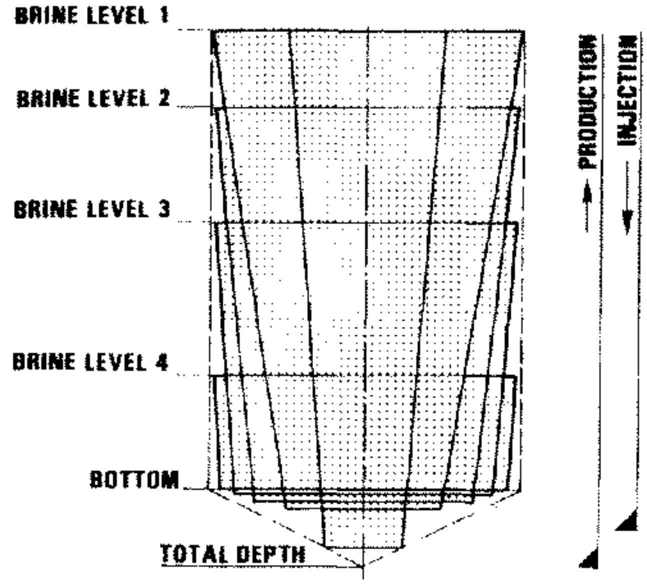

Figure 11. Disposal of MLW/LLW experimental cavern model cavern shape development

been able to be produced due to potassium's higher dissolution velocity.

It was not possible to carry out an echometric survey of the final caverns. The final cavern form was therefore ascertained as follows in each case:

- Measurement of the cavern partial volume in thicknesses of 20–50 cm (see graph in Figure 13)
- Plotting of these values under the assumption of circular shape development (Figure 14)
- The cylindrical shape development around the borehole axis was confirmed later on by installation of thermosensors with extendable measurement arms.

Filling of Cavern

In each of the model caverns thermosensors (developed by the firm Nukem GmbH Hanau) were installed on extendable arms (Figure 15). These were passed through the well in the collapsed condition and then positioned in the cavern in such a way as to ensure that the lowest sensor was fitted immediately above the cavern sump. The arms of the thermosensors were opened out via a wireline, so as to enable the remaining thermosensors to assume a position adjacent to the cavern wall.

NiCr-Ni-elements were selected as thermosensors which were then linked up to the data recorder via a data line. To determine the humidity in the concrete, two Vaisala humidity sensors were suspended in the caverns at the end of a filling. The pressure development capacity in the cavern was controlled via Glötzel pressure recorders.

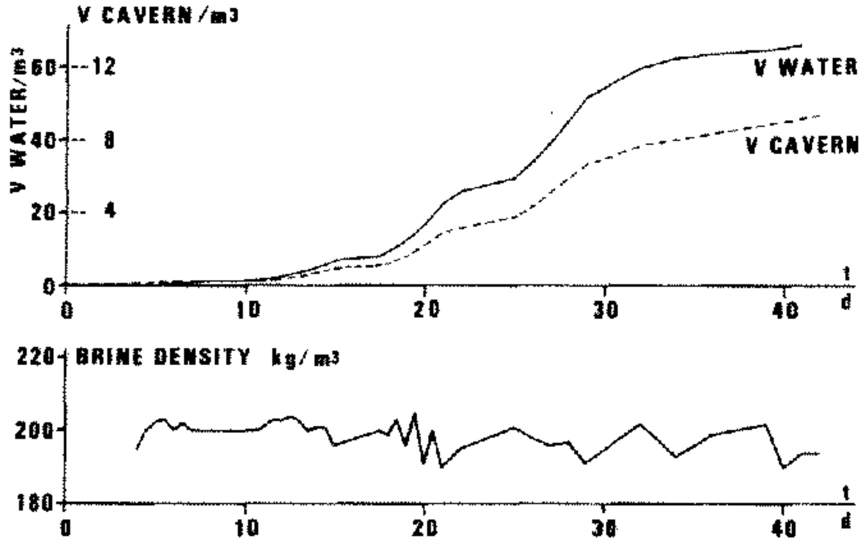

Figure 12. Disposal of MLW/LLW experimental model cavern vol., water req., brine density

Slurry/Pellet Composition

The aim is to finally dispose of the maximum volume of cement-consolidated radioactive waste in the smallest possible underground cavity in the salt. Boundary conditions were the transportability of the slurry over approximately 1,000 m, observance of an upper temperature limit of 90°C, as well as the long-term physico-chemical stability of the mixture.

From previous production tests a ratio of

PELLETS : CEMENT = 60 : 40 Vol %

proved favourable.

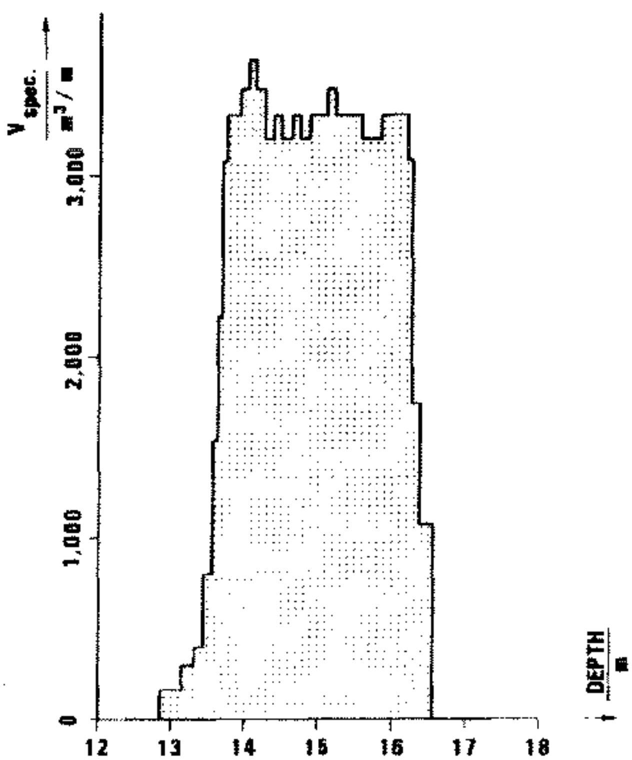

Figure 13. Disposal of MLW/LLW experimental cavern model volumetric distribution of K1

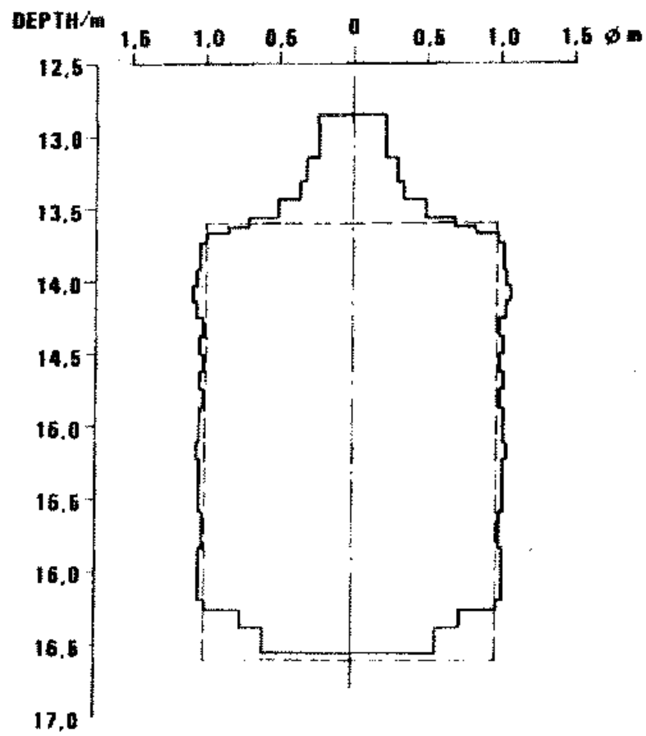

Figure 14. Disposal of MLW/LLW experimental cavern model final actual form K1

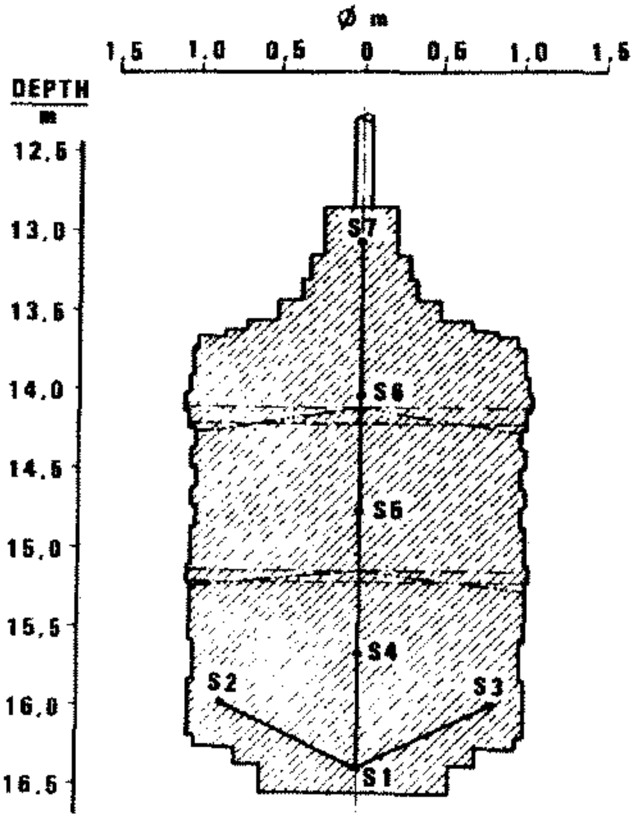

Figure 15. Disposal of MLW/LLW array of temperature sensors 1–7

The mixture was preset as shown in Table 3.

The preset water/cement relation of 0.45 could be increased in gradual stages, if this were necessary for the fill. The theoretical, i.e., without pore content, maximum possible density is = 2.298 kg/dm³. To determine the overall requirement of backfilling material an air-pore content of 12% is assumed.

A free-falling mixer for a fresh concrete volume of approximately 200 liters was available. Each mixture was based on a quantity of 100 kg cement. The pellets were supplied in so-called "big bags" of approximately 1.2 tons weight. These were added by using a set of scales fitted on the loading device. The concrete additives had been previously packed in portions and were applied to the dry material.

TABLE 3

	Mass kg	Mass %	Volume dm³	Volume %
Cement	100	22.10	33.33	16.92
Water	45	9.94	45.00	22.85
Pellets	307	67.85	118.08	59.98
Retardant HR7	0.300	0.07	0.30	0.15
Liquefier CFR2	0.200	0.04	0.20	0.10
Total	452.50	100.00	196.91	100.00

Approximately two thirds of the required water volume was preloaded in the mixing drum. After filling with the dry material, the remaining water was added while the drum rotated. The mixing time was 3 minutes. This produced a homogeneous mixing of the liquefier and retardant with the remaining components. Upon conclusion of the mixing time for the slurry, viscosity tests decided on its flow characteristics. If the values were still below the desired consistency, more water was added and mixed for one more minute.

For the first 3 caverns, the mixture composition was constant but the filling rate variable. When filling cavern K1 the amount of water added was varied to obtain optimal flow characteristics of the slurry. For cavern K2 filling in one stage was intended. Here the temperature curve, maximum temperature as well as the time of its occurrence, is intended to serve as the basis for filling cavern K5. Filling of cavern K5 was planned in two equal stages. The second load should be started when the maximum temperature had been reached in the first load.

Filling of the last two caverns was put off until transportation tests over 50 m to 1000 m produced optimal mixtures at this point. The mechanical properties should be examined on the basis of these optimal mixtures. During filling of cavern K1 it was shown that despite the previous production tests the parameters achieved above ground are not necessarily reproducible underground. Therefore, the mixing time was increased from an initial 2 minutes to 5 minutes and then reduced again to 4 minutes, from the fourth load onward. This seemed necessary in order to allow the additive agents to become more effective due to formation of a more homogeneous mix.

The water/cement value of 0.45 is the minimum required for flowability. This value had to be increased in each start-up phase. The grain size distribution of the pellets varied between the big bags and a cement percentage of 40 volume % led to difficulties in pumping.

The mixtures were passed via a hopper from the free-falling mixer through the 3-inch drop pipe from the borehole into the cavern. At the transition between hopper and pipeline, blockages were formed during discharge and these led to interruptions in the filling of the cavern.

On the production line, a layer of cement was formed on the borehole wall which was not removed. Due to the long periods of interruption between loading of cavern K1 this layer was always able to cure. This caused the borehole to block prematurely, and therefore a second filling borehole had to be drilled into the cavern.

During fill, the actual fill level was constantly logged in the cavern and compared with the calculated level according to volume of the cavern. Based on the theoretical and the actual level the angle of the slurry surface could be evaluated. The first fill was intended to indicate boundary conditions and the alternatives of the different parameters. Results of changes had to be recorded. Even the operating personnel had to familiarize themselves with the procedure. The individual steps had to be coordinated. The fact that coordination has been successful is shown by the reduction in the filling time from an initial 3 hours 40 minutes to 1 hour.

Measurement Results

The temperature development within the caverns was measured in each case by using 7 thermosensors. This is dependent on the heat released by the cement during the setting reaction, as well as on the heat losses through the concrete, salt rock and, in special cases, the residual cavity when partially filled. Particular significance is attributed to the absolute maximum temperature, time of its occurrence and the mutual interaction in the case of multi-stage filling.

The data thus obtained serve as the basis for a calculation model, by means of which appropriate parameter variation is then applied to the filling system of a 75,000-m^3 cavern.

The measurement device with the temperature sensors was already installed several days prior to fill, thus enabling the initial cavern temperatures to be determined (Figure 16, Temperature development in cavern 2). The number of days are counted consecutively for the respective first fill. The first measurement starts one day prior to first fill. All curves show a short cooling phase at the day of filling, followed by the achievement of maximum temperature within a period of 1–3 days. The falling leg of the temperature curves flatten rapidly. Four weeks after the respective first fill, the temperature of none of the caverns is more than 10°C above the initial temperature. After 45 days during the 1/1 fill, the temperature is only 1–3°C higher than prior to the backfilling of the cavern area.

Cavern K1, unlike cavern K2, would be filled in batches of 1/6 volumes. This means that the five temperature sensors T1 and T4–7 arranged above one another are not always in the centre of a batch and therefore do not record the respective maximum temperatures.

Due to a defect in measurement technique it was not possible to plot the temperature curves of all batches. The highest temperatures measured in K2 were 59.2°C (T4; load 2), respectively, 64.4°C (T5; load 4). The highest temperatures occurred 30 h and 27 h, respectively, after the start of filling.

It was shown that the temperatures in the remaining cavity at the beginning of a new batch after 28 days had not yet returned to the initial values. Despite the relatively long cooling phases, the measurements showed temperature increases of, on average, 2/10°C for the residual cavern. Also cooling within the first hours of curing is clearly indicated in the unfilled part of the cavern. The heat flow in the concrete can best be observed at the third and fourth load but can, however, also be observed at load 5. There is a rise in temperature at thermo-element T1 during load 3 after 10 days, load 4 after 7 days and load 5 after 9 days. On the 44th measurement day the sensor T7 shows a distinct jump in the temperature curve. This is presumed to be due to a defect in the thermo-element. The measurements were ended after 168 days.

INVESTIGATION ON 75,000-m^3 CAVERNS

Geology

The geology is similar to that of the Gorleben site (salt dome selected for radioactive waste disposal). Until availability of the documents from the deephole drilling pro-

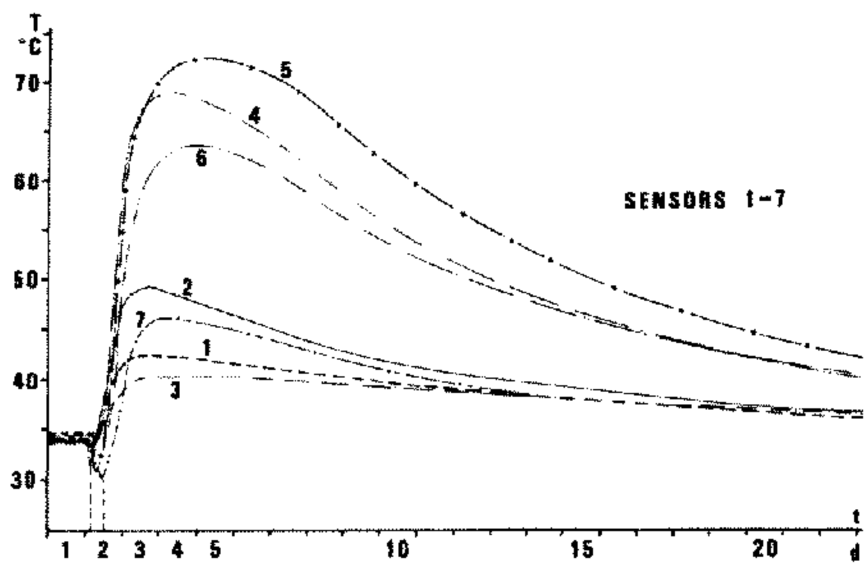

Figure 16. Disposal of MLW/LLW temperature curves in filled cavern 2

gramme which is currently underway, the following rough classification of the geological rock mass is taken as basis:

0-250 m—Unconsolidated to partially consolidated rocks of the Quarternary and Tertiary period possibly with discordant underlying Mesozoic rocks of lesser thickness

250-300 m—Caprock layers in the transition from overburden to the Zechstein beds

300 m upward—Saltdome with partially inverse stratification. Possible occurrence of varying thicknesses of anhydrite and layers of clay. Furthermore, a more marked folding of the Carnallite layers is assumed.

Deephole Drilling

In order to completely determine the state of the art concerning the construction of large calibre deephole wells for the storage concept, the Institut für Tiefbohrkunde and Erdölgewinnung at the Technical University of Clausthal ordered the preparation of a model that takes into consideration the possible drilling techniques, necessary equipment as well as protection of the hole by means of casing and cementation under the given planning predata.

The drilling program is intended for a construction of the caverns by solution mining. For this technology a final casing diameter of 11¾″ is required (Figure 17). The selected casing programme—the cementations and test methods—ensures an extremely high degree of safety against water inrush from the overburden water-filled formations into the cavity.

Leaching Concepts and Surveys

The basic method for constructing an effective cavity in the salt by solution mining has already been described and published many times. It is therefore assumed to be generally known. The schematic diagram of a leaching process is shown in Figure 27.

Within the scope of the planning put forward the following additional requirements had to be solved:

1. Construction of 3 caverns, each of 75,000 m^3 effective volume with a cylindrical shape, as well as a roof approximating an ellipsoid
2. Each cavern is intended to serve as depository for MLW and LLW over a period of 5 years
3. The brine has to be removed from the caverns by a suitable technical method prior to filling of the MLW/LLW
4. The caverns must be ready for operation at the latest by the respective start of fill
5. With the exception of the last cavern there should, where possible, always be a reserve cavern available.

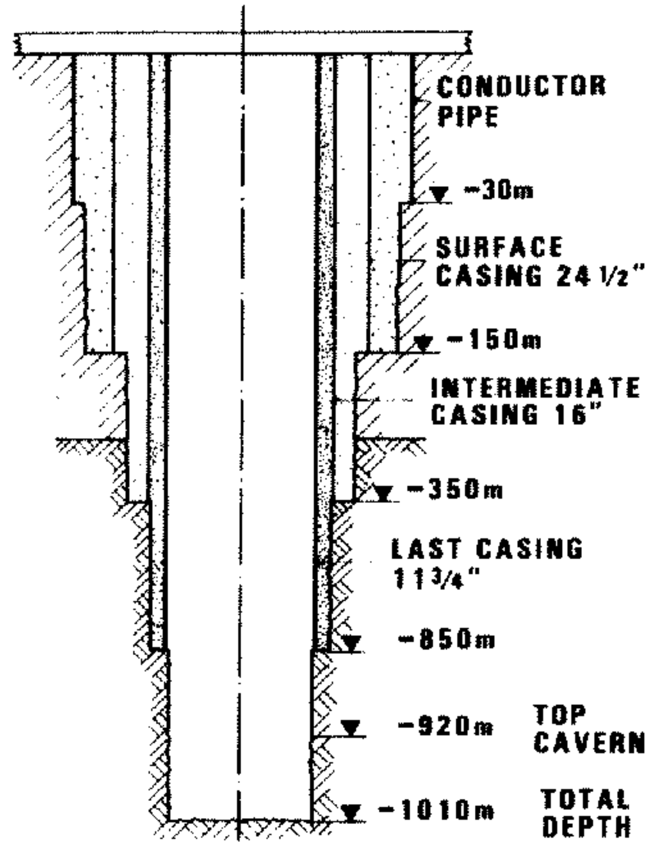

Figure 17. Disposal of MLW/LLW cavern well casing scheme

With regard to the cavern array, there are two variants concerning location of the caverns:

1. Setting up of 2 superposed caverns from one borehole; setting up of the cavern from a second borehole (Figure 18)
2. Setting up of all 3 caverns from one individual well, in the same depth location (Figure 19).

Within these basic variants the time schedule—start of leaching, leaching phase, withdrawal—can be varied. From the wide variety of possibilities the most important will be shown in the following, together with their advantages and disadvantages.

Variant 1 (Figure 20)

Two caverns superposed from one well, third cavern from an additional well.

Here cavern No. 1 is leached first. Immediately after this cavern has been completely leached, cavern No. 3 is incorporated in the leaching process. Emptying of this cavern can be undertaken, depending on the type of withdrawal immediately after completion of leaching or shortly before start of the changeover work for the depository operation. The last cavern (No. 2) is incorporated into the

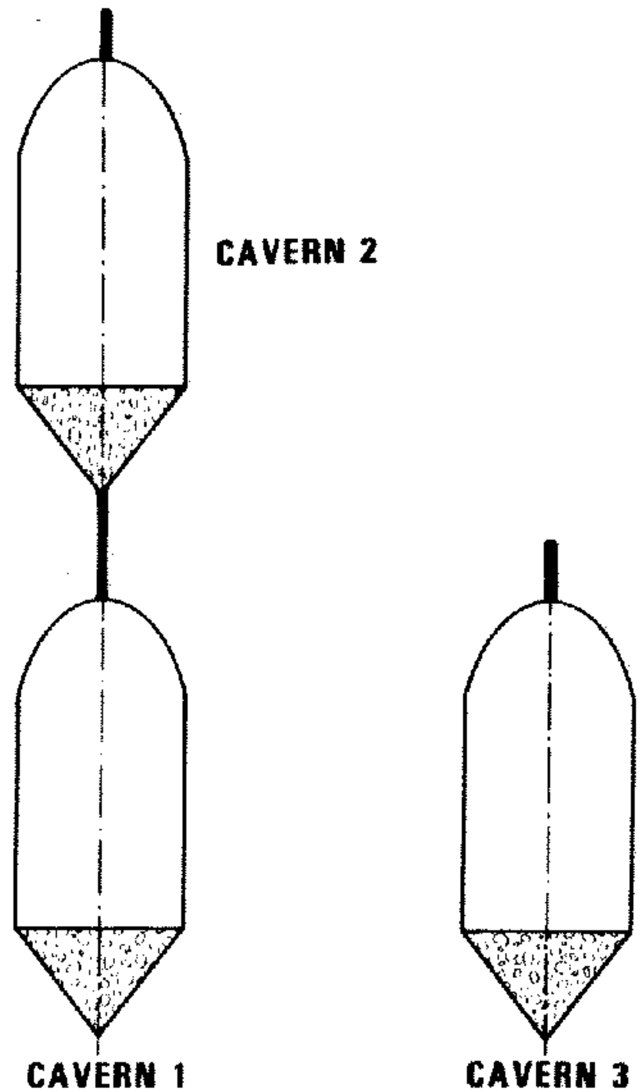

Figure 18. Disposal of MLW/LLW cavern array variant 1

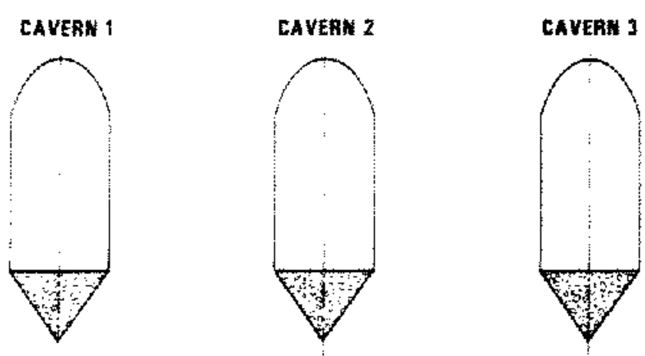

Figure 19. Disposal of MLW/LLW cavern array, variant 2

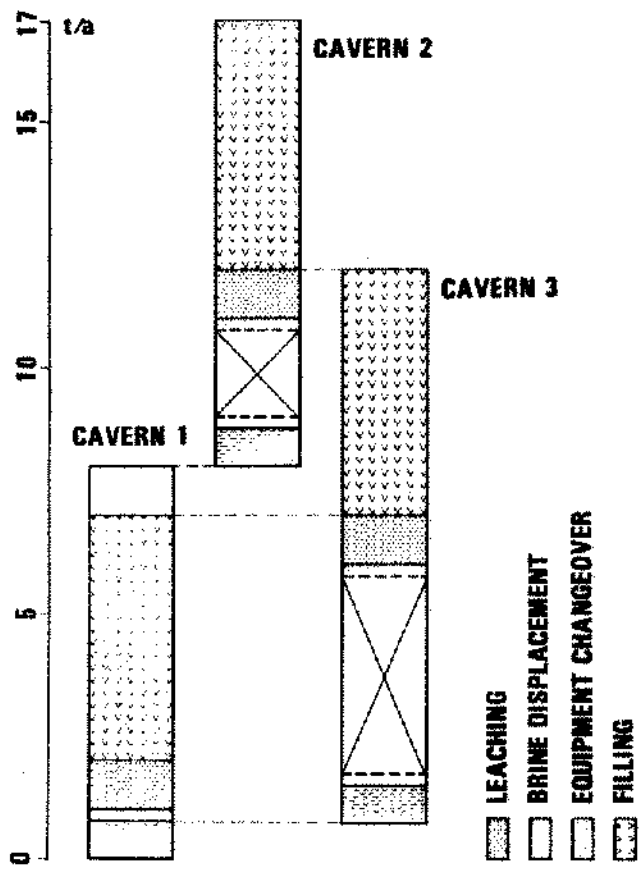

Figure 20. Disposal of MLW/LLW time schedule, variant 1

leaching process after filling and sealing of cavern No. 1: The entire development of this variant over a period of approximately 17 years can be seen in Figure 20.

The advantages of this variant are:

- There is almost always a reserve cavern available
- The leaching installations are only to be designed for the leaching rate of one cavern at a time.

The disadvantages of this variant are:

- The brine installations must be kept operational over a long period
- The leaching process is interrupted temporarily and therefore requires intermittent personnel.

Variant 2 (Figure 21)

Three caverns at the same depth, accessible in each case via a separate borehole.

As can be seen from the time schedule the next cavern in each case is leached shortly before the previously completed cavern is filled, i.e., the start of leaching of the 2nd and 3rd caverns is approximately 2 years prior to completion of fill of the previous caverns.

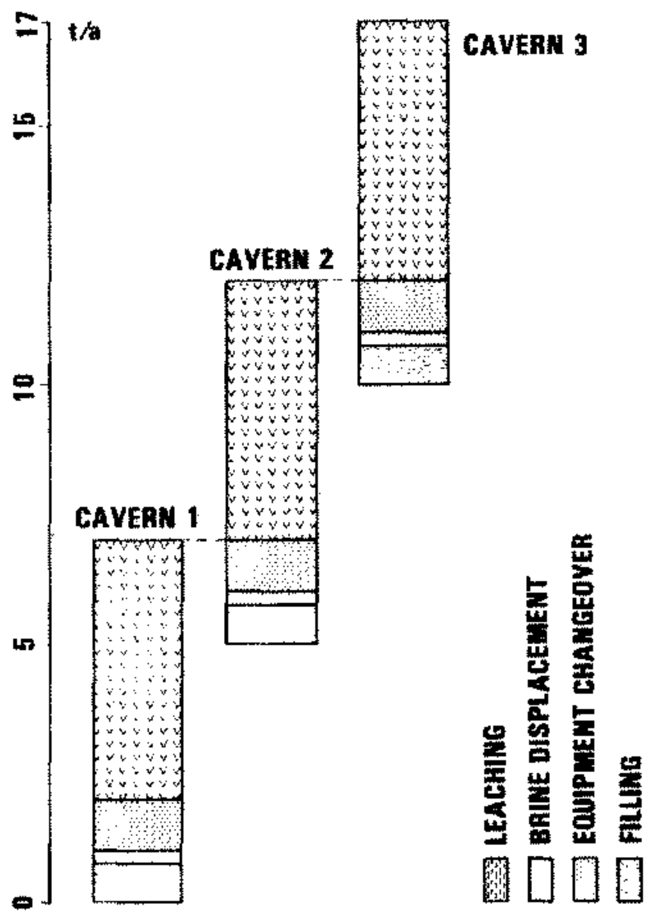

Figure 21. Disposal of MLW/LLW time schedule, variant 2

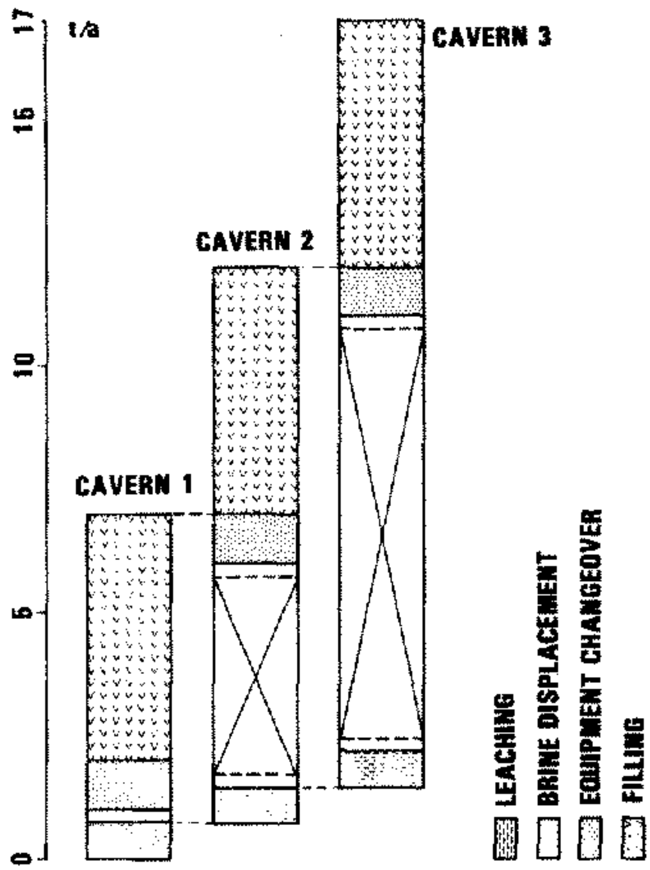

Figure 22. Disposal of MLW/LLW time schedule, variant 3

The advantages of this alternative are:

- The caverns are not open any longer than absolutely necessary
- The investment costs for wells and leaching operation occur in each case at the latest possible time.

The disadvantages of this alternative are:

- In the event of technical failure of the filled cavern, no reserve cavern is available
- The leaching operation is temporarily interrupted and therefore requires personnel.

Variant 3 (Figure 22)

Three caverns at the same depth, accessible in each case via a separate borehole.

With this variant all three caverns are leached consecutively immediately after one another. Cavern No. 1 is emptied immediately after completion of leaching, caverns No. 2 and 3 also immediately after completion of leaching or shortly before start of changeover work for storage operation.

The advantages of this alternative are:

- There is nearly always a reserve cavern available
- The leaching process is concluded after approximately 2 years for all 3 caverns.

The disadvantages of this alternative are:

- Caverns No. 2 and 3 are for a longer period only filled with brine, respectively, after emptying under atmospheric pressure
- All investments for boreholes and leaching operation occur very early on.

Variant 4 (Figure 23)

Three caverns at the same depth, accessible in each case via a separate borehole.

With this alternative all 3 caverns are simultaneously put into leaching operation and completed. After completion of leaching the first cavern is emptied and changed over for the deposition.

The advantages of this alternative are:

- There is always a reserve cavern available
- Marked reduction in leaching operation costs, as the

entire leaching period can be reduced to a third in comparison with the previous alternatives.

The disadvantages of this alternative are:

- Caverns No. 2 and 3 stand only filled with brine over a longer period after emptying under atmospheric pressure
- All investments for boreholes and leaching operation are incurred first
- The construction costs for the leaching equipment are higher due to the 3 times larger total leaching rate.

Within the investigation undertaken Variant 1 with 2 superposed caverns from one borehole was not further pursued, as it offers no further essential advantages apart from a better utilization of the salt dome. The fact that in this case only 2 instead of 3 boreholes are required is not considered as an essential advantage, as here greater construction problems are to be expected.

Technical designs were made, therefore, only for variant 2 with the following alternatives:

- Simultaneous leaching of 3 caverns
- Consecutive leaching of 3 caverns.

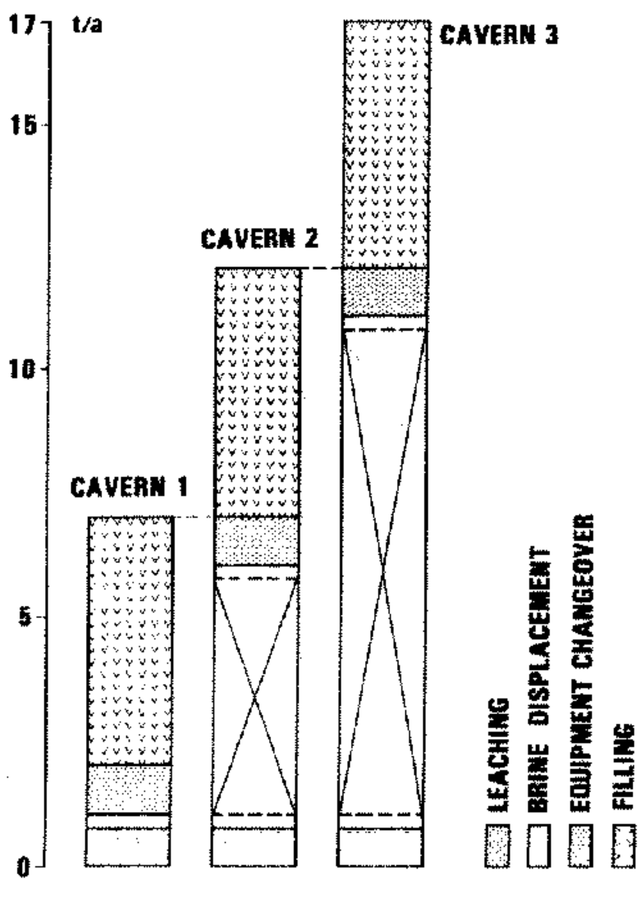

Figure 23. Disposal of MLW/LLW time schedule, variant 4

For this purpose a leaching rate of maximum 150 m^3/h and cavern was set. A leaching rate time curve can be seen in Figure 24. To check the desired cavern form at normal leaching run, 3 echometric logs are to be carried out, respectively, after a leaching volume of

20 000 m^3
65 000 m^3
75 000 m^3.

The necessary technical equipment for the leaching operation essentially consists of that shown in Table 4.

Emptying of Caverns

After completion of the leaching process and prior to filling of the depository material the brine in the cavern must be removed. It is, in fact, technically possible to fill in the cavern with a cement/pellet mixture and thus at the same time to displace the brine from the cavern; as a contamination of the brine with the radioactive waste cannot be excluded, the caverns must be previously emptied.

For such an emptying process there are basically two technical possibilities available:

1. Emptying by means of submersible pumps installed in the cavern
2. Withdrawal of brine by displacement with compressed gas, e.g., air.

Emptying by Submersible Pump

For this purpose an electrically driven submersible pump is installed on a conductor pipe into the cavern. A schematic diagram of the arrangement is shown in Figure 25. Because in the case of the pumps offered on the market the drive motor is below the pump section and thus requires an overpressure of several m water column in the pump, the brine can be pumped off totally only by means of an additional backup pressure of 2–4 bar. This backup pressure is applied in the final phase of withdrawal via, e.g., a mobile compressor.

Using the method shown here, caverns have already been emptied for the storage of compressed air.

Withdrawal via Displacement with Compressed Air

With this procedure the brine is displaced via an installed tubing string by pumping in compressed air through the annulus. With, e.g., a total cavern depth of approximately 1000 m, air is required with approximately 140 bars of pressure. The diagram of this procedure can be seen in Figure 26.

In order to be able to empty the caverns within a reasonable time with this method, a brine withdrawal rate of 100–150 m^3/h is necessary. The air compressor required for this purpose has the technical data shown in Table 5.

Both methods have already been applied several times

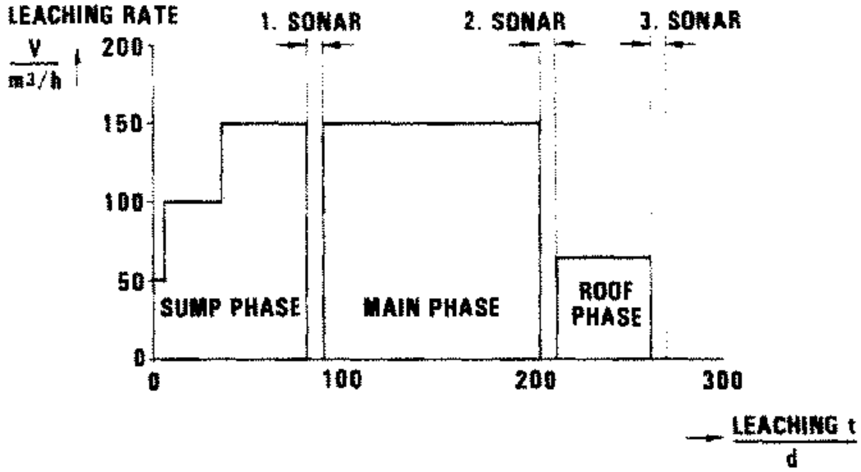

Figure 24. Disposal of MLW/LLW leaching schedule for 75,000 m^3 caverns

TABLE 4

	Leaching of	
	3 caverns simultaneously	1 cavern
Freshwater rate	450 m^3/h	150 m^3/h
Freshwater and brine rate/cavern	150 m^3/h	150 m^3/h
Main pump station	450 m^3/h	150 m^3/h
Pipeline diameter	250 mm	150 mm

for the final emptying of caverns; emptying by compressed gas is, however, only economically feasible if the compressor required for the later storage disposal operation can be further used. If the investment and operation costs apply only to withdrawal, then there is a ratio of approximately

$$1:2.$$

In this case, the costs are favourable to the alternative of using submersible pumps.

Filling of Caverns

The above-ground transport of the pellets is effected from the reprocessing plant to the cavern location by means of transport containers. The pellets are mixed with the cement slurry in a so-called "hot cell." This cement suspension is filled from a loading station, fitted with an agitator, via a pipeline into the cavern. Because of the rheological behaviour of the pellet/cement mixture, the transport occurs in a vertical pipeline, with approximately 60 m inner diameter, merely due to gravitation. The mean flow velocity is about 0.3 m/sec. The tests carried out by the Nukem Corporation and the Institut für Fördertechnik of the University of Karlsruhe prove the functionability of the planned procedure. Product behaviour can be monitored by means of measurement probes, which are

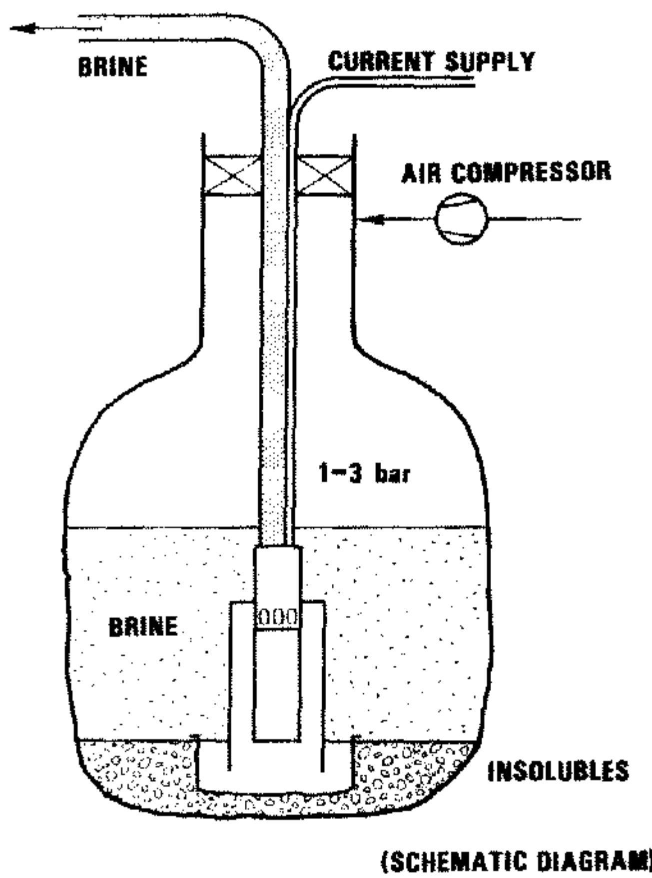

Figure 25. Disposal of MLW/LLW displacement of brine by submersible pump

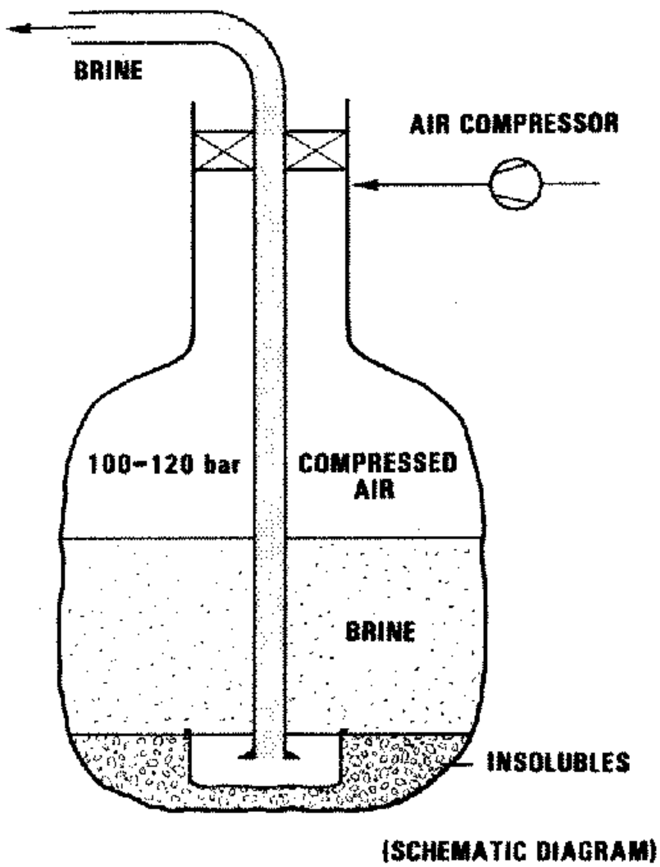

Figure 26. Disposal of MLW/LLW disposal of brine by compressed air

lowered into the cavern during the operation via the deep borehole.

Cavern Costs

The following costs for the construction of an effective cavern volume totalling 225,000 m^3 (spread out over 3 caverns, each 75,000 m^3) constructed in a depth of 800–1000 m in salt are based on the findings established in 1981. According to the cost increase since then, the prices determined at that time have been increased by approximately 20% in order to update them for the year 1983.

As this investigation dealt with a study with no specific location, and as furthermore the costs for conventionally mined caverns are to be compared with the costs determined here, the following are not included in the subsequently listed m^3 price:

- drilling
- land acquisition
- operation site routes
- salt mining rights
- brine displacement.

The costs per m^3 of storage volume free of brine are for the variants as follows:

	DM
Simultaneous leaching of 3 caverns	
a) Withdrawal by submersible pump	66.--
b) Withdrawal by compressed air	80.--
Consecutive leaching of three caverns	
a) Leaching with submersible pump	68.50
b) Leaching with compressed air	81.00

Time Requirement

In the overall time planning it was established that each cavern is filled over a period of five years, i.e., the system with three caverns is capable of handling the generation of MLW and LLW over a period of 15 years. The preliminary period up to the start of leaching operation has not been further investigated in the present study. It can, however, be estimated from the experiences gained in comparable leaching projects as approximately 2 years for the pre-in-

TABLE 5

Volume flow	7 000 m^3 V_n/h
Suction pressure	1 bar
Ultimate pressure	140 bar
Number of compressor stages	5
Drive output	approx. 1 400 kW

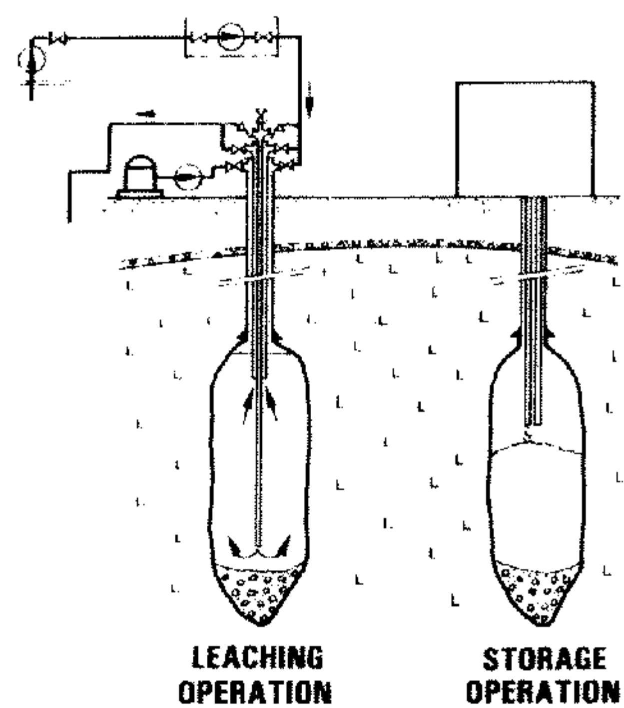

Figure 27. Disposal of MLW/LLW principle leaching and storage diagram

vestigation, drilling of leaching wells and setting up of leaching installations.

The leaching operation itself requires approximately 9 months with the selected rate of 150 m^3/h and a single cavern volume of 75,000 m^3. The brine withdrawal using both investigated methods in each case needs approximately 3 months. Thus the first cavern is emptied 12 months after start of the leaching operation. An additional 12 months was estimated for the changeover to deposition operation. Thus as far as the cavern is concerned, the storage of LLW and MLW can be begun 24 months after the start of the leaching operation.

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