PETROLEUM ENGINEERING TECHNIQUES FOR HLW DISPOSAL

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ABSTRACT

This paper describes why petroleum engineering techniques are of importance and can be used for underground disposal of HLW (high-level radioactive waste). It is focused on rock salt as a geological host medium in combination with disposal of the HLW canisters in boreholes drilled from the surface. Both permanent disposal and disposal with the option to retrieve the waste are considered. The paper starts with a description of the disposal procedure. Next disposal in deep boreholes is treated. Then the possible use of deviated boreholes and of multiple boreholes is discussed. Also waste isolation aspects and the implications of the HLW heat generation are treated. It appears that the use of deep boreholes can be beneficial, and also that – to a certain extent – borehole deviation offers possibilities. The benefits of using multiple boreholes are questionable for permanent disposal, while this technique cannot be applied for retrievable disposal. For the use of casing material, the additional temperature rise due to the HLW heat generation must be taken into account.

INTRODUCTION

It cannot be denied that in Western Europe enthusiasm for nuclear energy is declining, particularly in Germany, the Netherlands and Sweden. For waste disposal this implies that solutions on a smaller scale than formerly envisaged may become interesting alternatives. It is common knowledge that, in some disposal configurations, techniques similar to those in use in the oil and gas industry are practiced.

From the oil and gas industry new developments can be mentioned, in particular in the field of drilling engineering. From these we mention deep drilling, deviated drilling, multilateral drilling, measurement while drilling, and smart wells concepts. The aim of this paper is to combine the two above-mentioned elements, viz. (a) disposal of HLW (high-level radioactive waste) in boreholes, which is an alternative, small-scale disposal solution, and (b) new or improved petroleum engineering techniques which can be used in disposal operations, by treating a number of subjects. After a general treatment of underground disposal of radioactive waste and of disposal of HLW in boreholes, we subsequently pay attention to: deep boreholes, possibilities of directional drilling and multiple boreholes, and isolation. Lastly we briefly discuss temperature effects, because these are of special importance and are quite different for underground disposal compared to activities related to oil and gas production.

UNDERGROUND DISPOSAL OF RADIOACTIVE WASTE

For subsurface disposal of radioactive waste, quite a number of designs for underground repositories are available. In a number of cases these repositories are already under construction. From these we mention Yucca Mountain (Nevada, USA; geological medium volcanic tuff) and Gorleben (Germany; geological medium rock salt). The layouts of these repositories are somewhat similar to those of a conventional mine. There are shafts, galleries and excavated rooms. Differences with a mine are, among other points:

- The purpose in excavating the mine/repository. Evidently the interest is not in the excavated materials, but in the created space in the underground.
- Apart from the excavated rooms, which can be used for disposal of the LLW (low-level radioactive waste), there is a region with galleries provided with horizontal or vertical boreholes to accommodate the HLW. Spreading of this type of waste is necessary because of the heat generation of this waste. The spreading ensures that the temperature rise in the host medium remains limited.
- Sealing and abandonment activities are much more crucial than in the case of an excavation mine, because the main objective of underground disposal is isolation of the waste from the biosphere.

Obviously the layout of a repository is not only influenced by factors as depth, amounts of waste and general geological circumstances, but also by the nature of the host medium. The amount of geological media considered to be suitable for disposal of highly toxic solid waste products is limited. Of these we mention granite (e.g. Sweden), clay (e.g. Belgium), volcanic tuff (USA) and rock salt (Germany, the Netherlands, USA). From now on we will only consider disposal in rock salt, although the analysis and discussion presented below may also be, to a certain extent, applicable for host media other than rock salt.

In 1986 a study was carried out, on behalf of the Dutch Ministry of Economic Affairs, on disposal of radioactive waste in rock salt in the Netherlands (1). In this study not only a mine repository was considered, but also an alternative thereof, viz. deep boreholes (in rock salt) drilled from the surface of the earth, for the HLW canisters, in combination with a leached-out salt cavern (or a number of salt caverns) for the LLW. It appeared that the alternative was a realistic one: disposal in deep boreholes and in a salt cavern is feasible, cost-effective and can be carried out safely. Later on the attention for the alternative diminished, because the Dutch Government introduced a retrievability requirement for the waste. Incorporation of waste retrievability is feasible for a mine repository (2) and for the deep boreholes (3), but not for a salt cavern (4). As disposal in (deep) boreholes is the main subject of this paper, we proceed with a short description of this technique.

DISPOSAL OF HLW IN BOREHOLES

To start with we assume that the objective of the HLW disposal is permanent disposal. A hole is drilled into the salt formation in a manner as is normally practiced in the oil and gas industry. This implies drilling a hole to a depth just above the salt formation, and strengthening the hole by installing a casing string, with cement between this string and the surrounding formations. Then drilling is continued, into the salt, with drilling fluid containing dissolved salt to prevent unwanted washout of the borehole. Furthermore the drilling fluid must have a relatively high density, to ensure that convergence of the borehole is minimal. When a sufficiently long interval is the salt has been drilled, the drilling operation is complete. The next phase is the disposal phase: the HLW canisters are lowered into the borehole. Subsequently the drilling fluid surrounding the canisters is replaced by cement. When this has been done, a length interval of about 100 m remains, in the salt, between the top of the cement and the casing shoe. Then the drilling fluid is pumped out of the borehole, and the open interval in the salt filled with (wet) crushed salt (just as in the case of a salt cavern for waste disposal, see Crotogino (5)). This crushed salt will be compacted in due time and in this way will completely isolate the HLW inside the salt formation. Finally the upper part of the borehole is sealed by placement of a number of cement plugs.

In case it must remain possible to retrieve the HLW canisters, the procedure as given above cannot be used. This has to do with the following considerations:

- When the borehole is re-opened, the cement plugs will have to be removed by drilling. Cement debris will fall down, which will considerably hinder a retrieval operation.
- It will be very difficult to continue drilling in such a way, that the new borehole ends exactly above the uppermost HLW canister.
- The canisters are surrounded by cement and, consequently, it is almost impossible to retrieve them in an undamaged state.

The first measure to be taken to make waste retrieval possible is to install casing over the entire length of the borehole. After this has been done, the drilling fluid must be pumped out of the borehole. Subsequently a limited number of HLW canisters can be placed (this number must be limited to ensure that the lowermost canister is not damaged by (the weight of) the other canisters). Then the borehole must be sealed in some way, awaiting a decision to retrieve or not to retrieve. This can be realized by installing a special plug consisting of metal discs and cement at the top of the borehole in such a way that, during re-opening, this plug can be completely removed, without debris falling into the borehole. Details of this method can be found in an earlier paper (3). Then, after a considerable time period (some tens of years), it is assumed that a decision is made concerning waste retrieval. This will lead to one of the two following series of activities:

- In case it is decided to retrieve the waste, the borehole seal is broken and removed. Subsequently the canisters are taken out of the borehole. Then the borehole is re-sealed by installing a number of cement plugs (e.g. three, one at the top and two other plugs at suitable depths).
- In case it is decided not to retrieve the waste, the following procedure is recommended. Firstly, the borehole seal is broken and removed. Secondly, cement is brought into the borehole, so that the space between casing and canisters is filled up. Thirdly, the borehole section above the canisters (but still in the salt formation), is milled away over a suitable length interval (some tens of meters up to, say, 100 m). Fourthly, that part of the borehole of which the casing is milled away is filled up with crushed salt. Finally the borehole is sealed by the

installation of cement plugs. In this way the end result is very similar to the end result for permanent disposal as described earlier.

DEEP BOREHOLES

For waste disposal usually depths of a few hundred meters down to somewhat more than 1000 m are considered. However, to be able to reach larger depths can be attractive from a safety point of view. The essential idea behind underground disposal is to isolate the very toxic waste products from the biosphere. In the case of rock salt, the salt itself is the most important safety guard or barrier. In rock salt minute amounts of water are present, but this water is unable to flow. Consequently, there is no groundwater flow in the salt itself, only in the surrounding geological formations. However, after a very long time period has elapsed, it is thinkable that the waste will come into contact with groundwater (after the salt barrier has disappeared though dissolution). Then the vertical distance between the waste and the biosphere becomes important. In this sense a large depth is beneficial, because (a) it will enhance considerably the time period after which dissolved waste products will reach the biosphere and (b) it will lead to much smaller maximum concentrations of the waste products in the groundwater. This concentration decrease will result from spreading over a much larger volume of water than in the case of less deep disposal.

For the oil and gas industry, working at depths of, say, 2000 m is not uncommon and, consequently, also for disposal in deep boreholes this can be realized. The main difference with boreholes as used in the oil and gas industry is the borehole diameter or, more specifically, the inner diameter of the casing. This has to be large to accommodate the HLW canisters, of which the diameter is of the order of 40-45 cm. Although there is a tendency in the oil and gas industry to aim at boreholes of smaller sizes, there is no reason to assume that difficulties will arise with larger sized boreholes. Firstly, for large depths, drilling fluids are available of rather large density (6), so that an adequate pressure in the borehole can be maintained, and the stability of the borehole during the drilling phase can be ensured. Secondly, adequate casing material is necessary. Here three points are of importance:

- Large diameter casings are available for use at lower depths. The only question, which can be posed, is whether this casing material is of sufficient strength to withstand the pressures at larger depths. If this is not the case, special casings have to be made. This should be not difficult, because strength increase can simply be achieved by increasing the thickness of the casing wall.
- With a combination of large depth and large diameter casings the weight of the casing string before it is installed and cemented will be much larger than normally encountered in the oil and gas industry. This implies that the drilling rig should be much sturdier than a "normal" drilling rig.
- Requirements concerning long-term stability of the casing (e.g. resistance to corrosion) will not essentially differ from the requirements for an oil well or a gas well casing. For permanent disposal the long-term stability is unimportant because the protecting barrier is not the casing but the salt formation. For retrievable disposal (see above) this is obviously not the case. However, the time period during which the casing must remain intact is of the order of a few tens of years to about 100 years (7). The necessary minimum lifetime is therefore of, roughly, the same order of magnitude as that of oil and gas wells. Moreover, in the case of oil and gas wells the casing will be continuously subjected to flow of gas, oil, (salty) water, and suspended solids. Special casing material in the case of HLW disposal seems therefore unnecessary. We will come back to this subject later on, when we discuss temperature effects.

DIRECTIONAL DRILLING AND MULTIPLE BOREHOLES

The last few years many developments can be mentioned on directional drilling and multiple boreholes. Directional drilling implies that the boreholes are not vertical but, at some depth, start to make an angle with the vertical. Initially these angles were not large, but nowadays horizontal or nearly horizontal boreholes (thus with an angle of approximately 90º) are drilled quite frequently. Naturally the build-up of the angle is very gradual, but this also depends on the diameter of the borehole: for small diameters the curvature (usually expressed in degrees per 100 ft) can be quite large. Drilling of multiple boreholes ("multilaterals") implies that, starting from one common borehole, two, three or more boreholes are drilled. Assume that a borehole has been drilled and completed. Then, at a certain depth, a hole is drilled in the casing wall and this hole is used as starting point for a second borehole (branch). The new borehole can be open (i.e. no casing present) or can be provided with casing. Obviously it is more difficult to construct a second borehole with casing than one without. In this way different levels of complexity can be distinguished (8).

In the case of permanent disposal, directional drilling and multiple boreholes provide, in principle, a number of additional possibilities for disposal concepts. With directional drilling that part of the borehole used for disposal does not need to be precisely below the location at the surface from which the disposal activities are carried out. This is similar to the practice in the oil and gas industry, where directional drilling is frequently used to reach an oil or a gas reservoir, located near the shore but still under the sea, starting from a land-based drilling rig. Directional drilling can also be used in case, once a start has been made with drilling the hole, it should appear that a disposal region not directly below the borehole, but e.g. 200 m parallel to it, is more suitable. It is obvious, however, that the angle with the vertical must not be too large, so that the waste canisters can still be lowered by making use of their own weight. Multiple boreholes can also be used, but here a potential difficulty must be mentioned. The borehole, at the depth of the branch, must be constructed in such a way that it is possible for a HLW canister to go smoothly over from the central hole into the branch. Firstly, this implies that the build-up of the angle must be very gradual to prevent that a canister can get stuck. Secondly, the new borehole (including the branch) must be quite smooth. This last requirement is not always necessary in the oil and gas industry, because it is superfluous for fluid flow. However, in case it is foreseen that repair or work-over equipment must be able to pass in a downward direction, it is desirable to have a smooth borehole. It is expected that it will be feasible to design an appropriate construction. Then the main problem is not in the build-up of the angle or in the smooth casing, but in the unusually large size of the underground construction.

With permanent disposal in a borehole and in an additional branch the disposal procedure can go as follows:

- A borehole is constructed in the way described earlier. HLW canisters are installed and cemented, the drilling fluid is removed and crushed salt is stacked upon the cemented waste canisters. At the bottom of the casing, near the casing shoe, a thick cement plug is placed.
- In the casing, at the appropriate depth, a so-called whipstock is installed. This device ensures that drilling through the casing wall becomes possible. In this way a new, slightly deviated borehole can be drilled, which can be subsequently consolidated with a new casing (to the top of the salt formation). Then the same procedure as already described can be used (installing canisters, cementing, removing drilling fluid, stacking crushed salt, placing a cement plug). It is obvious that repetition of this procedure is only feasible as long as each new casing (which must be smaller than the previous one), permits the passing of HLW canisters. Therefore there is a limit to the number of branches originating from one borehole. A reasonable guess is one borehole with a maximum of two branches.

An interesting alternative is to introduce branches below the casing shoe. This seems simpler, because now it is not necessary to drill sideways through the casing wall and installation of a new casing string is also unnecessary. Furthermore this procedure will permit more branches, because the inner diameter of the casing does not decrease with every additional branch. However, an appropriate procedure for this alternative with respect to the disposal interval has yet to be worked out.

Concerning use of directional drilling and multiple boreholes for HLW disposal with the option to retrieve the waste, we can state the following. Slightly deviated boreholes can also be used is this case. The main point is, that retrieval of the canisters must not be hindered, and there is no reason to suppose that this will be the case. Concerning multiple boreholes it can be assumed that use of these will seriously diminish the chances of being able to retrieve HLW canisters. With the introduction of a (new) branch, the canisters installed in the previous branch or in the original borehole will become difficult to reach. Consequently, it seems wise not to consider retrievable disposal in combination with multiple boreholes.

ISOLATION OF THE WASTE

In the preceding paragraphs attention was already given to some aspects of isolation. Here we want to treat this subject more extensively, by mentioning the following points:

- *Depth, crushed salt*. A larger disposal depth improves the level of isolation from the biosphere; this was already explained in an earlier paragraph. The same applies for the function of crushed salt as a material to restore the rock salt to the conditions present before a borehole was drilled.
- *Special surface seal.* This special seal, to be used for (temporary) isolation in the case of retrievable disposal, was also discussed already earlier in the paper.
- *Deep boreholes*. With increasing depth the underground stresses also increase. This leads to a slight increase of the difficulties of drilling, notably in connection with borehole stability. However, these difficulties can be

overcome by using appropriate drilling fluids. Moreover, the maximum depth level that is considered in underground disposal is by far not extreme. This disadvantage goes over in an advantage once the disposal operation has ended. The high stress level ensures that the waste is solidly contained in the rock salt formation, and that the crushed salt is relatively rapidly transformed into a material closely resembling natural salt. These statements are true for permanent disposal, but equally true for retrievable disposal after the proposed procedure described earlier (removing surface seal, milling part of the casing, etc.) has been followed. Consequently, a relatively large depth is also beneficial from the stress point of view.

- *Deviated boreholes*. Use of a deviated borehole instead of a vertical borehole does not have influence on the isolation level, apart from the circumstance that deviated boreholes lead to more flexibility, so that an optimal choice can be made concerning the most suitable disposal region in the salt.
- *Multiple boreholes*. Use of multiple boreholes instead of single ones has no influence on the isolation of the waste.
- *Rock salt as geological host medium, influence temperature*. Rock salt is a suitable material for waste isolation because of three favorable properties. Already mentioned was that rock salt does not contain flowing water. Furthermore, in a rock salt formation, there is a tendency that created spaces, boreholes etc. will converge and then close as time progresses, which is evidently very advantageous from an isolation point of view. Also cracks or fractures, in case these should be formed (e.g. as a result of thermal stresses), will have only a very limited lifetime. Lastly, the thermal conductivity of rock salt is, for a geological material, quite high (about 5 W/m.K (9), while 1.7 W/m.K (10) is the value for average rock). The consequence hereof is that the generated HLW heat is lost to the surroundings more rapidly for rock salt than for other geological host media.

TEMPERATURE EFFECTS

With increasing depth also the temperature increases. The normal geothermal gradient is of the order of 3°C per 100 m, while in rock salt – due to the relatively high thermal conductivity – this figure is lower, of the order of 2°C per 100 m. Thus it is quite common to have, in drilling situations in the oil and gas industry, a local temperature of the order of, say, 50-100 °C. However, disposal of HLW implies that the waste will generate heat for quite some time, and this will lead to an additional temperature rise. The casing material, especially in the case of retrievable disposal, must be able to withstand these temperatures, in the sense that the strength must still be sufficiently high for the highest temperatures that can be expected. This means that materials must be used which have favorable properties in this respect. To this we add that the temperature increases, in the case of retrievable disposal, will not be too high because the amount of waste canisters per borehole is limited (see an earlier paragraph). Furthermore we mention that surface storage of the HLW for a limited time period (e.g. 10-20 years) will lead to reduction of the temperature increase in the underground, because the heat generation exponentially decays with a "half-time" of about 30 years (1). For the additional temperature increase we expect an order of magnitude of not much more than 50°C, which is not too extreme and will not pose problems in connection with casing material.

DISCUSSION AND CONCLUSIONS

At the start of the paper we mentioned smart wells concepts and measurement while drilling, but these subjects were not yet discussed. A smart well is a well in which there is a connection between the continuation of the drilling operation (sometimes there is then already production of fluids) and relevant measurements carried out during drilling. Subsequently, evaluation of the measurements gives information on the best way to proceed drilling (e.g. using or not using multiple boreholes), leading to new measurements etc. This sophisticated way of operation, although quite important for the oil and gas industry, does not provide opportunities for waste disposal. This is because, usually, the precise locations of the boreholes have already been chosen, and need not be altered unless rock salt of insufficient quality is encountered. To establish this the measurement while drilling (MWD) technique can be helpful. Smart wells concepts seem, however, of little use for disposal of HLW in boreholes.

In the paper a number of petroleum engineering subjects related to underground disposal were treated. Conclusions, which can be drawn on these subjects, are the following:

- *Deep boreholes.* With increasing depth a larger distance to the biosphere is realized. This makes special measures necessary (e.g. longer casing string, special drilling fluid). It will also lead to higher disposal costs. The end situation, however, is very favorable in the sense that the waste is extremely well isolated, not only because of the large distance to the surface, but also because the closure of the salt around the waste is more rapid and more satisfactory. Consequently, deep boreholes are very suitable for HLW disposal, and this is valid for both permanent and retrievable disposal.

- *Deviated boreholes.* Moderately deviated boreholes can be used both for permanent and retrievable disposal. Care must be taken to limit the angle with the vertical in such a way, that HLW canisters can be easily transported downwards. Use of this type of boreholes leads to a larger flexibility in drilling operations and in the choice of a disposal region.
- *Multiple boreholes.* The use of multiple boreholes is a possibility but can, at this stage, not yet be recommended. In the case of permanent disposal, it will have the advantage of cost savings. A disadvantage, however, is that it will be difficult to realize the smooth lowering of HLW canisters into a new branch. Also the problem of an additional casing for each new branch was already raised. A new, special, design for the situation near the branch is needed and would have to be developed. For retrievable disposal, multiple boreholes cannot be used, because with a new branch the earlier one (or the original borehole) must be shut off.
- *Isolation and temperature effects.* On these subjects we can be concise. Isolation of the HLW in the rock salt can be realized perfectly, mainly because of the favorable properties of salt as a geological host medium. Obviously, a boundary condition is that the correct technical measures are taken. Concerning the additional temperature rise due the HLW heat generation: these need to be taken into account in connection with the choice of the casing material, which must be – especially in the case of retrievable disposal – of sufficient strength at the higher local temperatures which can be expected.

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