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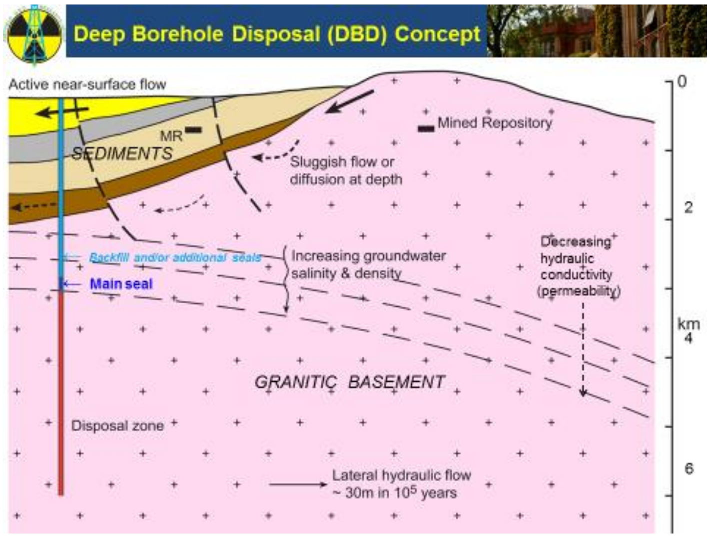
DEEP BOREHOLE DISPOSAL OF SPENT NUCLEAR FUEL

Fergus G F Gibb, *BSc, PhD, FGS*

Emeritus Professor of Petrology & Geochemistry
Department of Materials Science & Engineering
The University of Sheffield, United Kingdom

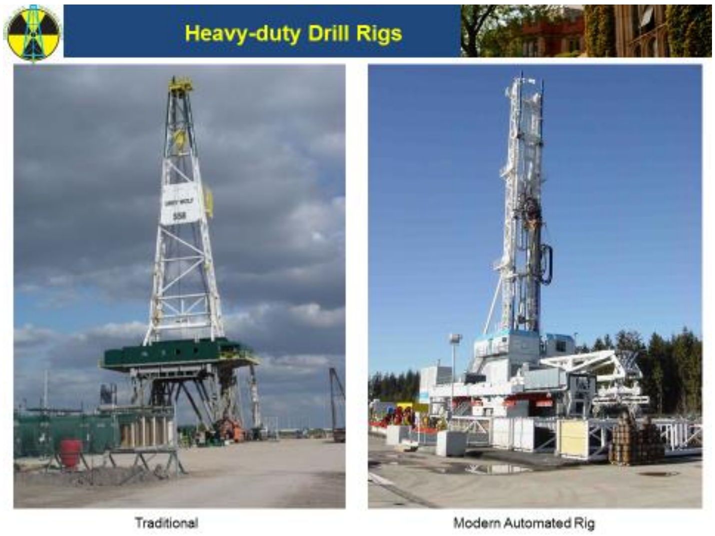
I first became interested in radioactive waste disposal back in the 1970's and the more I read about mined repositories only a few hundred metres deep, the more concerned I became that they could not deliver the spatial and temporal isolation needed for spent fuel and high level wastes. As an earth scientist I was convinced that geology *must* have a better answer and so began over 35 years of research into deep borehole disposal. In the beginning I waited expectantly for the nuclear industry's experts on geological disposal to show me why boreholes are not that 'better answer'. I'm still waiting.



Deep borehole disposal involves drilling large diameter, fully cased, boreholes 4-6 km into the granitic basement of the continental crust, deploying the waste packages in the lower part of the hole and sealing them in. Note that above the disposal zone the hole is sealed & backfilled all the way to the surface.

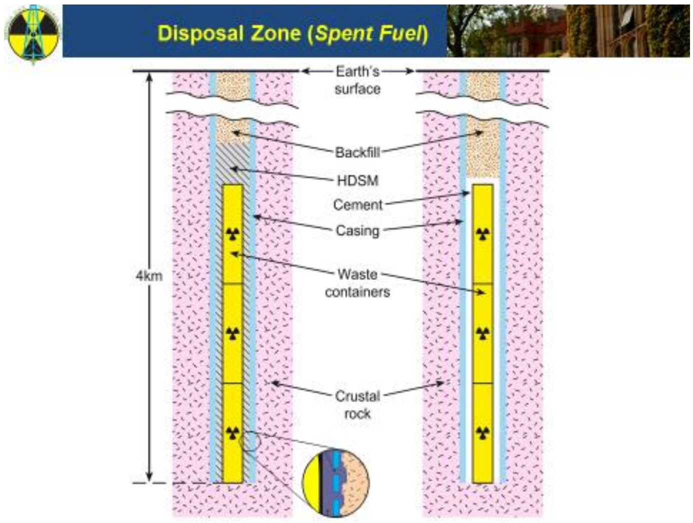
At depths up to ten times greater than mined repositories, it capitalises on the very low permeabilities usually found at such depths. As you go deeper the groundwater changes from fresh to saline and the deeper you go the saltier it gets. Below 1 or 2 km any fluids in the rocks will be brines out of physical & chemical contact with near-surface circulating fresh groundwaters.

This isolation is due to a density stratification that has often been stable for millions of years and should remain so far into the future, unaffected by climate change, sea-level rise, glaciations or even earthquakes. This deterrent to vertical flow combines with low lateral flow rates to ensure that anything that does eventually escape from the disposal zone goes effectively nowhere in 1 Ma, and certainly not up towards the biosphere.



These are the types of drill rig that would be needed to drill 56 cm diameter holes to 4 or 5 km depth.

This is the sort of coiled tubing rig needed for emplacing waste packages, retrieving them if necessary, and sealing the hole. It is much smaller than the drill rig.



This illustrates the configuration within the Disposal Zone. Note that the annular space between the waste packages and the borehole wall is filled with either cement or a special High Density Support Matrix, depending on the temperatures involved. These are emplaced with the packages and prevent or delay groundwater access to the containers and possible corrosion. Together with the seals & backfill above the disposal zone, this filling also prevents the borehole itself becoming an easier route back to the biosphere than the surrounding geology for any fluids carrying corrosion products and escaped radionuclides.

Key Milestones

1989 **Early Swedish work** *(e.g. Juhlin & Sandstedt) – Not pursued*

1990's **Support from British Nuclear Fuels Ltd.**

No Interest from WMOs *Disposal of UK's HLW could be brought forward 35 years using deep boreholes (RWM, 2011).*

2006 **UK - CoRWM Report.** *- Recommended the option of deep boreholes be kept open.*

2010 **USA – Termination of Yucca Mountain repository.**

2012 **Presidential Blue Ribbon Commission Report** *– Included a recommendation that deep boreholes be investigated and taken forward to a practical demonstration.*

2015 **US DOE & Sandia NL - Deep Borehole Field Test** *Cancelled*

2016 **International Meeting on Deep Borehole Disposal (Sheffield)** *– Presented a 'position statement' on deep borehole disposal.*

Some milestones during our 35 year investigation. In the late 1980's we were encouraged by some excellent, pioneering, Swedish work on deep boreholes but unfortunately, SKB did not really pursue this beyond the 1990's.   In the 1990's the then British Nuclear Fuels Ltd. saw the potential of DBD and supported our research.

During this period we tried to interest national waste management organisations, like UK Nirex, in the concept but they were 'locked in' to mined repositories and not interested. However, their successors, Radioactive Waste Management Ltd. did later acknowledge that disposal of the UK's high-level wastes could be brought forward by some 35 years if deep boreholes were used.

In 2006 the Committee on Radioactive Waste Management recommended that the UK's wastes should go to a repository but that the option of deep boreholes should be kept open.

In 2010 the Obama administration terminated funding for the Yucca Mountain repository for US spent fuel, as it was 12 years overdue, had already cost $15 B with a final cost estimate of $96 B, and had run into serious technical, political & legal difficulties. The Blue Ribbon Commission was set up to look into America's nuclear future and in 2012 it recommended, among other things, that deep boreholes be investigated and taken forward to a practical demonstration. This led to a lot of work being done to develop the Deep Borehole Field Test, led by Sandia National Labs, with Sheffield University, MIT and others involved.

In 2016 an international scientific meeting on DBD was held in Sheffield – and some important conclusions were presented in a 'position statement' on DBD.

Unfortunately, a few months ago, just as the US Department of Energy was about to sign the contract for drilling the DBFT, Mr Trump, who is a climate change sceptic and anti-nuclear as he wishes US energy policy to be based on burning fossil fuels, cancelled it.

Deep boreholes offer many potential advantages over a mined repository. Some, like safety, are especially relevant to spent fuel disposal and Sweden, and I'll show these in bold. The order of magnitude greater depth, combined with very low groundwater flow rates and density stratification, ensures there is no way back to the human environment for radionuclides before they have decayed to radiologically safe levels. The Sheffield meeting recognised DBD could readily meet the national and international safety standards currently applied to disposal.

The environmental impact of drilling a hole, even at a remote site, would be significant, although much less than constructing a repository. Importantly however, the drill rig would only be on-site for less than a year. After the hole is drilled and cased a much smaller and less obtrusive coiled tubing rig would suffice for package deployment and sealing, significantly reducing impact. Once the hole is sealed, the rigs removed and the site remediated, the environmental impact is effectively zero.

Disruption would last less than 4 years and, for a multi-hole programme, operations could be concurrent and dispersed. Contrast this with a repository which takes 25 years to construct & would remain open for many decades. In the case of Forsmark it would operate for over 40 years after completion. Boreholes would also improve 'inter-generation equity'.

The footprint of a borehole is tiny. Even for a multi borehole array it is small as the holes need to be only 50m apart. Half a dozen would fit on a football pitch and we estimate Sweden's 12,000 tons of spent fuel would need fewer than 20 holes.

At around $60 M per hole a borehole disposal programme would be more cost effective than a mined repository. Three years ago, using SKB's own figures, we calculated that – *excluding packaging* – disposal of spent fuel in the Forsmark repository would cost around $476,000 per ton. A single deep borehole taking 620 tons of spent fuel rods gave an estimated disposal cost around $84,000 per ton. Furthermore, DBD requires only simple steel containers compared to the massive and expensive copper canisters for KBS-3, so *including packaging*, we calculate the cost of borehole disposal of spent fuel would be well under 20% of that for a mined repository.

Much of the continental crust has granitic basement with low hydraulic conductivities at appropriate depths for DBD making it relatively easy to find a geologically suitable site.

The 4 - 5 km deep, 56 cm diameter borehole needed for spent fuel could be drilled in under a year, and take less than 3 years to fill and seal. So a borehole disposal could be completed in under 4 years – a fraction of the time it takes to construct a repository.

Boreholes can be at many small sites rather than one large one, even down to an individual nuclear power plant disposing of its own waste on or near-site and greatly reducing transport needs.

Non-proliferation is a serious consideration and, for fissile materials, deep boreholes offer unbeatable security as covert recovery of waste packages would be quite impossible. As Sweden has only spent fuel this may be less of an issue than for countries with inventories of plutonium and highly enriched uranium, but expediting the disposal of spent fuel would greatly reduce the security threat.

Borehole disposal is insensitive to the composition of the waste - as long as it is solid - and to its heat output. Unlike a repository there is no need for many decades of post-reactor cooling before disposal.

Deep boreholes allow a small disposal programme to be expanded easily or terminated at any point with no further cost. It is effectively a pay as you go system, in contrast to a mined repository where most of the cost is incurred before any waste is emplaced.

Unlike engineered barrier systems, the geological barrier can demonstrably survive for hundreds of millions of years so there is no doubt that the isolation delivered by several kilometres of the right geology can outlast the 100,000 to 1 million years required by some safety cases.

The 2011 Fukushima accident emphasised the need for all nuclear installations to be able to withstand the effects of seismic events. Shocks & shear waves would have no effect on the density stratification of the saline groundwaters in the basement rock so, even if an earthquake damaged the spent fuel containers, the surrounding groundwater into which radionuclides could leach out would remain safely isolated from the human environment. There would be no threat to containment.

Perceived Problems

1. **"Stuck" Packages.**	*Engineered out*
2. **Dropped Packages**	*Containers undamaged*
3. **Retrievability**	*Same as a mined repository*
4. **Package Corrosion**	*Delayed or Prevented & Contained*
5. **Decay Heating**	

In oil wells, geophysical logging tools are often lowered downhole and occasionally become stuck and have to be abandoned. This has led to the suggestion that containers of spent fuel could become stuck during emplacement in the boreholes. However, unlike most oil wells, deep disposal boreholes are cased all the way from the surface to the bottom, creating a perfectly smooth steel tube.

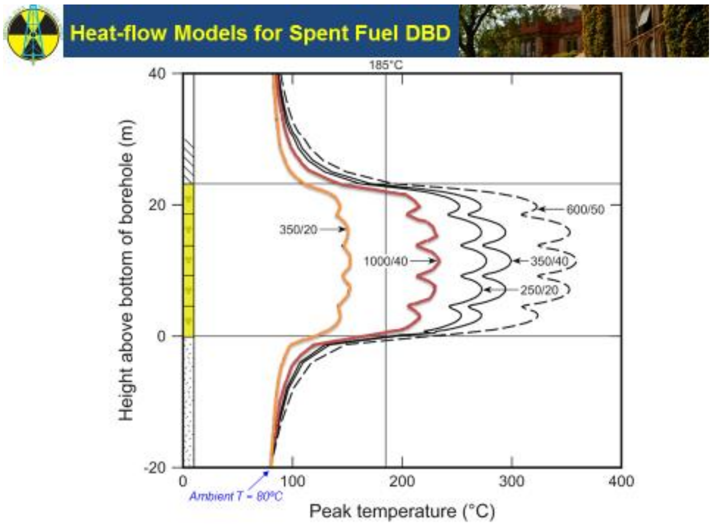
Adequate clearance between the casing and the packages and running callipers ahead of each emplacement reduces any possibility of jamming effectively to zero and, in the very unlikely event of a package becoming stuck, the coiled tubing rig could easily pull it back out. Sticking can therefore be engineered out.

Concern has been expressed about a waste package being dropped down the hole during emplacement and becoming damaged. However, the hydraulic damping effect in the fluid-filled borehole results in terminal velocities too low to damage the robust steel containers.

Waste packages deployed in a deep borehole can be recovered easily by re-attaching the coiled tube and reversing the emplacement process. This is straightforward up to the end of the operational phase but after the borehole is sealed up retrieval of the packages becomes very difficult and expensive. This is exactly the same as a repository after sealing and closure, although the operational phase of a borehole is much shorter.

If the saline groundwater gets to the steel casing and waste packages it could cause corrosion and gas generation, eventually leading to container failure. Using sealing materials to fill the spaces between the packages and borehole wall will keep water out for a very long time, if not indefinitely. If and when the containers do corrode, filling the disposal zone annulus, combined with sealing and backfilling the borehole all the way to the surface, would prevent the hole itself becoming a by-pass to the geological barrier against upward movement of fluids.

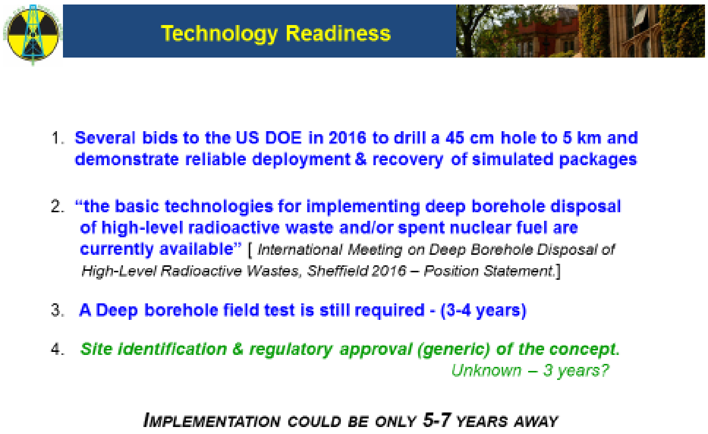
Decay heat from the waste will cause significant temperature elevation in and around the disposal zone creating a potential driving force for groundwater convection that could disrupt the critical density stratification. Let us look at this more closely.



These are results from thermal modelling for 5 containers of spent fuel at the bottom of a borehole for various combinations of fuel type, number of rods per container and age of the fuel in years. The ambient temperature around the hole is taken as 80°C and the lines plot the maximum temperatures reached at the container surface against height. The red & orange lines are for UO_2 fuel with a burn-up of 65 GWd/t, which is significantly more than any Swedish spent fuel, so these are conservatively high temperatures.

Temperatures in and around the hole rise quite rapidly, peaking 3 to 10 years after disposal, then decline slowly, returning to within a few degrees of ambient between two hundred and a thousand years later. The modelling also shows that the thermal effects extend outwards from the borehole for only about 20 m. Any convection will therefore last only for hundreds of years after disposal and calculations show that in this time, any material from the disposal zone could only be transported upwards for a few hundred metres.

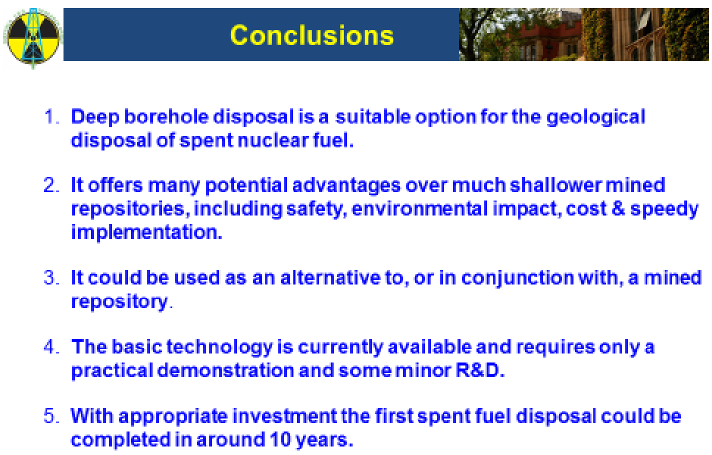
This is very important for the time the borehole seals have to retain their integrity to prevent the hole from becoming a conduit for upward flow of fluids. Once convection ceases, the natural density stratification of the groundwaters will be re-established in and around the borehole, restoring the geological barrier and making the borehole seals redundant - so the seals need to last for only a thousand years or so.



It is often asserted that DBD is several decades away as the necessary technology is not available and would take many years to develop. *This is simply not true*. Last year several consortia submitted bids to the US Department of Energy to drill the Deep Borehole Field Test and demonstrate the emplacement and recovery of simulated waste packages. Given the punitive clauses on drilling contracts, this would not have happened had they not been completely confident of success.

The "position statement" issued after the 2016 Sheffield meeting attended by most of the world's leading deep borehole scientists & representatives of the drilling and nuclear waste industries concluded that "the basic technologies for implementing deep borehole disposal of high-level radioactive waste and/or spent nuclear fuel are currently available", although they did recognise the need for some engineering refinements and testing.

Of course, a deep borehole field test is still required and would take 3 or 4 years, but following a successful outcome to the field test, identification of a site, and regulatory approval for the generic concept, implementation could begin. The last two are unknowns, but realistically could be done in 2-3 years, which could mean implementation need be only 5-7 years away.



DBD is a suitable option for the geological disposal of spent nuclear fuel.

It offers many potential advantages over much shallower mined repositories, including safety, environmental impact, cost effectiveness and speed of implementation.

It could be used as an alternative to, or in conjunction with, a mined repository.

The basic technology is currently available and requires only a practical demonstration and some minor R&D.

With appropriate effort and investment the first disposal of spent fuel could be completed in around 10 years.