LESSONS LEARNED FROM NUCLEAR DECOMMISSIONING AND WASTE MANAGEMENT RELEVANT TO END OF RESPONSIBILITY FOR LANDFILLS

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SUMMARY: The present status with regard to long-term behaviour of seals in landfills is analysed in with regard to lessons learned from nuclear waste disposal and decommissioning of nuclear facilities. It is found that detailed planning is warranted and required for technical as well as financial reasons. Existing knowledge is insufficient and needs to be supplemented e. g. by studies of ageing mechanisms and by investigations of natural and anthropogenic analogues.

1. INTRODUCTION

Trends are no monopoly of *"haut couture"* and fashion design. They occur everywhere, even in science and technology. It is to be expected that trends occur after new areas have been opened up as a result of major discoveries or inventions. However, in many cases, trends take place only after considerable incubation or initiation times.

For instance, the phenomenon of global warming has been known and communicated for about 100 years. Not only in the scientific literature, but also in popular and well circulated literature.(Arrhenius, 1919)

The hazards and risks associated with radiation were well known when the first (anthropogenic) nuclear chain reaction was started in 1942, but it took until the 1970's until the consequences of man-made radionuclides became studied seriously in Sweden (Swedish Government 1976). Of 517 reports published by AB Atomenergi from our national nuclear technology development programme during the years 1956 to 1977, only two deal with nuclear waste. A total of around 1,55 x 10^9 € was spent by the Government on this research which ended rather abruptly during the 1970'ies (Lindskog and Sjöblom 2008). Since the mid-seventies, a total of about 2 G€ have instead been spent on nuclear waste technology research in Sweden. Similar developments have taken place internationally.

It is only during the last few decades that the most immediate of the concerns associated with landfilling of domestic and other non-nuclear waste have been dealt with, namely dispersion of potentially hazardous substances through leaching by meteoric water and emission of gases. In most cases, short-term effects - < 30 years perspective – have been studied, while long-term performance has received less attention, in comparison. For instance, (Carlsson, 2004) puts forward that it is difficult to make prognoses over long times and therefore refrains from including such costs in his report (cf. Section 5.3). It is to be recognized, though, that considerable efforts are spent worldwide on qualifying various materials for use as seals in covers of landfills, see e.g. (Brännvall, 2010).

The Swedish Environmental Code, Chapter 2, requires amongst other things the following:

- Sufficient knowledge
- Compliance with the Polluter Pays Principle (PPP)
- Use of Best Available Technology (BAT)

The requirement on sufficient knowledge may imply that BAT is not sufficient, in which case new knowledge and / or technology will have to be found and developed.

These requirements are general and apply to landfills after closure as well. Thus, it is assumed in the present paper that the PPP should be interpreted to imply that the health and environment of future generations should be protected to the same level as that which applies to us who live today. Consequently, costs for remedial actions can be neglected - as in (Carlsson, 2004) - only if it can reasonably be shown that that the cover of a landfill will maintain its intended function for as long as it is needed.

In a so-called “general advice” accompanying an ordinance (Swedish Environmental Protection Agency 2004), our EPA states that a landfill for non-hazardous waste must maintain its intended function for several hundred years, and a landfill for hazardous waste for thousands of years.

Another indication can be found by comparing the concentrations allowed in non-hazardous waste with the maximum leaching allowed in the acceptance criteria for disposal at a landfill for non-hazardous waste. This leads to the numerical result that a landfill in which e. g. ash from incineration has been deposited to a thickness of 10 meters might need to be designed to maintain its integrity for more than one million years. In the case of Sweden, such a time is hypothetical since the next glaciation is expected to take place in less than 10^5 years.

2. OBJECTIVES AND SCOPE

The objectives and scope of the present paper are as follows

- To briefly summarize - for a few types of seals for landfill covers - the potential for functioning as intended in the long term.
- To share some lessons learned from the areas of nuclear waste management and the decommissioning of nuclear facilities
- To make a brief comparison with lessons learned from landfilling and contaminated soils
- To analyse the implications of the combined requirements on knowledge, BAT and PPP for seals in covers of landfills.

3. LANDFILLING

The landfill directive (European Union, 1999) and its implementations in various national legislations imposes limits regarding the maximum flow of water through a landfill (in terms of mass flow density), and the concentration of potential pollutants in such water. The limit on flow applies after a landfill has been covered, and the limits on leaching constitute acceptance criteria for the waste.

The long-term behaviour of such systems is dependent on the prerequisites for the leaching, including whether the potential pollutants are sorbed on the surface or occur throughout the bulk of the material. Of great importance is also whether the material is entirely stable in contact with water or not. Material sorbed on the surface may release out in a moderately long time, and may thus not require that the cover of a landfill be stable over a very long time.

Material undergoing ageing phenomena (diagenesis) may change its properties substantially over time. In fly ash, for instance, such changes occur over short as well as long times, and have, in most cases, a profound influence on the leaching (Sjöblom 2011, Brännvall 2010). The anticipated long-term behaviour of the seal in the cover depends on the character of the seal itself as well as on possible reactions between the seal and the surrounding materials, including the waste. It is not trivial to select the sealing material that best corresponds to the requirements of best available technology.

- Geomembranes are made of e. g. polyethylene or polyvinyl chloride. Presence of antioxidants is frequently important for their stability, and the rate of deterioration may increase considerably when the antioxidants have become consumed. Stress corrosion is also an issue as well as brittle behaviour for low loads over long times. Geomembranes have been used for only a few decades and natural analogues are not available.
- Geo clay liners are made of two sheets of synthetic fabric with bentonite clay in-between. The two sheets are joined by either needle punching or stitching. The bentonite clay contains the mineral montmorillonite (sodium rich type) which swells strongly on contact with water, thus forming an efficient seal. The long term shear strength depends on the ageing properties of the polymer material joining the two sheets. Bentonite itself is sensitive to chemicals, including salt. The installations are usually sensitive to differential settlements of the underlying waste. Natural analogues exist for the bentonite clay, see e. g. (Brundin et al 2001, Meer 2007).
- Natural clays can provide a considerable chemical buffer capacity, but have in most cases a much higher hydraulic conductivity as compared to bentonite, Natural clays can show variations in properties. The sources for suitable clays are quite rare in Sweden.
- Ashes from combustion of wood based fuels are recycled materials that may be compared with natural clays in terms of chemical buffer capacity and hydraulic conductivity. Natural and anthropogenic cements constitute analogues. Details can be found in (Sjöblom and Tham 2009). It might be added that no literature has been found on the influence of salt in a landfill seal, but general literature on soil suggests that the hydraulic conductivity might increase if the salt is lost.
- Mixtures of ashes and activated sewage sludge constitute recycled materials and may form tight seals in the short term. However, claims of long-term stability have been repudiated based on anthropogenic and natural analogues (Sjöblom and Tham 2009).
- It is not trivial to select the sealing material that best corresponds to the requirements of best available technology.

4. LESSONS LEARNED FROM NUCLEAR WASTE MANAGEMENT AND DECOMMISSIONING

4.1 Nuclear waste management

Before 1972, Swedish short-lived radioactive waste was disposed of by sea dumping. Our first nuclear reactor of modern design was started during the same year. Consequently, nuclear waste volumes in interim stores increased until a final repository for short-lived waste was taken into operation in 1988. It comprises cavities in crystalline rock, and was the first of its kind.

In March 2011 - after 25 years of intensive research (cf. Section 1) - the Swedish Nuclear Fuel and Waste Management Company (SKB) submitted an application to the Swedish

Radiation Safety Authority (SSM) to construct a repository for the spent nuclear fuel.

The time and efforts required for the underlying research have probably exceeded the expectations of most people, and in the end, one has to assess whether the remaining uncertainties can be tolerated in view of the costs as well as the need to implement a solution. Essential features in this regard include that the technical barriers – copper and bentonite clay – as well as the natural barrier – crystalline rock – all have natural analogues (including native copper). In addition, copper has anthropogenic analogues.

The plans for disposal of other long-lived waste are considerably less detailed.

Internationally, no country has yet commissioned a repository for spent nuclear fuel or high-level waste from reprocessing of such fuel. Reprocessing implies that the fuel is dissolved and the fission products separated. The latter solution is then evaporated, calcined and vitrified to a borosilicate glass which has natural as well as anthropogenic analogues (Sjöblom et al 2011).

4.2 Decommissioning of nuclear facilities

It has been known since the nuclear facilities were erected that they were to be decommissioned at substantial cost due to contamination by radionuclides. However, it is only relatively recently that decommissioning has become an integral part of the planning prerequisites for new nuclear facilities.

Radiological data feasible for the operation of a facility has often been used also for the planning for decommissioning - for which purpose it is usually inadequate. Actually, it has been found that detailed planning is imperative, and that radiological surveying, selection of techniques for decommissioning and identification of potential cost raisers warrant careful attention.

Moreover, it has been observed repeatedly that special attention is warranted for cases where there is a difference in time between the operation of a facility and the subsequent fulfilment of the environmental liabilities. Careful planning - already at an early stage - is necessary in such cases in order for the costs to be reasonably accurately estimated. This is a very treacherous aspect since the timing of the planning may well be dictated by financial prerequisites rather than by technical issues.

It is therefore crucial that the design prerequisites and requirements be well known before the waste is being deposited so that it can be appropriately sorted, treated and perhaps also packaged. If not, it might become necessary to go into waste archaeology, in which case our clear experience is that it is usually much easier to do it all correctly from the beginning, see e. g. (Lindskog and Sjöblom 2008 and 2009)

4.2 Brief comparison with landfilling and contaminated soil

No reports have been found on remediation of landfill covers constructed in accordance with modern regulation in Sweden. This is to be expected since all such installations are quite new.

The Swedish EPA is responsible for the financing of remediations that refer to industrial activities that have taken place before the year 1969. There are many such sites and around 50 M€ are paid out each year. No comprehensive reporting has been found on the relation between estimated costs and incurred costs in these projects, and this experience is shared with the Swedish National Audit Office, see (Riksrevisionen 2011).

International data is available, however, and (Fogleman 2005), see Chapter 15, informs that in 1979, US EPA estimated that remediation of sites posing a significant risk to health and environment would cost around 6 billion US \$. Today, according to the same source, some estimates exceed 1 trillion ($1*10^{12}$) US \$.

5. ANALYSIS AND DISCUSSION

5.1 Prediction of long-term behaviour

It is important that the challenges for long-term predictions be fully recognized. Common misconceptions in this regard include the following:

- At thermal equilibrium, all elements appear as a major element in one phase or another
- Thermal equilibrium can be achieved in practice
- Reaction rates can be estimated from the energies determined in the calculations
- Rates determined experimentally can be extrapolated to long times

These statements are far from universally true.

For instance, in oxide systems, minor elements do not usually form phases of their own, but are instead included in the phases formed by the major elements in the form of solid solution. Such "dilution" of minor elements is strongly favoured by the gain in entropy which strongly influences the Gibbs free energy.(Sjöblom 2009)

Thermal equilibrium is rarely achieved in real systems in conjunction with precipitation and dissolution, e. g. during diagenesis. One reason for this is that such phenomena are often incongruent.

Although there are co-variations between bonding energies and rates of reactions for similar cases, there exists no general correlation. For example, the activation barrier to forming and breaking of hydrogen bonds in monomethylammonium chloride changes from about 32 to 4 kJ/mole in a phase transition while the strength of the bonding - as evidenced by infrared data - remains approximately the same. (Sjöblom 1975)

Rates of reactions are frequently assumed to follow an Arrhenius' type of relationship. This presupposes amongst other things that the reaction in question depends on only one mechanism. The mechanisms can be widely different for different ranges of parameters. Consequently, in order for extrapolation outside the range of parameters studied to be justified, one must be able to show that the mechanisms involved are the same. Moreover, some phenomena, e. g. stress corrosion and ageing in the presence of inhibitors, are associated with incubation or initiation times during which not much appears to happen, but after which catastrophic break downs may take place.

Proof regarding long-term behaviour might, in principle, be achieved by detailed studies of mechanisms together with e g *ab initio* theoretical calculations, but for real systems, such as for long-term performance of a landfill, this is not possible or practicable.

What remains is the possibility to use natural and anthropogenic analogues which have been about for the duration of time in question. It is desirable that there exists a number of analogues that ideally span the space of parameters for the cases in question. Such analogues can be expected to unveil phenomena that evidence themselves only after a long time, and also provide a basis for estimates on the kinetics involved.

5.2 End of license versus end of responsibilities

Legislation in Sweden states that environmental liability is a collective responsibility. The Government thus is free to sue anyone involved (e. g. owner or operator) for all or part of the liability. It might therefore be tempting to draw the conclusion that there is little need for early financial planning since finance is assured.

However, a glance at the list of enterprises on the stock market today and a couple of decades ago indicates clearly that there is a definite eventuality that there might not be anyone around to sue (c. f. the financial collapse of Enron in the US). Moreover, and perhaps even more importantly, it is imperative that the planning for actions intended to take place perhaps decades in the future be carried out now (cf. above).

It should be observed, in this regard, that end of license is not the same as end of responsibilities. The former normally takes place as a result of a decision of the owners and operators, and sometimes as a result of Authority actions when the licensing conditions have not been met. End of responsibility may be decided by a Competent Authority when it has found that there exists no further obligations and that there is no environmental liability left.

5.3 Annual reporting and other financial legislation

The level of financial securities required for an operating license under the Swedish Environmental Code is typically determined using a relatively simple generic model, e. g. one developed on commission by the Swedish EPA (Carlsson 2004).

Ideally, this amount should be the same as the environmental liability included in the annual report in accordance with the Annual Reports Act (Annual Reports Act 1995). Large companies are obligated to follow the International Financial Reporting Standards and International Accounting Standards (IFRS/IAS) (IASB 2010) issued by the International Accounting Standards Board while small companies have to follow the general advice issued by Swedish Accounting Standards Board (in Swedish: Bokföringsnämnden, BFN). Both have strict requirements on how liabilities are to be calculated, at least in principle.

The international standard IFRS/IAS (IASB 2010) as well as an ASTM standard (ASTM 2007) provide relatively detailed instructions as to how the liability is to be evaluated. They presuppose and put forward that exact figures can and must be provided even for complex undertakings decades ahead in the future. In cases of uncertainty, the declaration should contain a risk analysis type of approach for cost estimation, including descriptions of scenarios together with assessments of their respective costs and relative probability.

Deviations in this regard are dealt with in the Swedish Penal Law which states that companies are obligated to present an “essentially correct financial situation” or the responsible persons may face up to six years in prison. See (Lindskog and Sjöblom 2009) for further detail.

The impression from (Carlsson 2004) is that many companies in Sweden who have liabilities do not declare them. It also appears that most of the companies who do declare their liabilities do so but using taxed assets. The reason for this is said to be (Carlsson 2004) fear to get in trouble with the tax authorities. Such a practice is, however, not in concordance with the tax legislation. The issue was dealt with the Swedish Government already in 1977 when it concluded in a proposition that money set aside to cover environmental liabilities should not generate taxation. (Lindskog and Sjöblom 2008, Söderberg 2005) The proposition became law during the subsequent year. Still today there is no taxation in our system for covering nuclear liabilities using segregated funds. Another, less flattering, explanation to the practice of setting aside taxed funds may be that it then has no negative influence on the bonuses paid to the managements.

5. CONCLUSIONS

The main conclusion are as follows.

- Awareness comes in trends. Actors in the area of landfilling need to foresee what may be reasonable bases for future trends.
- Long-term effects do not usually evidence themselves in the short-term, but have to be searched for in order to be found and identified sufficiently early.

- Timely action is essential, since "waste archaeology" and other unplanned remedial actions are usually much more costly than doing things right from the beginning.
- Identification of issues of interest and significance requires relatively detailed studies already at early stages.
- The fundamental difficulties of long-term predictions and the associated high value of comprehensive studies of anthropogenic and natural analogues should be fully realized.
- BAT may not be enough. There is also a requirement on sufficient knowledge.
- Lessons learned from completed projects in related areas (such as nuclear waste and decommissioning) can provide valuable input to the planning
- Frequently, the requirements on correct declaration of the financial situation are harsher than the technical ones with regard to detailed and early planning.
- In many cases, it should be the need for financial planning that determines the timing of the technical planning.
- Long-term environmental liabilities are debts that we owe to future generations. It is essential that such liabilities be correctly balanced against financial assets which can be used at the time when they are needed. Such assets do not represent any income and should consequently not be taxed.
- End of responsibilities takes place when all obligations have been fulfilled. It is entirely different from end of license.

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