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Deep Geologic Repository Project

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1. INTRODUCTION

Ion exchange (IX) resins degrade slowly but measurably under aerobic conditions, and at best very slowly under anaerobic conditions. This is consistent with the behaviour of polystyrene, which forms the resin backbone. There are also suggestions that gases observed from resins may be from degradation of impurities or other materials present in the resins, rather than the bulk polymer (Kaplan et al. 1979).

Nonetheless, for OPG's Deep Geologic Repository (DGR) for L&ILW, the postclosure safety assessment (SA) assumes that the bulk resins fully degrade (Quintessa et al. 2011). Degradation rate data for IX resins were summarized in the Postclosure SA Data report (Quintessa and Geofirma 2011a). These include data from two recent studies - Bracke et al. (2004) and Husain and Jain (2003) - where field data (gas generation) from IX resin wastes were used to estimate resin degradation rates. The latter includes headspace gases measured in IX resin containers at Western Waste Management Facility (WWMF), so the degradation estimates are directly applicable to the IX resins to be emplaced in the DGR.

In addition to the references previously summarized in the Postclosure SA Data report (Quintessa and Geofirma 2011a), the literature was further surveyed for other data relevant to ion exchange resin, including polystyrene degradation. The values assumed in other safety assessments were also noted. The results are given in Section 2.

However in summary there is limited data for anaerobic degradation of IX resins or polystyrene, but the rate is clearly low. It is expected that the low rate would be most accurately measured under in-situ conditions with real waste materials, and that the conditions would take several years to equilibrate, as the microbial conditions become anaerobic and stabilized. Thus laboratory tests are useful but not definitive. At the DGR, it is expected that information would become available through long term studies carried out within the repository, and would be available in several decades to help support a decision at that time to close the repository.

The uncertainty in resin degradation rates in particular, and gas generation in general, is considered in the postclosure safety assessment (Quintessa et al. 2011). In particular, the reference case maximizes the generation of gas by assuming:

- all the bulk resins fully degrade;
- organic degradation reactions proceed to gas generation, i.e., there is no significant carbon in intermediate solid or soluble species;
- all nutrients other than carbon and water are available to support microbial activity;
- all relevant microbial groups are present in the repository;
- microbes are active in spite of high groundwater salinity, dissolved metals and possibly high alkalinity; and
- there is enough water available to support microbial activity.

In addition, a number of variant cases are considered in which the various gas generation rates and other parameters are varied. These are described in Section 8.8.2.4 of the PSR (OPG

2011). The conclusion from these variant cases is that the repository stabilizes at generally similar pressures corresponding to approximately the natural equilibrium hydrostatic head. In addition, a calculation case with an upper bound value of the resin degradation rate was analysed. The results are given in Section 3.

Finally, it is emphasized that the release of C-14 from the moderator IX resins, the largest source of C-14, is modelled as occurring independently from the actual degradation of the bulk polymer (see Appendix E, Quintessa 2011) since the C-14 is primarily sorbed on the surface of the resin. The release of C-14 as gas is modelled as either off-gassing at constant rate from the unsaturated resins, or as instantly released for the portion of the resins that become saturated with water filling the repository.

2. RESIN DEGRADATION RATE REVIEW

Measured or estimated resin degradation data are summarized in Table 1.

Data on IX resin degradation under anaerobic conditions are given in Wiborgh et al. (1986) as part of a review of gas formation and transport for the Swiss radioactive waste disposal program. The authors (Wiborgh et al. 1986) note that the porous structure of the resins increases the surface available to microorganisms. They give a resin degradation rate of up to 0.01 moles of gas $\text{kg}^{-1} \text{a}^{-1}$ or approximately $3 \times 10^{-4} \text{a}^{-1}$.

In the 1980's, experimental investigations into the biodegradation of ion exchange media by Bowerman et al. (1988) employed a mixed microbial culture isolated from resin waste samples to test the susceptibility of a range of ion exchange media to microbial attack. These results indicated that most growth was seen when the resins contained organic anions such as citrate or where they were subject to radiation damage; although some growth was seen in cultures where the resins were equilibrated with inorganic salts only. Data on carbon dioxide evolution from dewatered resins incubated at 37°C are provided in the report. The resins concerned were taken from filter units of the High Flux Beam reactor at BNL and consisted of Amberlite IR-200 cation exchange resins and a mixed resin composed of Amberlite IR-200 and IRA-400. Although not explicitly stated in the report, it appears that these resins were incubated under aerobic conditions. Consequently the degradation rate was calculated using the aerobic degradation of the polystyrene backbone of the resins. Taking the average values published, calculated rates of resin degradation are $9.8 \times 10^{-4} \text{a}^{-1}$ for cation exchange resins and $4.3 \times 10^{-4} \text{a}^{-1}$ for the mixed resins.

The biological degradation of resins was exploited by Finland's IVO company as a biological treatment process (Tusa et al. 1989; Tusa 1992); however, details of the process are limited. Husain and Jain (2003) described the process as involving a unique polystyrene degrading culture. No attempt to characterise the population was carried out, but the process appears to be an anaerobic one. No rates are available.

EPRI investigated biogas generation from IX resins in the late 1990's, and found that the gas was being generated from cellulose fibres contaminating the resins rather than microbial

degradation of the resins themselves (EPRI 1998). Resin degradation data on OPG stored resins can be calculated from Husain and Jain (2003) who provided both carbon dioxide and methane generation rates. Taking the geometric mean values quoted and assuming complete resin degradation, it was possible to calculate resin degradation rates of $1.8 \times 10^{-9} \text{ a}^{-1}$ (based on the methane generation rate) and $1.1 \times 10^{-7} \text{ a}^{-1}$ (based on the carbon dioxide generation rate) (Husain and Jain 2003). Since this data is from OPG IX resins, it is relevant to the degradation of these resins in the DGR.

Data on gaseous releases of tritium and C-14 from these OPG stored resins also provides relevant information. In particular, the release rates were estimated as $4 \times 10^{-4} \text{ a}^{-1}$ for tritium and $5 \times 10^{-4} \text{ a}^{-1}$ for C-14 (OPG 2011, p.388, based on data from Husain and Jain 2003). These rates would be a bounding estimate for the resin degradation rate itself, as tritium and C-14 would be released by other processes as well. About 30% of the tritium was released as HT, which indicates that conditions were at least in part anaerobic, and therefore also relevant to DGR anaerobic conditions.

Data on resin degradation has also been generated by the German radioactive waste disposal program (Kannen and Muller 1999; Bracke and Muller 2003; Bracke et al. 2004; Bracke and Muller 2007). The data appears to come from a combination of real waste packages and laboratory-based experiments. The rates are expressed in terms of m^3 of gas generated per tonne of waste per year. This data were converted to resin degradation rates using the stoichiometry of the reaction, and a temperature of 20°C .

IX resins are essentially composed of a cross linked polystyrene backbone with additional exchange sites. Consequently, experimental data on polystyrene degradation in non-nuclear contexts have potential relevance to the postclosure behaviour of IX resins. The environmental importance of waste plastics means that considerable effort has been invested into the determining the biodegradability of common plastics such as polystyrene (Shah et al. 2008; Tokiwa et al. 2009; Sivan 2011), with the general consensus being that polystyrenes are at best sparingly biodegradable. The polystyrene biodegradation studies have tended to focus on aerobic systems with relatively short incubation times (weeks to months) (Guillet et al. 1974; Jones et al. 1974; Sielicki et al. 1978; Kaplan et al. 1979; Mor and Sivan 2008; Atiq et al. 2010). Under these conditions, degradation rates were low with some authors suggesting that the observed activity may be due to the degradation of impurities rather than the bulk polymer (Kaplan et al. 1979). The limited biodegradation identified in these studies is consistent with long term soil burial trials (32 years) where no evidence of polystyrene biodegradation was found (Otake et al. 1995).

Photodegradation has been shown to enhance the degradability of polystyrene under aerobic conditions (Guillet et al. 1974). This UV driven oxidation process reduces the mechanical strength of polystyrene via ring opening reactions resulting in backbone cleavage (Singh and Sharma 2008), which presumably increases the active sites on which microbes can act. Similar processes occurring via radiation damage during the storage of waste resins might explain the observation of microbial activity associated with waste IX resins.

Experimental work (Sielicki et al. 1978; Kaplan et al. 1979) on radio-labelled polystyrene has generated a limited amount of data on aerobic polystyrene degradation. The rates generated by these studies are considerable faster than those calculated from IX resin studies. The authors carried out these experiments under conditions thought to favour polystyrene degradation which may explain the enhanced degradation rates observed. The higher values seem too high for IX resins as they imply that the resins would have significantly degraded within about 10 years, which is not consistent with practical experience with IX resins.

The microbial degradation of styrene under oxidising conditions has been extensively investigated (O'Leary et al. 2002; Mooney et al. 2006), but there has been significantly less research into the anaerobic degradation of styrene. However, methanogenic consortia have been shown to degrade styrene as sole carbon source (Grbić-Galić et al. 1990). In this case styrene degraded to a range of organic intermediates and carbon dioxide. Taking the carbon dioxide figures as a representation of the amount of styrene that had completely degraded to gas as is of interest here, rates of styrene degradation ranged from 0.14 to 0.4 a⁻¹. This is an order of magnitude faster than the most rapid rate of polystyrene degradation identified (Kaplan et al. 1979, Sielicki et al. 1978). It is consistent with the T2GGM polystyrene degradation model (Quintessa and Geofirma 2011b), which considers the rate-limiting step for polystyrene degradation to be the breakup of polystyrene, rather than the degradation of styrene.

Table 1: Measured or Estimated Resin Degradation Rates

Source	Degradation Rate (a ⁻¹)		Comment
	Aerobic	Anaerobic	
Kaplan et al. (1979)	1.9x10 ⁻² to 2.7x10 ⁻²		Polystyrene data
Sielicki et al. (1978)	5.6x10 ⁻² to 9.6x10 ⁻²		Polystyrene data; not consistent with IX resin durability
Bowerman et al. (1988)	4.3x10 ⁻⁴ to 9.8x10 ⁻⁴		Inferred from IX resin field data
Wiborgh et al. (1986)		0 to 3.0x10 ⁻⁴	Not experimentally derived, inferred from theoretical understanding
Husain and Jain (2003)		1.8x10 ⁻⁹ to 1.0x10 ⁻⁷	Inferred from IX resin field data (gas)
Husain and Jain (2003)		< 5x10 ⁻⁴	Inferred from IX resin field data (H-3 and C-14). May include partially aerobic conditions.
Bracke et al. (2004)		1.6x10 ⁻⁵ to 6.5x10 ⁻⁴	Inferred from IX resin field data (gas)

Table 2 summarizes the estimates of resin and plastic degradation rates have been used in different repository postclosure safety assessments.

Table 2: Anaerobic Plastic Degradation Rates Adopted for Various Repository Assessments

Source	Anaerobic Degradation Rate, a ⁻¹	Comment
WIPP (Cohen 2006)	< 10 ⁻⁵	Plastics are considered to be recalcitrant; with little degradation over 10 ka period.
UK LLW (LLWR 2011)	Recalcitrant	General assumption for plastics
Nagra LLW (Nagra 2004)	~ 7x10 ⁻⁴	General plastics, resin and bitumen in LLW, but noted that these are about a factor of ten higher than measurements.
Yim and Caron (2006)	9x10 ⁻⁴ 3.5x10 ⁻⁴	Moderately biodegradable plastics Recalcitrant organics
SFR (Moreno 2001)	3x10 ⁻⁵	Resins, bitumen, plastics, rubber

A number of studies have indicated that plastic waste components such as PVC and polyurethane are recalcitrant under repository conditions (Grant et al. 1997; BNFL 2002). BNFL (2002) stated in documentation supporting the 2002 Drigg safety case that: “*The current available information would suggest that the majority of the higher molecular weight polymers would remain undegraded for a considerable length of time, particularly addition polymers.*” This position is supported by the work of Francis et al. (1997) who found no evidence of biodegradation of electron beam irradiated plastic and rubber. This position is reflected in the safety cases carried out for the UK’s LLW repository, with plastic and rubber waste components being considered to be recalcitrant in both 2002 and recent 2011 safety cases (LLWR 2011).

A recent review by Cohen (2006) for the WIPP project concluded that some degradation of plastics and rubbers “*may occur over 10,000 years in the WIPP repository.*” This conclusion appears to be based on the fact that oxidation and radiation damage may enhance biodegradation of these materials or generate soluble intermediates amenable to microbial attack. The authors point out that much of the evidence for the microbial degradation of these materials comes from aerobic systems, but they do not rule out the possibility of anaerobic microbial degradation. Gas generation assessment for the WIPP indicate that the gas generation potential of plastics and rubbers in the waste would increase the best estimate value of 0.1 moles of gas per kilogram of organic material per year, by approximately 1% (US DOE 1995).

Nagra (2004) uses a gas generation rate of 0.05 mol kg⁻¹ a⁻¹ for general plastics, resin and bitumen in LLW, equivalent to a degradation rate of about 7x10⁻⁴ a⁻¹, but noted that these are about a factor of ten higher than measurements (Nagra 2004). This is a high rate of degradation

which may reflect the inclusion of bitumen within this classification, since bitumen has some relatively easily degradable components. Yim and Caron (2006) propose rates of $9 \times 10^{-4} \text{ a}^{-1}$ for moderately biodegradable plastics, and $3.5 \times 10^{-4} \text{ a}^{-1}$ for recalcitrant organics. These relatively high degradation rates are at odds with the position taken by the UK LLWR and WIPP where plastics are assumed to have significantly lower degradation potential (LLWR 2011).

Gas generation issues related to the Swedish SFR LLW repository have been considered by Moreno (2001). This assessment considers cellulose degradation as the main source of biogenic gases and takes a similar view of the degradation of resins as other assessments stating: “...material such as ion-exchange resins and bitumen are thought to degrade so slowly that the gas formation rate can be neglected.” The gas formation rates employed by Moreno (2001) are derived from those previously published by Wiborgh et al. (1986) with a gas generation rate of 0.002 mole gas/year/kg of waste being employed. Taking the waste to be entirely composed of IX resins this equates to a resin degradation rate of $3 \times 10^{-5} \text{ a}^{-1}$.

In summary, for aerobic degradation, the recommended value in the Postclosure SA Data report (App. F, Quintessa and Geofirma 2011a) is $5 \times 10^{-4} \text{ a}^{-1}$ with a range of $1 \times 10^{-4} \text{ a}^{-1}$ to $1 \times 10^{-3} \text{ a}^{-1}$. Additional data on aerobic polystyrene degradation is reported here, which indicates higher degradation rates. Not including the Sielicki et al (1979) polystyrene values as they are inconsistent with observed resin stability, the updated aerobic rates have a range from $4 \times 10^{-4} \text{ a}^{-1}$ to $3 \times 10^{-2} \text{ a}^{-1}$. Therefore a rate of $4 \times 10^{-3} \text{ a}^{-1}$ with a range of $4 \times 10^{-4} \text{ a}^{-1}$ to $4 \times 10^{-2} \text{ a}^{-1}$ is recommended for IX resin modelling and sensitivity studies. This is higher than previously used; however, the aerobic degradation period is short and not important in the Postclosure SA.

In the case of anaerobic degradation, the recommended value in the Postclosure SA Data report (App. F, Quintessa and Geofirma 2011a) is $5 \times 10^{-5} \text{ a}^{-1}$ with a range of $5 \times 10^{-6} \text{ a}^{-1}$ to $5 \times 10^{-4} \text{ a}^{-1}$. No directly applicable new data was found in the present review. The evidence indicates low rates, even though some studies have conservatively assumed higher rates - sometimes grouping resins with other non-cellulosic organics. The original recommended values are still reasonable; however, the maximum relevant reported value of $7 \times 10^{-4} \text{ a}^{-1}$ can be adopted for a bounding estimate.

3. EFFECT OF HIGHER RESIN DEGRADATION RATES

To test the importance of the resin degradation rate, a calculation case (NE-11-RD) was analysed in which the resin (and plastics and rubber) degradation rate was set to 0.04 a^{-1} under aerobic conditions and $7 \times 10^{-4} \text{ a}^{-1}$ under anaerobic conditions, which are the maximum reported values from this updated review, and about a factor of 80 and 14 higher than the PSR reference values for aerobic and anaerobic conditions, respectively.

The NE-11-RD case is the same as the NE-11-SBC case, except with increased resin (and plastic and rubber) degradation rates. Note that the “-11-“ case identifier indicates that these cases were run in 2011 and are, therefore, not in the Preliminary Safety Report. The NE-11-SBC case is very similar to the NE-SBC simplified base case presented in the PSR, but includes a closer geometrical representation of the final preliminary design and updates several

geological parameters for consistency with the final Geosynthesis. The NE-11-SBC results are very close to those for NE-SBC.

Repository pressure and repository saturation are presented in Figures 1 and 2. The peak levels are similar to the NE-11-SBC levels.

The pressure for the NE-11-RD increased degradation rate case is generally higher than for NE-11-SBC, but reaching the same long-term pressure. Since resins and plastics and rubbers are degrading more quickly, more CO₂ is produced earlier. Relative to NE-11-SBC, this allows earlier consumption of H₂ by methanogenesis, leading to more methane in the 10 ka time frame (Figure 3).

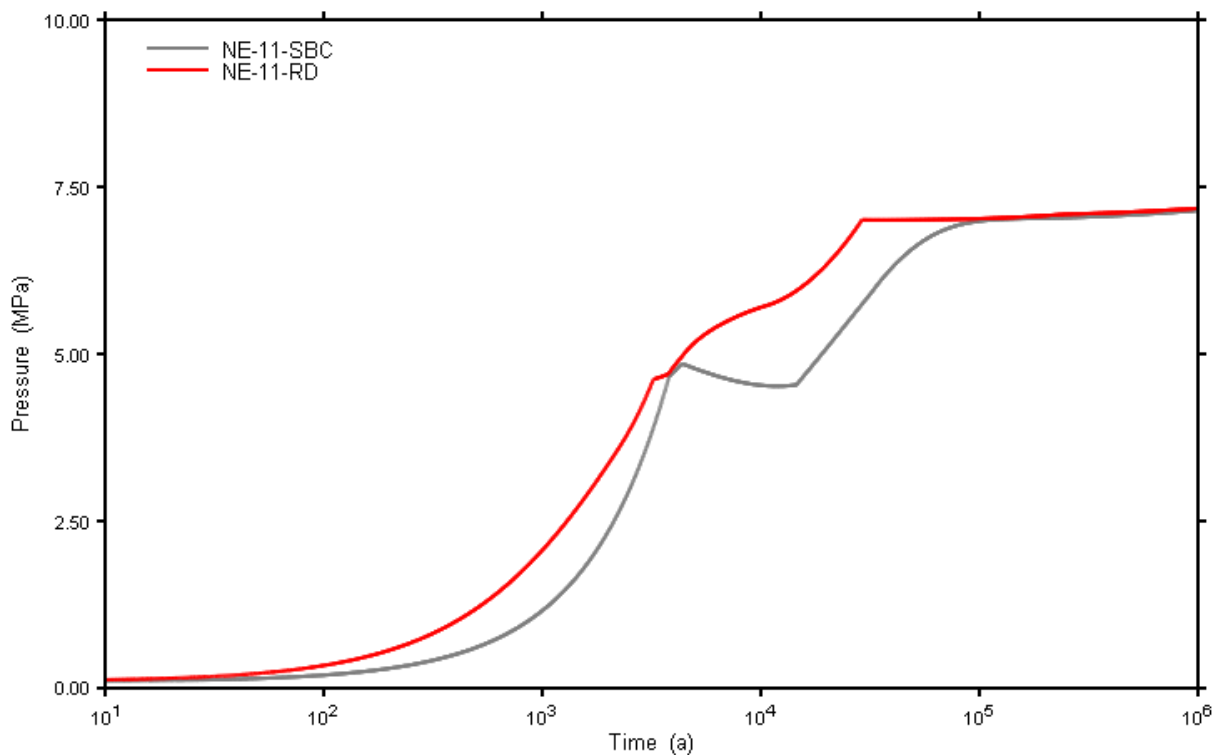


Figure 1: NE-11-RD Repository Pressure

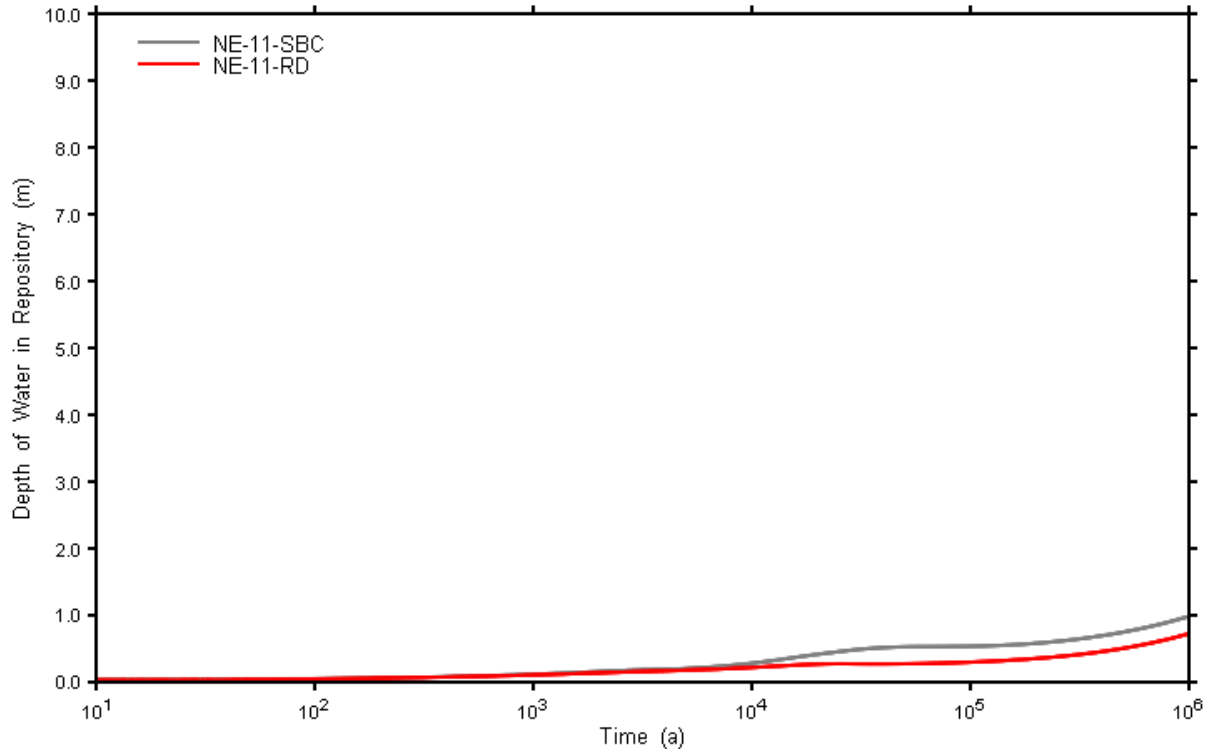


Figure 2: NE-11-RD Repository Saturation (based on 7 m room height plus 10 m rock fall)

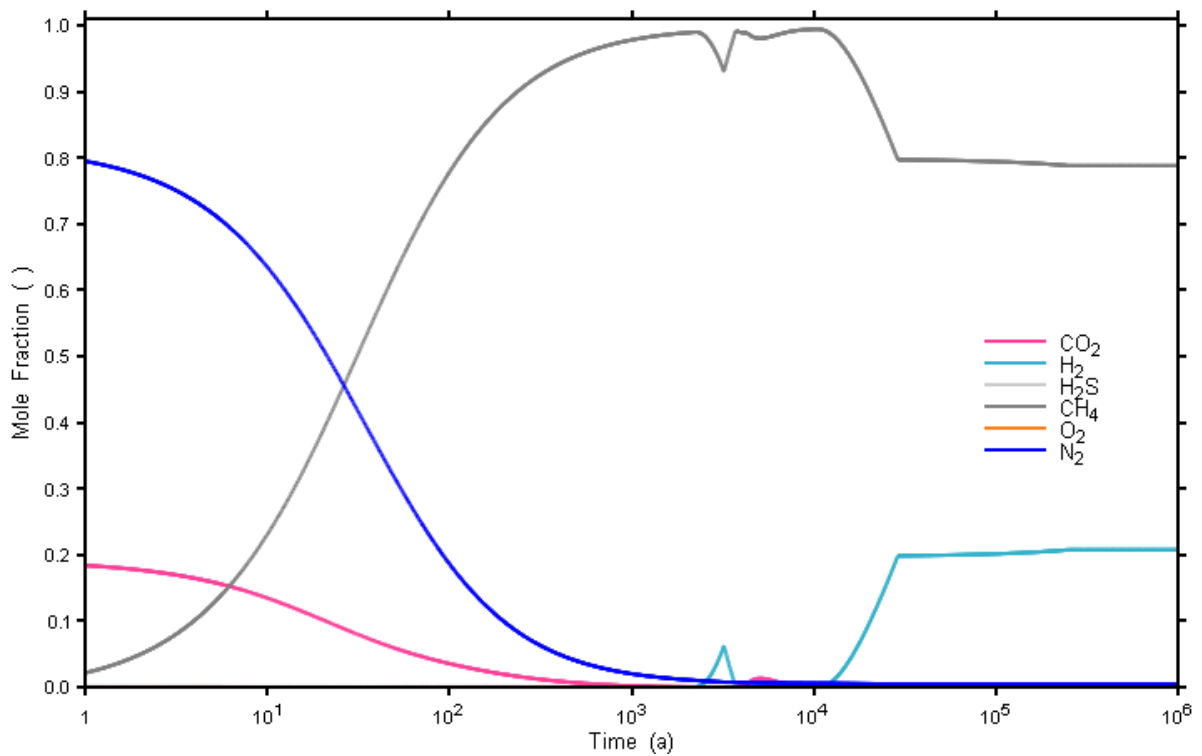


Figure 3: NE-11-RD Gas Molar Fractions

Figures 4 and 5 show the groundwater and gas flows in the shaft. Again, the results are very similar to those for the NE-11-SBC base case. The flow magnitudes are very small and at times downwards. There is little groundwater or gas flow upwards from repository out of the shaft. There would be no significant impact for this case with higher resin degradation rates.

4. CONCLUSION

In conclusion, there is limited data for anaerobic degradation of IX resins, but the rate is clearly low. The reference value and tested range are consistent with the data. The postclosure reference case maximizes the generation of gas because:

- All organics, including resins, are assumed to completely degrade;
- All organics, including resins, are assumed to degrade to form gas rather than intermediate species;
- Sufficient water is assumed present to support degradation; and
- Other conditions are assumed to support degradation processes (e.g. microbes are active even under the potentially high salinity, and other nutrients are available).

The uncertainty in resin degradation rates was addressed in the postclosure safety assessment through variant cases in which the gas generation rates and related parameters are varied. In particular, a special case is presented in this report with the resin degradation rate set to the maximum value estimated from the data. These calculations indicate that the repository pressure tends to equilibrate at generally similar pressures, independent of the specific gas generation rate assumptions.

The calculation results, including this high resin degradation rate, show that the resulting gas is contained within the geosphere and does not compromise the predictions for low doses in the biosphere.

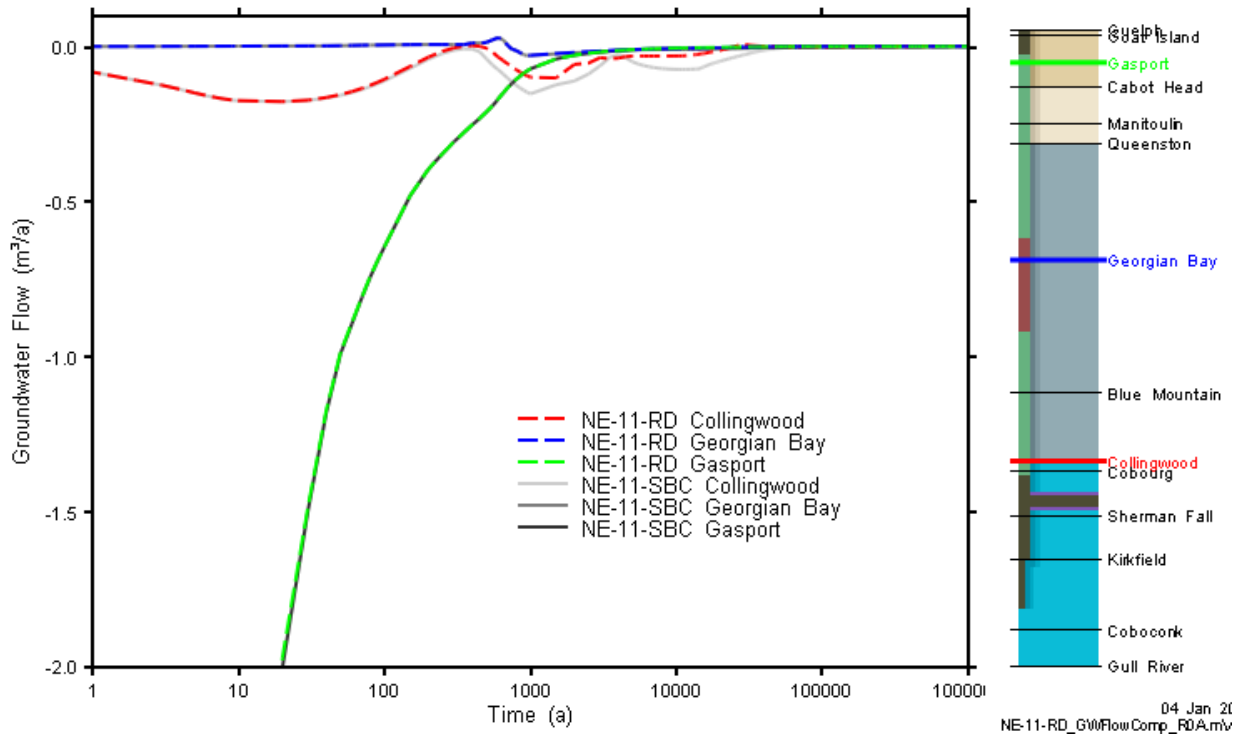


Figure 4: NE-11-RD Shaft Groundwater Flows

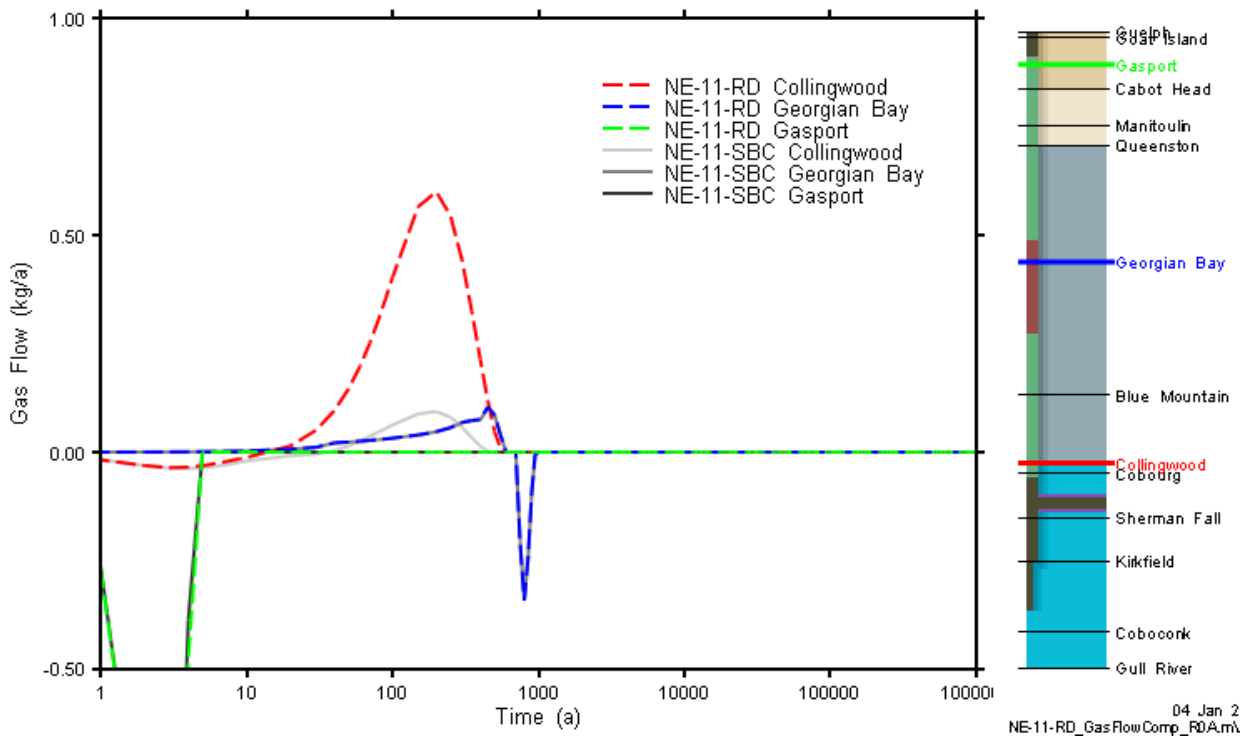


Figure 5: NE-11-RD Shaft Gas Flows

5. REFERENCES

- Atiq, N., S. Ahmed, M. I. Ali, S. Andleeb, B. Ahmad and G. Robson. 2010. Isolation and identification of polystyrene biodegrading bacteria from soil. *African Journal of Microbiology Research* 4(14): 1537-1541.
- BNFL. 2002. Potential for the Degradation of High Molecular Weight Synthetic Organic Polymers. British Nuclear Fuels Limited report DTP/90.B. UK.
- Bowerman, B. S., J. H. Clinton and S. R. Cowdery. 1988. Biodegradation of Ion Exchange Media. Brookhaven National Laboratories, NUREG/CR-5221, USA.
- Bracke, G. and W. Muller. 2003. Modelling Gas Generation of Intermediate and Low Level Radioactive Wastes. ICEM '03, 9th International Conference on Environmental Remediation and Radioactive Waste Management, Oxford, UK.
- Bracke, G. and W. Muller. 2007. Considerations on the Release of C-14 from a Closed Final Repository for Low-Level Radioactive Waste. Waste Management (WM'07). Tucson, USA.
- Bracke, G., W. Muller, K. Kugel and D. Cologne. 2004. Derivation of Gas Generation Rates for the Morsleben Radioactive Waste Repository (ERAM). Proceedings of DisTec 2004, April 26-28, Berlin, Germany.
- Cohen, S. 2006. Preliminary Review of the Degradation of Cellulosic, Plastic and Rubber Materials in the Waste Isolation Pilot Plant, and Possible Effects on Magnesium Oxide Safety Factor Calculations. US EPA Document EP-D-05-002S. Vienna, USA.
- EPRI. 1998. Preventing Gas Generation in Low Level Waste – Final Report. Electric Power Research Institute Technical Report EPRI TR-111019. Palo Alto, USA.
- Francis, A. J., J. B. Gillow and M. R. Giles. 1997. Microbial Gas Generation Under Expected Waste Isolation Pilot Plant Repository Conditions. Sandia National Laboratories SAND96-2582. Albuquerque, USA.
- Grant, W. D., G. J. Holtom, A. Rosevear and D. Widdowson. 1997. A Review of Environmental Microbiology Relevant to the Disposal of Radioactive Waste in a Deep Underground Repository. UK Nirex Report NSS R329. Harwell, UK.
- Grbić-Galić, D., N. Churchman-Eisel and I. Mraković. 1990. Microbial transformation of styrene by anaerobic consortia. *Journal of Applied Microbiology* 69(2): 247-260.
- Guillet, J. E., T. W. Regulski and T. B. McAneney. 1974. Biodegradability of photodegraded polymers. II. Tracer studies of biooxidation of Ecolyte PS polystyrene. *Environmental Science & Technology* 8(10): 923-925.

Husain, A. and D. Jain. 2003. Chemical radiochemical and microbiological characterisation of the contents of resin liners sampled at the Western Waste Management Facility in 2002. Kinectrics Report 9820-090-RA-0001-R00. Toronto, Canada.

Jones, P. H., D. Prasad, M. Heskins, M. H. Morgan and J. E. Guillet. 1974. Biodegradability of photodegraded polymers. I. Development of experimental procedures. *Environmental Science & Technology* 8(10): 919-923.

Kannen, H. and W. Muller. 1999. Gas generation of radioactive wastes - comparison between laboratory experiments and measurements on real waste. Proceeding 7th Inter. Conf. on Radioactive Waste Management and Environmental Remediation, Nagoya, Japan.

Kaplan, D. L., R. Hartenstein and J. Sutter. 1979. Biodegradation of polystyrene, poly(methyl methacrylate), and phenol formaldehyde. *Appl. Environ. Microbiol.* 38(3): 551-553.

LLWR. 2011. The 2011 Environmental Safety Case: Near Field. LLW Repository Ltd, LLWR/ESC/R(11)10021. Cumbria, UK.

Mooney, A., P. G. Ward and K. E. O'Connor. 2006. Microbial degradation of styrene: biochemical, molecular genetics and perspectives for biotechnology applications. *Applied Microbial Biotechnology* 72: 1-10.

Mor, R. and A. Sivan. 2008. Biofilm formation and partial biodegradation of polystyrene by the actinomycete; *Rhodococcus ruber*. *Biodegradation* 19(6): 851-858.

Moreno, L. 2001. Project Safe: Gas Related Processes in the SFR. SKB Report R-01-11. Stockholm, Sweden.

Nagra. 2004. Effects of Post-disposal Gas Generation in a Repository for Spent Fuel, High level Waste and Long-lived Intermediate Level Waste Sited in Opalinus Clay. Nagra Technical Report 04-06. Wettingen, Switzerland.

O'Leary, N. D., K. E. O'Connor and A. D. W. Dobson. 2002. Biochemistry, genetics and physiology of microbial styrene degradation. *FEMS Microbiology Reviews* 26(4): 403-417.

OPG. 2011. Deep Geologic Repository for Low and Intermediate Level Waste – Preliminary Safety Report. Ontario Power Generation report 00216-SR-01320-00001 R000. Toronto, Canada.

Otake, Y., T. Kobayashi, H. Asabe, N. Murakami and K. Ono. 1995. Biodegradation of low-density polyethylene, polystyrene, polyvinyl chloride, and urea formaldehyde resin buried under soil for over 32 years. *Journal of Applied Polymer Science* 56(13): 1789-1796.

Quintessa. 2011. Postclosure Safety Assessment: Analysis of the Normal Evolution Scenario. Quintessa Ltd. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-26 R000. Toronto, Canada. (available at www.nwmo.ca/dgrpostclosuresafetyassessmentreports)

Quintessa and Geofirma. 2011a. Postclosure Safety Assessment: Data. Quintessa Ltd. and Geofirma Engineering Ltd. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-32 R000. Toronto, Canada. (available at www.nwmo.ca/dgrpostclosuresafetyassessmentreports)

Quintessa and Geofirma. 2011b. T2GGM Version 2: Gas Generation and Transport Code. Quintessa Ltd. and Geofirma Engineering Ltd. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-33. Toronto, Canada. (available at www.nwmo.ca/dgrpostclosuresafetyassessmentreports)

Quintessa, Geofirma and Senes. 2011. Postclosure Safety Assessment Report. Quintessa Ltd., Geofirma Engineering Ltd. and SENES Consultants Ltd. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-25 R000. Toronto, Canada.

Shah, A. A., F. Hasan, A. Hameed and S. Ahmed. 2008. Biological degradation of plastics: A comprehensive review. *Biotechnology Advances* 26(3): 246-265.

Sielicki, M., D. D. Focht and J. P. Martin. 1978. Microbial degradation of [¹⁴C]polystyrene and 1,3-diphenylbutane. *Canadian Journal of Microbiology* 24(7): 798-803.

Singh, B. and N. Sharma. 2008. Mechanistic implications of plastic degradation. *Polymer Degradation and Stability* 93(3): 561-584.

Sivan, A. 2011. New perspectives in plastic biodegradation. *Current Opinion in Biotechnology* 22(3): 422-426.

Tokiwa, Y., B. P. Calabia, C. U. Ugwu and S. Aiba. 2009. Biodegradability of plastics. *Int. J. Mol. Sci.* 10: 3722-3742.

Tusa, E. 1989. Method for volume reduction of low activity organic wastes from nuclear power plants by anaerobic decomposition. United States Patent Office.

Tusa, E. 1992. IVO's resin eating bacteria make light work of waste treatment. *Nuclear Engineering International* 2: 39.

US DOE. 1995. WIPP Remote-Handled Transuranic Waste Study: Appendix D Gas Generation Mechanisms. U.S. Department of Energy DOE/CAO 95-1095, Carlsbad, USA.

Wiborgh, M., Höglund L.O. and K. Pers. 1986. Gas Formation in a L/ILW Repository and Gas Transport in the Host Rock. Nagra Technical Report 85-17. S. Baden, Switzerland.

Yim, M.-S. and F. Caron. 2006. Life cycle and management of carbon-14 from nuclear power generation. Progress in Nuclear Energy 48(1): 2-36.