

# T2GGM Version 3.1: Gas Generation and Transport Code

NWMO TR-2012-23

November 2012

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## ABSTRACT

**Title:** T2GGM Version 3.1: Gas Generation and Transport Code  
**Report No.:** NWMO TR-2012-23  
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### Abstract

T2GGM Version 3.1 is a software package that can be used to analyze the generation and transport of gases and groundwater in a deep geologic repository. The current version is Version 3.1. It includes gas generation from low and intermediate level waste, and gas generation from the corrosion of used fuel containers under relevant conditions.

This report provides a reference manual for the T2GGM software. It includes the theory for the gas generation model, the user guide with descriptions of the software inputs and outputs, a summary of the verification that the software has undergone and software validation.

T2GGM includes the following capabilities:

- Corrosion product and hydrogen gas generation from corrosion of steels and other alloys under aerobic and anaerobic conditions;
- CO<sub>2</sub> and CH<sub>4</sub> gas generation from degradation of organic materials under aerobic and anaerobic conditions;
- H<sub>2</sub> gas reactions, including methanogenesis with CO<sub>2</sub>;
- Biomass generation, decay and recycling;
- Exchange of gas and water between the repository and the surrounding geosphere; and
- Two-phase flow of water and gas within the geosphere.

Key results include the gas pressure and water saturation levels within a repository, as well as flow rates of water and gas within the geosphere. T2GGM does not include radionuclide transport and decay.

T2GGM is comprised of two coupled models: a Gas Generation Model (GGM) used to model the generation of gas within a repository due to corrosion and microbial degradation of the various materials present, and a TOUGH2 model for gas-water transport from the repository through the geosphere.



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## 1. INTRODUCTION

The long-term safety assessment of deep geological repositories may involve the analysis of behaviour of gases within and from the repository. This assessment requires the calculation of the generation and build-up of gas in the repository and the movement of gas from the repository to the surface environment. The gas generation and movement needs to be coupled with the availability and movement of groundwater.

T2GGM has been developed to undertake these calculations. It is comprised of two coupled models: a Gas Generation Model (GGM) used to model the generation of gas within a repository due to corrosion and microbial degradation of the various materials present, and the TOUGH2 model (Pruess et al. 1999) for gas and water transport from the repository and within the geosphere (Figure 1-1). Key outputs from this software are the peak repository pressure, repository saturation, and total flux of gases from the geosphere to surface.

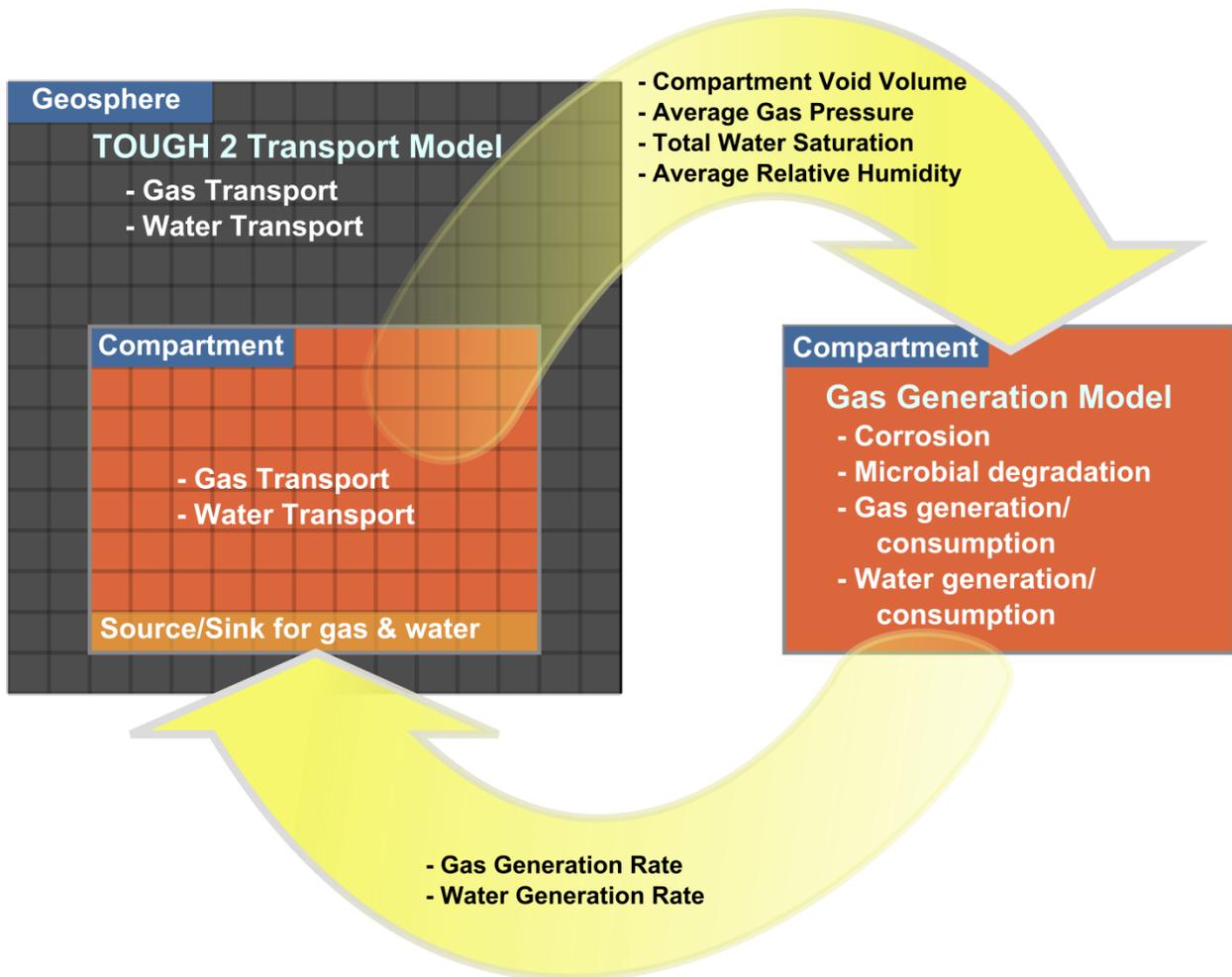


Figure 1-1: Coupling Gas Generation and Transport in T2GGM

This reference manual includes the following documentation for T2GGM:

- Program Abstract (Section 2);
- GGM Theory (Section 3);
- TOUGH2 Theory (Section 4);
- Verification (Section 5);
- Validation (Section 6); and
- User Manual (Section 7).

## 2. PROGRAM ABSTRACT

T2GGM Version 3.1 is comprised of two coupled models: a gas generation model (GGM Version 3.1) used to model the generation of gas within a repository due to corrosion and microbial degradation of the various materials or waste streams present, and the TOUGH2 Version 2.0 model for gas transport from the repository through the geosphere. Key output parameters from this software are the peak repository pressure, repository saturation, and total flux of gases from or to the geosphere.

GGM Version 3.1 is implemented as a FORTRAN module that is used by TOUGH2 in its own gas generation and repository saturation calculations. GGM includes a kinetic description of the various microbial and corrosion processes that lead to the generation and consumption of various gases. Mass-balance equations are given for each of the species included in the model, including three forms of organic waste (cellulose, ion-exchange (IX) resins, and plastics and rubbers), four metallic waste forms and container materials (carbon and galvanized steel, passivated carbon steel, stainless steel and nickel-based alloys, and zirconium alloys), six different gases ( $\text{CO}_2$ ,  $\text{N}_2$ ,  $\text{O}_2$ ,  $\text{H}_2$ ,  $\text{H}_2\text{S}$ , and  $\text{CH}_4$ ), five terminal electron acceptors ( $\text{O}_2$ ,  $\text{NO}_3^-$ ,  $\text{Fe(III)}$ ,  $\text{SO}_4^{2-}$ , and  $\text{CO}_2$ ), five forms of biomass (aerobes, denitrifiers, iron reducers, sulphate reducers, and methanogens), five types of corrosion product ( $\text{FeOOH}$ ,  $\text{FeCO}_3$ ,  $\text{Fe}_3\text{O}_4$ ,  $\text{Fe}_2\text{O}_3$  and  $\text{FeS}$ ), water, and  $\text{MgO}$ , which could be added to the repository to mitigate the effects of  $\text{CO}_2$  generation.

TOUGH2 is a multi-phase flow and heat transport program for fluid mixtures. TOUGH2 is the collective name for a family of numeric models that simulate multi-phase flow and transport developed and maintained by the Earth Sciences Division of Lawrence Berkeley National Laboratory. TOUGH2 uses different Equations-of-State (EOS) modules to simulate different combinations of liquids and gases. T2GGM Version 3.1 includes TOUGH2 Version 2.0 with the EOS3 V1.01 equation-of-state module (ideal gas - air and water) (Pruess et al. 1999). T2GGM-MP Version 3.1 is a version of T2GGM that couples GGM with TOUGH2-MP Version 2.0. TOUGH2-MP uses multiple processors to undertake its calculations in order to improve run times. The majority of this documentation covers both the single and multiple processor versions of T2GGM. Sections that relate to single- or multi-processor functionality only are indicated as such. Several modifications have been implemented in TOUGH2 (both single and multi-processor versions) providing the user with a greater range of capabilities, including:

- The option to use the modified van Genuchten model provided in iTOUGH2 (Finsterle 1999), a set of capillary pressure and relative permeability equations that are widely used in modeling two-phase flow in low-permeability media;
- User specification of gas (air,  $\text{CH}_4$ ,  $\text{CO}_2$ ,  $\text{H}_2$ , Ne or user-specified);
- 1D hydro-mechanical capability, to provide the ability to assess the effects of a uniformly applied glacial stress;
- Time-varying permeability, useful in cases of degraded or evolving engineered materials or excavated damage zone (EDZ); and
- Time-varying Dirichlet boundary conditions.

While the version of T2GGM documented here (i.e., Version 3.1) uses the TOUGH2 EOS3 module that is limited to two components (gas and water), it should be noted that TOUGH2 has several modules available. For example, EOS7R models water, brine, air and two radionuclides. Replacing EOS3 with one of these modules is relatively straightforward.

## 2.1 CAPABILITIES

T2GGM Version 3.1 includes the following capabilities:

- Corrosion product and hydrogen gas generation from corrosion of steels and other alloys under aerobic and anaerobic conditions suitable for application to an L&ILW repository;
- Corrosion product and hydrogen gas generation from the high temperature corrosion of steel containers in the presence of a bentonite buffer suitable for application to a repository for used fuel;
- CO<sub>2</sub>-enhanced corrosion of carbon steel and passive alloys;
- CO<sub>2</sub> and CH<sub>4</sub> gas generation from degradation of organic materials under aerobic and anaerobic conditions;
- Degradation of cellulose, IX resins, and plastics and rubbers at different rates based on the terminal electron acceptor;
- H<sub>2</sub> gas reactions, including methanogenesis with CO<sub>2</sub>;
- Biomass generation, decay and recycling;
- Limitation of both microbial and corrosion reactions by the availability of water;
- Carbon, iron and water are mass balanced within repository reactions;
- Exchange of gas and water between the repository and the surrounding geosphere;
- The ability to subdivide the volume within which gas generation takes place into multiple compartments, each of which can be allocated its own associated inventory and evolved independently with coupling provided through gas and water transport;
- Calculation of the generation and build-up of gas in each repository volume;
- Two-phase flow of water and gas within the geosphere with gas dissolution according to Henry's law;
- Heat flow coupled to two-phase flow of water and gas.
- The ability to assess the use of magnesium oxide as a gas-mitigation method, and other strategies that may affect the consumption of gas in the repository;
- 1D hydro-mechanical model to assess the effects of a uniformly applied glacial stress;
- Time-variable permeability, allowing the permeability properties of certain materials, such as engineered materials or EDZ, to evolve or degrade with time.
- Time-variable Dirichlet boundary conditions; and
- The ability to stop and restart the simulations.

## 2.2 LIMITATIONS

T2GGM Version 3.1 is subject to the following limitations:

- Heat generation can only be modelled as a TOUGH2 input source or sink;
- T2GGM does not model radionuclide transport and decay;
- Repository corrosion and gas reaction rates are first order in a primary reactant, and in particular are not dependent on the amount of microbial biomass;
- Metal corrosion and organic decomposition is described by a constant or temperature dependent corrosion rate for the relevant conditions (aerobic/anaerobic, saturated/unsaturated);

- Organics are modelled as either cellulose or styrene;
- Oxygen, nitrates and sulphates can be depleted from an initial supply only (with the initial inventory of sulphates and Fe(III) being defined by the initial volume of water and a user-specified initial concentration), and O, N and S may not be strictly conserved. It is assumed that any long-term fluxes of nitrates, sulphates and Fe(III) into/out of the repository do not have significant impacts on gas processes;
- All gas in the geosphere is modelled as a single gas (either air, CH<sub>4</sub>, CO<sub>2</sub> or H<sub>2</sub>); all gases released from the repository are converted into this gas on an equivalent molar basis (e.g., if GGM calculates a generation rate of 1 mol s<sup>-1</sup> of H<sub>2</sub> and 2 mol s<sup>-1</sup> of CH<sub>4</sub>, then it is converted into 3 mol s<sup>-1</sup> of the selected gas, and then converted to a mass rate at the selected gas molecular weight for use by TOUGH2); and
- Groundwater in the geosphere is modelled as freshwater. Saline water will affect water flow due to differences in the viscosity and density of the water, and the impact of these differences must be evaluated on a case by case basis.
- The terminal electron acceptor processes are expected to dominate in a fixed sequence of stages. This is appropriate for closed systems, but may not be appropriate when there are long-term net fluxes of TEAs (sulphates/nitrates/iron-based species) from/to the repository.
- Advection and diffusion of dissolved species (dissolved gases, nitrates, sulphates) into or out of the repository is not modelled by GGM. The model may not be suitable if the host rock maintains large concentrations of sulphates/nitrates and this is coupled with large water inflow to the repository.

### 3. THEORY – GGM

#### 3.1 INTRODUCTION

Gas generation within the repository may be important to both operational and post-closure safety. During the operational phase, when air is still present, care must be taken to avoid the formation of flammable gas mixtures in closed spaces. Following closure and consumption of O<sub>2</sub>, the build-up of gas within the sealed repository affects the resaturation time and can lead to the release of gaseous radionuclides. Gas is generated and consumed by various microbial and corrosion processes. For example, microbial degradation of organic components of the waste or other materials left in the repository produces CO<sub>2</sub> and CH<sub>4</sub>. Corrosion of metallic waste forms and container materials consumes O<sub>2</sub> and CO<sub>2</sub>, and produces H<sub>2</sub> under anaerobic<sup>1</sup> conditions.

This section describes GGM Version 3.1, the gas generation model for the T2GGM Version 3.1. The model incorporates a detailed description of the kinetics of microbial degradation of the organic wastes and accounts for the possible limitation of both microbial and corrosion processes due to the availability of water. In addition, GGM can be used to assess the effect of different gas-mitigation methods and other processes that may lead to the consumption of gas in the repository.

This theory section provides a detailed specification of all the equations solved by GGM Version 3.1. The microbial processes and corrosion processes described in Section 3.2 and Section 3.3, respectively, have been chosen for application to a deep geologic repository (DGR) for L&ILW, for which repository temperatures are expected to be relatively constant at around 20 °C. Thus for these processes, reaction rates are constant and do not contain any explicit temperature dependence. In Section 3.4, corrosion processes are presented that have been chosen for application to a clay-backfilled repository for used fuel. For this application, high initial temperatures are expected and so the corrosion rates have temperature dependence built in explicitly, and the model includes a staged representation of the breakthrough of water to the container through a bentonite buffer. It is not intended for L&ILW processes and used fuel processes to be used simultaneously<sup>2</sup>. Additional processes that can be relevant to both L&ILW and used fuel repositories (e.g., gas mitigation) are presented in Section 3.5, and general model and coding information is provided in Section 3.6. Section 3.7 describes the approach taken to modelling the partitioning of gas between the water-unsaturated and water-saturated phases. Section 3.8 describes the approach taken to modelling relative humidity. Section 3.9 describes the approach taken to modelling water-limited conditions.

A detailed list of the model parameters referenced throughout this section is given in Table 3-1.

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<sup>1</sup> Here, the term anaerobic is used to describe not only the absence of air (oxygen), but also more generally to describe environments in which one or more redox couples control the redox potential at relatively negative values of Eh.

<sup>2</sup> Processes can be disabled by setting relevant reaction rates to zero.

### 3.2 MICROBIAL GAS GENERATION PROCESSES FOR APPLICATION TO L&ILW

#### 3.2.1 Degradation of Organic Waste Components

GGM considers three classes of organic wastes that may be present in a repository containing low and intermediate level waste:

1. Cellulosic materials;
2. IX resins; and
3. Plastics and rubbers.

All three of these groups represent polymeric organic materials. The microbial degradation of polymeric organics follows a generic sequence of events (Figure 3-1) (Rittmann and McCarty 2001). Firstly, the polymer is converted into soluble intermediates, which are then subject to microbial oxidation reactions, the exact nature of which depends on the prevailing geochemical conditions. Microbes either couple the oxidation of these soluble intermediates to the reduction of Terminal Electron Acceptors (TEAs) or subject them to fermentation (Barlaz 1997, Pedersen 2000, Rittmann and McCarty 2001). Under ideal conditions, microbial systems employ a range of TEAs in oxidation-reduction reactions that are consumed in a well-defined order depending on the amount of energy provided by each reaction (Zehnder and Stumm 1988). This order is outlined below:

- Oxygen followed by;
- Nitrate followed by;
- Ferric ion (Fe III) followed by;
- Manganese (Mn IV) followed by;
- Sulphate followed by; and
- Carbon dioxide.

In subsurface environments the simultaneous consumption of terminal electron acceptors does occur due to local heterogeneity and the presence of microbial microsites. However, the general trend of sequential terminal electron consumption is seen in subsurface environments' pollution plumes, for example Williams et al. (2001). Consequently, the sequential consumption of terminal electron acceptors within the model is justifiable on the basis of reaction thermodynamics (Zehnder and Stumm 1988) and environmental observations (e.g., Williams et al. 2001).

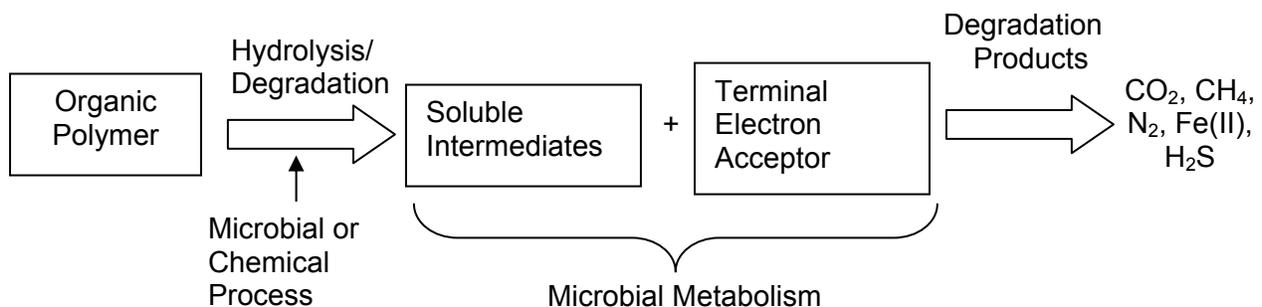
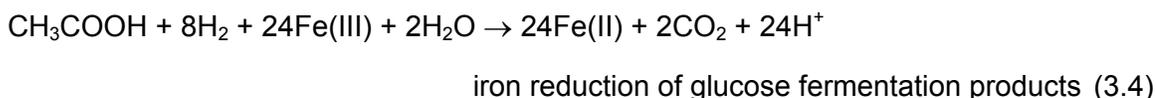
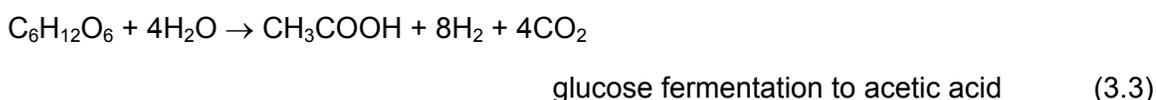
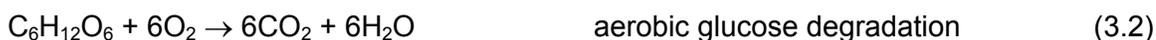


Figure 3-1: Microbial Degradation of Polymeric Substrates

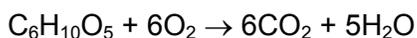
Under oxidizing conditions when oxygen, and to a lesser extent nitrate, is used as a terminal electron acceptor, the degradation of polymeric substrates such as cellulose progresses to completion (Equations (3.1) and (3.2)). When oxygen is depleted and anaerobic conditions are established, polymeric substrates tend to undergo fermentation first, with the fermentation end products then being oxidized by TEA processes (Equations (3.3) and (3.4)) (Leschine 1995, Pedersen 2000). Fermentation is carried out by a varied group of microbes and consequently a wide range of fermentation end products (carboxylic acids and alcohols) are possible (Leschine 1995, Barlaz 1997, Rittmann and McCarty 2001), with Equation (3.3) showing the fermentation of glucose to acetic acid. The consumption of these fermentation end products during iron reduction is illustrated in Equation (3.4).



### 3.2.1.1 Modelling Organic Waste Degradation

The microbial degradation of polymeric substrates and the subsequent generation of gas is a complex multistage process involving a large array of microbial species (Pedersen 2000, Grant et al. 1997). However, for modelling purposes, this can be simplified by the fact that the conversion of polymeric substrates such as cellulose to their soluble intermediates is often the rate-limiting step in the gas generation process (Rittmann and McCarty 2001). This allows the microbial oxidation of polymeric substrates to be coupled directly to the reduction of the relevant TEA. The degradation of polymeric substrates then becomes a single-stage process with the consumption of TEAs being instantaneous and controlled by the rate of polymer degradation. This partial-equilibrium approach has been applied in other modelling studies (McNab and Narasimhan 1994, Postma and Jakobsen 1996), since it significantly simplifies the modelling of microbially driven systems and reduces the number of kinetic parameters required to run the model. The application of this approach to gas generation modelling can be justified on the basis that it is conservative from a gas generation perspective, since it maximizes gas generation by preventing the accumulation of intermediate products and ensuring gas generating processes proceed to completion.

Balanced reactions coupling the oxidation of organic waste components to the reduction of TEAs can be constructed using the approach outlined by Rittmann and McCarty (2001). Taking cellulose as an example, its hydrolysis to glucose is outlined in Equation (3.1) with its oxidation under aerobic conditions being outlined in Equation (3.2). However, if the rate of glucose oxidation is taken to be instantaneous when compared to the rate of cellulose hydrolysis then the overall reaction can be written as:

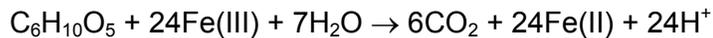


where the controlling reaction rate is that for cellulose hydrolysis, Equation (3.1).

Note that the rate of hydrolysis (and of the degradation of polystyrene into styrene) is redox dependent and so an aerobic rate and an anaerobic rate are considered.

The above approach closely resembles microbial cellulose degradation under oxidizing conditions where the polymer is completely degraded to carbon dioxide and water (Leschine 1995). However, under anaerobic conditions when fermentation occurs, the instantaneous consumption of fermentation end products is not always observed, resulting in the accumulation of carboxylic acids such as acetic acid and butyric acid. This accumulation generally occurs because the microbes responsible for the degradation of these products are inhibited by low pH, a process known as acid souring in landfill sites (p. 62, EA 2004). In anaerobic hypersaline environment the accumulation of volatile fatty acids has also been observed (Ollivier et al. 1994). The accumulation of fermentation end products such as acetic acid is not included in the model, allowing the degradation of polymeric organics to be modelled as a series of single-stage processes. As before, this approach is justified on the basis that it is conservative since it maximizes gas generation by preventing the accumulation of soluble organic intermediates.

Employing this approach, the metabolism of cellulose degradation (oxidation) under iron-reducing conditions, which is described in Equations (3.1), (3.3), and (3.4), can be simplified to:



degradation of cellulose under iron-reducing conditions (3.6)

where again the controlling reaction rate is that for cellulose hydrolysis, Equation (3.1).

### **Origins of Microbes**

The model assumes that all microbial groups required to catalyze the processes modelled are present within the repository. This assumption is justified on the basis that it is conservative from a gas generation perspective, since it ensures gas generation processes proceed to completion. In reality, microbes are ubiquitous in terrestrial, man-made and subsurface environments (Pedersen 2000). Microbes will enter the repository during the construction and operational phases on vehicles, materials, people and in the air. In addition, the waste will carry its own microbial load. Microbial gas generation in stored and disposed wastes has been reported by a number of authors (Molnar et al. 2006, Molnar et al. 2000, Kannen and Muller 1999). Groundwater entering the repository could also carry a microbial load compatible with the saline conditions at depth.

### **Terminal Electron Acceptors**

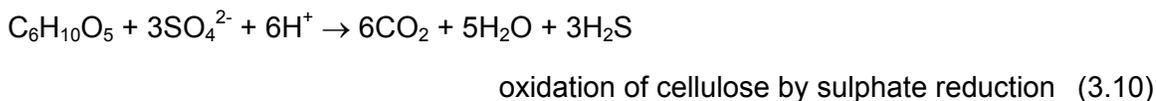
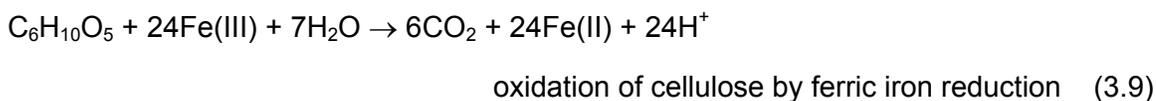
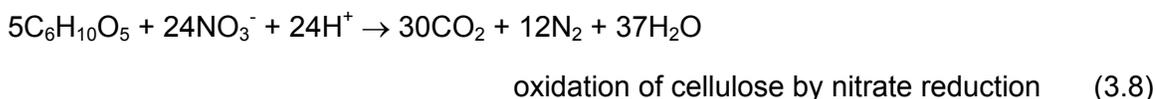
The model includes oxygen, nitrate, ferric iron, sulphate, and carbon dioxide as terminal electron acceptors. Oxygen is included, since it will be present in the repository atmosphere postclosure. Sources of nitrate are less obvious, but may include blast explosive residue from repository construction, the groundwater, and also a chemical used in the nuclear industry and present in the wastes. Ferric iron is included, since it is a product of aerobic corrosion and sulphate is included since it may be present in the local groundwater. The inclusion of sulphate also allows gas mitigation options involving the precipitation of metal sulphides to be investigated. Finally, carbon dioxide is included since it is a major gaseous product of microbial degradation processes. With the exception of carbon dioxide, any or all of the processes

associated with these terminal electron acceptors within the model can be turned off by setting the relevant input concentration to zero.

Terminal electron acceptors are theoretically consumed in a defined sequence (Section 3.2.1) starting with oxygen and finishing with carbon dioxide. This sequence is reflected in the model with a given TEA only being consumed once the previous one has been depleted. Finally, when all the competing TEAs have been depleted, carbon dioxide consumption and methane production will occur. The removal of TEAs is not modelled kinetically, but is controlled by the rate of organic waste degradation and the stoichiometry of the relevant reaction in a partial equilibrium approach similar to that employed by McNab and Narasimhan (1994) and Postma and Jakobsen (1996).

### **Degradation of Cellulose**

The degradation of cellulosic materials has been extensively studied (Leschine 1995) and modelled (Rittmann and McCarty 2001). Consequently the degradation pathways are well established (Leschine 1995, Barlaz 1997). Taking the approach outlined in Section 3.2.1.1, cellulose degradation is modelled via the following equations constructed using the approach outlined by Rittmann and McCarty (2001):



where the reaction rate for all these is that for cellulose hydrolysis, Equation (3.1).

### **Degradation of IX Resins**

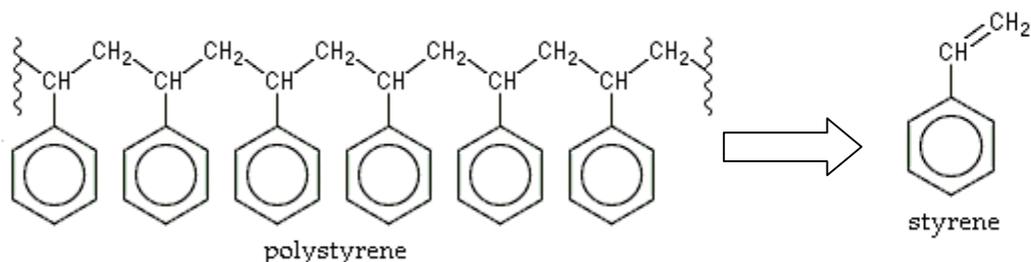
There may be significant amounts of IX resins in the intermediate-level waste inventory, and as such, these resins are potentially a significant source of biogenic gases. However, there is disagreement as to the biodegradability of these materials. For example, Grant et al. (1997) listed IX resins as being recalcitrant under repository conditions. However, a number of authors have suggested that these resins are subject to microbial degradation and subsequent gas generation. For example, Bracke et al. (2003, 2004) report gas generation rates from resin wastes in interim storage and attribute a microbial gas generation rate to the degradation of these wastes. Bowerman et al. (1988) investigated the biodegradation of IX media using a mixed microbial culture isolated from resin waste samples, and found microbial growth under various conditions, although it is noted that the work appear to have been carried out under aerobic conditions. 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).

Although the chemical nature of IX resins suggests that they would not be biodegradable, particularly under anaerobic conditions, data from waste resins indicate that degradation is possible. There are a number of scenarios that explain the observed data:

- Organic contaminants adsorbed on the resins and corrosion hydrogen are supporting the gas generation and microbial communities rather than direct biodegradation of the resins;
- Radiolytic and/or chemical degradation is generating soluble intermediates which are subject to biodegradation; and
- The resins are subject to microbial degradation.

There are insufficient data to determine which of these options is correct and it is possible that all three are operating simultaneously. For generality, IX resin degradation is included in the model.

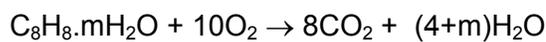
Water coolant IX resins are typically cross-linked polystyrene based, with various functional groups and water attached. The resins are therefore modelled via the degradation of polystyrene with bound water  $(C_8H_8 \cdot mH_2O)_n$  to styrene with bound water  $(C_8H_8 \cdot mH_2O)$  as in Figure 3-2, and then to final degradation products. The initial degradation is considered to be the rate-limiting step. This is comparable to the cellulose degradation model. This assumption is justified on the basis that it maximizes the amount of gas generated from this component of the waste inventory and is compatible with a mechanistic approach to the modelling of a water balance.



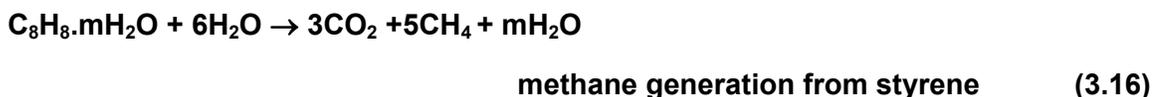
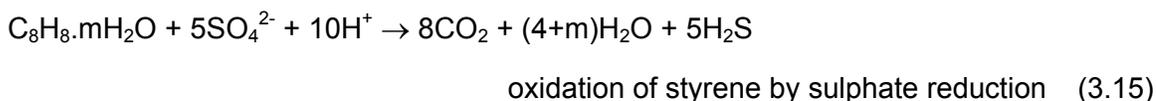
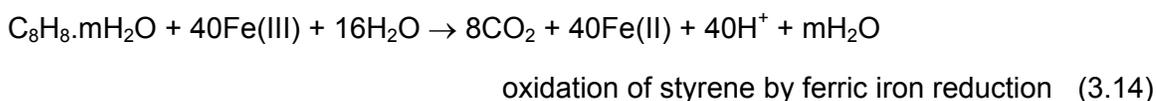
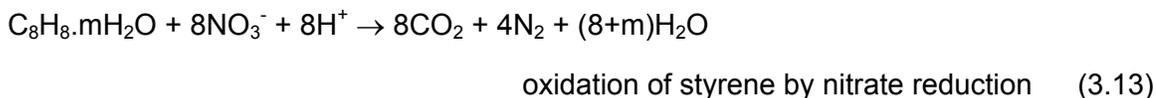
**Figure 3-2: Polystyrene Degradation**

The degradation of styrene is coupled to the reduction of the relevant TEAs in the same manner as outlined for cellulose. The microbial degradation of styrene under oxidizing conditions has been extensively investigated (Mooney et al. 2006) but there is little information regarding its degradation in reducing environments. The anaerobic degradation of other aromatic compounds has been reported (Lovely 2000, Spormann and Widdel 2000, Karthikeyan and Bhandari 2001) but only where terminal electron acceptors such as ferric iron and sulphate are available.

The degradation of IX resins is modelled using a set of degradation pathways constructed using the approach outlined by Rittmann and McCarty (2001), but with the release of bound water. These pathways are outlined below:



oxidation of styrene by molecular oxygen (3.12)



where the reaction rates for all these are that for polystyrene degradation and m represents the number of moles of bound water per mole of styrene monomer in the initial resin material.

Note that resins typically consist of anion and/or cation functional groups on the polystyrene divinylbenzene backbone, in addition to the bound water. These functional groups comprise a significant fraction of the mass of the resins, but do not usually contain much carbon and therefore do not contribute significantly to potential gas generation. In the GGM model, the presence of these mass components is taken into account when determining the number of moles of polystyrene divinylbenzene backbone per unit mass of dry resin so as to obtain a good estimate of the gas generating potential.

### **Degradation of Plastics and Rubber**

The plastic and rubber components of radioactive waste represent a heterogeneous mix of materials such as PVC, polyethylene, neoprene, nitrile, and latex. The heterogeneous nature of this waste category makes it difficult to model since the degradation of each material would have to be modelled explicitly with an individual inventory and reaction scheme for each component.

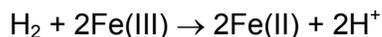
A number of authors have suggested that plastic waste components such as polythene, PVC and polyurethane are recalcitrant under repository conditions (Grant et al. 1997, BNFL 2002). British Nuclear Fuels Limited (BNFL 2002) stated in documentation supporting the 2002 Drigg safety case that: "*The current 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.

A more recent review by Cohen (2006) for the Waste Isolation Pilot Plant (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. However, they do not rule out the possibility of anaerobic microbial degradation.

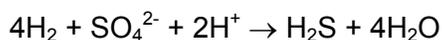
In order to assess the impact of potential plastic and rubber degradation on the overall gas generation in the repository these components are modelled in the same manner as IX resins, i.e., as polystyrene, but with a separate initial inventory and rate constants.

### 3.2.1.2 Microbial Hydrogen Metabolism

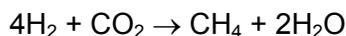
In radioactive waste disposal sites, significant amounts of hydrogen may be produced via anaerobic corrosion of metals. Hydrogen is also a common product of anaerobic microbial metabolism and consequently there are a large number of microbial processes able to process hydrogen (Grant et al. 1997, Pedersen 2000). The oxidation of hydrogen takes place under anaerobic conditions and is therefore coupled with the reduction of ferric iron, sulphate and carbon dioxide:



hydrogen oxidation via iron reduction (3.17)



hydrogen oxidation via sulphate reduction (3.18)



methane generation from hydrogen oxidation (3.19)

where the corresponding rate constants are expressed in terms of the rate of consumption of  $\text{H}_2$ .

The ferric ion  $\text{Fe(III)}$  is assumed primarily present as  $\text{FeOOH}$  within the saturated region. The sulphate reaction also only occurs in the saturated region. The methane generation can occur anywhere within the system, if there is enough humidity to support microbial processes.

The corrosion hydrogen generation and microbial hydrogen consumption are independent of each other, each having independent rates of reaction. The accumulation of hydrogen within the system is controlled by the relative rates of anaerobic corrosion and microbial hydrogen consumption. If the rate of microbial hydrogen consumption is higher than that of corrosion and associated hydrogen generation, then the rate of corrosion becomes the rate-limiting step in the process. Consequently hydrogen consumption progresses instantaneously as long as sufficient TEA capacity is present. This case reflects the low levels of hydrogen detected in radioactive waste degradation experiments where significant amounts of corrodible metal are present (Beadle et al. 2001, Grey 2002 and Small et al. 2005).

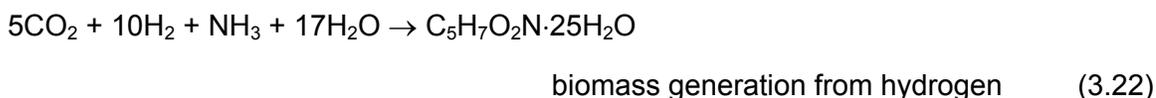
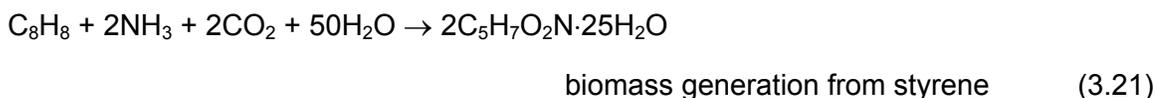
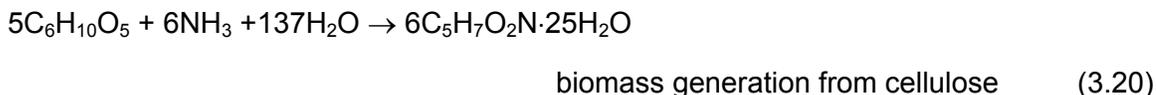
### 3.2.1.3 Microbial Biomass

#### **Biomass Production**

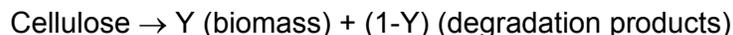
When microbes degrade materials, some of the feed material is used to produce new biomass. Biological systems require more water than that required for the reactions they catalyze, since cells are typically 80 wt% water. Therefore, any attempt to model water within microbially active systems needs to account for the amount of water required to maintain microbial cells. This means that biomass production and degradation has to be modelled since significant amounts of water may be held up in microbial biomass. Consequently, although there may be sufficient

water to complete the oxidation-reduction reactions, there may be insufficient water to support the production of microbial cells (Wang and Francis 2005).

The amount of water needed to support microbial biomass can be calculated using an empirical formula for microbial dry biomass such as  $C_5H_7O_2N$  (Rittmann and McCarty 2001), which indicates that 1 mole of biomass would weigh 113 g. Since biomass is 80 wt% water then each mole of biomass also requires approximately 25 moles of water<sup>3</sup>. This requirement for water can then be integrated into the biomass generation reactions outlined below (in the model, we conservatively assume that there is always sufficient  $NH_3$  to support these reactions):



Cellulose degradation will involve both degradation products as outlined in Equations (3.7) to (3.11), as well as production of biomass as per Equation (3.20) using the energy from the degradation reactions (and  $CO_2$  per Equation (3.21)). The overall reaction rate is described by the effective cellulose degradation rate, but with the cellulose mass divided between biomass and degradation products according to an empirical yield coefficient, Y:



The rate of production of biomass is controlled, as with the degradation products, by the degradation rate of cellulose or styrene, or the rate of the methane-generation reaction Equation (3.19).

### **Biomass Decay**

Microbial biomass is subject to natural turnover since cells have finite lifetimes. Biomass contains a range of compounds, which have different degradabilities. Some microbial cell components are recalcitrant to further degradation and accumulate in the environment. In the present model, two classes of biomass compounds are considered – easily recycled and recalcitrant.

The fraction  $K_R$  of dead hydrated biomass that is readily recycled is modelled according to the reverse of Equation (3.20):




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<sup>3</sup> The molar mass of dry biomass is approximately  $113 \text{ g mol}^{-1}$ . Since the 113 g represents 20% of the whole, the remaining 80% which is water is equivalent to 452 g, which is 25.1 moles of water.

It is assumed that the recycled biomass can be represented as cellulose, with each mole of biomass ( $C_5H_7O_2N$ ) producing 5/6 mol of cellulose ( $C_6H_{10}O_5$ ). The energy to drive this process comes from the oxidation of the organic material itself. This approach to biomass recycling is adopted since it is considered conservative with respect to gas generation.

The remaining fraction of biomass is recalcitrant ( $1 - K_R$ ) and does not degrade further, except that upon death, the cells will release the water they hold - 25 mol  $H_2O$  are released per mol recalcitrant dead biomass.

### **Threshold for Biomass Activity**

Water activity ( $A_w$ ) is the ratio of the vapour pressure of water in a material to the vapour pressure of pure water at the same temperature. Relative humidity of air (RH) is the ratio of the vapour pressure of water in air to the water saturation vapour pressure. When vapour and temperature are at equilibrium, the water activity of a material is equal to the relative humidity of the surrounding air:

$$RH = A_w \quad (3.24)$$

$A_w$  is important because biological activity ceases at an  $A_w$  below 0.6<sup>4</sup> with the lower limit for bacteria being 0.75 (Brown 1976, Wang and Francis 2005). Consequently, to model microbially driven reactions in the repository, it is necessary to check the water activity or RH. Microbial processes should be allowed to proceed within the vapour phase for sufficiently high RH. Rate constants for all the biomass generation reactions and microbial processes that normally occur only under saturated conditions are ramped smoothly down to zero as the RH drops from 0.8 to 0.6. If the rate of water consumption is rapid compared with the rate of water ingress, it is feasible that the relative humidity, or water activity, could fall below that required to sustain microbial activity.

### **3.2.2 Reaction Kinetics**

The degradation of polymeric organic substrates is modelled as being first order with respect to their amounts (Equation (3.25)):

$$-\frac{dQ_i}{dt} = V_{i,j} \cdot Q_i \quad \text{degradation of polymeric substrates} \quad (3.25)$$

where  $Q_i$  [mol] is the amount of substrate  $i$  ( $i = C, R, P$  for cellulose, IX resins, and plastics and rubbers, respectively) and  $V_{i,j}$  [ $s^{-1}$ ] is the degradation rate constant for substrate  $i$  under conditions  $j$  ( $j = a, b, c, d, e$  for aerobic respiration, denitrification, iron reduction, sulphate reduction, and methanogenesis, respectively).  $V_{i,j} = V_i$  if substrate  $j$  is being consumed, and 0 otherwise, where  $V_i$  [ $s^{-1}$ ] is the degradation rate of cellulose, IX resin, or plastics and rubbers.

This is an approach commonly applied to the modelling of the degradation of polymeric organic substrates (Pavlostathis and Giraldo-Gomez 1991, Rittmann and McCarty 2001, IWA 2002).

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<sup>4</sup> Note that some fungi can live at an  $A_w$  close to 0.6. Fungi are generally considered to be better adapted to low water availability. However fungi are generally aerobic organisms and would not be expected to play an important role in an anaerobic deep geologic environment.

The rates of all the microbial reactions modelled are determined by the rate of polymer degradation. This constrains the number of input kinetic parameters required to run the model to an aerobic and an anaerobic rate for each of the three polymeric substrates modelled.

The model is set up to allow the polymer degradation rates to be modified depending on the prevailing environmental conditions. Generally speaking, as the system moves from oxidizing to reducing conditions, degradation rates slow down. The model simulates this by having independent polymer degradation rates for when specific TEAs dominate. This is not the same as having the removal of the TEAs being kinetically controlled.

Biomass generation is coupled to polymer degradation via a yield coefficient that determines how organic carbon is partitioned between energy generation and biomass production, Equation (3.26). This yield coefficient depends on the TEA consumed since the yield decreases as the available energy generation decreases.

$$\frac{dX}{dt} = Y_j \frac{dQ_i}{dt} - XD \quad \text{biomass generation} \quad (3.26)$$

where  $X$  [mol] is the quantity of biomass,  $Y_j$  [-] is the biomass yield coefficient for condition  $j$ , and  $D$  [ $s^{-1}$ ] is the biomass decay rate.

The production and consumption of gaseous products is also coupled to polymer degradation via the yield coefficient and a stoichiometric coefficient relevant to that product

$$\frac{dQ_k}{dt} = J_{ki}(1 - Y_j) \frac{dQ_i}{dt} \quad \text{product generation} \quad (3.27)$$

where  $Q_k$  [mol] is the number of moles of product  $k$  ( $k = CO_2, H_2, N_2, H_2S, CH_4$ ) and  $J_{ki}$  [-] is the stoichiometric coefficient for product  $k$  formed from organic substrate  $i$ .

### 3.2.3 Summary of Microbial Modelling

The modelling of the microbial reactions includes the following features:

1. A mechanistic basis for treatment of microbial processes;
2. The inclusion of different rates of degradation of organic substrates based on either oxidizing or reducing conditions;
3. The possible limitation of microbial processes by the availability of water;
4. Separate treatment of cellulose, IX resins, and plastics and rubbers;
5. The inclusion of  $H_2$ -mediated microbial processes; and
6. The recycling of dead biomass.

## 3.3 CORROSION GAS GENERATION PROCESSES FOR APPLICATION TO L&ILW

### 3.3.1 Corrosion Reactions

The various metallic waste forms and container materials considered in the model are: carbon and galvanized steels, passivated carbon steel, stainless steel and nickel alloys, and zirconium alloys.

Corrosion of the metallic wastes and container materials occurs under both aerobic and anaerobic conditions and in unsaturated (i.e., humid) and saturated (i.e., submerged)

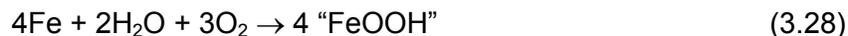
environments. Under aerobic conditions, corrosion is generally supported by the cathodic reduction of dissolved  $O_2$ , although simultaneous reduction of  $O_2$  and  $H_2O$  is possible for some materials. Once the initially trapped atmospheric  $O_2$  has been consumed, corrosion is supported by the reduction of  $H_2O$  only. The effect of oxidizing radiolysis products is not included, as the radiation fields for the various low and intermediate level wastes are insignificant.

Aqueous corrosion processes are possible in humid atmospheres provided the relative humidity is sufficiently high. The relevant vapour phase rate constants are ramped smoothly down to zero between 80% and 60% relative humidity.

### 3.3.1.1 Carbon and Galvanized Steels

The inventory of carbon and galvanized steels in the repository will comprise various carbon steel wastes, as well as carbon and galvanized steel waste containers. Galvanized and carbon steels are treated as a single metallic source. Although the short-term rate of atmospheric corrosion of galvanized steel is lower than that of carbon steel, the thickness of the zinc layer on galvanized steel represents only a small fraction of the overall container wall thickness. Furthermore, there is little difference in the corrosion rate of these two materials under saturated conditions. Therefore, the corrosion of both materials is represented by the corrosion of Fe as carbon steel (C-steel).

The aerobic corrosion of C-steel under saturated and unsaturated conditions is given by the reaction:



where "FeOOH" represents an un-specified ferric oxyhydroxide species, which may also contain groundwater species ( $Cl^-$ ,  $SO_4^{2-}$ ,  $CO_3^{2-}$ ) in various forms of green rust (King and Stroes-Gascoyne 2000). Since FeOOH is only an intermediate species, the degree of hydration of the corrosion product need not be specified for the overall water mass-balance calculation (see below).

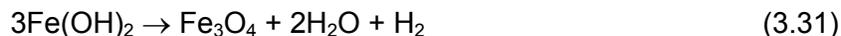
As the environment becomes anaerobic, the Fe(III) corrosion product is converted to Fe(II) via



Under anaerobic conditions, the corrosion of C-steel is supported by the reduction of  $H_2O$



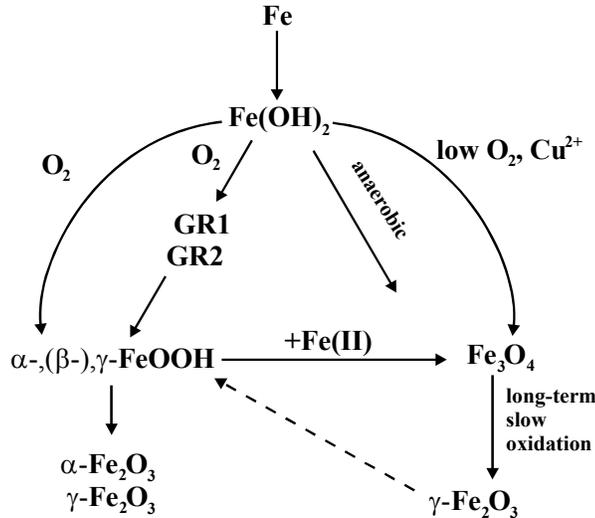
Ferrous hydroxide may also convert to magnetite via the Schikkor reaction (Shreir 1976)



with the formation of additional  $H_2$ .

The nature of the long-term stable anaerobic corrosion product,  $Fe(OH)_2$  or  $Fe_3O_4$ , determines the maximum amount of  $H_2$  that can be produced from the corrosion of carbon steel. If  $Fe(OH)_2$  is the stable corrosion product, then 1 mole of  $H_2$  is produced for each mole of Fe corroded. Conversely, if  $Fe_3O_4$  is the stable corrosion product, then 1.33 moles of  $H_2$  are produced for each mole of Fe corroded.

King and Stroes-Gascoyne (2000) reviewed the nature of corrosion products formed during the corrosion of carbon steel in natural waters. Figure 3-3 shows an overall reaction scheme that accounts for the majority of observations reported in the literature<sup>5</sup>. Ferrous hydroxide ( $\text{Fe}(\text{OH})_2$ ) is generally an intermediate species in the aerobic and anaerobic oxidation of carbon steel, even at temperatures  $<80^\circ\text{C}$  where the conversion of  $\text{Fe}(\text{OH})_2$  to  $\text{Fe}_3\text{O}_4$  via the Schikkor reaction is generally regarded as slow. There is no evidence in the literature for the formation of  $\text{Fe}(\text{OH})_2$  as the main end product of the reduction of  $\text{Fe}(\text{III})$  corrosion products.



**Figure 3-3: Generalized Reaction Scheme for the Formation and Transformation of Corrosion Product Films on C-steel<sup>6</sup>**

Therefore, based on the evidence summarized above, the stable product of the corrosion of carbon steel is taken to be  $\text{Fe}_3\text{O}_4$  rather than  $\text{Fe}(\text{OH})_2$ . The overall reaction for the anaerobic corrosion of C-steel (Equations (3.30) and (3.31)) can then be written as



and the overall reduction of  $\text{FeOOH}$  under anaerobic conditions can be written as



<sup>5</sup> Not all the details in the figure are applicable to corrosion in a DGR, but the entire mechanism is shown for completeness, and to demonstrate the depth of understanding of the corrosion of steels in natural waters.

<sup>6</sup> GR1 and GR2 stand for Green Rust 1 and Green Rust 2, two forms of  $\text{Fe}(\text{III})$  oxyhydroxide that contain varying amounts of  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{CO}_3^{2-}$ . The  $\alpha$ ,  $\beta$  and  $\gamma$  variants correspond to different crystal structures:  $\alpha$ - $\text{FeOOH}$  is goethite;  $\beta$ - $\text{FeOOH}$  is akaganeite;  $\gamma$ - $\text{FeOOH}$  is lepidocrocite;  $\alpha$ - $\text{Fe}_2\text{O}_3$  is haematite; and  $\gamma$ - $\text{Fe}_2\text{O}_3$  is magnetite.

In GGM, the aerobic corrosion of C-steel is represented by Equation (3.28), the conversion of FeOOH under anaerobic conditions by Equation (3.33), and the anaerobic corrosion of C-steel by Equation (3.32).

These latter two processes represent a conservative approach to the calculation of the quantity of H<sub>2</sub> generated since, if Fe(OH)<sub>2</sub> rather than Fe<sub>3</sub>O<sub>4</sub> is the stable long-term anaerobic corrosion product, less H<sub>2</sub> will be generated.

Carbon steel undergoes accelerated corrosion in the presence of high CO<sub>2</sub> partial pressures (de Waard and Milliams 1976). The enhanced corrosion rate is primarily a consequence of the decrease in pH that accompanies the dissolution of CO<sub>2</sub> in water to form carbonic acid (H<sub>2</sub>CO<sub>3</sub>). However, because of the high HCO<sub>3</sub><sup>-</sup> concentration, the stable corrosion product is FeCO<sub>3</sub> rather than Fe<sub>3</sub>O<sub>4</sub>. The corrosion of carbon steel in CO<sub>2</sub>-containing environments is given by



Because of the importance of this process in the oil and gas industry, there have been a large number of studies to determine the effect of the CO<sub>2</sub> partial pressure, P<sub>CO2</sub>, on the corrosion rate of carbon steel (ASM 1987, 2003, 2005). Many of these studies have been performed under conditions of high rates of mass transport such as might be encountered in pipelines, and the absolute corrosion rates reported are not relevant to the environmental conditions within a DGR. However, these studies indicate a dependence of the corrosion rate on (P<sub>CO2</sub>)<sup>q</sup>, where q is typically of the order of 0.66 (de Waard and Milliams 1976; de Waard and Lotz 1993; de Waard et al. 1991, 1995). The empirical model used to derive a value for q was fitted to data for CO<sub>2</sub> partial pressures up to 1 MPa.

In GGM, the corrosion rate of carbon and galvanized steel is taken to be a function of the CO<sub>2</sub> partial pressure, with the overall corrosion reaction given by Equation (3.34). Although the pH of the environment is not specifically calculated within the model, the use of an enhanced corrosion rate in the presence of CO<sub>2</sub> implicitly takes into account the acidification resulting from the dissolution of CO<sub>2</sub> in the aqueous phase. In terms of the model, the rate of reaction given by Equation (3.34) is treated as a multiplier of the anaerobic corrosion rate (see Equation (3.38)). (Under aerobic conditions, the degree of enhancement is minimal as O<sub>2</sub>, rather than H<sup>+</sup>, is the dominant oxidant). Therefore, depending upon the partial pressure of CO<sub>2</sub>, the anaerobic corrosion rate is enhanced by an appropriate factor. If there is no CO<sub>2</sub> present, the factor is 1. The relative amounts of Fe<sub>3</sub>O<sub>4</sub> and FeCO<sub>3</sub> formed are determined by the values of the respective rate constants and, in the case of FeCO<sub>3</sub>, by the P<sub>CO2</sub>.

### 3.3.1.2 Passivated Carbon Steel

Passivated carbon steel comprises waste forms grouted in cementitious materials and structural steel (rebar, rails, etc.) in contact with concrete. These materials are treated separately from the plain carbon and galvanized steel inventories because of the effect of the cementitious material on the corrosion rate. The high pH environment in the cement results in passivation of the carbon steel and, consequently, a lower corrosion rate.

Although the rate of corrosion of passivated carbon steel is lower, the mechanism is treated in exactly the same fashion as for the plain carbon and galvanized steel. Thus, the aerobic and anaerobic corrosion of passivated carbon steel are given by Equations (3.28) and (3.32), respectively, and the reduction of FeOOH is given by Equation (3.33). In alkaline environments, Fe<sub>3</sub>O<sub>4</sub> is more stable than Fe(OH)<sub>2</sub> (Pourbaix 1974) and is likely to be the stable long-term corrosion product.

At the elevated pH expected to persist for some time in cementitious materials,  $\text{Fe}_3\text{O}_4$  is thermodynamically more stable than  $\text{FeCO}_3$ . Therefore, enhanced corrosion of passivated carbon steel due to the presence of elevated  $\text{CO}_2$  partial pressures is not included in GGM.

### 3.3.1.3 Stainless Steels and Nickel Alloys

Stainless steels and nickel alloys are present as container materials and as used reactor components such as from steam generators or pressure tube end fittings. These materials contain Fe, Ni, Cr, Mo, and other minor alloying elements, in amounts dependent on the composition of the particular alloy.

Corrosion of these alloys proceeds with the formation of a protective, or passive, film typically comprising Cr(III) or Ni(II), and possibly small amounts of other alloying elements (ASM 1987, 2003, 2005; Clayton and Olefjord 1995). Over long periods of time, however, other elements within the alloy, notably Fe, must also be oxidized since the amount of Cr in the alloys is limited. There is currently an incomplete understanding of how passive materials corrode over long periods of time, both from the viewpoint of the stability of the Cr-rich passive film that forms initially and from the viewpoint of how the corrosion behaviour evolves as the elements responsible for passivity become consumed.

In the absence of a complete understanding of their long-term corrosion behaviour, the corrosion of the passive materials is treated in GGM in the same manner as carbon steel, and they are assumed to fully oxidize although at a slower rate.

Thus, the aerobic and anaerobic corrosion of stainless steel are assumed to be given by Equations (3.28) and (3.32), respectively, and it is further assumed that oxidized corrosion products formed during the aerobic phase are subsequently reduced by a reaction analogous to Equation (3.33). This is an acceptable assumption for the corrosion of stainless steels, since these materials contain a high percentage of Fe (typically 60-80%, Sedriks 1996). For the Ni-based alloys, the assumption is considered reasonable, even though the aerobic corrosion products formed for these materials, Cr(III) and Ni(II), are not reduced during the aerobic-anaerobic transition in the same manner as Fe(III). However, the degree of aerobic corrosion of the passive materials is minimal, since not only is the inventory of  $\text{O}_2$  relatively small compared with the inventory of organic and metallic materials, but the  $\text{O}_2$  that is present also tends to be consumed by degradation of cellulose and/or the corrosion of carbon and galvanized steel rather than by the corrosion of the passive materials. Under anaerobic conditions, the Ni-based alloys are assumed to corrode to corrosion products with an average metal to oxygen ratio of 1.33, as with Fe. The predominant valence for Ni corrosion products is +2, compared with a value of 2.67 for Fe in the form of  $\text{Fe}_3\text{O}_4$ . Therefore, this overstates by ~33% the amount of  $\text{H}_2$  generated during the anaerobic phase from Ni. This is a sufficient approximation, since these alloys are also not dominant in the waste.

The corrosion rates of passive materials are higher under sour-service conditions, i.e., in the presence of  $\text{CO}_2$  and  $\text{H}_2\text{S}$  gases (ASM 1987, 2003, 2005). The pressure of  $\text{CO}_2$  developed in a deep repository could approach that typically found in down hole applications in the oil and gas industry. Therefore, the passive alloys undergo accelerated corrosion and the formation of carbonate-containing corrosion products, as for carbon and galvanized steels (Equation (3.34)).

### 3.3.1.4 Zirconium Alloys

Zirconium alloy waste may comprise fuel sheaths/hulls, pressure tubes and/or other components of the decommissioned reactors. Typically these alloys contain small amounts of Nb, which is approximated as oxidizing similar to Zr.

Under aerobic conditions the corrosion of Zr is given by



and under anaerobic conditions by



The oxide film on zirconium alloys is a stable, effective barrier to corrosion. There are few reports of the use of Zr alloys exposed to aqueous environments with high pressures of CO<sub>2</sub>. Neither the corrosion rate nor the nature of the corrosion products is affected by the presence of high CO<sub>2</sub> partial pressure.

### 3.3.2 Reaction Kinetics

The general expression for the consumption of the metallic wastes and container materials is given by

$$-\frac{dQ_\ell}{dt} = h \sum_{m=1,2} \frac{A_{\ell,1}\rho_\ell}{M_\ell} R_{\ell,m,1} + \varepsilon \sum_{m=1,2} \frac{A_{\ell,2}\rho_\ell}{M_\ell} R_{\ell,m,2} \quad (3.37)$$

where  $Q_\ell$  [mol] is the quantity of metallic material  $\ell$  (where  $\ell = 1, 2, 3, 4$  for carbon and galvanized steel, passivated carbon steel, passive alloys, and Zr alloys, respectively),  $\rho_\ell$  [kg·m<sup>-3</sup>] and  $M_\ell$  [kg·mol<sup>-1</sup>] are the density and equivalent atomic mass of metallic material  $\ell$ , respectively,  $A_{\ell,n}$  [m<sup>2</sup>] is the surface area of material  $\ell$  exposed to the vapour phase ( $n = 1$ ) and submerged ( $n = 2$ ), and  $R_{\ell,m,n}$  [m·s<sup>-1</sup>] is the corrosion rate of material  $\ell$  under redox conditions  $m$  ( $m = 1, 2$  for aerobic and anaerobic conditions, respectively) and degree of saturation  $n$  ( $n = 1, 2$  for unsaturated and saturated conditions, respectively). The fraction of the surface area submerged is taken to be equal to the degree of saturation  $S$ , with the fraction exposed to the vapour phase equal to  $(1 - S)$ .  $R_{\ell,m,n}$  is zero if conditions are not in the appropriate redox regime; i.e.,  $R_{\ell,1,n} = 0$  under anaerobic conditions, and  $R_{\ell,2,n} = 0$  under aerobic conditions.  $h$  and  $\varepsilon$  are scaling factors used to model the effects of relative humidity and water-limited conditions, respectively. They are defined in Table 3-1.

Corrosion of carbon and galvanized steels, and the stainless steel and Ni-based passive alloys, is also enhanced by the presence of CO<sub>2</sub>. In the repository, CO<sub>2</sub>-enhanced corrosion will occur primarily under anaerobic conditions ( $m = 2$ ) but could be possible under both saturated and unsaturated conditions ( $n = 1, 2$  respectively).

In GGM, the effect of CO<sub>2</sub> on the rate of corrosion (expressed as a rate of consumption in mol·s<sup>-1</sup>) is given by

$$-\frac{dQ_{\ell}}{dt} = \frac{\rho_{\ell}}{M_{\ell}} \left( hA_{\ell,1}R_{\ell,1,1} + h \left( 1 + \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q \right) A_{\ell,1}R_{\ell,2,1} + \varepsilon A_{\ell,2}R_{\ell,1,2} + \varepsilon \left( 1 + \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q \right) A_{\ell,2}R_{\ell,2,2} \right) \quad (3.38)$$

where  $\ell = 1, 3$  (carbon and galvanized steel, and stainless steel and Ni-based alloys, respectively), and  $P_{CO_2}^{ref}$  [Pa] is a reference CO<sub>2</sub> partial pressure at which the corrosion rate is twice the value in the absence of CO<sub>2</sub>.

The consumption and generation of various gases (O<sub>2</sub>, CO<sub>2</sub>, and H<sub>2</sub>), corrosion products (FeOOH, FeCO<sub>3</sub>, and Fe<sub>3</sub>O<sub>4</sub>), and of H<sub>2</sub>O are estimated from the respective corrosion rates using appropriate stoichiometric coefficients from Equations (3.28) and (3.32)-(3.36).

As noted in Section 3.3.1.3, the long-term corrosion behaviour of stainless steels and Ni-based alloys is described by the same stoichiometric equations used for carbon and galvanized steel.

The same corrosion rates are used for stainless steel and nickel alloys. Based on evidence from the literature, any differences in the corrosion rates for these alloys is within the reproducibility of the reported corrosion rate of approximately half an order of magnitude. Under anaerobic conditions, the amount of H<sub>2</sub> produced by corrosion depends on the metal/oxygen ratio in the respective oxide formed for each metal. As noted above (Section 3.3.1.3), this can result in an approximately 33% variation in the rate of H<sub>2</sub> generation between stainless steels and Ni-based alloys. This variation, however, is again within the reproducibility of the measured corrosion rates and the use of the same corrosion rates for stainless steels and passive Ni alloys is, therefore, justified. A detailed list of input parameters for GGM is given in Table 3-1.

### 3.3.3 Summary of Corrosion Modelling for Application to a Repository for L&ILW

The basic corrosion model includes:

1. Aerobic and anaerobic corrosion of carbon and galvanized steel, passivated carbon steel, stainless steel and nickel alloys, and zirconium alloys;
2. Corrosion under saturated and unsaturated conditions;
3. Consumption of O<sub>2</sub> and CO<sub>2</sub> and, under anaerobic conditions, the generation of H<sub>2</sub>;
4. The reductive dissolution of Fe(III) formed during the aerobic period;
5. Treatment of the corrosion of carbon and galvanized steel and passive alloys in the presence of CO<sub>2</sub>, leading to enhanced corrosion rates and the formation of FeCO<sub>3</sub>, and in the absence of CO<sub>2</sub> leading to the formation of Fe<sub>3</sub>O<sub>4</sub>; and
6. Rationalization for the formation of Fe<sub>3</sub>O<sub>4</sub> as a long-term, stable corrosion product.

### 3.4 CORROSION GAS GENERATION PROCESSES FOR APPLICATION TO USED FUEL

The corrosion model in this section has been developed for NWMO's Fifth Case Study (5CS), which is investigating a repository within a hypothetical sedimentary formation. It is designed for application to a steel used fuel container (UFC) in the presence of a bentonite buffer at room-scale, so that the near-field response of the geosphere and engineered sealing materials to its corrosion and consequent gas generation can be assessed.

### 3.4.1 Background

Corrosion of carbon steel (C-steel) used fuel containers has a number of impacts on the performance of the repository system. First, corrosion in its various forms is the major contributing factor to container failure (King 2007), following which the release of radionuclides to the near field becomes possible. Second, dissolved ferrous species can interact with bentonite and convert swelling smectite clays to non-swelling illitic forms, resulting in a partial loss of swelling capacity (Wersin et al. 2007). Third, anaerobic corrosion will result in the generation of hydrogen that may form a gaseous H<sub>2</sub> phase in the repository, the presence of which could impact the migration of radionuclides. This section is focussed primarily on the estimation of the rate of H<sub>2</sub> generation due to corrosion of the container.

The corrosion behaviour of the container will change with time as the environment in the repository evolves. From a corrosion perspective, the most important environmental factors are the UFC temperature, the redox conditions, the degree of saturation of the buffer material, and the composition of the bentonite pore water in contact with the UFC. For a DGR in low-permeability sedimentary host rock, saturation of the DGR may take tens of thousands of years. This slow saturation has led to the definition of four phases in the evolution of the environment, namely:

- An early aerobic period prior to the onset of aqueous corrosion;
- An unsaturated aerobic phase following the condensation of liquid water on the container surface;
- An unsaturated anaerobic phase once all of the initially trapped O<sub>2</sub> has been consumed; and
- A long-term saturated anaerobic phase once the buffer material has become completely saturated by groundwater.

Hydrogen is produced by the cathodic reduction of H<sub>2</sub>O or H<sup>+</sup>. The vast majority of H<sub>2</sub> that will be produced in the repository will result from the uniform corrosion of C-steel during the (unsaturated and saturated) anaerobic phase. Hydrogen can be produced under aerobic conditions due to the reduction of H<sup>+</sup> in acidic environments in pits, crevices, or porous corrosion products formed as a result of the hydrolysis of Fe(III) species (Akiyama et al. 2010, Tsuru et al. 2005)). Local reduction of H<sup>+</sup> may lead to enhanced hydrogen absorption and environmentally assisted cracking (King 2009) but will not lead to the generation of significant H<sub>2</sub> and is not considered further here.

Hydrogen generated by corrosion can undergo a number of subsequent processes. The H<sub>2</sub> that is evolved could be consumed by microbes (Pedersen 2000) in those parts of the near- and far-fields in which the environment is conducive to microbial activity (namely a water activity greater than 0.96, Stroes-Gascoyne et al. 2006, 2007, 2008). Another fraction of the hydrogen will be absorbed by the C-steel as atomic H, either from adsorbed H atoms prior to their evolution as H<sub>2</sub> or via the dissociative absorption of gaseous H<sub>2</sub>. Absorbed H will diffuse through the container wall and desorb on the inner surface as H<sub>2</sub> gas. This process will continue until the H<sub>2</sub> partial pressure inside the container is the same as that outside. Thus, the container acts as a sink for a fraction of the H produced through anaerobic corrosion.

The remainder of this section deals with the rate of generation of H<sub>2</sub>, rather than its fate in the repository. The environmental conditions in the repository are first considered, with emphasis on those conditions that affect the rate of corrosion (H<sub>2</sub> generation). Next, the uniform corrosion

behaviour of C-steel for each the four main phases in the evolution of the repository environment is summarised, with discussion of the transition between the various phases.

### 3.4.2 Environmental Conditions

The environment in the repository will evolve with time as (i) the initially trapped O<sub>2</sub> is consumed, (ii) the heat output from the container decays, and (iii) the repository saturates with incoming groundwater. The latter effect may be particularly important for a repository in sedimentary rock of low hydraulic conductivity as it may take tens of thousands of years for the DGR to saturate.

The corrosion behaviour of the container will also change with time in response to this environmental evolution. A series of four phases of corrosion behaviour can be defined, namely:

- Phase 1      A period during the initial thermal transient when the relative humidity in the repository is below that necessary for the formation of liquid H<sub>2</sub>O on the container surface. Corrosion during this phase will be limited to slow air oxidation.
- Phase 2:      An early phase of unsaturated aerobic conditions prior to saturation of the repository and during which corrosion is supported by the reduction of the O<sub>2</sub> trapped initially in the pores of the buffer and backfill materials.
- Phase 3:      An intermediate unsaturated anaerobic phase following the consumption of the O<sub>2</sub> but prior to the saturation of the repository. Corrosion during this period is supported by the cathodic reduction of H<sub>2</sub>O accompanied by the evolution of H<sub>2</sub>.
- Phase 4:      A long-term saturated anaerobic period following saturation of the repository. As for Phase 3, corrosion during Phase 4 is supported by the cathodic reduction of H<sub>2</sub>O accompanied by the evolution of H<sub>2</sub>.

In addition to the evolution of the redox conditions and the degree of saturation, the temperature will also change during these different phases. The precise time dependence of the container temperature will depend on the rate of saturation, which is not known *ab initio*. However, in general, it is clear that Phases 1 and 2 will be warmer than Phase 3, with Phase 4 encompassing the period of long-term ambient conditions.

The onset of aqueous corrosion (i.e., the transition from Phase 1 to Phase 2) is dependent on the relative humidity (RH) at the container surface. Aqueous corrosion is possible above a critical or threshold RH that is determined by the nature of the surface and the presence of surface contaminants. Water condenses on porous surfaces or corrosion products by capillary condensation. Salts absorb moisture from the atmosphere in a process known as deliquescence at a critical deliquescence RH (DRH) that is a function of temperature and the type of salt. Salts that are highly soluble deliquesce at lower RH than sparingly soluble salts.

A number of other environmental parameters, in addition to the temperature, RH, and redox conditions, also affect the uniform corrosion behaviour of the container, including:

Pore-water chemistry: Under saturated conditions, the container surface will be in contact with bentonite pore water. At least initially, the composition of the pore water

|                     |   |
|---------------------|---|
|                     | may differ from that of the ground water. Eventually, however, the pore water will equilibrate with the ground water.   |
| pH                  | Calcite minerals in the bentonite will effectively buffer the pH in the range pH 7-8.   |
| Mass transport:     | The low hydraulic conductivity of compacted sodium bentonite will limit mass transport to diffusion only. During the aerobic phase, the rate of corrosion may be limited by the rate of transport of O <sub>2</sub> to the container surface, although the diffusivity of O <sub>2</sub> in unsaturated bentonite is high (King et al. 1996). |
| Radiation:          | Gamma radiolysis of water will produce oxidizing and reducing radiolysis products. However, the maximum surface absorbed dose rate for a 10-cm-thick C-steel UFC will be <1 Gy·h <sup>-1</sup> and there will be no significant effect on the corrosion rate (Shoesmith and King 1999).   |
| Operational phase:  | It is implicitly assumed that there is no significant corrosion prior to the sealing of the repository. An extended operational phase could allow O <sub>2</sub> ingress and additional corrosion of the container.   |
| Microbial activity: | Microbial activity is suppressed by the presence of highly compacted bentonite and saline solutions (Stroes-Gascoyne et al. 2006, 2007, 2008). Therefore, microbial activity is unlikely close to the container and there will be no effect on the uniform corrosion behaviour.   |
| Stress:             | Applied and residual stresses affect the environmentally assisted cracking behaviour of the container but have no effect on uniform corrosion.  |
| Mineral impurities: | Mineral impurities in the host rock (e.g., pyrite) will have an insignificant effect on the uniform corrosion behaviour of the container.   |

### 3.4.3 Summary of Reaction Stoichiometries and Rate Expressions

The corrosion is described through the identification of four phases designed to capture the slow breakthrough of water to the containers through the bentonite buffer with decreasing temperatures:

- Phase 1: Dry Air Oxidation;
- Phase 2: Aerobic Unsaturated Conditions;
- Phase 3: Anaerobic Unsaturated Conditions; and
- Phase 4: Anaerobic Saturated Conditions.

It is important to note that these four phases do not necessarily occur sequentially. Phases 1 and 2 both occur under aerobic conditions and the degree to which the Phase 1 and Phase 2 corrosion processes are active depends on the relative humidity. The Phase 3 and 4 corrosion processes proceed under anaerobic conditions after Phase 1 and Phase 2. The degree to which the Phase 3 and Phase 4 corrosion processes are active depends on whether or not liquid water has moved through to the container walls or not. The Phase 3 process also depends on relative humidity. The conceptual model used to switch the corrosion processes on and off depending on the relative humidity and saturation is described in Section 3.4.5.

### 3.4.4 Basic Rates

This section summarizes the corrosion process and basic rates for each phase, following Appendix A, and converts to SI units for consistency with the rest of the GGM theory.

#### 3.4.4.1 Phase 1: Dry Air Oxidation

Prior to the formation of liquid water on the container surface, corrosion will take the form of slow oxidation in "dry" air. (Dry air may contain some water vapour but insufficient to form a liquid phase). Oxidation of the UFC will result in the formation of a duplex  $\text{Fe}_3\text{O}_4/\text{Fe}_2\text{O}_3$  surface film (Desgranges et al. 2003). Oxide growth can be modelled in terms of the reaction:



Oxidation kinetics for Fe and a low-alloy steel have been found to follow both parabolic and logarithmic rate laws, although parabolic kinetics have generally been assumed for modelling purposes (Desgranges et al. 2003, Larose and Rapp 1997, Terlain et al. 2001). The weight gain  $W$  ( $\text{kg m}^{-2}$ ), as a function of time  $t$  (s), is given by:

$$W^2 = K_p \cdot t \quad (3.40)$$

where  $K_p$  ( $\text{kg}^2 \text{m}^{-4} \text{s}^{-1}$ ) is the temperature-dependent parabolic rate constant given by the Arrhenius form:

$$K_p = K_0 \exp(-E_a/RT) \quad (3.41)$$

where  $K_0$  ( $\text{kg}^2 \text{m}^{-4} \text{s}^{-1}$ ) is a pre-exponential factor and  $E_a$  ( $\text{J mol}^{-1}$ ) the activation energy. Therefore the penetration rate of the corrosion front into the container,  $R_1$  ( $\text{m s}^{-1}$ ) is written as

$$R_1(t, T; t_1, D_1, E_1) = \frac{D_1}{\sqrt{t - t_1}} \exp\left(-\frac{E_1}{2RT}\right) \quad (3.42)$$

for times  $t > t_1$  where  $D_1$  ( $\text{m s}^{-1/2}$ ) is a basic corrosion rate constant;  $E_1$  ( $\text{J mol}^{-1}$ ) is the molar activation energy;  $R$  ( $\text{J K}^{-1} \text{mol}^{-1}$ ) is the molar gas constant;  $T$  (K) is the temperature;  $t_1$  (s) is the time at which the corrosion starts (emplacement time); and  $t$  (s) is the time. The rate is evaluated as zero for times  $t \leq t_1$ .

#### 3.4.4.2 Phase 2: Aerobic Unsaturated Conditions

Once the container surface is wetted by liquid water, a period of aerobic corrosion under unsaturated conditions is expected to occur (assuming that all of the initially trapped  $\text{O}_2$  has not been consumed by oxidation of the container). Corrosion will result in the consumption of  $\text{O}_2$  and  $\text{H}_2\text{O}$ , but not the generation of  $\text{H}_2$ . The nature of the corrosion reaction depends, in part, on the presence of anions such  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{CO}_3^{2-}$ , which will lead to the formation of various forms of green rust. Since the nature of the surface deposits is not precisely known, the overall corrosion reaction will be described here by the formation of a hydrated Fe(III) species:



with the  $\alpha$ - and  $\gamma$ - forms representing goethite and lepidocrocite, respectively. Depending on the RH and the distribution of surface salt contaminants, the corrosion reaction may be more or less localized. Localized corrosion will be favoured by low RH and a sparse distribution of surface salts.

Based on a review of aerobic corrosion rates, with an emphasis on data from studies with backfill, Foct and Gras (2003) proposed an Arrhenius expression for the aerobic corrosion rate. Therefore Phase 2 corrosion (aerobic unsaturated conditions) is represented by the process:



for which the penetration rate of the corrosion front into the container,  $R_2$  ( $\text{m s}^{-1}$ ) is written as

$$R_2(T; D_2, E_2) = D_2 \exp\left(-\frac{E_2}{RT}\right) \quad (3.45)$$

where  $D_2$  ( $\text{m s}^{-1}$ ) is a basic penetration rate constant;  $E_2$  ( $\text{J mol}^{-1}$ ) is the molar activation energy;  $R$  ( $\text{J K}^{-1} \text{mol}^{-1}$ ) is the molar gas constant; and  $T$  (K) is the temperature.

#### 3.4.4.3 Phase 3: Anaerobic Unsaturated Conditions

In the absence of  $\text{O}_2$ , C-steel corrodes with the evolution of  $\text{H}_2$ :



Ferrous hydroxide can convert to magnetite via the Schikkor reaction:



The overall stoichiometry for the formation of  $\text{Fe}_3\text{O}_4$ , therefore, and the most conservative from the viewpoint of  $\text{H}_2$  production, as follows::



This is used to represent Phase 3 corrosion (anaerobic unsaturated conditions). Based on studies of anaerobic corrosion of C-Steel from the literature by Newman et al. (2010) and Debruyne (1990), the penetration rate of the corrosion front into the container,  $R_3$  ( $\text{m s}^{-1}$ ) under conditions of high relative humidity, is written as

$$R_3(T; D_3, E_3) = D_3 \exp\left(-\frac{E_3}{RT}\right) \quad (3.49)$$

where  $D_3$  ( $\text{m s}^{-1}$ ) is a basic penetration rate constant;  $E_3$  ( $\text{J mol}^{-1}$ ) is the molar activation energy;  $R$  ( $\text{J K}^{-1} \text{mol}^{-1}$ ) is the molar gas constant; and  $T$  (K) is the temperature.

#### 3.4.4.4 Phase 4: Anaerobic Saturated Conditions

In the presence of compacted bentonite, C-steel corrodes with the formation of a carbonate-containing corrosion product (Papillon et al. 2003; King 2007, 2008). The source of carbonate is calcite and other carbonate minerals in the bentonite (or in the host rock). The overall

stoichiometry of the reaction for Phase 4 corrosion (anaerobic saturated conditions) can be written as:



Following Gras (1996), the penetration rate of the corrosion front into the container,  $R_4$  ( $\text{m s}^{-1}$ ) can be written in Arrhenius format as:

$$R_4(T; D_4, E_4) = D_4 \exp\left(-\frac{E_4}{RT}\right) \quad (3.51)$$

where  $D_4$  ( $\text{m s}^{-1}$ ) is a basic penetration rate constant;  $E_4$  ( $\text{J mol}^{-1}$ ) is the molar activation energy;  $R$  ( $\text{J K}^{-1} \text{mol}^{-1}$ ) is the molar gas constant; and  $T$  (K) is the temperature.

### 3.4.5 Corrosion Process Activation

Section 3.4.4 gives the basic rate expressions for the processes associated with each of the four corrosion phases. The activation of each of these processes and the actual rate at which they proceed is dependent on the temperature, saturation and relative humidity within the volume of interest. The volume of interest in the current context is a portion of the grid used by TOUGH2 to discretize the space surrounding the used fuel container and extending into the bentonite; a 'compartment'. In this section, we define the mathematics controlling the actual rate at which carbon steel inventory in a given compartment is consumed.

In the following, the symbol  $\Omega$  is given the value 1 under aerobic conditions and 0 under anaerobic conditions.

#### 3.4.5.1 Phase 1 and Phase 2: Aerobic, High Temperature

It is assumed that during these two phases the temperature is sufficiently high and that it is sufficiently early that liquid water is prevented from coming into contact with the container surface. Therefore, the corrosion rate is independent of the saturation. The Phase 1 process occurs under low RH conditions and switches off as RH increases, while the Phase 2 process switches on as RH increases. Therefore the Phase 1 and Phase 2 processes may potentially overlap.

As with the L&ILW corrosion model (Section 3.3), corrosion processes are configured to become activated over a range of relative humidity values. To characterize the effect of relative humidity on the corrosion rates, the code uses a relative humidity modulation factor,  $h$  (-), which is defined as zero below the lower limit, one above the upper limit, and as increasing monotonically between the two. The exact form depends on the parameterization of the GGM. See Section 3.8.

Defining  $\rho_1$  ( $\text{kg m}^{-3}$ ) and  $M_1$  ( $\text{kg mol}^{-1}$ ) as the density and molar mass of carbon steel and  $A_1$  ( $\text{m}^2$ ) as the total surface area of carbon steel within the compartment, the overall rate of consumption of Fe in  $\text{mol s}^{-1}$  can then be expressed as

$$\Phi_1 = \Omega \frac{\rho_1 A_1 (1 - h)}{M_1} R_1(t, T; t_1, D_1, E_1) \quad (3.52)$$

for Phase 1 (dry air oxidation), and

$$\Phi_2 = \Omega \frac{\rho_1 A_1 h}{M_1} R_2(T; D_2, E_2) \quad (3.53)$$

for Phase 2 (aerobic unsaturated conditions). The  $\Omega$  terms ensure that these processes are only active under aerobic conditions.

### 3.4.5.2 Phase 3 and Phase 4: Anaerobic, Temperature Descending

It is assumed each compartment extends deep enough into the bentonite so it may contain drier and wetter zones. At the start of the anaerobic phase the container will still be hot. There will be a 'dry' zone close to the container that will remain free from liquid water. Further away from the container there may be a 'wet' zone with free liquid water. Overall, the water saturation for the compartment may be non-zero - but the corrosion rate will initially remain saturation independent. The Phase 3 process will switch on as the RH increases.

Eventually the liquid water will break through and contact the container surface, but the water may not be filling the entire pore space of the compartment (due to the resaturation transient and because gas is being produced) so the contact with water might be localized. The liquid water will transport with it the carbonate required for the Phase 4 process. Therefore, the Phase 4 process switches on as this happens.

The break-through of the water to the container surface is modelled as follows. A parameter ( $d$ ) that can be interpreted as the ratio of the expected bentonite wet-zone thickness to the ratio of the thickness of the compartment as measured away from the container wall is introduced. (Alternatively, this can be thought of as the saturation above which the breakthrough occurs for each compartment.) Then, while the saturation is below  $d$  it is assumed that the free water is located in a wet-zone of the compartment, away from the container and so corrosion follows Phase 3. As the saturation increases from  $d$  to 1 it is assumed that the water breaks through to the container surface and corrosion follows Phase 4.

Then, defining  $\delta$  as a variable that increases linearly from 0 to 1 as the saturation ( $S$ ) increases from  $d$  to 1;

$$\delta(S; d) = \begin{cases} 0 & \text{when } S < d, \\ \frac{S - d}{1 - d} & \text{when } S \geq d, \end{cases} \quad (3.54)$$

the overall rate of consumption of Fe in mol s<sup>-1</sup> can be expressed as:

$$\Phi_3 = (1 - \Omega)(1 - \delta) \frac{\rho_1 A_1 h}{M_1} R_3(T; D_3, E_3) \quad (3.55)$$

for Phase 3 (anaerobic unsaturated conditions), and

$$\Phi_4 = (1 - \Omega)\delta \frac{\rho_1 A_1 h}{M_1} R_4(T; D_4, E_4) \quad (3.56)$$

for Phase 4 (anaerobic saturated conditions) provided O<sub>2</sub> is not present, or is zero otherwise. The  $(1 - \Omega)$  terms ensure that these processes are only active under anaerobic conditions.

Implicit in the above model is the assumption that no CO<sub>3</sub><sup>2-</sup> is transported to the container surface via the water vapour during Phase 3, even when the RH is high. The expressions above

are configured to switch off the Phase 3 process under wet container conditions (as the saturation increases from  $d$  to 1).

### 3.4.5.3 Summary of the Carbon Steel Consumption Rate

The rate expressions for the four corrosion phases given in Section 3.4.5.1 and Section 3.4.5.2 can be combined to give the following expression for the total rate of consumption ( $\text{mol s}^{-1}$ ) of carbon steel due to corrosion:

$$\frac{\rho_1 A_1}{M_1} \left[ \frac{\Omega \{(1-h)R_1(t, T; t_1, D_1, E_1) + hR_2(T; D_2, E_2)\}}{+(1-\Omega)\{(1-\delta)hR_3(T; D_3, E_3) + \delta R_4(T; D_4, E_4)\}} \right] \quad (3.57)$$

where:

- $\rho_1$  ( $\text{kg m}^{-3}$ ) and  $M_1$  ( $\text{kg mol}^{-1}$ ) are the density and molar mass of carbon steel;
- $A_1$  ( $\text{m}^2$ ) as the total surface area of carbon steel within the compartment;
- $\Omega$  (-) is 1 under aerobic conditions and 0 under anaerobic conditions;
- $h$  (-) varies from 0 to 1 as the relative humidity changes from the lower to upper thresholds;
- $\delta$  (-) changes from 0 to 1 as liquid water breaks through to the container surface; and
- $R_1$  to  $R_4$  ( $\text{m s}^{-1}$ ) are the basic temperature and time dependent corrosion rates given in Section 3.4.4.

## 3.5 ADDITIONAL PROCESSES

### 3.5.1 Gas Mitigation Processes

There are a number of processes by which the impact of gas production in the repository could be mitigated, either by design or because of inherent reactions within the repository.

Two natural processes that will result in the consumption of gas are included. First, the conversion of  $\text{H}_2$  and  $\text{CO}_2$  to  $\text{CH}_4$  is modelled as part of the microbial reaction scheme (Equation (3.19), Section 3.2.1.2). Methanogenesis is an important cause of gas consumption, since five moles of gas (four moles of  $\text{H}_2$  and one mole of  $\text{CO}_2$ ) are consumed for every mole of  $\text{CH}_4$  produced.

Second, reaction between  $\text{H}_2\text{S}$  and dissolved metal ions, primarily  $\text{Fe(II)}$ , will result in the formation (and rapid precipitation due to low solubility) of metal sulphides. Since  $\text{Fe(II)}$  will be the principal dissolved metal ion in the repository, the precipitation of metal sulphides is represented by

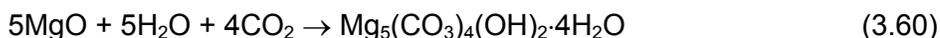


where the stoichiometry of iron sulphide is uncertain, but is here represented by the species "FeS". The kinetics of the precipitation of iron sulphide are taken to be first order with respect to the concentration of  $\text{H}_2\text{S}$ , on the basis that  $\text{Fe(II)}$  is likely to be present in excess in the system, and is given by

$$-\frac{dQ_{\text{H}_2\text{S}}}{dt} = V_{\text{FeS}} C_{\text{H}_2\text{S}} S V_v \quad (3.59)$$

where  $dQ_{\text{H}_2\text{S}}/dt$  [ $\text{mol s}^{-1}$ ] is the rate of change of the amount of  $\text{H}_2\text{S}$  in the repository,  $C_{\text{H}_2\text{S}}$  [ $\text{mol m}^{-3}$ ] is the concentration of  $\text{H}_2\text{S}$ ,  $SV_V$  [ $\text{m}^3$ ] is the saturated volume, and  $V_{\text{FeS}}$  [ $\text{s}^{-1}$ ] is the first-order rate constant for the formation and precipitation of  $\text{FeS}$ , respectively.

“Gas scavengers” can also be deliberately added to the repository. For example, magnesium oxide is added to the WIPP facility to consume  $\text{CO}_2$  via the precipitation of magnesium carbonate (Krumhansl et al. 2000). In GGM, this reaction is included to enable the effect of this gas mitigation strategy to be estimated:



The rate of  $\text{CO}_2$  removal by precipitation of magnesium carbonate is represented by

$$-\frac{dQ_{\text{CO}_2}}{dt} = \frac{4}{5} Q_{\text{MgO}} V_{\text{MgO}} \quad (3.61)$$

where  $dQ_{\text{CO}_2}/dt$  [ $\text{mol s}^{-1}$ ] is the rate of change of the amount of  $\text{CO}_2$  in the repository, respectively,  $Q_{\text{MgO}}$  [ $\text{mol}$ ] is the quantity of  $\text{MgO}$ , and  $V_{\text{MgO}}$  [ $\text{s}^{-1}$ ] is the first-order rate constant for the loss of  $\text{MgO}$ .

### 3.5.2 Carbonation of Concrete

Another potential sink for  $\text{CO}_2$  in the repository is the carbonation of the cementitious material. The carbonation of concrete is represented by



This process could consume significant quantities of  $\text{CO}_2$ , especially if the repository is grouted. However, this reaction is not currently included in GGM.

### 3.5.3 Water Availability

Once saturation in the repository reaches zero, the water consuming saturated phase reactions become limited by the rate of ingress of water from the geosphere. Rate constants for water-limited processes occurring in the vapour phase, including microbial processes, biomass generation and corrosion, are relative humidity dependent as described in Section 3.2.1.3, Section 3.3.1 and Section 3.4.5. Other processes in the vapour phase are always active.

### 3.5.4 Gas Leakage and Influx

Gas can leak from the repository and be transported through the geosphere or, depending on the conditions, can move into the repository from the geosphere. The flow of gas through the geosphere is modelled by TOUGH2 independently of GGM using information about gas and water generation rates within the repository provided by GGM. The gas flow modelling enables the gas pressure at the repository to be calculated and fed back to GGM, which in turn uses this information to reassess the total number of moles of gas in the repository, to calculate the number of moles of gas which have leaked from or flowed into the repository and to repartition the gas in the repository between the vapour and saturated phases. When gas flows from the geosphere into the repository, its composition is assumed to match the composition of the existing gas within the repository. The validity of this assumption needs to be evaluated on a case by case basis depending on the assumed geosphere bulk gas and whether gas flowing

into the repository is returning gas previously generated within the repository or 'fresh' bulk gas from the geosphere.

### 3.6 IMPLEMENTATION OF GGM

The definitions of all model parameters appearing in GGM model equations, including reactants, products and rate constants are given in Table 3-1.

**Table 3-1: List of Model Parameters for the Gas Generation Model and their Internal Units.**

| Symbol     | Definition   | L&ILW | UF | Units              |
|------------|--|-------|----|--------------------|
| $A_l$      | The total surface area of metal $l$ .  | ✓     | ✓  | $m^2$              |
| $A_{l,n}$  | Surface area of metal $l$ under saturation conditions $n$                    | ✓     |    | $m^2$              |
| $A_{1,1}$  | Surface area of carbon and galvanized steel exposed to vapour phase          | ✓     |    | $m^2$              |
| $A_{1,2}$  | Surface area of carbon and galvanized steel exposed to solution phase        | ✓     |    | $m^2$              |
| $A_{2,1}$  | Surface area of passivated carbon steel exposed to vapour phase              | ✓     |    | $m^2$              |
| $A_{2,2}$  | Surface area of passivated carbon steel exposed to solution phase            | ✓     |    | $m^2$              |
| $A_{3,1}$  | Surface area of stainless steel and Ni-based alloy exposed to vapour phase   | ✓     |    | $m^2$              |
| $A_{3,2}$  | Surface area of stainless steel and Ni-based alloy exposed to solution phase | ✓     |    | $m^2$              |
| $A_{4,1}$  | Surface area of Zr alloy exposed to vapour phase                             | ✓     |    | $m^2$              |
| $A_{4,2}$  | Surface area of Zr alloy exposed to solution phase                           | ✓     |    | $m^2$              |
| $C_k$      | Concentration of product $k$ in the water                                    | ✓     |    | $mol \cdot m^{-3}$ |
| $C_{CO_2}$ | Concentration of dissolved carbon dioxide in the water                       | ✓     |    | $mol \cdot m^{-3}$ |
| $C_{H_2}$  | Concentration of dissolved hydrogen in the water                             | ✓     | ✓  | $mol \cdot m^{-3}$ |
| $C_{H_2S}$ | Concentration of dissolved hydrogen sulphide in the water                    | ✓     |    | $mol \cdot m^{-3}$ |
| $C_{CH_4}$ | Concentration of dissolved methane in the water                              | ✓     |    | $mol \cdot m^{-3}$ |
| $C_{O_2}$  | Concentration of dissolved oxygen in the water                               | ✓     | ✓  | $mol \cdot m^{-3}$ |

| Symbol     | Definition  | L&ILW | UF | Units                          |
|------------|---|-------|----|--------------------------------|
| $C_{N_2}$  | Concentration of dissolved nitrogen in the water  | ✓     |    | $\text{mol}\cdot\text{m}^{-3}$ |
| $C_{NO_3}$ | Concentration of dissolved nitrate in the water   | ✓     |    | $\text{mol}\cdot\text{m}^{-3}$ |
| $C_{SO_4}$ | Concentration of dissolved sulphate   | ✓     |    | $\text{mol}\cdot\text{m}^{-3}$ |
| D          | Biomass decay rate  | ✓     |    | $\text{s}^{-1}$                |
| $D_p$      | The basic rate constant for the phase p corrosion of carbon steel under non-isothermal conditions.  |       | ✓  | Mixed                          |
| $D_1$      | The basic rate constant for the phase 1 (dry-air oxidation) corrosion of carbon steel under non-isothermal conditions.  |       | ✓  | $\text{m s}^{-1/2}$            |
| $D_2$      | The basic rate constant for the phase 2 (aerobic unsaturated) corrosion of carbon steel under non-isothermal conditions.  |       | ✓  | $\text{m s}^{-1}$              |
| $D_3$      | The basic rate constant for the phase 3 (anaerobic unsaturated) corrosion of carbon steel under non-isothermal conditions.  |       | ✓  | $\text{m s}^{-1}$              |
| $D_4$      | The basic rate constant for the phase 4 (anaerobic saturated) corrosion of carbon steel under non-isothermal conditions.  |       | ✓  | $\text{m s}^{-1}$              |
| d          | The ratio of the expected bentonite wet-zone thickness to the ratio of the thickness of the compartment as measured away from the container wall. Alternatively, this can be thought of as the saturation above which water breaks through to the container wall. |       | ✓  | Unitless                       |
| $\delta$   | $\max(0, (S-d)/(1-d))$ . This increases linearly from 0 to 1 as the saturation increases from $d$ to 1 and is used to model the breakthrough of water to the container wall within a compartment.   |       | ✓  | Unitless                       |
| $\epsilon$ | A constant with value between 0 and 1 chosen to balance the rate of consumption of water due to saturated phase reactions with the rate of ingress of water when at zero saturation. Has the value 1 under partially or fully saturated conditions.               | ✓     |    | Unitless                       |
| $E_p$      | The molar activation energy for the phase p corrosion of carbon steel under non-isothermal conditions.  |       | ✓  | $\text{J mol}^{-1}$            |

| Symbol                   | Definition   | L&ILW | UF | Units   |
|--------------------------|--|-------|----|---|
| $E_1$                    | The molar activation energy for the phase 1 (dry-air oxidation) corrosion of carbon steel under non-isothermal conditions.     |       | ✓  | $\text{J mol}^{-1}$                               |
| $E_2$                    | The molar activation energy for the phase 2 (aerobic unsaturated) corrosion of carbon steel under non-isothermal conditions.   |       | ✓  | $\text{J mol}^{-1}$                               |
| $E_3$                    | The molar activation energy for the phase 3 (anaerobic unsaturated) corrosion of carbon steel under non-isothermal conditions. |       | ✓  | $\text{J mol}^{-1}$                               |
| $E_4$                    | The molar activation energy for the phase 4 (anaerobic saturated) corrosion of carbon steel under non-isothermal conditions.   |       | ✓  | $\text{J mol}^{-1}$                               |
| $\gamma$                 | The number of seconds per year   |       | ✓  | $\text{s y}^{-1}$                                 |
| $g$                      | $S+h(1-S)$ . This factor is used to scale processes that are RH dependent in the vapour phase.                                 |       | ✓  | Unitless  |
| $h$                      | A RH modulation function, varying from 0 to 1 in the range $\text{RH}_{\min}$ to $\text{RH}_{\max}$                            | ✓     | ✓  | Unitless  |
| $J_{ki}$                 | Stoichiometric coefficient for product $k$ formed from organic substrate $i$   | ✓     |    | Unitless  |
| $J_{\text{H}_2\text{O}}$ | Flux of water into the volume  | ✓     | ✓  | $\text{mol}\cdot\text{s}^{-1}$                    |
| $K_i$                    | Solubility constant for species $i$  | ✓     |    | $\text{mol}\cdot\text{m}^{-3}\cdot\text{Pa}^{-1}$ |
| $K_{\text{CO}_2}$        | Solubility constant for carbon dioxide   | ✓     |    | $\text{mol}\cdot\text{m}^{-3}\cdot\text{Pa}^{-1}$ |
| $K_{\text{H}_2}$         | Solubility constant for hydrogen   | ✓     | ✓  | $\text{mol}\cdot\text{m}^{-3}\cdot\text{Pa}^{-1}$ |
| $K_{\text{H}_2\text{S}}$ | Solubility constant for hydrogen sulphide  | ✓     |    | $\text{mol}\cdot\text{m}^{-3}\cdot\text{Pa}^{-1}$ |
| $K_{\text{CH}_4}$        | Solubility constant for methane  | ✓     |    | $\text{mol}\cdot\text{m}^{-3}\cdot\text{Pa}^{-1}$ |
| $K_{\text{O}_2}$         | Solubility constant for oxygen   | ✓     | ✓  | $\text{mol}\cdot\text{m}^{-3}\cdot\text{Pa}^{-1}$ |
| $K_{\text{N}_2}$         | Solubility constant for nitrogen   | ✓     |    | $\text{mol}\cdot\text{m}^{-3}\cdot\text{Pa}^{-1}$ |
| $K_R$                    | Fraction of dead biomass recycled into cellulose   | ✓     |    | Unitless  |
| $m$                      | The number of moles of bound water per mole of styrene monomer   | ✓     |    | -   |
| $M_\ell$                 | Effective molecular mass of metal $\ell$   | ✓     |    | $\text{kg}\cdot\text{mol}^{-1}$                   |
| $M_1$                    | Effective molecular mass of carbon and galvanized steel  | ✓     | ✓  | $\text{kg}\cdot\text{mol}^{-1}$                   |
| $M_2$                    | Effective molecular mass of passivated carbon steel  | ✓     |    | $\text{kg}\cdot\text{mol}^{-1}$                   |

| Symbol           | Definition   | L&ILW | UF | Units                |
|------------------|--|-------|----|----------------------|
| $M_3$            | Effective molecular mass of stainless steel and Ni-based alloys            | ✓     |    | kg·mol <sup>-1</sup> |
| $M_4$            | Effective molecular mass of Zr alloys                                      | ✓     |    | kg·mol <sup>-1</sup> |
| $\Omega$         | 1 under aerobic conditions and 0 under anaerobic conditions                |       | ✓  | Unitless             |
| $P_i$            | Partial pressure of gaseous species i                                      | ✓     |    | Pa                   |
| $P_{CO_2}$       | Partial pressure of carbon dioxide   | ✓     |    | Pa                   |
| $P_{CO_2}^{ref}$ | Reference partial pressure of CO <sub>2</sub> for enhancement of corrosion | ✓     |    | Pa                   |
| $P_{H_2}$        | Partial pressure of hydrogen   | ✓     | ✓  | Pa                   |
| $P_{H_2S}$       | Partial pressure of hydrogen sulphide                                      | ✓     |    | Pa                   |
| $P_{CH_4}$       | Partial pressure of methane  | ✓     |    | Pa                   |
| $P_{O_2}$        | Partial pressure of oxygen   | ✓     | ✓  | Pa                   |
| $P_{N_2}$        | Partial pressure of nitrogen   | ✓     |    | Pa                   |
| $q$              | Exponent for enhancement of corrosion rate by CO <sub>2</sub>              | ✓     |    | Unitless             |
| $q_{CO_2}$       | Amount of gaseous carbon dioxide in the volume                             | ✓     |    | mol                  |
| $q_{H_2}$        | Amount of gaseous hydrogen in the volume                                   | ✓     | ✓  | mol                  |
| $q_{H_2S}$       | Amount of gaseous hydrogen sulphide in the volume                          | ✓     |    | mol                  |
| $q_{CH_4}$       | Amount of gaseous methane in the volume                                    | ✓     |    | mol                  |
| $q_{O_2}$        | Amount of gaseous oxygen in the volume                                     | ✓     | ✓  | mol                  |
| $q_{N_2}$        | Amount of gaseous nitrogen in the volume                                   | ✓     |    | mol                  |
| $Q_\ell$         | Quantity of metallic material $\ell$                                       | ✓     | ✓  | mol                  |
| $Q_1$            | Quantity of carbon and galvanized steel                                    | ✓     | ✓  | mol                  |
| $Q_2$            | Quantity of passivated carbon steel  | ✓     |    | mol                  |
| $Q_3$            | Quantity of stainless steel and Ni-based alloys                            | ✓     |    | mol                  |
| $Q_4$            | Quantity of Zr alloys  | ✓     |    | mol                  |
| $Q_{FeOOH}$      | Quantity of iron oxyhydroxide  | ✓     | ✓  | mol                  |
| $Q_{FeCO_3}$     | Quantity of iron carbonate   | ✓     | ✓  | mol                  |
| $Q_{Fe_3O_4}$    | Quantity of magnetite  | ✓     | ✓  | mol                  |
| $Q_{FeS}$        | Quantity of iron sulphide  | ✓     |    | mol                  |

| Symbol          | Definition   | L&ILW | UF | Units            |
|-----------------|--|-------|----|------------------|
| $Q_{Fe_2O_3}$   | Quantity of iron (III) oxide   |       | ✓  | mol              |
| $Q_{H_2O}$      | Quantity of water  | ✓     | ✓  | mol              |
| $Q_{MgO}$       | Quantity of magnesium oxide  | ✓     |    | mol              |
| $Q_C$           | Quantity of (dry) cellulose monomer  | ✓     |    | mol              |
| $Q_R$           | Quantity of styrene monomer from (dry) IX resin waste  | ✓     |    | mol              |
| $Q_P$           | Quantity of styrene monomer from (dry) plastics and rubbers  | ✓     |    | mol              |
| $Q_{CO_2}$      | Quantity of carbon dioxide in the volume   | ✓     |    | mol              |
| $Q_{H_2}$       | Quantity of hydrogen in the volume   | ✓     | ✓  | mol              |
| $Q_{H_2S}$      | Quantity of hydrogen sulphide in the volume  | ✓     |    | mol              |
| $Q_{CH_4}$      | Quantity of methane in the volume  | ✓     |    | mol              |
| $Q_{O_2}$       | Quantity of oxygen in the volume   | ✓     | ✓  | mol              |
| $Q_{N_2}$       | Quantity of nitrogen in the volume   | ✓     |    | mol              |
| $Q_{CO_3^{2-}}$ | Quantity of carbonate ions in the volume   |       | ✓  | mol              |
| $R_{\ell,m,n}$  | Corrosion rate of metal $\ell$ under redox conditions $m$ and degree of saturation $n$ within a L&ILW repository | ✓     |    | $m \cdot s^{-1}$ |
| $R_{1,1,1}$     | Corrosion rate of carbon and galvanized steel under aerobic unsaturated conditions within a L&ILW repository     | ✓     |    | $m \cdot s^{-1}$ |
| $R_{1,2,1}$     | Corrosion rate of carbon and galvanized steel under anaerobic unsaturated conditions within a L&ILW repository   | ✓     |    | $m \cdot s^{-1}$ |
| $R_{1,1,2}$     | Corrosion rate of carbon and galvanized steel under aerobic saturated conditions within a L&ILW repository       | ✓     |    | $m \cdot s^{-1}$ |
| $R_{1,2,2}$     | Corrosion rate of carbon and galvanized steel under anaerobic saturated conditions within a L&ILW repository     | ✓     |    | $m \cdot s^{-1}$ |
| $R_{2,1,1}$     | Corrosion rate of passivated carbon steel under aerobic unsaturated conditions within a L&ILW repository         | ✓     |    | $m \cdot s^{-1}$ |
| $R_{2,2,1}$     | Corrosion rate of passivated carbon steel under anaerobic unsaturated conditions within a L&ILW repository       | ✓     |    | $m \cdot s^{-1}$ |

| Symbol        | Definition  | L&ILW | UF | Units             |
|---------------|---|-------|----|-------------------|
| $R_{2,1,2}$   | Corrosion rate of passivated carbon steel under aerobic saturated conditions within a L&ILW repository                              | ✓     |    | $m \cdot s^{-1}$  |
| $R_{2,2,2}$   | Corrosion rate of passivated carbon steel under anaerobic saturated conditions within a L&ILW repository                            | ✓     |    | $m \cdot s^{-1}$  |
| $R_{3,1,1}$   | Corrosion rate of stainless steel and Ni-based alloys under aerobic unsaturated conditions within a L&ILW repository                | ✓     |    | $m \cdot s^{-1}$  |
| $R_{3,2,1}$   | Corrosion rate of stainless steel and Ni-based alloys under anaerobic unsaturated conditions within a L&ILW repository              | ✓     |    | $m \cdot s^{-1}$  |
| $R_{3,1,2}$   | Corrosion rate of stainless steel and Ni-based alloys under aerobic saturated conditions within a L&ILW repository                  | ✓     |    | $m \cdot s^{-1}$  |
| $R_{3,2,2}$   | Corrosion rate of stainless steel and Ni-based alloys under anaerobic saturated conditions within a L&ILW repository                | ✓     |    | $m \cdot s^{-1}$  |
| $R_{4,1,1}$   | Corrosion rate of Zr alloys under aerobic unsaturated conditions within a L&ILW repository  | ✓     |    | $m \cdot s^{-1}$  |
| $R_{4,2,1}$   | Corrosion rate of Zr alloys under anaerobic unsaturated conditions within a L&ILW repository  | ✓     |    | $m \cdot s^{-1}$  |
| $R_{4,1,2}$   | Corrosion rate of Zr alloys under aerobic saturated conditions within a L&ILW repository  | ✓     |    | $m \cdot s^{-1}$  |
| $R_{4,2,2}$   | Corrosion rate of Zr alloys under anaerobic saturated conditions within a L&ILW repository  | ✓     |    | $m \cdot s^{-1}$  |
| $RH_{min}$    | A Relative Humidity value (fractional) below which all vapour phase corrosion and microbial reactions are modelled to have ceased.  | ✓     | ✓  | Unitless          |
| $RH_{max}$    | A Relative Humidity value (fractional) above which all vapour phase corrosion and microbial reactions are modelled as fully active. | ✓     | ✓  | Unitless          |
| $\rho_{\ell}$ | Density of metal $\ell$   | ✓     |    | $kg \cdot m^{-3}$ |
| $\rho_1$      | Density of carbon and galvanized steel  | ✓     | ✓  | $kg \cdot m^{-3}$ |
| $\rho_2$      | Density of passivated carbon steel  | ✓     |    | $kg \cdot m^{-3}$ |
| $\rho_3$      | Density of stainless steel and Ni-based alloys  | ✓     |    | $kg \cdot m^{-3}$ |
| $\rho_4$      | Density of Zr alloys  | ✓     |    | $kg \cdot m^{-3}$ |

| Symbol           | Definition  | L&ILW | UF | Units           |
|------------------|---|-------|----|-----------------|
| S                | Degree of saturation. Ratio of volume of free water within volume (excludes bound water) and void volume.               | ✓     | ✓  | Unitless        |
| t                | Time  |       | ✓  | S               |
| t <sub>1</sub>   | The time at which Phase 1 corrosion starts under non-isothermal conditions. This is equivalent to the emplacement time. |       | ✓  | S               |
| T                | Temperature   |       | ✓  | K               |
| V <sub>i,j</sub> | Rate constant for the degradation or organic substrate i under microbial condition j                                    | ✓     |    | s <sup>-1</sup> |
| V <sub>C,a</sub> | Rate constant for the aerobic degradation of cellulose  | ✓     |    | s <sup>-1</sup> |
| V <sub>C,b</sub> | Rate constant for the oxidation of cellulose by nitrate reduction   | ✓     |    | s <sup>-1</sup> |
| V <sub>C,c</sub> | Rate constant for the oxidation of cellulose by ferric ion reduction  | ✓     |    | s <sup>-1</sup> |
| V <sub>C,d</sub> | Rate constant for the oxidation of cellulose by sulphate reduction  | ✓     |    | s <sup>-1</sup> |
| V <sub>C,e</sub> | Rate constant for the generation of methane from cellulose  | ✓     |    | s <sup>-1</sup> |
| V <sub>R,a</sub> | Rate constant for the aerobic degradation of IX resins  | ✓     |    | s <sup>-1</sup> |
| V <sub>R,b</sub> | Rate constant for the oxidation of IX resins by nitrate reduction   | ✓     |    | s <sup>-1</sup> |
| V <sub>R,c</sub> | Rate constant for the oxidation of IX resins by ferric ion reduction  | ✓     |    | s <sup>-1</sup> |
| V <sub>R,d</sub> | Rate constant for the oxidation of IX resins by sulphate reduction  | ✓     |    | s <sup>-1</sup> |
| V <sub>R,e</sub> | Rate constant for the generation of methane from IX resins  | ✓     |    | s <sup>-1</sup> |
| V <sub>P,a</sub> | Rate constant for the aerobic degradation of plastics and rubbers   | ✓     |    | s <sup>-1</sup> |
| V <sub>P,b</sub> | Rate constant for the oxidation of plastics and rubbers by nitrate reduction  | ✓     |    | s <sup>-1</sup> |
| V <sub>P,c</sub> | Rate constant for the oxidation of plastics and rubbers by ferric ion reduction   | ✓     |    | s <sup>-1</sup> |
| V <sub>P,d</sub> | Rate constant for the oxidation of plastics and rubbers by sulphate reduction   | ✓     |    | s <sup>-1</sup> |

| Symbol      | Definition   | L&ILW | UF | Units    |
|-------------|--|-------|----|----------|
| $V_{P,e}$   | Rate constant for the generation of methane from plastics and rubbers      | ✓     |    | $s^{-1}$ |
| $V_{FeS}$   | Rate constant for the precipitation of FeS                                 | ✓     |    | $s^{-1}$ |
| $V_{FeOOH}$ | Rate constant for the reductive dissolution of FeOOH                       | ✓     |    | $s^{-1}$ |
| $V_{MgO}$   | Rate constant for the conversion of magnesium oxide to magnesium carbonate | ✓     |    | $s^{-1}$ |
| $V_{H1}$    | Rate constant for the microbial oxidation of $H_2$ via iron reduction      | ✓     |    | $s^{-1}$ |
| $V_{H2}$    | Rate constant for the microbial oxidation of $H_2$ via sulphate reduction  | ✓     |    | $s^{-1}$ |
| $V_{H3}$    | Rate constant for the microbial generation of methane from $H_2$ oxidation | ✓     |    | $s^{-1}$ |
| $V_v$       | Void volume  | ✓     | ✓  | $m^3$    |
| $X$         | Biomass  | ✓     |    | mol      |
| $X_a$       | Biomass of aerobes   | ✓     |    | mol      |
| $X_b$       | Biomass of denitrifiers  | ✓     |    | mol      |
| $X_c$       | Biomass of iron reducers   | ✓     |    | mol      |
| $X_d$       | Biomass of sulphate reducers   | ✓     |    | mol      |
| $X_e$       | Biomass of methanogens   | ✓     |    | mol      |
| $X_{dead}$  | Dead and non-recyclable biomass  | ✓     |    | mol      |
| $X_{tot}$   | Live (hydrated) biomass  | ✓     |    | mol      |
| $Y_j$       | Biomass yield coefficient for microbial condition j                        | ✓     |    | Unitless |
| $Y_a$       | Biomass yield coefficient for aerobes                                      | ✓     |    | Unitless |
| $Y_b$       | Biomass yield coefficient for denitrifiers                                 | ✓     |    | Unitless |
| $Y_c$       | Biomass yield coefficient for iron reducers                                | ✓     |    | Unitless |
| $Y_d$       | Biomass yield coefficient for sulphate reducers                            | ✓     |    | Unitless |
| $Y_e$       | Biomass yield coefficient for methanogens                                  | ✓     |    | Unitless |

Note: A tick indicates that this parameter is used by the associated repository model.

### 3.6.1 Mass-Balance Equations

The equations provided in this section combine terms from all processes – including those applicable to both the L&ILW and Used Fuel repository models. In practice the user is responsible for selecting a relevant subset of processes via the choice of appropriate rate constants. Rate constants and inventories for processes that are not relevant to the given

application should be set to zero. See Table 3-1 for an indication of the parameters that are relevant to each application.

### 3.6.1.1 Organics

The three types of organic material considered are cellulose, IX resins, and plastics and rubbers. The mass-balance equations for each of these species are:

$$-\frac{dQ_C}{dt} = \varepsilon g(V_{C,a} + V_{C,b} + V_{C,c} + V_{C,d} + V_{C,e})Q_C - \frac{5}{6}K_R(X_a + X_b + X_c + X_d + X_e)D \quad (3.63)$$

for cellulose,

$$-\frac{dQ_R}{dt} = \varepsilon g(V_{R,a} + V_{R,b} + V_{R,c} + V_{R,d} + V_{R,e})Q_R \quad (3.64)$$

for IX resins, and

$$-\frac{dQ_P}{dt} = \varepsilon g(V_{P,a} + V_{P,b} + V_{P,c} + V_{P,d} + V_{P,e})Q_P \quad (3.65)$$

for plastics and rubbers, where  $V_{i,j}$  [ $s^{-1}$ ] is the degradation rate constant for substrate  $i$  ( $i = C, R, P$  for cellulose, IX resins, and plastics and rubbers, respectively) under conditions  $j$  ( $j = a, b, c, d, e$  for aerobic respiration, denitrification, iron reduction, sulphate reduction, and methanogenesis, respectively).  $V_{i,j} = V_i$  if  $j$  is the currently active TEA, and  $V_{i,j} = 0$  otherwise, where  $V_i$  is the input degradation rate of organic substrate  $i$ . The constant  $\varepsilon$  in the above equations always has a value between 0 and 1. When the saturation is positive, it is equal to 1, but when the saturation is zero, it is reduced (if necessary) so as to balance the rate of consumption of water due to saturated phase reactions with the rate of ingress of water into the repository.

### 3.6.1.2 Metallic Materials

The rates of metal corrosion (in  $\text{mol}\cdot\text{s}^{-1}$ ) are given by

$$-\frac{dQ_1}{dt} = \frac{\rho_1}{M_1} \left( hA_{1,1}R_{1,1,1} + h \left( 1 + \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q \right) A_{1,1}R_{1,2,1} + \varepsilon A_{1,2}R_{1,1,2} + \varepsilon \left( 1 + \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q \right) A_{1,2}R_{1,2,2} \right) + \frac{1}{2} V_{FeOOH} Q_{FeOOH} + \Phi_1 + \Phi_2 + \Phi_3 + \Phi_4 \quad (3.66)$$

for carbon and galvanized steel,

$$-\frac{dQ_2}{dt} = \frac{\rho_2}{M_2} (hA_{2,1}R_{2,1,1} + hA_{2,1}R_{2,2,1} + \varepsilon A_{2,2}R_{2,1,2} + \varepsilon A_{2,2}R_{2,2,2}) \quad (3.67)$$

for passivated carbon steel,

$$-\frac{dQ_3}{dt} = \frac{\rho_3}{M_3} \left( hA_{3,1}R_{3,1,1} + h \left( 1 + \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q \right) A_{3,1}R_{3,2,1} + \varepsilon A_{3,2}R_{3,1,2} + \varepsilon \left( 1 + \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q \right) A_{3,2}R_{3,2,2} \right) \quad (3.68)$$

for stainless steel and Ni-based alloys, and

$$-\frac{dQ_4}{dt} = \frac{\rho_4}{M_4} (hA_{4,1}R_{4,1,1} + hA_{4,1}R_{4,2,1} + \varepsilon A_{4,2}R_{4,1,2} + \varepsilon A_{4,2}R_{4,2,2}) \quad (3.69)$$

for Zr alloys, where  $V_{FeOOH}$  is the first-order rate constant for the reduction of FeOOH via Equation (3.33) and the other terms are defined in Equation (3.37), Equation (3.38) and Table 3-1.

### 3.6.1.3 Gases

Six gaseous species are considered  $O_2$ ,  $N_2$ ,  $CO_2$ ,  $H_2$ ,  $H_2S$ , and  $CH_4$ . The total number of moles of gas is constantly being adjusted to take into account the flux of gas into or out of the repository (see Section 3.5.4). All gases partition between the gaseous and aqueous phases according to Equation (3.97), Equation (3.98) and Equation (3.99).

The contributions to the rate of change of the total number of moles of gas molecules within the repository due to reactions for the gaseous species are given below.

$$\begin{aligned} -\frac{dQ_{O_2}}{dt} = & \varepsilon g(1 - Y_a)[6V_{C,a}Q_C + 10V_{R,a}Q_R + 10V_{P,a}Q_P] \\ & + \left[ \frac{3\rho_1}{4M_1} (hA_{1,1}R_{1,1,1} + \varepsilon A_{1,2}R_{1,1,2}) + \frac{3\rho_2}{4M_2} (hA_{2,1}R_{2,1,1} + \varepsilon A_{2,2}R_{2,1,2}) \right] \\ & + \left[ \frac{3\rho_3}{4M_3} (hA_{3,1}R_{3,1,1} + \varepsilon A_{3,2}R_{3,1,2}) + \frac{\rho_4}{M_4} (hA_{4,1}R_{4,1,1} + \varepsilon A_{4,2}R_{4,1,2}) \right] \\ & + \frac{3}{4} \Phi_1 + \frac{3}{4} \Phi_2 \end{aligned} \quad (3.70)$$

for  $O_2$ ,

$$\frac{dQ_{N_2}}{dt} = \varepsilon g(1 - Y_b)[2.4V_{C,b}Q_C + 4V_{R,b}Q_R + 4V_{P,b}Q_P] \quad (3.71)$$

for  $N_2$ ,

$$\begin{aligned}
 \frac{dQ_{CO_2}}{dt} = & \varepsilon g(1-Y_a)[6V_{C,a}Q_C + 8V_{R,a}Q_R + 8V_{P,a}Q_P] + \varepsilon g(1-Y_b)[6V_{C,b}Q_C + 8V_{R,b}Q_R + 8V_{P,b}Q_P] \\
 & + \varepsilon g(1-Y_c)[6V_{C,c}Q_C + 8V_{R,c}Q_R + 8V_{P,c}Q_P] + \varepsilon g(1-Y_d)[6V_{C,d}Q_C + 8V_{R,d}Q_R + 8V_{P,d}Q_P] \\
 & + \varepsilon g(1-Y_e)[3V_{C,e}Q_C + 3V_{R,e}Q_R + 3V_{P,e}Q_P] - \varepsilon g \frac{(1-Y_e)}{4} V_{H_3}(C_{CO_2}SV_v + hq_{CO_2}) \\
 & - 2\varepsilon g(Y_a V_{R,a} + Y_b V_{R,b} + Y_c V_{R,c} + Y_d V_{R,d} + Y_e V_{R,e})Q_R \\
 & - 2\varepsilon g(Y_a V_{P,a} + Y_b V_{P,b} + Y_c V_{P,c} + Y_d V_{P,d} + Y_e V_{P,e})Q_P \\
 & - \frac{1}{2} \varepsilon g(Y_c V_{H_1}Q_{FeOOH} + Y_d V_{H_2}C_{SO_4}SV_v + Y_e V_{H_3}(C_{CO_2}SV_v + hq_{CO_2})) \\
 & - \frac{\rho_1}{M_1} \left[ \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q (hA_{1,1}R_{1,2,1} + \varepsilon A_{1,2}R_{1,2,2}) \right] - \frac{\rho_3}{M_3} \left[ \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q (hA_{3,1}R_{3,2,1} + \varepsilon A_{3,2}R_{3,2,2}) \right] \\
 & - \frac{4}{5} \varepsilon V_{MgO}Q_{MgO}
 \end{aligned} \tag{3.72}$$

for CO<sub>2</sub>,

$$\begin{aligned}
 \frac{dQ_{H_2}}{dt} = & -\varepsilon g(1-Y_c)V_{H_1}Q_{FeOOH} - \varepsilon g(1-Y_d)V_{H_2}C_{SO_4}SV_v - \varepsilon g(1-Y_e)V_{H_3}(C_{CO_2}SV_v + hq_{CO_2}) \\
 & - \varepsilon gY_c V_{H_1}C_{FeOOH}SV_v - \varepsilon gY_d V_{H_2}C_{SO_4}SV_v - \varepsilon gY_e V_{H_3}(C_{CO_2}SV_v + hq_{CO_2}) \\
 & + \frac{4}{3} \frac{\rho_1}{M_1} \left[ \left( 1 + \frac{3}{4} \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q \right) (hA_{1,1}R_{1,2,1} + \varepsilon A_{1,2}R_{1,2,2}) \right] \\
 & + \frac{4}{3} \frac{\rho_2}{M_2} (hA_{2,1}R_{2,2,1} + \varepsilon A_{2,2}R_{2,2,2}) + \frac{4}{3} \frac{\rho_3}{M_3} \left[ \left( 1 + \frac{3}{4} \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q \right) (hA_{3,1}R_{3,2,1} + \varepsilon A_{3,2}R_{3,2,2}) \right] \\
 & + \frac{2\rho_4}{M_4} (hA_{4,1}R_{4,2,1} + \varepsilon A_{4,2}R_{4,2,2}) + \frac{1}{2} V_{FeOOH}Q_{FeOOH} + \frac{4}{3} \Phi_3 + \Phi_4
 \end{aligned} \tag{3.73}$$

for H<sub>2</sub>,

$$\begin{aligned}
 \frac{dQ_{H_2S}}{dt} = & \varepsilon g(1-Y_d)[3V_{C,d}Q_C + 5V_{R,d}Q_R + 5V_{P,d}Q_P] \\
 & + \varepsilon g \frac{(1-Y_d)}{4} V_{H_2}C_{SO_4}SV_v - V_{FeS}C_{H_2S}SV_v
 \end{aligned} \tag{3.74}$$

for H<sub>2</sub>S, and

$$\frac{dQ_{CH_4}}{dt} = \varepsilon g(1-Y_e)[3V_{C,e}Q_C + 5V_{R,e}Q_R + 5V_{P,e}Q_P] + \varepsilon g \frac{(1-Y_e)}{4} V_{H_3}(C_{CO_2}SV_v + hq_{CO_2}) \tag{3.75}$$

for CH<sub>4</sub>.

### 3.6.1.4 Terminal Electron Acceptors

In addition to O<sub>2</sub>, Fe(III), and CO<sub>2</sub>, GGM also includes two other terminal electron acceptors, namely: nitrate and sulphate ions. The mass-balance equations for these latter two species are given by:

$$-\frac{dC_{NO_3}}{dt} = \varepsilon g \frac{(1-Y_b)}{SV_v} [4.8V_{C,b}Q_C + 8V_{R,b}Q_R + 8V_{P,b}Q_P] \quad (3.76)$$

for  $NO_3^-$ , and

$$-\frac{dC_{SO_4}}{dt} = \varepsilon g \frac{(1-Y_d)}{SV_v} [3V_{C,d}Q_C + 5V_{R,d}Q_R + 5V_{P,d}Q_P] + \varepsilon g \frac{(1-Y_d)}{4} V_{H_2} C_{SO_4} \quad (3.77)$$

for  $SO_4^{2-}$ .

### 3.6.1.5 Biomass

Biomass is generated as a result of microbial metabolism, growth and decay of which consumes and produces water and needs to be tracked for an accurate water mass balance.

The biomass mass balances are given by

$$\frac{dX_a}{dt} = \varepsilon g Y_a \left( \frac{6}{5} V_{C,a} Q_C + 2V_{R,a} Q_R + 2V_{P,a} Q_P \right) - X_a D \quad (3.78)$$

for aerobes,

$$\frac{dX_b}{dt} = \varepsilon g Y_b \left( \frac{6}{5} V_{C,b} Q_C + 2V_{R,b} Q_R + 2V_{P,b} Q_P \right) - X_b D \quad (3.79)$$

for denitrifiers,

$$\frac{dX_c}{dt} = \varepsilon g Y_c \left( \frac{6}{5} V_{C,c} Q_C + 2V_{R,c} Q_R + 2V_{P,c} Q_P + \frac{1}{10} V_{HI} Q_{FeOOH} \right) - X_c D \quad (3.80)$$

for iron reducers,

$$\frac{dX_d}{dt} = \varepsilon g Y_d \left( \frac{6}{5} V_{C,d} Q_C + 2V_{R,d} Q_R + 2V_{P,d} Q_P + \frac{1}{10} SV_v V_{H_2} C_{SO_4} \right) - X_d D \quad (3.81)$$

for sulphate reducers, and

$$\frac{dX_e}{dt} = \varepsilon g Y_e \left( \frac{6}{5} V_{C,e} Q_C + 2V_{R,e} Q_R + 2V_{P,e} Q_P + \frac{1}{10} V_{H_3} (C_{CO_2} SV_v + hq_{CO_2}) \right) - X_e D \quad (3.82)$$

for methanogens.

The total quantity of live (hydrated) biomass is given by  $X_{tot} = X_a + X_b + X_c + X_d + X_e$ . The total quantity of dead (dehydrated) biomass that cannot be recycled ( $X_{dead}$ ) is also tracked in the code, and is given by:

$$\frac{dX_{dead}}{dt} = (1-K_R)(X_a + X_b + X_c + X_d + X_e)D. \quad (3.83)$$

### 3.6.1.6 Corrosion Products

A number of different corrosion products are tracked in the code, including FeOOH, FeCO<sub>3</sub>, Fe<sub>3</sub>O<sub>4</sub>, Fe<sub>2</sub>O<sub>3</sub> and FeS. The mass-balance equations for these species are given by:

$$\begin{aligned} \frac{dQ_{\text{FeOOH}}}{dt} = & -\varepsilon g(1 - Y_c) [24V_{C,c}Q_C + 40V_{R,c}Q_R + 40V_{P,c}Q_P] - 2\varepsilon g(1 - Y_c)V_{H1}Q_{\text{FeOOH}} \\ & + \left[ \frac{\rho_1}{M_1} (hA_{1,1}R_{1,1,1} + \varepsilon A_{1,2}R_{1,1,2}) + \frac{\rho_2}{M_2} (hA_{2,1}R_{2,1,1} + \varepsilon A_{2,2}R_{2,1,2}) + \frac{\rho_3}{M_3} (hA_{3,1}R_{3,1,1} + \varepsilon A_{3,2}R_{3,1,2}) \right] \\ & - Q_{\text{FeOOH}}V_{\text{FeOOH}} + \Phi_2 \end{aligned} \quad (3.84)$$

for FeOOH,

$$\frac{dQ_{\text{FeCO}_3}}{dt} = \frac{\rho_1}{M_1} \left( \frac{P_{\text{CO}_2}}{P_{\text{CO}_2}^{\text{ref}}} \right)^q (hA_{1,1}R_{1,2,1} + \varepsilon A_{1,2}R_{1,2,2}) + \frac{\rho_3}{M_3} \left( \frac{P_{\text{CO}_2}}{P_{\text{CO}_2}^{\text{ref}}} \right)^q (hA_{3,1}R_{3,2,1} + \varepsilon A_{3,2}R_{3,2,2}) \quad (3.85)$$

for FeCO<sub>3</sub>,

$$\begin{aligned} \frac{dQ_{\text{Fe}_3\text{O}_4}}{dt} = & \frac{\rho_1}{3M_1} (hA_{1,1}R_{1,2,1} + \varepsilon A_{1,2}R_{1,2,2}) + \frac{\rho_2}{3M_2} (hA_{2,1}R_{2,2,1} + \varepsilon A_{2,2}R_{2,2,2}) \\ & + \frac{\rho_3}{3M_3} (hA_{3,1}R_{3,2,1} + \varepsilon A_{3,2}R_{3,2,2}) + \frac{1}{2} V_{\text{FeOOH}} Q_{\text{FeOOH}} + \frac{1}{3} \Phi_3 + \Phi_4 \end{aligned} \quad (3.86)$$

for Fe<sub>3</sub>O<sub>4</sub>,

$$\frac{dQ_{\text{Fe}_2\text{O}_3}}{dt} = \frac{1}{2} \Phi_1 \quad (3.87)$$

for Fe<sub>2</sub>O<sub>3</sub> and

$$\frac{dQ_{\text{FeS}}}{dt} = SV_V V_{\text{FeS}} C_{\text{H}_2\text{S}} \quad (3.88)$$

for FeS.

### 3.6.1.7 Water

Water is consumed and produced by both microbial and corrosion reactions. The rate of generation of water is given by:

$$\frac{dQ_{\text{H}_2\text{O}}}{dt} = -\varepsilon \frac{dC}{dt} + \frac{dD}{dt} \quad (3.89)$$

where

$$\begin{aligned}
 \frac{dC}{dt} = & -S \left\{ \begin{aligned}
 & (1 - Y_a)[5V_{C,a}Q_C + 4V_{R,a}Q_R + 4V_{P,a}Q_P] + (1 - Y_b)[7.4V_{C,b}Q_C + 8V_{R,b}Q_R + 8V_{P,b}Q_P] \\
 & - (1 - Y_c)[7V_{C,c}Q_C + 16V_{R,c}Q_R + 16V_{P,c}Q_P] + (1 - Y_d)[5V_{C,d}Q_C + 4V_{R,d}Q_R + 4V_{P,d}Q_P] \\
 & - (1 - Y_e)[V_{C,e}Q_C + 6V_{R,e}Q_R + 6V_{P,e}Q_P] + (1 - Y_d)SV_v V_{H_2}C_{SO_4} \\
 & + \frac{1}{2}(1 - Y_e)V_{H_3}(C_{CO_2}SV_v + hq_{CO_2}) \\
 & - 27.4(Y_a V_{C,a} + Y_b V_{C,b} + Y_c V_{C,c} + Y_d V_{C,d} + Y_e V_{C,e})Q_C \\
 & - 50(Y_a V_{R,a} + Y_b V_{R,b} + Y_c V_{R,c} + Y_d V_{R,d} + Y_e V_{R,e})Q_R \\
 & - 50(Y_a V_{P,a} + Y_b V_{P,b} + Y_c V_{P,c} + Y_d V_{P,d} + Y_e V_{P,e})Q_P \\
 & - \frac{17}{10}(Y_c V_{H_1}Q_{FeOOH} + Y_d V_{H_2}C_{SO_4}SV_v + Y_e V_{H_3}(C_{CO_2}SV_v + hq_{CO_2})) \\
 & - V_{MgO}Q_{MgO}
 \end{aligned} \right\} \\
 & + \frac{\rho_1}{2M_1}(A_{1,2}R_{1,1,2}) + \frac{\rho_2}{2M_2}(A_{2,2}R_{2,1,2}) + \frac{\rho_3}{2M_3}(A_{3,2}R_{3,1,2}) \\
 & + \frac{4}{3} \frac{\rho_1}{M_1} \left[ \left( 1 + \frac{3}{4} \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q \right) (A_{1,2}R_{1,2,2}) \right] + \frac{4}{3} \frac{\rho_2}{M_2} [A_{2,2}R_{2,2,2}] \\
 & + \frac{4}{3} \frac{\rho_3}{M_3} \left[ \left( 1 + \frac{3}{4} \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q \right) (A_{3,2}R_{3,2,2}) \right] + \frac{2\rho_4}{M_4} [A_{4,2}R_{4,2,2}] \\
 & + 2\Phi_4
 \end{aligned} \tag{3.90}$$

is the rate of consumption of water due to processes that operate under saturated conditions only, and

$$\begin{aligned}
 \frac{dD}{dt} = & (1-S)h \left\{ \begin{aligned}
 & (1-Y_a)[5V_{C,a}Q_C + 4V_{R,a}Q_R + 4V_{P,a}Q_P] + (1-Y_b)[7.4V_{C,b}Q_C + 8V_{R,b}Q_R + 8V_{P,b}Q_P] \\
 & - (1-Y_c)[7V_{C,c}Q_C + 16V_{R,c}Q_R + 16V_{P,c}Q_P] + (1-Y_d)[5V_{C,d}Q_C + 4V_{R,d}Q_R + 4V_{P,d}Q_P] \\
 & - (1-Y_e)[V_{C,e}Q_C + 6V_{R,e}Q_R + 6V_{P,e}Q_P] + (1-Y_d)SV_v V_{H_2}C_{SO_4} \\
 & + \frac{1}{2}(1-Y_e)V_{H_3}(C_{CO_2}SV_v + hq_{CO_2}) \\
 & - 27.4(Y_a V_{C,a} + Y_b V_{C,b} + Y_c V_{C,c} + Y_d V_{C,d} + Y_e V_{C,e})Q_C \\
 & - 50(Y_a V_{R,a} + Y_b V_{R,b} + Y_c V_{R,c} + Y_d V_{R,d} + Y_e V_{R,e})Q_R \\
 & - 50(Y_a V_{P,a} + Y_b V_{P,b} + Y_c V_{P,c} + Y_d V_{P,d} + Y_e V_{P,e})Q_P \\
 & - \frac{17}{10}(Y_c V_{H_1}Q_{FeOOH} + Y_d V_{H_2}C_{SO_4}SV_v + Y_e V_{H_3}(C_{CO_2}SV_v + hq_{CO_2})) \\
 & - V_{MgO}Q_{MgO}
 \end{aligned} \right\} \\
 & + 25(1-K_R)(X_a + X_b + X_c + X_d + X_e)D + \frac{137}{6}K_R(X_a + X_b + X_c + X_d + X_e)D \\
 & - \frac{\rho_1}{2M_1}(A_{1,1}hR_{1,1,1}) - \frac{\rho_2}{2M_2}(A_{2,1}hR_{2,1,1}) - \frac{\rho_3}{2M_3}(A_{3,1}hR_{3,1,1}) \\
 & - \frac{4}{3} \frac{\rho_1}{M_1} \left[ \left( 1 + \frac{3}{4} \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q \right) (A_{1,1}hR_{1,2,1}) \right] - \frac{4}{3} \frac{\rho_2}{M_2} [A_{2,1}hR_{2,2,1}] \\
 & - \frac{4}{3} \frac{\rho_3}{M_3} \left[ \left( 1 + \frac{3}{4} \left( \frac{P_{CO_2}}{P_{CO_2}^{ref}} \right)^q \right) (A_{3,1}hR_{3,2,1}) \right] - \frac{2\rho_4}{M_4} [A_{4,1}hR_{4,2,1}] \\
 & - \frac{1}{2}\Phi_2 - \frac{4}{3}\Phi_3
 \end{aligned} \tag{3.91}$$

is the rate of generation of water due to the remaining terms, including the death of biomass and vapour phase processes.

### 3.6.1.8 Other Species

If MgO is added to the repository to mitigate the effect of CO<sub>2</sub>, it is necessary to track the amount of remaining MgO. The amount of the product (Mg<sub>5</sub>(CO<sub>3</sub>)<sub>4</sub>(OH)<sub>2</sub>·4H<sub>2</sub>O) is not specifically calculated in the code, but can be obtained from the loss of MgO and the stoichiometry of the reaction in Equation (3.60).

The mass-balance equation for MgO is given by:

$$-\frac{dQ_{MgO}}{dt} = V_{MgO}Q_{MgO} \tag{3.92}$$

The depletion of carbonate ions due to Phase 4 corrosion of used fuel containers from an initial specified inventory is modelled as follows:

$$\frac{dQ_{CO_3^{2-}}}{dt} = -\Phi_4 \tag{3.93}$$

### 3.6.2 Assumptions

A number of assumptions have been made in the development of GGM. Table 3-2, Table 3-3 and Table 3-4 list the assumptions for a L&ILW repository and their basis for the conceptual microbial model, the conceptual corrosion model, and the overall gas generation model, respectively. The assumptions implicit in the model for the corrosion of used fuel containers are given in Table 3-5.

**Table 3-2: Assumptions Included in Conceptual Microbial Model for a L&ILW Repository**

| Assumption   | Basis   |
|--|---|
| Conversion of organic polymer to its soluble intermediates is the rate-limiting step in the degradation of organics.         | Mechanistically justifiable and simplifies modelling of microbial processes.  |
| Degradation of IX resins is possible.  | Degradation of IX resins is allowed, but they can be treated as recalcitrant by setting the appropriate rate constants to zero.   |
| Degradation of plastics and rubbers is possible and can be treated in the same manner as the degradation of IX resins.       | Degradation of plastics and rubbers is allowed, but they can be treated as recalcitrant by setting the appropriate rate constants to zero. The treatment of plastics and rubbers in the same manner as IX resins is a simplification, but preserves the basic conversion process from organic carbon to CH <sub>4</sub> and CO <sub>2</sub> . |
| Kinetics of degradation of organic material are first order.   | Reasonable assumption provided that value for rate constant is derived from experimental data on the same basis. Supported by the modelling of hydrolysis of polymers such as cellulose in other environments.  |
| Microbial activity slows as the A <sub>w</sub> falls below 0.8, and ceases at a water activity (A <sub>w</sub> ) below 0.6.. | Consistent with data (Shreir 1976) and mechanistically justifiable.   |
| Microbial kinetics are independent of the amount of biomass.   | Simplifies the modelling of microbial kinetic processes. Essentially assumes that there is enough biomass that the rate has saturated (e.g., surfaces are fully covered by microbes).   |
| Nitrogen is not limiting for microbial growth.   | Simplifies the modelling of microbial processes by limiting the number of species in the model. It is also conservative with respect to gas generation, since it ensures microbial reactions proceed to completion.   |
| There is sufficient pH-buffering capacity in the environment to permit consumption of acidic fermentation products.          | Simplifies modelling of microbial processes. It is also conservative with respect to gas generation since it ensures microbial reactions proceed to completion.   |
| Decay of one "mole" of biomass   | Reasonable assumption based on mean water   |

| <b>Assumption</b>   | <b>Basis</b>  |
|---|---|
| generates 25 moles of water.  | content of biomass of 80% (by weight).  |
| 9 moles of bound water are freed per mole of styrene monomer as it degrades.                | Calculation based on 40% bound water by weight for the resins and 8 moles of styrene monomer per 10 moles of dry resin (which include functional groups).   |
| Carbon from a fraction of the dead biomass is recycled.                                     | Consistent with mechanistic understanding.  |
| Availability of phosphorus and sulphur do not limit microbial growth.                       | Simplifying assumption for modelling purposes. It is also conservative with respect to gas generation since it ensures microbial reactions proceed to completion.   |
| All microbes required to catalyze the reactions modelled are present within the repository. | This is also conservative with respect to gas generation since it ensures microbial reactions proceed to completion. Also mechanistically supportable since microbes will enter the repository via a range of routes. |

**Table 3-3: Assumptions Included in Conceptual Corrosion Model for a L&ILW Repository**

| <b>Assumption</b>  | <b>Basis</b>   |
|--|--|
| Vapour phase corrosion becomes active in the range 60-80% RH.  | Mechanistically justifiable and commonly observed threshold from atmospheric corrosion studies.  |
| Magnetite is the stable long-term anaerobic corrosion product of the corrosion of steel.   | Reasonable assumption based on information available in the literature. Conservative in terms of the maximum amount of H <sub>2</sub> produced.  |
| Corrosion of stainless steel and Ni-based alloys can be represented by the formation of FeOOH and Fe <sub>3</sub> O <sub>4</sub> under aerobic and anaerobic conditions, respectively. | Simplifying assumption for modelling purposes. Reasonable assumption for stainless steels, which typically contain 60-80% Fe. Reasonable for Ni-based alloys as corrosion rate is low and amount of "Fe(III)" predicted to be formed from these materials is small compared with that formed from carbon and galvanized steels. Differences in amounts of H <sub>2</sub> formed because of difference in valences of corrosion products can be adjusted through value of initial inventory of these materials. |
| CO <sub>2</sub> -enhanced corrosion occurs for carbon and galvanized steel and stainless steel and Ni-based alloys only.   | Reasonable assumption based on evidence in the literature. Passive carbon steels are less likely to be affected due to pH-buffering capacity of cementitious materials (the assumed passivating agent). No evidence for enhanced effect of CO <sub>2</sub> on Zr alloys.   |

**Table 3-4: Assumptions Included in the Overall Gas Generation Model for a L&ILW Repository**

| Assumption   | Basis  |
|--|--|
| Transport of species in the repository is rapid on the timescale of interest and no concentration gradients develop.   | Simplifies modelling by removing the need to predict the spatial dependence of the concentrations of various species. Reasonable assumption for long time scale (years or more) of interest for a repository.  |
| All Fe(III) formed is present as FeOOH and is available for microbial consumption and/or reductive dissolution.  | Ferric corrosion products will likely be present as a mixture of $\text{Cl}^-$ , $\text{SO}_4^{2-}$ , and $\text{CO}_3^{2-}$ -containing forms of Green Rust. However, provided the water mass balance is accurately predicted, the actual form of corrosion product is relatively unimportant since the concentrations of $\text{Cl}^-$ and $\text{SO}_4^{2-}$ are not tracked in the model. The solubility of Fe(III) is likely to be limited at the near-neutral to moderately alkaline pH values expected in the repository, so the assumption that the Fe(III) is available for microbial metabolism may result in an over-estimate of the extent of microbial iron reduction in the model. |
| Assumes first-order kinetics for the formation of magnesium carbonates from MgO.   | Consistent with mechanistic understanding.   |
| Kinetics of FeS precipitation are first order with respect to the concentration of $\text{H}_2\text{S}$ .  | Reasonable assumption based on known kinetics of reaction.   |
| Excess Fe(II) available for precipitation of FeS.  | Reasonable assumption based on large surface area and quantity of ferrous materials in repository and fact that sulphide will only be formed under anaerobic conditions.   |
| Gas generation reactions and water transport are assumed to take place under isothermal conditions (based on a typical temperature of around 20 °C at the repository horizon). | Temperatures in an L&ILW DGR are expected to be around geosphere conditions due to the low heat sources. Long-term thermal changes in the geosphere will be driven by glacial cycling. At OPG's DGR, repository temperatures are expected to reach a minimum of 17 °C under glacial conditions compared with 22 °C at the present date.  |

**Table 3-5: Assumptions Included in Conceptual Corrosion Model for a Used Fuel Repository**

| Assumption   | Basis  |
|--|--|
| Vapour phase corrosion becomes active in the range 60-80% RH.  | Mechanistically justifiable and commonly observed threshold from atmospheric corrosion studies. See Newman et al. (2010) and on evidence from the atmospheric corrosion literature (Leygraf and Graedel 2000, Rozenfeld 1972). |
| Local reduction of H <sup>+</sup> , which may lead to enhanced hydrogen absorption and environmentally assisted cracking (King 2009), is not considered.   | It will not lead to the generation of significant quantities of H <sub>2</sub> .   |
| There is no significant corrosion prior to the sealing of the repository.  | An extended operational phase could allow O <sub>2</sub> ingress and additional corrosion of the container.  |
| There will likely be a transformation of corrosion products as the environmental conditions evolve, but this is not considered. For example, the reductive dissolution of Fe(III) solids formed during Phases 1 and 2 could support additional Fe dissolution but this is not explicitly considered. | These are considered to be second order effects.   |

### 3.6.3 Problem Solution Method

The GGM model described here is implemented using FORTRAN 77 subroutines, thus enabling it to be driven by TOUGH2, which is also written in FORTRAN 77 (J3 2008).

GGM consists of first-order coupled differential equations given by the mass balance equations and non-differential equations, such as Henry's law. The mass balance equations are evolved forward in time using a modified Euler time stepping scheme, and the non-differential equations are solved for the remaining variables at each time step. Reactions are generally ceased once any of the reactants have been exhausted. One special case that is treated differently is water, for which there may be resupply to the repository at a slow rate and for which rates of affected processes may be reduced so that the total rate of consumption of water balances the rate of ingress.

In this model, gas is generated via degradation reactions in the saturated part of the repository and under unsaturated conditions if the relative humidity exceeds  $RH_{min}$  (typically set to 60%). The gas repartitions between the saturated and unsaturated parts of the repository according to Henry's Law effectively instantaneously. Gas partitioning has been treated mathematically to ensure that its numerical discretization can be implemented in a manner consistent with all the other processes and can be treated by evolving differential equations for the total number of moles in the repository. Details of this treatment of gas repartitioning are given in Section 3.7.

The GGM code has a large number of variables that are highly coupled. GGM uses an adaptive time stepping algorithm that chooses a time resolution sufficient to capture the changes that can

occur on the disparate timescales of the various physical processes. There is also coupling with TOUGH2 via gas and water generation, pressure, saturation, relative humidity and void volume. For efficiency, GGM does not require TOUGH2 and GGM to take the same time steps. GGM provides TOUGH2 with a suggested maximum time step based on the current rate of change of the GGM inputs and outputs.

### 3.7 GAS REPARTITIONING

#### 3.7.1 Mathematical Encapsulation

Consider an enclosed volume  $V$  ( $m^3$ ), with saturation  $S$  (-), at temperature  $T$  (K). Several ideal gas species exist in the volume. The total number of moles of gas  $i$  in the volume is known to be  $N_i$ . The gas partitions itself between the unsaturated and the saturated phases according to Henry's law. The equilibrium partial pressure,  $p_i$  (Pa), and number of moles of gas  $i$ ,  $n_i$  (mol), in the unsaturated phase and the concentration of gas in solution in the saturated phase,  $c_i$  (mol  $m^{-3}$ ), are the unknown variables.

Writing expressions for the total number of moles of gas in the system, the ideal gas law and Henry's law gives three equations for the three unknowns:

$$N_i = n_i + c_i SV \quad (3.94)$$

$$p_i(1 - S)V = n_i RT \quad (3.95)$$

$$c_i = p_i K_i \quad (3.96)$$

where  $R$  ( $m^3 Pa K^{-1} mol^{-1}$ ) is the molar gas constant and  $K_i$  ( $mol m^{-3} Pa^{-1}$ ) is the solubility constant for gas  $i$ . These can be solved readily to give:

$$c_i = \frac{N_i}{V} \frac{RTK_i}{1 + S(RTK_i - 1)} \quad (3.97)$$

$$p_i = \frac{1}{K_i} c_i \quad (3.98)$$

$$n_i = N_i - c_i SV \quad (3.99)$$

#### 3.7.2 Implications for GGM

The total gas generation rate,  $Q_{air}$  ( $mol s^{-1}$ ), can be calculated as:

$$\begin{aligned} Q_{air} &= \sum_i \frac{\partial n_i}{\partial t} \\ &= \sum_i \left( \frac{\partial N_i}{\partial t} - \frac{\partial c_i}{\partial t} SV - c_i \frac{\partial S}{\partial t} V \right) \\ &= \sum_i \left[ f_i V \frac{S(1-S)}{1 + S(RTK_i - 1)} - RTK_i N_i \frac{\partial S}{\partial t} \left( \frac{1}{1 + S(RTK_i - 1)} \right)^2 \right] \end{aligned} \quad (3.100)$$

using Equations (3.97) and (3.99).

The initial partial pressure of each gas in the repository is specified rather than the initial total number of moles. However, it is the initial total number of moles that is required as an initial condition for the mass balance equations. To determine the initial total number of moles of each gas in the repository,  $N_i^{(0)}$ , from the initial partial pressure,  $p_i^{(0)}$ , Equation (3.97) and Equation (3.98) are rearranged to give:

$$N_i^{(0)} = p_i^{(0)} V \frac{1 + S(RTK_i - 1)}{RT} \quad (3.101)$$

### 3.8 RELATIVE HUMIDITY MODULATION

There are two options available for the relative humidity modulation function,  $h$ : a linear ramp and a smoothed linear ramp. These are described in the following sections.

For the L&ILW repository model, the modulation is applied directly to all vapour phase corrosion rate constants:  $R_{111}$ ,  $R_{121}$ ,  $R_{211}$ ,  $R_{221}$ ,  $R_{311}$ ,  $R_{321}$ ,  $R_{411}$ ,  $R_{421}$ . For the corrosion of used fuel containers, the model for relative humidity dependence is given in Section 3.4.5. It is applied to the vapour phase fraction of all microbial processes (apart from the death of biomass, which is assumed to continue at its normal rate),  $g$ , via the expression:

$$g = S + (1 - S)h. \quad (3.102)$$

The affected microbial rate constants are:  $V_{H1}$ ,  $V_{H2}$ ,  $V_{H3}$ ,  $V_{C,a}$ ,  $V_{C,b}$ ,  $V_{C,c}$ ,  $V_{C,d}$ ,  $V_{C,e}$ ,  $V_{R,a}$ ,  $V_{R,b}$ ,  $V_{R,c}$ ,  $V_{R,d}$ ,  $V_{R,e}$ ,  $V_{P,a}$ ,  $V_{P,b}$ ,  $V_{P,c}$ ,  $V_{P,d}$ ,  $V_{P,e}$ .

#### 3.8.1 Type 1: Linear Ramp

The relative humidity modulation function is taken as varying linearly between  $RH_{\min}=0.6$  and  $RH_{\max}=0.8$ :

$$h(RH) = \begin{cases} 1 & 1 < X \\ X & 0 < X < 1, \\ 0 & X < 0 \end{cases} \quad \text{where} \quad X = \left( \frac{RH - RH_{\min}}{RH_{\max} - RH_{\min}} \right) \quad (3.103)$$

#### 3.8.2 Type 2: Smoothed Linear Ramp

This is a variation on the linear ramp that has a continuous first derivative due to the introduction of curvature at end of the ramp. The following values are hard-wired:  $\beta=0.1$ ,  $\varepsilon=0.05$ .

$$h(RH) = \begin{cases} 1 - \frac{(1-X)^2}{B + A(1-X)} & 1 - \beta < X \\ \varepsilon + C(X - \beta) & \beta < X < 1 - \beta \\ \frac{X^2}{B + AX} & X < \beta \end{cases} \quad (3.104)$$

Where:

$$X = \left( \frac{RH - RH_{\min}}{RH_{\max} - RH_{\min}} \right), \quad A = \frac{\beta(2 - \alpha\gamma)}{\varepsilon}, \quad B = \frac{\beta^2}{\varepsilon} \left( \frac{\alpha\beta}{\varepsilon} - 1 \right), \quad C = \frac{1 - 2\varepsilon}{1 - 2\beta}$$

### 3.9 WATER-LIMITING CONDITIONS

Considering the water balance for the repository:

$$\frac{dA_{H_2O}}{dt} = \frac{dQ_{H_2O}}{dt} + J_{H_2O} = -\varepsilon \frac{dC}{dt} + \frac{dD}{dt} + J_{H_2O} \quad (3.105)$$

where  $dA_{H_2O}/dt$  ( $\text{mol s}^{-1}$ ) is the rate of change of the amount of water in the repository,  $dQ_{H_2O}/dt$  ( $\text{mol s}^{-1}$ ) is the rate of production of water via the gas generation reactions, which splits into components  $dC/dt$  and  $dD/dt$  given by Equations (3.90) and (3.91) and  $J_{H_2O}$  ( $\text{mol s}^{-1}$ ) is the rate of ingress of water into the repository.

Under normal circumstances, the water consuming saturated phase reactions will proceed at their normal rate and  $\varepsilon = 1$  will be set. Once zero saturation has been reached, if water consuming reactions continue to proceed at a sufficient rate, the saturation will remain zero and  $dA_{H_2O}/dt = 0$ . Under such circumstances, the saturated phase water-consuming reactions to consume water that naturally will be allowed to enter the repository, but not to draw water into the repository. This is achieved by choosing  $\varepsilon$  so that the rate of saturated phase water consumption is balanced by the natural rate of water ingress. Then:

$$\varepsilon = \frac{\frac{dD}{dt} + J_{H_2O}}{\frac{dC}{dt}} \quad (3.106)$$

holds, provided that the rate of water consumption due to saturated phase processes,  $dC/dt$ , is positive and the rate of increase of water due to other gas generation reactions and water ingress is less than the rate of water consumption. This ensures that  $0 \leq \varepsilon \leq 1$ .

#### 3.9.1 The Molar Mass of Gas

GGM keeps track of the number of moles of each gas species within the repository. As part of its gas calculations, GGM uses the molar masses of the gas species, which are supplied as input parameters. One output of the GGM is the gas generation rate. Note that the required quantity is the equivalent rate of generation of TOUGH2 bulk gas in  $\text{kg s}^{-1}$  ( $Q_{T2}$ ), rather than the internal rate of change of mass of gas as would be calculated directly by GGM ( $Q_{GGM}$ ).

The latter would be calculated as the sum over gas components of the products of the individual gas-component generation rates in  $\text{mol s}^{-1}$  and the molar masses of those components:

$$Q_{GGM} = \sum_g R_g \mu_g \quad (3.107)$$

where  $Q_{GGM}$  ( $\text{kg s}^{-1}$ ) is the total internal gas generation rate, and  $R_g$  ( $\text{mol s}^{-1}$ ) and  $\mu_g$  ( $\text{kg mol}^{-1}$ ) are the rate of generation and molar mass of GGM gas component  $g$ , respectively.

The actual rate of generation required by TOUGH2 is obtained by taking the total rate of change of number of moles and multiplying by the molar mass of bulk gas as supplied by TOUGH2 (via the PEMMA subroutine argument) as follows:

$$Q_{T2} = P_{EMMA} \sum_g R_g \quad (3.108)$$

where  $Q_{T2}$  ( $\text{kg s}^{-1}$ ) is the total rate of change of mass of TOUGH2 bulk gas due to gas generation,  $P_{EMMA}$  ( $\text{kg mol}^{-1}$ ) is the molar mass of TOUGH2 bulk gas and  $R_g$  ( $\text{mol s}^{-1}$ ) is the rate of generation of GGM gas component  $g$ .

#### 4. THEORY – TOUGH2

TOUGH2 is a general-purpose numerical simulation program for multi-phase fluid and heat flow in porous and fractured media developed by the Lawrence Berkeley National Laboratory (Pruess et al. 1999). TOUGH2 is modular, setting up equations and solving them in a general form, with specific definitions for the fluid mixture, such as phase components and primary variables, provided in a single fluid property or Equation-of-State (EOS) module. Only one EOS module can be linked to TOUGH2 at a time, and T2GGM uses the EOS3 module, which simulates the transport of air and water.

TOUGH2 describes advective fluid flow using a multi-phase extension of Darcy's law and diffusive flow using a multi-phase extension of Fick's law. For numerical simulation, equations are solved at each node within a discretized space. Space discretization uses the Integral Finite Difference (IFD) method. In contrast to most field modeling approaches, the IFD method does not assume any spatial configuration or connectivity of nodes. Elements (or blocks) define the volumetric properties of nodes. Connections define the flows between nodes. There is no *a priori* assumption about how nodes are connected.

The EOS3 module defines two-phase flow of water and air, or single-phase flow of water or air. Thermophysical properties of water are represented by steam-table equations, while the air is treated as ideal gas. Dissolution of air in water is modeled with Henry's law. For T2GGM Version 3.1, an option is provided to represent the gas phase by an alternative gas, either CH<sub>4</sub>, CO<sub>2</sub> or H<sub>2</sub>.

The phase relationship between gas and liquid is based on a capillary pressure function and a relative permeability function. T2GGM includes the standard functions available within TOUGH2/EOS3. Additionally, a modified Van Genuchten formulation was ported from iTOUGH2 (Finsterle 1999). This modified formulation addresses a shortcoming with the standard van Genuchten model where capillary pressure goes to infinity as liquid saturation approaches the residual liquid saturation value. In the modified formulation, the capillary pressure function is extended as a linear function at low saturations.

Several additional subroutine calls were added to TOUGH2 which are responsible for managing the interface with GGM in order to perform tasks such as initialization, time stepping and updating of sources and sinks based on GGM output data.

TOUGH2 modifications in T2GGM Version 3.1 also include options to provide time-variable permeability, time-variable Dirichlet boundary conditions and a simple 1D hydro-mechanical model to assess the effects of a uniformly applied glacial stress. Time-variable permeability and boundary conditions are straightforward modifications that are extensions of existing TOUGH2 or TOUGH2-MP features, whereby existing values of permeability or boundary conditions are updated from input functions at the beginning of each time step. The theory behind the 1D hydro-mechanical model is described in detail in Section 4.1.

T2GGM Version 3.1 includes a parallel version, based on TOUGH2-MP. The TOUGH2-MP version uses the same GGM code as T2GGM, but requires a slightly different interface on the TOUGH2 side of the code. The different interface is required to address the parallelization of the code: TOUGH2-MP partitions the grid and assigns each processor a portion of the grid. Consequently, the TOUGH2-GGM interface must collect the appropriate parameters required by GGM from the appropriate processors (namely the processors conducting calculation on the repository nodes), and similarly, must distribute GGM outputs to these same processors.

#### 4.1 SIMPLE 1D HYDRO-MECHANICAL MODEL

The effect of future glaciation on groundwater and gas transport in the formations surrounding a deep geologic repository for radioactive waste is an important issue. In a sedimentary setting, the units providing geological confinement can have small but significant gas saturations. The presence of gas in formations is expected to greatly reduce the magnitude of hydro-mechanical coupling. Modelling systems such as TOUGH-FLAC (Rutqvist and Tsang 2003) combine the two-phase flow capability of TOUGH2 with mechanical simulators, but these simulators are demanding to use, in terms of computational and human effort, and may require some approximation in accounting for the markedly increased fluid compressibility in a gas-water system.

To avoid these limitations, a simple one-dimensional (1D) hydro-mechanical coupling algorithm was implemented directly in TOUGH2. The algorithm relies on the simplifying assumptions of horizontally bedded formations and uni-axial strain. These limitations do not preclude modelling the effects of relatively uniform changes in mechanical loading over a large area, such as occurs during continental glaciations or laterally extensive erosion/deposition events. The approach used was inspired by the methods described for pure vertical strain and single phase flow in Wang (2000) and Neuzil (2003), and is similar to that implemented in FRAC3DVS-OPG (Therrien et al. 2010), but has been extended to two-phase flow systems.

In TOUGH2, the mass balance equation can be written as follows (Pruess et al. 1999):

$$\frac{d}{dt} \int_{V_n} M^\kappa dV_n = \int_{\Gamma_n} F^\kappa \cdot \mathbf{n} d\Gamma_n + \int_{V_n} q^\kappa dV_n \quad (4.1)$$

This expression integrates over the subdomain  $V_n$ , which is bounded by the surface  $\Gamma_n$ , with  $\mathbf{n}$  being an inward pointing vector, normal to the surface element  $d\Gamma_n$ . The symbol  $\kappa$  represents the mass component (i.e., water, air). Hydromechanical coupling under a homogeneous and laterally extensive load is implemented within the mass accumulation term, which has the following general form (Pruess et al. 1999):

$$M^\kappa = \phi \sum_\psi S_\psi \rho_\psi X_\psi^\kappa \quad (4.2)$$

where

$\phi$  = porosity (-);

$S_\psi$  = saturation of phase  $\psi$  (-);

$\rho_\psi$  = density of phase  $\psi$  (kg/m<sup>3</sup>), a function of pressure and phase compressibility;

$X_\psi^\kappa$  = mass fraction of component kappa in phase  $\psi$  (-).

Unlike single-phase codes, porosity ( $\phi$ ) in TOUGH2 is not constant, but is updated at the end of each iteration to account for changes in pressure. The change in porosity as a function of the pressure is analogous to the addition or subtraction of water from storage in single-phase codes. The expression for the updated porosity for the current timestep ( $\phi_t$ ), including hydro-mechanical effects, is:

$$\phi_t = \phi_{t-1} + \phi_{t-1} C_{pore} dp + S_{S-1D} \zeta d\sigma_{zz} \quad (4.3)$$

where

$\phi_{t-1}$  = porosity of previous timestep(-);

$C_{pore}$  = pore compressibility (Pa<sup>-1</sup>), COM in the ROCKS record;

$dp$  = change in pressure during timestep  $t - 1$  (Pa);

$S_{S-1D}$  = specific storage (Pa<sup>-1</sup>);

$\zeta$  = 1-dimensional loading efficiency (-);

$d\sigma_{zz}$  = change in vertical load during timestep  $t - 1$  (Pa).

The third term in Equation (4.3), namely  $\phi_{t-1}C_{pore}dp$ , represents the change in porosity due to the change in pore pressure during timestep  $t - 1$ . This expression has always been in TOUGH2, and is analogous to the storage term in single-phase flow mass balance equations. The fourth term in Equation (4.3), ( $\phi_{t-1}S_{S-1D}\zeta d\sigma_{zz}$ ) is the new hydro-mechanical term, and represents the change in porosity due to the change in vertical load during timestep  $t - 1$ . The terms of Equation (4.3) which are unique to the hydro-mechanical formulation are the one-dimensional loading efficiency ( $\zeta$ ), the change in vertical load ( $d\sigma_{zz}$ ), and the one-dimensional (uniaxial) specific storage ( $S_{S-1D}$ ).

The hydro-mechanical capability requires the one-dimensional loading efficiency to be defined for each material type. This parameter is used to determine what percentage of the applied vertical stress is borne by the pore-fluids. The equation used to calculate one-dimensional loading efficiency ( $\zeta$ ) is (Neuzil 2003):

$$\zeta = \frac{\beta(1+\nu)}{3(1-\nu)-2\alpha\beta(1-2\nu)} \quad (4.4)$$

where

$\beta$  = Skempton's coefficient (-)

$\alpha$  = Biot-Willis coefficient (-)

$\nu$  = Poisson's Ratio (-)

Strictly speaking  $S_{S-1D}$  should be calculated according to Equations (4.5) through (4.9) (Wang 2000; Neuzil 2003):

$$S_{S-1D} = \left(\frac{1}{K} - \frac{1}{K_S}\right)(1 - \lambda) + \phi \left(\frac{1}{K_f} - \frac{1}{K_\phi}\right) \quad (4.5)$$

$$\frac{1}{K_S} = \frac{1-\alpha}{K} \quad (4.6)$$

$$\lambda = \frac{2\alpha(1-2\nu)}{3(1-\nu)} \quad (4.7)$$

$$\frac{1}{K_f} = \frac{S_w}{K_w} + \frac{S_g}{K_g} \quad (4.8)$$

$$\frac{1}{K_\phi} = -\frac{1}{\phi} \left[ \left(\frac{1}{K} - \frac{1}{K_S}\right) \left(\frac{1}{\beta} - 1\right) - \frac{\phi}{K_f} \right] \quad (4.9)$$

where

$K$  = Drained bulk modulus (Pa), ( $1/K = \phi C_{pore}$ );

$K_S$  = Unjacketed bulk modulus, often denoted solid phase bulk modulus (Pa);

$K_f$  = Effective fluid bulk modulus (Pa);

$S_w$  = Water saturation (-);

$S_g$  = Gas saturation (-);

$K_w$  = Water bulk modulus, calculated by TOUGH2 (Pa);

$K_g$  = Gas bulk modulus, calculated by TOUGH2 (Pa);

$K_\phi$  = Unjacketed pore compressibility (Pa).

Although the storage coefficient is not used directly in TOUGH2, the implementation of pore compressibility in TOUGH2 is equivalent to a storage coefficient defined as follows:

$$S_S = \frac{1}{K} + \frac{\phi}{K_f} \quad (4.10)$$

This equation is a simplified version of Equation (4.5), which implicitly assumes incompressible grains ( $\alpha = 1$ ). In order for the pressure effects of externally applied loads and changes in pore pressure to be expressed in a consistent fashion, it is necessary to use this simplified form of the storage coefficient equation.

At first glance, it appears that the 1D hydro-mechanical term is a function of fluid compressibility, and thereby gas saturation; however, the term  $S_{S-1D} \zeta$  (see Equation (4.3)) reduces to:

$$S_{S-1D} \zeta = \frac{\left(\frac{1}{K} - \frac{1}{K_S}\right)(1+\nu)}{3(1-\nu)} \quad (4.11)$$

Thus, this formulation is a function of material parameters which we assume (in a linear poroelastic model), do not change significantly (i.e.  $S_{S-1D} \zeta$  is a constant).

A judicious choice of the input parameters  $\zeta$  and  $C_{pore}$  allows us to use a simplified expression to calculate  $S_{S-1D} \zeta$ , which is also consistent with the definition of the storage coefficient in TOUGH2:

$$S_{S-1D} \zeta = \phi \left( C_{pore} + \frac{1}{K_{water}} \right) \zeta \quad (4.12)$$

The input value  $C_{pore}$  should be corrected to account for uniaxial rather than triaxial mechanical constraints.

This simple approach is a good estimate of the effect of hydro-mechanical coupling on in-situ pore pressures.

## **5. VERIFICATION**

### **5.1 INTRODUCTION**

Verification for T2GGM Version 3.0 and 3.1 is summarised here and is built upon the verification undertaken for previous versions (Quintessa and Geofirma 2011a).

Verification involves the checking of the software against its specifications. The types of verification undertaken are:

1. Performing unit tests for new code features;
2. Running a test suite to ensure plausible and accurate output that is consistent with the Theory Manual (Section 3); and
3. Review of the code for accuracy and maintainability.

Validation of the model, the determination of the accuracy and applicability of the software results with respect to their intended application, is discussed separately in Section 6.

GGM is developed and tested independently using a driver program to approximate geosphere behaviour, before being integrated with TOUGH2 for further testing. Historic and current GGM and T2GGM testing is summarised in Section 5.2 and 5.5 respectively. Results of GGM Testing for Versions 3.0 and 3.1 are described in Section 5.3 and 5.4. Results of T2GGM testing for Versions 3.0 and 3.1 are described in Section 5.6 and 5.7.

### **5.2 GGM VERIFICATION SUMMARY**

The GGM code was reviewed by a member of staff that was not otherwise involved in coding for GGM to check for accuracy of code modifications at Versions 1.0, 1.3 and 3.0. A review of the code to check for maintainability was also undertaken at Versions 1.0, 2.0 and 3.0. Tests designed to select solver parameters that provide suitable numerical convergence and stability of results were undertaken at Version 1.0 and 2.0. Unit tests have been undertaken for all major code modifications, including:

- Relative humidity, zero-saturation behaviour, subroutine reorganisation, time-step control, conservation of mass, and Version 2.0;
- Water mass balance and relative humidity at Version 2.1; and
- Multi-compartment functionality, file format changes, non-isothermal functionality, temperature dependent corrosion rates and restart capability at Version 3.0.

At Version 1.3, a test suite was set-up to ensure that GGM produces plausible output in a number of alternative calculation cases. For each test, mass balance and stability of results are checked. This test suite has since been run at Versions 1.3 and 2.0. This testing has been performed by a third party that is not involved in the development of the code. The test suite includes four sets of tests. Set 1 includes general tests for different combinations of processes under water-saturated conditions: corrosion, microbial degradation, biomass (with and without recycling). The tests in Set 2 include different initial inventories designed to check mass balance of key species (carbon and iron). Tests in Set 3 have been chosen to test the effect of different relative humidity behaviour. Tests in Set 4 are designed to test behaviour under conditions of low water saturation.

A more detailed summary of the testing of GGM undertaken for Versions 3.0 and 3.1 are given in the following sections.

### 5.3 GGM VERSION 3.0 VERIFICATION RESULTS

The following changes were made to GGM between Version 2.1 and 3.0:

1. The multiple compartment functionality and associated changes to the file format.
2. Changes to allow for time varying temperatures.
3. Changes to allow for temperature dependent corrosion rates.
4. Changes to allow for a restart capability.

The tests that were undertaken at each stage are summarised in Table 5-1 to Table 5-4. In addition to the tests outlined below, further tests were undertaken in the context of T2GGM to check that the updated code provides results that are compatible with previous versions. This testing is described in Section 5.6.1. Any issues identified during testing were corrected.

**Table 5-1: Stage 1 Tests: Multi-Compartment and File Format Changes**

| Test Number | Description   |
|-------------|---|
| 1.1         | Check that it is possible to reproduce an existing GGM Version 2.1 standalone case using a single compartment isothermal setup.                         |
| 1.2         | Check that it is possible to reproduce two different GGM Version 2.1 variant standalone cases using a two-compartment isothermal setup.                 |
| 1.3         | A combined compartment output file produced by the GGM was sent to Geofirma to ensure that it complies with the format required by their mView scripts. |

**Table 5-2: Stage 2 Tests: Non-Isothermal Functionality**

| Test Number | Description   |
|-------------|---|
| 2.1         | Check that by specifying a constant temperature, the existing isothermal results using the L&ILW corrosion processes can be reproduced.   |
| 2.2         | A standalone case is run with a constant saturation (and gas volume) and a prescribed time varying temperature (using the driver program). Gas pressures are checked to be varying in accordance with the changes in temperature. |

**Table 5-3: Stage 3 Tests: Temperature-Dependent Corrosion Rates**

| Test Number | Description   |
|-------------|---|
| 3.1         | The modulation functions are calculated for a range of input values to ensure that they have been correctly implemented |
| 3.2         | An existing case with a prescribed temperature profile is run and the resulting output is checked for plausibility.     |

**Table 5-4: Stage 4 Tests: Restart Capability**

| <b>Test Number</b> | <b>Description</b>   |
|--------------------|--|
| 4.1                | Compartment based input files are copied and given restart file names. The GGM is started in restart mode. The results are checked to ensure that the code produces identical results to a normal start. |
| 4.2                | A restart file is requested part way through a standalone run. The GGM is restarted from that point. The two sets of results are checked to ensure that they are the same after the restart.             |

#### **5.4 GGM VERSION 3.1 VERIFICATION RESULTS**

No changes were made to the GGM code between Versions 3.0 and 3.1 – the incrementation in the version number was made solely to maintain consistency with the T2GGM versioning. Since no changes were made to GGM, verification of GGM Version 3.1 was not required.

#### **5.5 T2GGM VERIFICATION SUMMARY**

Testing for T2GGM has focussed on unit tests for code modifications and updates to the GGM. These unit tests have included the following:

- relative humidity behaviour at Versions 1.0, 2.0, 2.1 and 3.0;
- zero-saturation behaviour at Version 1.0 and 2.0;
- verification of repository void volume changes at Version 1.3;
- verification of timestep control and alternative gases at Version 2.0;
- multiple compartment, time-varying permeability, time-varying boundary conditions, optimised time-step adjustment, alternative neon as and revised file formats at Version 3.0; and
- the 1D hydromechanical model and restart capability at Version 3.1.

Tests against analytical results have been employed where possible. For example:

- the maximum vapour pressure for the relative humidity calculation has been compared against Antoine’s equation at Version 3.0; and
- the 1D Hydromechanical Model model results have been compared with an analytical solution for one-dimensional consolidation (Terzaghi 1943) and coupling in a semi-infinite column with gradual loading (Lemieux et al. 2008).

In addition, tests have been undertaken to ensure that results produced with newer versions are consistent with those from earlier versions and to check numerical convergence and stability. The code has also been reviewed for maintainability.

A more detailed summary of the testing undertaken at Version 3.0 and 3.1 is given the following sections.

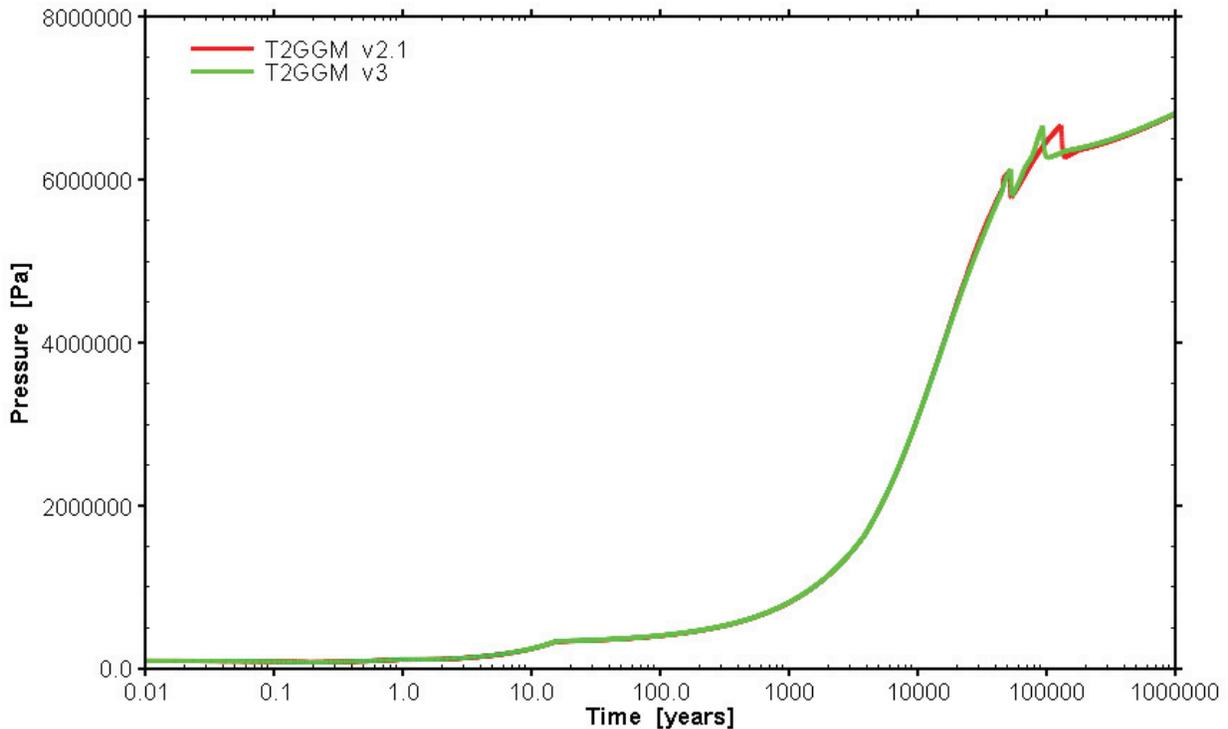
#### **5.6 T2GGM VERSION 3.0 VERIFICATION RESULTS**

The T2GGM Version 3.0 verification considers modifications made to the TOUGH2 components of T2GGM for Version 3.0. The first test, described in Section 5.6.1, also considers the full code, assuring that code modifications for Version 3.0 had no impact on previous Version 2.1

functionality. Most of the verification tests (Sections 5.6.2 through 5.6.7) use the following models: a 5CS Multiple Container model, a simple 2D test case with 1D flow for testing time-variable permeability, and a simple 1D test case for testing time-variable boundary conditions.

### 5.6.1 Previous Functionality

Modifications to T2GGM for Version 3.0 should not affect existing functions within T2GGM. 3DRS GG1 (Geofirma and Quintessa 2011) was used as the test case, and was run with both Version 2.1 and 3.0. For the non-water limited case the results were found to be the same. For the water-limited case, the general character of the results was the same, with some small differences in the timing at which the simulation ceases to be water-limited. This timing is very sensitive to convergence criteria, and due to changes in GGM time-stepping with Version 3.0, exactly the same results have not been obtained (see Figure 5-1). Reduction in either the GGM or the TOUGH2 convergence criteria improves results, however too low convergence criteria cause severe numeric instability. Optimal convergence criteria have not yet been determined.

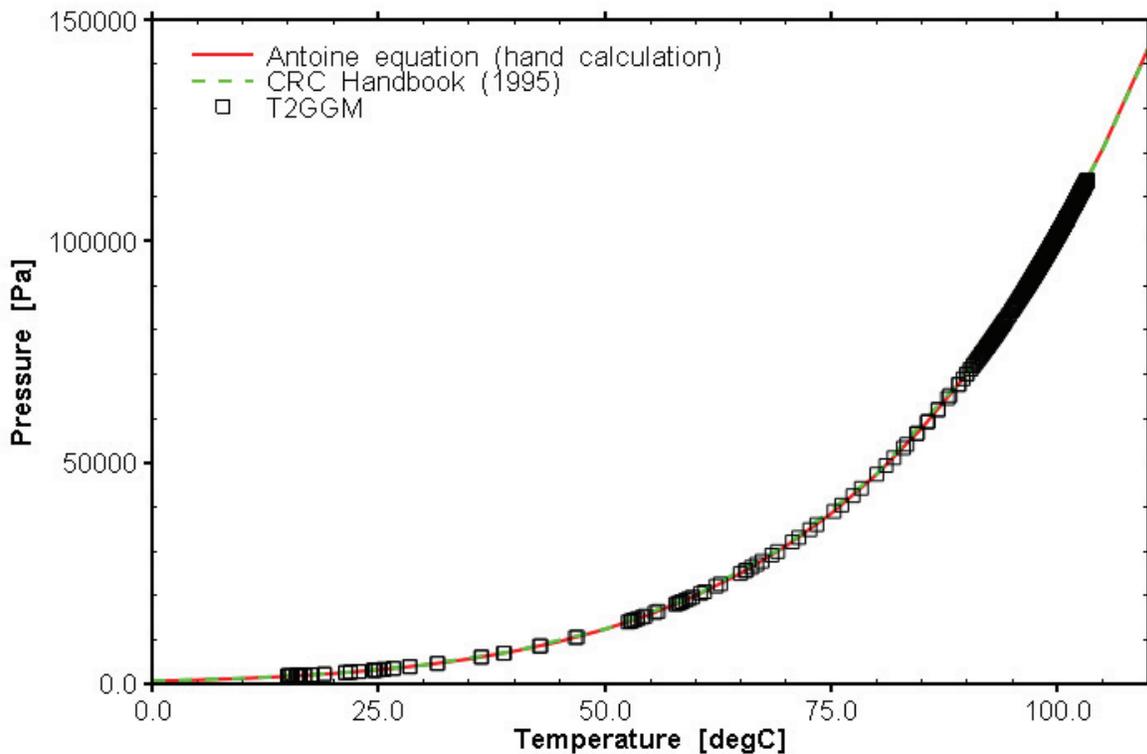


**Figure 5-1: Pressure in the GGM Container for 3DRS GG1 Water Limited Case, for both Version 2.1 and Version 3.0.**

Note that very small differences are also attributed to the value used for maximum vapour pressure. Version 2.1 uses a hard-coded maximum vapour pressure at 20°C (2340.05 Pa), whereas the simulation is isothermal at 22°C, which has a maximum vapour pressure of 2634.8 Pa using the Antoine equation. While this is only a 300 Pa difference, it can have a minor impact on resulting pressures in the form of a small offset. The maximum vapour pressure effects the calculation of RH and air pressure (gas pressure minus vapour pressure), both of which are inputs to GGM.

### 5.6.2 Relative Humidity Calculation

The relative humidity calculation is identical to previous versions of T2GGM, with the exception that the maximum vapour pressure is now temperature dependent using Antoine's equation. No specific output is available for the maximum vapour pressure calculated by the Antoine equation. Consequently, a debug file, containing temperature and resulting maximum vapour pressure, was written for the test case only. Using a 5CS Multiple Container model as the test case, the maximum vapour pressures output in the debug file were compared to hand calculations using the Antoine equation, as well as maximum water table values published in the CRC Handbook (1995). As shown in Figure 5-2, maximum vapour pressures were identical to hand calculations using Antoine's equation.



**Figure 5-2: Temperature-dependent Maximum Water Vapour Pressures as Calculated by T2GGM, Compared to Hand Calculations and Published Values**

### 5.6.3 Multiple Compartments

Resulting pressures, saturations and temperatures for each compartment provided in the GGM output files are compared to average pressures, saturations and temperatures for the compartment elements as calculated in mView from TOUGH2 output. The 5CS Multiple Container model, which contains two compartments, was used as the test case. Pressures, saturations and temperatures matched between T2GGM and GGM, for both compartments, although it should be noted that pressures calculated from T2GGM output were slightly higher than GGM (~0.5%), attributed to precision errors in the check calculations.

### 5.6.4 Time-varying Permeability

Time-varying permeability was tested using a simple 2D test case, with 1D flow. Permeabilities in the half of the grid were reduced by a factor of 0.1 part way through the simulation. Figure 5-3 shows the pressure results for the time-varying permeability test case. Note that the slight deviation in pressure at 5 m between the analytical hand-calculation and simulation results is due to differences in discretization. The test was considered successful as (1) early time pressure results (before permeability changes) compared exactly to a simulation with constant permeability, (2) late time pressure results were the same as a hand calculation of expected pressures due to the reduction in permeability, and (3) the change in pressure results occurred at the expected time based on the time-varying permeability definition.

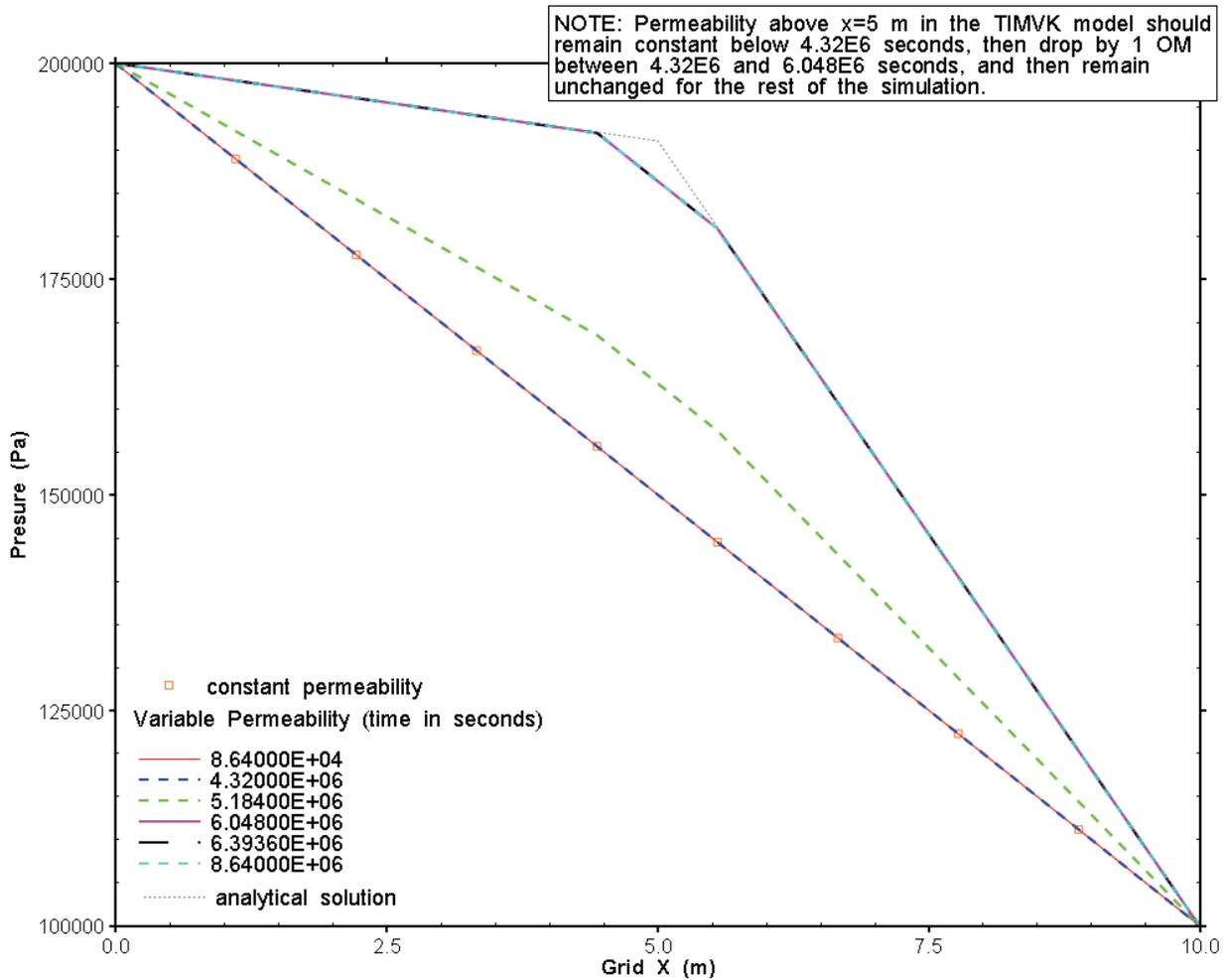


Figure 5-3: Results for Time-varying Permeability Test Case

### 5.6.5 Time-varying Boundary Conditions

A simple 1D test case verifies the correct implementation of time-variable boundary conditions. The test case modifies pressure, saturation and temperature in a single step change at a single boundary condition node. Inspection of the output file shows pressure, saturation and temperature at the boundary condition node to change according to the specification in the TIMBC input record.

### **5.6.6 Optimized Time-Step Adjustment**

The implementation of the optimized time-step adjustment is verified by inspection of the output file for the 5CS Multiple Container test case. Time step increases are by a factor of 1.8, as specified in the input record. Also, as specified in the input record, time step decreases are by a factor of 1.5, and a time step increase is not applied until at least 2 time steps have been completed.

### **5.6.7 Alternative Ne Gas**

The 1D test case for the time-variable boundary conditions was recalculated with neon as the gas, instead of air. The output file generated showed the correct values for neon (where the output file provides values for input read), and a hand calculation confirmed correct values of dissolved neon in liquid.

### **5.6.8 Revised File formats**

Revised file formats are verified by inspection of output files and post-processing of results from the 3DRS GG1 test case (Geofirma and Quintessa 2011), which has output times up to one million years. High precision times and format modifications were implemented to address output issues at longer times; these long output times are provided in this test case. High-precision times have been correctly implemented, as evidenced by the output times in the mView processed NOUT file (a binary file containing TOUGH2 nodal output for each output time). By examination of the output files, all output is correctly formatted (i.e. no overflow \*\*\* output). The new FOFT/COFT format, implemented in the GGMCALC.COMP output, is correctly read and processed within mView. Data in the GGMCALC.COMP output file (new FOFT/COFT format) matches the data in the GGMCALC table file (since there is only one compartment in this case, these two files should have identical data).

## **5.7 T2GGM VERSION 3.1 VERIFICATION RESULTS**

Modifications for Version 3.1 include the 1D hydro-mechanical model, as well as the restart capability.

### **5.7.1 1D Hydromechanical Model**

Three test cases are presented for the 1D hydro-mechanical model verification: the first two are fully water-saturated models compared to analytic solutions, and the third tests the model in a two-phase system. This third test verifies appropriate model execution rather than comparing to an analytic solution, as analytical solutions for partially gas saturated systems do not exist.

#### **5.7.1.1 1D Consolidation after Terzaghi (1943)**

For this full water-saturated case, model results are compared with the analytical solution for one-dimensional consolidation by Terzaghi (1943). In this problem, a layer of water-saturated rock is subjected to an instantaneously applied vertical load at the upper surface. The rock layer has a specified thickness ( $h$ ), and water is allowed to drain at the surface, where pressure is maintained constant. Hydraulic boundaries on all other sides are set as zero-flow. Mechanical boundary conditions on the vertical sides are roller boundaries, allowing only vertical movement. The analytical solution for pore pressure ( $P_p$ ) is as follows (Jaeger et al. 2007):

$$P_p(z, t) = \frac{\alpha M \sigma_{zz}}{(\lambda + 2G + \alpha^2 M)} * \sum_{i=1,3,\dots}^{\infty} \frac{4}{i\pi} \sin\left(\frac{i\pi z}{2h}\right) \exp\left(\frac{-i^2 \pi^2 k t}{4\mu S h^2}\right) \quad (5.1)$$

where:

- $\alpha$ = Biot-Willis coefficient (-);
- $t$ = time (s);
- $z$ = depth (m);
- $M$ = Biot modulus (Pa);
- $\sigma_{zz}$ = instantaneous vertical load (Pa);
- $\lambda$  = drained Lamé's modulus (Pa);
- $G$ = Shear modulus (Pa);
- $h$ = maximum depth (or thickness) of rock layer (m);
- $k$ = permeability ( $m^2$ );
- $\mu$ = dynamic viscosity ( $kg\ m^{-1}s^{-1}$ );
- $S$ = uniaxial storage coefficient ( $Pa^{-1}$ ).

A T2GGM model of a similar system was developed. As T2GGM applies load as a rate, it was not possible to obtain an instantaneous application of load. Instead, load was applied at such a rate that maximum loading was achieved within 0.1 years, which was short (i.e., nearly instantaneous) when compared to the total runtime of approximately 100 years. A second minor divergence between the numerical model and the analytical model is that TOUGH2 does not assume constant water density and compressibility, but calculates these as a function of temperature and pressure. However, over the pressure range examined here, the impact of this second divergence on results was minor.

Model properties are shown in Table 5-5. For comparison's sake, the mechanical parameters used are equivalent to those used for a similar verification exercise by Nasir et al. (2011), namely Young's modulus (E) of  $4 \times 10^7$  and Poisson's ratio ( $\nu$ ) of 0.3. The T2GGM model used a porosity of 0.1.

A comparison of analytical and numerical model results is shown in Figure 5-4. For this run the applied load ( $\sigma_{zz}$ ) was 3.0 MPa. The time axis is plotted as dimensionless time, defined as  $akt/\mu Sh^2$ . The agreement between numerical and analytical solutions is good, although the T2GGM model does seem to drain slightly faster at greater depths and times.

**Table 5-5: Model Properties for the Terzaghi (1943) Verification Case**

| Analytical       |                        | TOUGH2                  |                        |
|------------------|------------------------|-------------------------|------------------------|
| Property         | Value                  | Property                | Value                  |
| $k\ (m^2)$       | $2.04 \times 10^{-15}$ | $k\ (m^2)$              | $2.04 \times 10^{-15}$ |
| $S\ (Pa^{-1})^*$ | $1.86 \times 10^{-8}$  | $C_{pore}\ (Pa^{-1})^*$ | $1.86 \times 10^{-7}$  |
| $\alpha$         | varies                 | $\zeta$                 | varies                 |
| $h\ (m)$         | 1000                   | $h\ (m)$                | 1000                   |

\*S and  $C_{pore}$  are different parameters describing the compressibility of the rock. These parameters are equivalent, based on a rock compressibility of  $3.33 \times 10^7$  Pa.

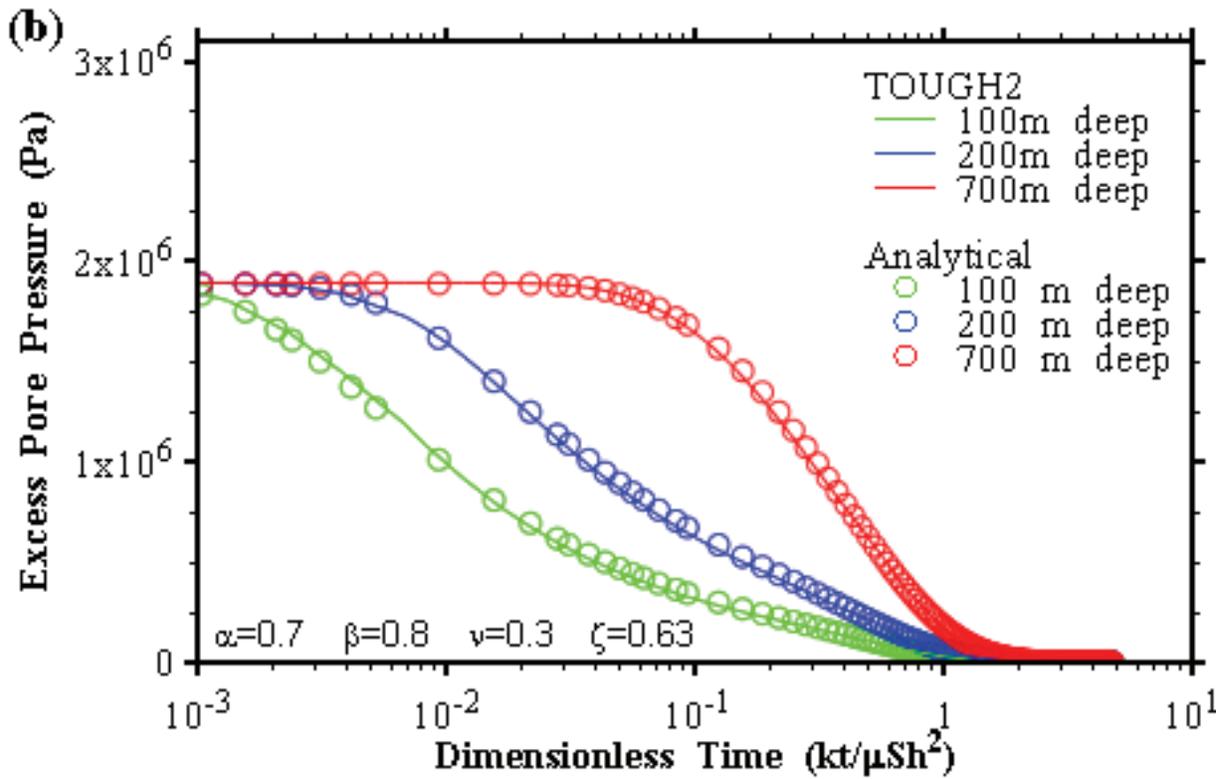
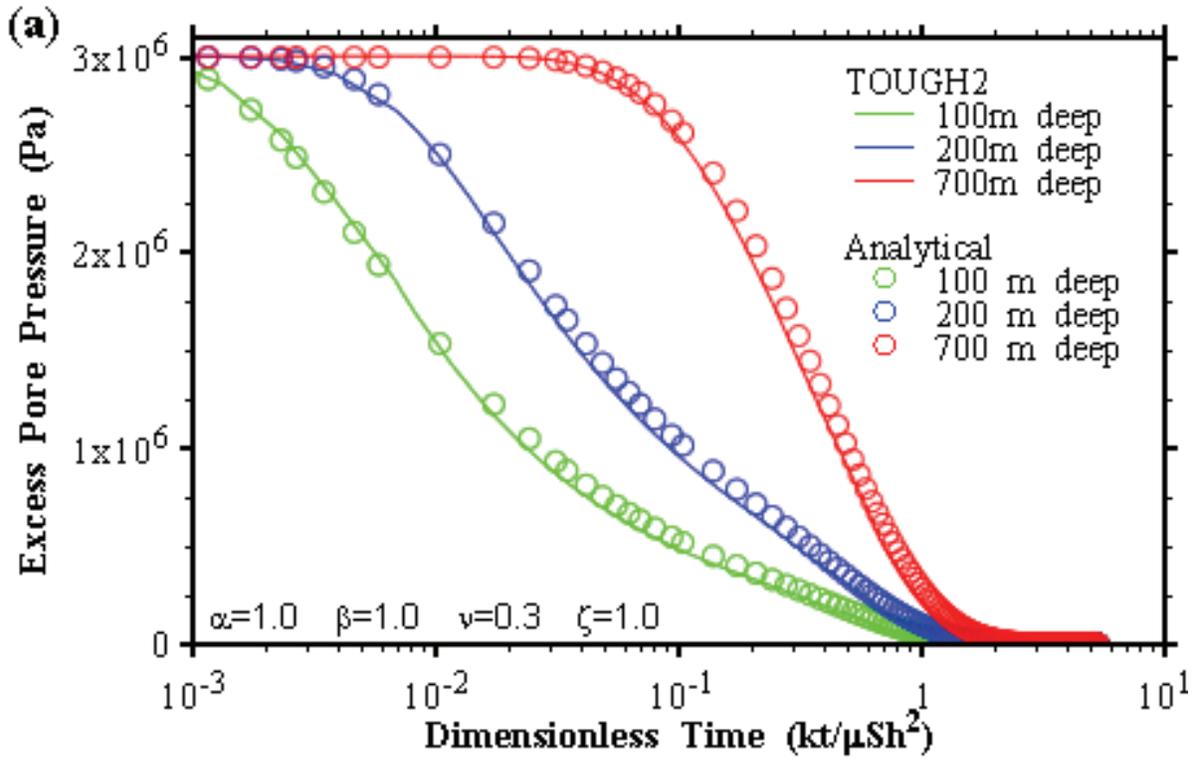


Figure 5-4: Analytical and T2GGM Pressure Time-Series, Various Depths, (a)  $\zeta = 1$ ,  
(b)  $\zeta = 0.63$

### 5.7.1.2 1D Hydromechanical Coupling in a Semi-infinite Column with Gradual Loading

For this fully-water saturated verification case, the analytical solution described in Lemieux et al. (2008) was used. This is an analytical solution for one-dimensional hydro-mechanical coupling in a semi-infinite column. In this model, the applied stress is continually increased as a linear function of time. The top of the column is drained (hydraulic head is held constant at zero) and the base of the column is at an infinite distance. The analytical solution to this problem is as follows:

$$h(z, t) = \frac{\zeta}{\rho g} \frac{d\sigma_{zz}}{dt} \left[ t - \left( t + \frac{z}{2D} \right) \operatorname{erfc} \left( \frac{z}{2\sqrt{Dt}} \right) + z \sqrt{\frac{t}{\pi D}} \exp \left( -\frac{z^2}{4Dt} \right) \right] \quad (5.2)$$

where:

$\zeta$  = one dimensional loading efficiency (-);

$\rho$  = fluid density (kg/m<sup>3</sup>);

$g$  = gravity (m/s<sup>2</sup>);

$d\sigma_{zz}/dt$  = stress application rate (Pa/s), a constant as discussed above;

$t$  = time (s);

$z$  = depth (m);

$D$  = hydraulic diffusivity (m<sup>2</sup>/s), hydraulic conductivity divided by specific storage.

Note that there is a slight difference between Equation (5.2) and the solution shown in Lemieux et al. (2008), which has a typographical error.

A similar system was modelled using T2GGM. Model properties are shown in Table 5-6. The primary difference between the numerical model and the analytical model was the total vertical depth of 7000 m for the numerical model. The analytical model is semi-infinite, but a greater depth in the numerical model would have led to pore pressures in excess of 100 MPa, which is a hard-coded cut-off beyond which the TOUGH2 EOS3 module does not function. The T2GGM model had a constant specified pressure of 100 kPa (~1 atm) at the top, a no-flow boundary at the base, and was water saturated throughout. As with the previous verification case, the analytical model assumes constant water density and compressibility unlike TOUGH2, which has a minor impact on results over the pressure range examined here.

**Table 5-6: Model Properties for the Second Verification Case\***

| Analytical               |                      | TOUGH2                                |                        |
|--------------------------|----------------------|---------------------------------------|------------------------|
| Property                 | Value                | Property                              | Value                  |
| $K_{zz}$ (m/a)           | $1.0 \times 10^{-3}$ | $k_{zz}$ (m <sup>2</sup> )            | $3.23 \times 10^{-18}$ |
| $S_s$ (m <sup>-1</sup> ) | $1.0 \times 10^{-6}$ | $C_{\text{pore}}$ (Pa <sup>-1</sup> ) | $5.70 \times 10^{-10}$ |
| $\zeta$                  | Varies               | $\zeta$                               | varies                 |

\*Values provided in this table are the input requirements for each model. The input requirements for each model are different (i.e., the analytical model requires hydraulic conductivity ( $K_{zz}$ ) and specific storage ( $S_s$ ) and the TOUGH2 model requires permeability ( $k_{zz}$ ) and pore compressibility ( $C_{\text{pore}}$ )), and the parameters provided for each model are equivalent once standard unit conversions and equations are applied.

The TOUGH2 pressure results were converted to hydraulic head, and compared against the analytical solution, as shown in Figure 5-5. Despite the slightly different assumptions between the two models, the TOUGH2 results are a good match with the analytical solution.

The impact of changing the loading efficiency was also assessed, in both the analytical and the T2GGM models (see Figure 5-6). Once again, the numerical and analytical models correspond very well. As expected, reducing the loading efficiency reduces the mechanically-induced pressure rise in the 1D column.

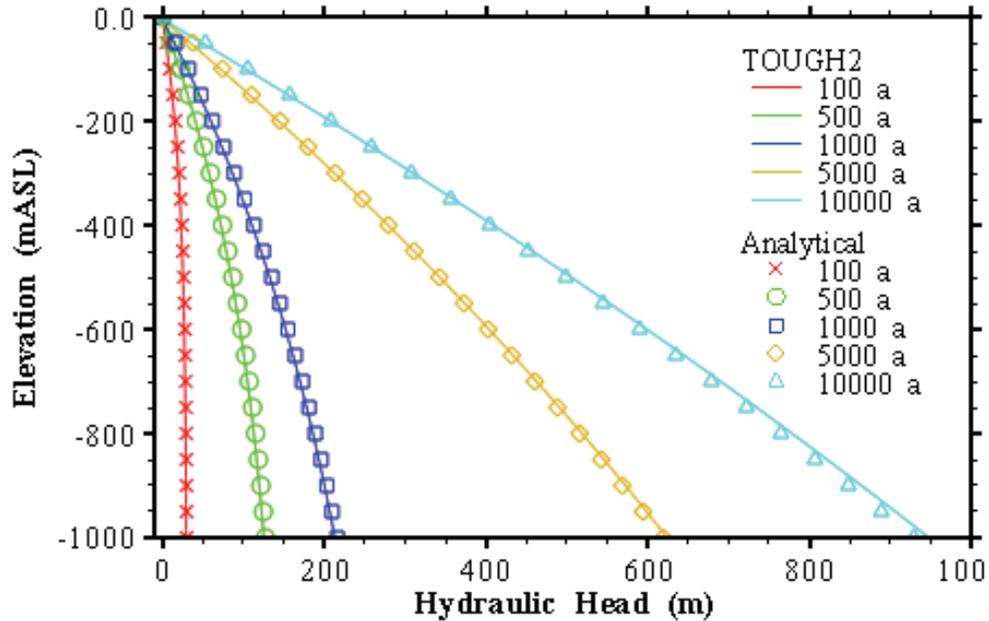


Figure 5-5: Analytical and T2GGM Calculated Hydraulic Head versus Depth at Different Times

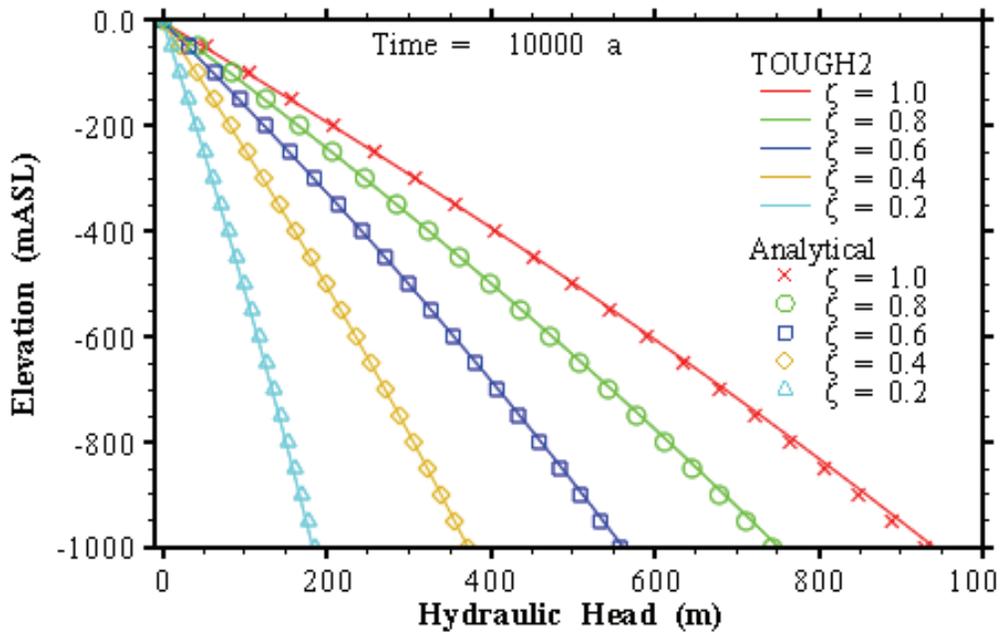


Figure 5-6: Analytical and T2GGM Calculated Hydraulic Head versus Depth at 10 000 years, for Different Loading Efficiencies ( $\zeta$ )

### 5.7.1.3 A Simple Two-phase Test Case

In this section, a homogeneous, one-dimensional model is used to examine the effects of gas in a hydro-mechanical system. It should be emphasized that this verification is by inspection only; analytical data does not exist to verify the two-phase component of the 1D hydro-mechanical model.

The example is simplified and artificial, but nevertheless allows us to focus on the effects of gas without the complexity inherent in most natural systems. This homogeneous system is loaded (as shown in Figure 5-7), and the change in water pressure (expressed in m H<sub>2</sub>O) under various conditions is assessed. The permeability is rather low to remove drainage effects, and a generic capillary pressure curve, typical of such low permeability rock, was used. Water pressure was initialized at hydrostatic, gas pressure was initialized in equilibrium with the water pressure as a function of the capillary pressure curve. Loading efficiency ( $\zeta$ ) was set to 0.7.

Figure 5-7 shows how the initial gas saturation affects the hydro-mechanical (HM) process: as gas saturation ( $S_G$ ) increases, the degree of HM coupling drops as gas is able to compress and minimize the pressure impact of a mechanical load. Porosity changes due to pressure-dependent compressibility (term 2 of Equation 4.3) compensate for any porosity changes due to mechanical loading, which are constant regardless of gas saturation (term 3 of Equation 4.3). Low gas saturations can still have a profound effect on the HM response. Also interesting to note, for the models with very low gas saturations, the changing shape of the curve indicates a transition from two-phase to fully saturated behavior as the increased pressure causes the gas in the system to dissolve.

The impact of alternate parameters, such as compressibility and depth, are described in detail within Walsh et al. (2012).

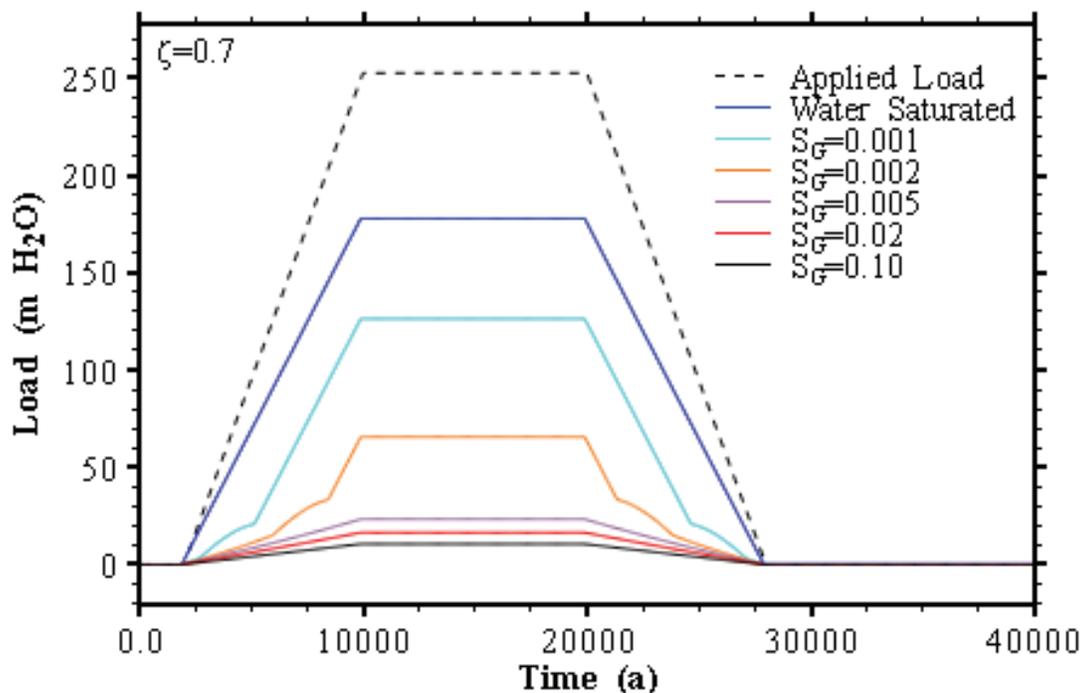
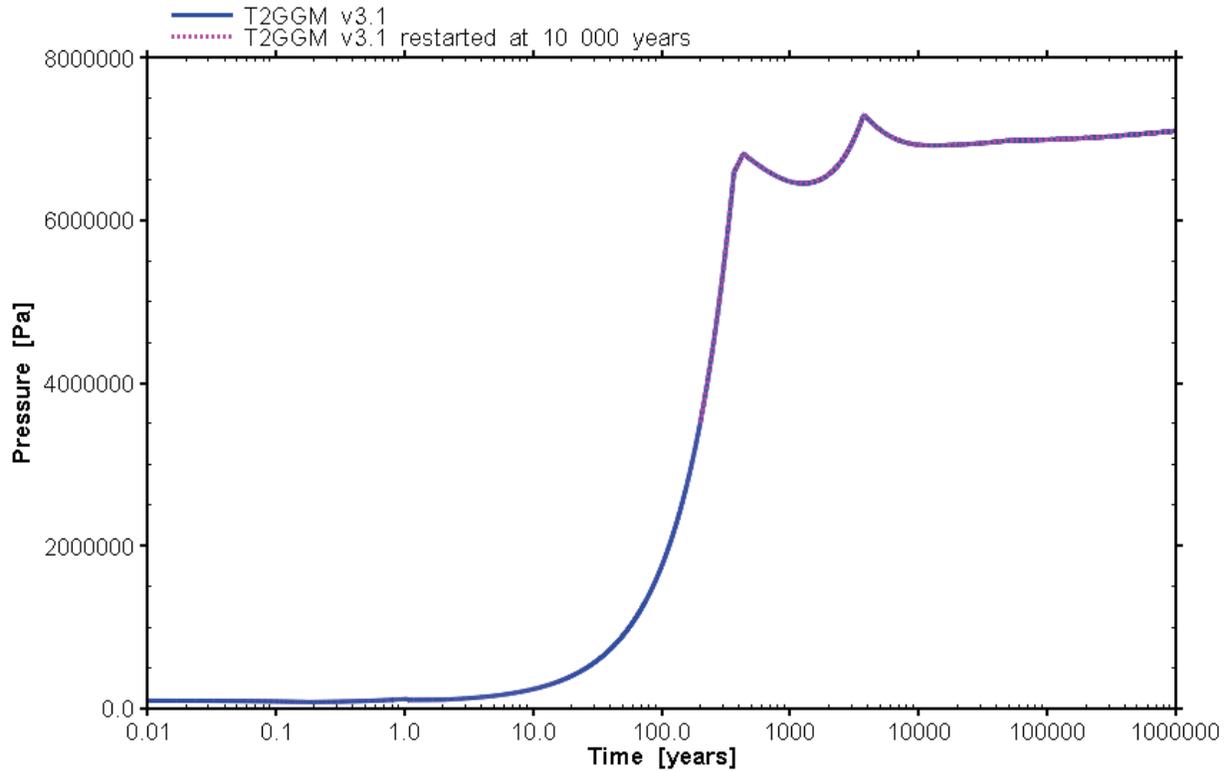


Figure 5-7: Effect of Gas Saturation

### 5.7.2 Restart Capability

3DRS GG1 NWL (Geofirma and Quintessa 2011) was used as the test case, and the original simulation run with Version 3.1 was restarted at 200 years. Figure 5-8 compares the pressure in the repository for the original simulation and the restarted simulation, showing results to be identical.



**Figure 5-8: Pressure in the GGM Container for 3DRS GG1 NWL Case, Comparing Version 3.1 and a Restart at 200 Years**

### 5.8 ANALYSIS SUMMARY

GGM Version 3.1 has been demonstrated to be able to solve the equations described in the Theory Manual (Section 3) accurately. It has been shown that GGM is suitable for use as a module that can be interfaced with the TOUGH2 gas transport code, the combined code being T2GGM Version 3.1. The standalone GGM typically takes several minutes to run and the integrated T2GGM code takes between several hours and several days to run depending on the case.

## 6. VALIDATION

Validation, as defined in the NWMO Software Procedures (NWMO 2010) involves determining the accuracy of the software results with respect to its intended application. The results of T2GGM are intended to calculate:

- The magnitude and timing of the peak gas pressure;
- The evolution of the repository saturation;
- The rates of gas and water generation within the repository; and
- The flux of gas and water through the geosphere.

Validation of T2GGM has been undertaken as a process of continuously testing the code and increasing confidence in the results. The approach taken to validation combines expert review, comparisons with independent calculations, and comparisons against experiments.

The main validations to date are below.

- The TOUGH2 gas transport model is a widely used model for two-phase flow and gas transport in geological media, including for deep geologic repositories (e.g., Talandier et al 2006, Nagra 2008, FORGE 2010, Bate et al. 2012).
- T2GGM has been used by NWMO in international projects:
  - Swiss HG-A gas permeation experiment at Mont Terri;
  - Swedish LASGIT gas experiment at Aspo; and
  - European code comparison on gas transport in repositories.
- T2GGM has been compared with FRAC3DVS for saturated system, obtaining consistent results (Section 7.3.3, Quintessa et al 2011).
- The GGM gas generation model is consistent with general literature and with approaches adopted in other waste management organizations for similar models. All results have undergone internal review by the experts responsible for developing GGM Theory. Results for T2GGM Version 1.2 also underwent external peer review.
- T2GGM Version 1.3 transport results were compared with an oil & gas industry-standard gas modelling code GEM for one reference case (ARC 2010). Due to inherent differences in the code purposes, only a limited comparison was possible, but the results were consistent.
- T2GGM Version 2.1 demonstrates mass balance for the key modelled species.
- At Version 2.0, GGM was compared against data from the Finnish large scale Gas Generation Experiment (GGE) (Appendix B, Quintessa and Geofirma, 2011a).

## 7. USER MANUAL

### 7.1 TOUGH2

For general usage of TOUGH2, please see the TOUGH2 User's Guide (Pruess et al. 1999). Specific details relating to the implementation of GGM and other TOUGH2 modifications are detailed in the following sections.

#### 7.1.1 GGM Input

GGM is invoked by the GGMIN keyword. GGMIN input following the keyword is specified in Table 7-1.

**Table 7-1: GGMIN Input**

| Line | Variables   | Format |
|------|---|--------|
| 1    | Version number. The current version number for the inputs described below is 1.   | I2     |
| 2    | NORMG– If not equal to zero, gas injection flow is distributed to all gas source elements with a gas saturation greater than zero.<br>NORML – If not equal to zero, liquid injection flow is distributed to all liquid sink elements with a liquid saturation greater than zero.<br>SCALEFACTORG – If not equal to zero, scale factors distribute GGM flows to the gas source elements are calculated at each time step based on the amount of gas available in each source element. These scale factors replace values read into the XGASSRC array described below. May increase run times, but increase model stability.<br>SCALEFACTORL – If not equal to zero, scale factors distribute GGM flows to the liquid sink elements are calculated at each time step based on the amount of water available in each sink element. These scale factors replace values read into the XLIQSNK array described below. May increase run times, but increase model stability. | 4I2    |
| 3    | VOLFAC – repository volume factor   | E15.0  |
| 4    | GASRSAT – Residual gas saturation, below which no gas can be removed from the repository (if QAIR is less than zero).   | *      |
| 5    | USELIQCTRL - flag (0, 1) to control whether liquid saturation limits are enforced. NORML is only applied if USELIQCTRL is set to 1.   | *      |
| 6    | LSATOFFVAL - used only if USELIQCTRL = 1. The liquid saturation below which no water is extracted from a liquid sink element. Water extraction is also eliminated for an element if the element RH is below RHMNLIM (see below). If one or more elements have saturations greater than LSATOFFVAL and NORML is true, then liquid injection flow is distributed. If all liquid sink elements are below LSATOFFVAL, then no liquid is extracted. If this condition is true, then RH is set to RHLIMMIN (see below) on subsequent time steps, until at least saturation in at least one liquid extraction element exceeds LSATONVAL.   | *      |
| 7    | LSATONVAL - the minimum saturation threshold required for one or more liquid extraction elements for liquid extraction to resume, after it has been previously terminated due to saturation at all liquid extraction nodes being less than LSATOFFVAL.  | *      |
| 8    | USERHCTRL - flag (0, 1) which determines whether RH input to GGM is scaled based on residual liquid saturations. This is the most effective way to balance GGM water consumption with geosphere inflow as it slows  | *      |

|    |  |                                |
|----|--|--------------------------------|
|    | down vapour phase reactions gradually as a saturation limit is reached.  |                                |
| 9  | RHLSATMIN - minimum liquid saturation for RH control   | *                              |
| 10 | RHLSATMAX - maximum liquid saturation for RH control   | *                              |
| 11 | <p>RHLIMMIN - RH value for minimum saturation and lower limit of element RH for liquid extraction from an element. This value should be equivalent to PRHMIN in order to maintain correspondence to GGM, however, it is included as a separate parameter for stability reasons: it may be practical to have a value greater than PRHMIN to minimize stability issues at single liquid sink elements if the repository does not become fully de-saturated with liquid (i.e., repository liquid saturation remains above LSATONVAL) over the course of the simulation.</p> <p>The code fragment below describes the scaling approach</p> <pre> IF ((RH.GT.RHLIMMIN).AND.(USERHCTRL.EQ.1))THEN   RHMULT = TANH((STOT-RHLSATMIN)/(0.5*(RHLSATMAX- RHLSATMIN)))   IF (RHMULT.GT.1.0) RHMULT = 1.0;   IF (RHMULT.LT.0.0) RHMULT = 0.0;   RH = RHLIMMIN + (RH - RHLIMMIN) * RHMULT; END IF </pre> | *                              |
| 12 | <p>GGM_RESTART_READ – If true, causes the GGM restart input to be read (instead of the normal input file).</p> <p>GGM_RESTART_WRITE – If true, causes GGM restart information to be written at each output time step.</p>  | 2L4                            |
| 13 | <p>NREPO – number of repository elements</p> <p>NCOMP – number of compartments</p>   | 2I5                            |
| 14 | <p>EREP(NREPO) – names of repository elements</p> <p>ICOMP(NREPO) – compartment ID of repository element</p>   | (A5, E) for NREPO lines        |
| 15 | NGASSRC – number of gas source elements  | I5                             |
| 16 | <p>EGASSRC(NREP) – names of gas source elements</p> <p>XGASSRC(NGASSRC) – scaling factor for each source element</p>   | (A5, E) for NGASSRC lines      |
| 17 | NLIQSNK – number of liquid sink elements   | I5                             |
| 18 | <p>ELIQSNK(NREP) – names of liquid sink elements</p> <p>XLIQSNK (NLIQSNK) – scaling factor for each sink element</p>   | (A5, E) for NLIQSNK lines      |
| 19 | NREPCONN – number of connections contributing water to the repository  | I5                             |
| 20 | <p>EREPCONN(NREPCONN) – names of connections contributing water to the repository</p> <p>EREPSIDE (NREPCONN) – names of element on repository side of the connection</p>   | (A10,1X,A5) for NREPCONN lines |

Note that gas source and liquid sink elements may be the same. Also note that although gas source and liquid sink elements are expected to be in the repository this is not checked. Nodes should be specified using standard TOUGH2 node naming conventions.

### 7.1.2 Alternative Gas Input

The EOS3 module used by T2GGM assumes that air is the gas, however, an alternative gas may be specified by changing the Henry's constant, molar mass, specific heat capacity (not used in isothermal T2GGM calculations), and viscosity. Viscosity is calculated as a temperature dependent variable within TOUGH2.

To specify a gas other than air, provide the ALTGAS input record, which specifies the alternative gas to be used, as well as alternative parameter values. Alternative gases that can be specified include CH<sub>4</sub>, CO<sub>2</sub>, H<sub>2</sub>, He and Ne. Default values for each gas are hard-coded into TOUGH2 subroutine EOS in a manner similar to the existing air parameters; however, the input record for ALTGAS provides the ability to override any of the default parameter values. Details of the inputs are specified in Table 7-2.

**Table 7-2: ALTGAS Input Record**

| Parameter   | Format | Description   |
|-------------|--------|---|
| ALTGA       | A5     | First line of record. Once these characters have been read, the following line is read, containing the parameters detailed below.   |
| ALTGAS      | A5     | Characters specifying the gas to use: AIR, CO2, CH4, H2, HE or NE.  |
| VISC_METHOD | I5     | Integer flag specifying the viscosity calculation to use. A value less than or equal to zero uses the EOS3 default viscosity calculation for air. Greater than zero uses the TMVOC based viscosity calculation specific to the gas specified by ALTGAS. |
| ALT_H       | E10.4  | Alternative value of Henry's constant to be used. Units are: (mole fraction) Pa <sup>-1</sup> .   |
| ALT_AMA     | E10.4  | Alternative value of molar mass to be used. Units are: g mol <sup>-1</sup> .  |
| ALT_CVGAS   | E10.4  | Alternative value of specific heat capacity to be used. Units are: J kg <sup>-1</sup> K <sup>-1</sup> .   |
| ALT_VISCG   | E10.4  | Alternative value of isothermal viscosity to be used. Units are: Pa s.  |

As previously mentioned, viscosity is calculated as a temperature dependent parameter specifically for air. New temperature dependent viscosity routines were included, based on routines found in TMVOC that consider the multiple gases, including CH<sub>4</sub>, CO<sub>2</sub>, H<sub>2</sub> and He. A temperature dependent function for neon was not readily available. Since neon is currently only used in the LASGIT project, which is isothermal, a constant value of 32.1 μPa s at 300 K (CRC 1995) was coded for neon viscosity.

The parameters defined for the gas are echoed in the standard output. Hard-coded values specified in the EOS subroutine are given in Table 7-3.

**Table 7-3: ALTGAS Constant Values**

| ALTGAS ID | Henry's Law Constant (H) (mole fraction Pa <sup>-1</sup> ) | Molecular Weight (AMA) (g mol <sup>-1</sup> ) | Specific Heat Capacity (CVGAS) (J kg <sup>-1</sup> K <sup>-1</sup> ) |
|-----------|--|---|--|
| AIR       | 1.0E-10  | 28.96   | 733  |
| H2        | 2.82E-11   | 2.016   | 0.0143   |

|     |           |         |        |
|-----|-----------|---------|--------|
| CO2 | 1.23E-09  | 44.00   | 839    |
| CH4 | 4.93E-11  | 16.043  | 2191   |
| HE  | 6.72E-11  | 4.003   | 5193.1 |
| NE  | 8.045E-11 | 20.1797 | 1030   |

### 7.1.3 1D Hydro-Mechanical Model

The 1D hydro-mechanical model allows specification of a time-varying, one-dimensional mechanical load, such as might be expected from glaciation effects, as described in Section 4.1. This model is invoked by using the TIMHM record, as detailed in Table 7-4. The input record must appear after the ROCKS record.

**Table 7-4: TIMHM Input Record**

| Parameter            | Format | Description   |
|----------------------|--------|---|
| TIMHM                | A5     | First line of record. Once these characters have been read, the following lines are read, containing the parameters detailed below.   |
| TIMHM.1 (first row)  |        |   |
| VER                  | I5     | version number  |
| twoPhase             | I5     | Integer flag specifying the equation used to calculate $S_{S-1D} \zeta$ : if greater than zero, Equation (4.11) is used, otherwise Equation (4.12) is used.   |
| calcKsKphi           | I5     | Integer flag: if greater than zero, $1/K_s$ is calculated according to Equation (4.6), otherwise $1/K_s$ is equal to zero. It is recommended that this flag be set to zero to maintain consistency with internal TOUGH2 assumptions.  |
| oneDCOM              | I5     | Integer flag: if greater than zero, the pore compressibility specified in the ROCKS parameters (COM) is assumed to be three-dimensional, otherwise it is assumed to be one-dimensional. It is recommended that this flag be set to zero to maintain consistency with internal TOUGH2 assumptions (and that the COM specified in ROCKS is a 1D compressibility). |
| compSAT              | I5     | Integer flag: if greater than zero, capillary pressure is corrected for changes in porosity (i.e. capillary pressure is at a saturation equal to the current saturation + the change in porosity). It is recommended that this flag be set to zero.   |
| TIMHM.2 (second row) |        |   |

| Parameter                        | Format | Description  |
|----------------------------------|--------|--|
| WATERCOM                         | E14.7  | Compressibility of water, only used if twoPhase equals zero (i.e. used in Equation (4.12)).  |
| TIMHM.3 (third row)              |        |  |
| nZeta                            | I5     | The number of material groups (i.e. specifies the number of TIMHM.4 rows to read)  |
| TIMHM.4 (rows 4 through 4+nZeta) |        |  |
| matName                          | *      | Material name, must match a name in the ROCKS record.  |
| Zeta                             | *      | 1D loading efficiency ( $\zeta$ ), only used if twoPhase equals zero (i.e. used in Equation (4.12)).                               |
| Nu                               | *      | Poisson's ratio ( $\nu$ ), only used if twoPhase greater than zero (used in Equation (4.11)). *                                    |
| Alpha                            | *      | Biot-Willis coefficient ( $\alpha$ ), used if twoPhase greater than zero (calculates 3D 1/K used in Equation (4.11) from 1D COM).* |
| TIMHM.5 (row (4+nZeta) + 1)      |        |  |
| npoint_HM                        | I5     | Number of points on the HM loading curve.  |
| TIMHM.6                          |        |  |
| timhm(i=1,npoint_HM)             | 4E14.7 | Times in HM loading curve.   |
| TIMHM.7                          |        |  |
| stresshm(i=1,npoint_HM)          | 4E14.7 | Loading rates in HM loading curve (in Pa/s).   |

\* Note that these parameters may be required under a different combination of flags (twoPhase, calcKsKphi and oneDCOM), and the requirements listed here are based on the recommended flag settings specified in this table. The echo of the input in the output record will specify which parameters are required for the current set of flags.

#### 7.1.4 Time-Variable Permeability

The user can specify a time-variable permeability function for a specified set of nodes. Using the inputs from the TIMVK input record, specified in Table 7-5, the absolute permeability for the specified elements is multiplied by the time-interpolated scale factor vkvals.

**Table 7-5: TIMVK Input Record**

| Parameter | Format | Description   |
|-----------|--------|---|
| TIMVK     | A5     | First line of record. Once these characters have been read, the remaining record is read, containing the parameters detailed below. |

| Parameter                          | Format | Description                              |
|------------------------------------|--------|--|
| ntptab_vk                          | *      | number of nodes                          |
| vkelem(i=1, ntptab_vk)             | *      | node ids                                 |
| npoint_vk                          | *      | number of times in permeability function |
| Timvkv, vkvals                     | *      | time, permeability scale factor          |
| Repeat last lines npoint_vk times. |        |  |

\*refers to free format

### 7.1.5 Time-Variable Boundary Conditions

Based on the TOUGH2-MP implementation, the time-varying pressure, saturation and temperature Dirichlet boundary condition uses an input TIMBC record, outlined in Table 7-6, and updates the pressure, saturation and temperature at each boundary condition element at the beginning of each new time step. This type of boundary condition only works with large volume boundary conditions, not with negative volume boundary conditions.

**Table 7-6: Time-varying Dirichlet Boundary Condition Input Record (TIMBC)**

| Parameter                            | Format | Description   |
|--------------------------------------|--------|---|
| TIMBC                                | A5     | First line of record. Once these characters have been read, the remaining record is read, containing the parameters detailed below. |
| version                              | I5     | Version number is expected to be 2 with the inclusion of temperature  |
| npoint, ntptab                       | 2I5    | number of time points, number of nodes  |
| timbcv(i=1,npoint)                   | 4E14.7 | Times   |
| bcelem                               | A5     | node id   |
| pgbcel(i=1,npoint)                   | 4E14.7 | Gas pressures (Pa)  |
| sgbcel(i=1,npoint)                   | 4E14.7 | Gas saturation (10+gas saturation, as in INCON) or air mass fraction  |
| tgbcel(i=1,npoint)                   | 4E14.7 | Temperature   |
| Repeat last four lines ntptab times. |        |   |

Note that the interpolation routine for saturations assumes boundary condition at a single node is always two-phase or single phase i.e., a single node always has a gas saturation (values between 10 and 11), or an air mass fraction (values between 0 and 1).

### 7.1.6 Time Stepping Options

The time step input record (TSTEP) allows the modeller greater control over time-step changes. The input record is described in Table 7-7.

**Table 7-7: Time Step Adjustment Input Record (TSTEP)**

| Parameter                   | Format     | Description  |
|-----------------------------|------------|--|
| TSTEP                       | A5         | First line of record. Once these characters have been read, the remaining record is read, containing the parameters detailed below.  |
| version                     | I5         | currently only one version   |
| incfact, decfact, maxtshold | 2E10.5, I5 | <p>incfact - increment time step factor, default 2. Time steps are only increased if the number of iterations is less than MOP(16) and maxtshold steps after the last time step reduction. Default TOUGH2 time stepping uses a time step multiplier of 2 whenever the number of iterations is less than MOP(16). It is suggested that a multiplier of 2 is aggressive and a smaller value be used (e.g. 1.5).</p> <p>decfact - decrement time step factor, default 2. Default TOUGH2 time stepping reduces time steps by a factor of REDLT, which has a default value of 4.</p> <p>maxtshold - after a time step decrease, the time step is not increased until maxtshold time steps have completed, default 5</p> |

### 7.1.7 Modified van Genuchten Capillary Pressure and Relative Permeability Functions

The modified van Genuchten capillary pressure and relative permeability functions are invoked using ICP and IRP = 14 in the ROCKS section.

### 7.1.8 Relative Humidity Calculation

T2GGM calculates relative humidity based on the average vapour pressure of the repository elements divided by the maximum water vapour pressure. For T2GGM Version 3.0 and later, the temperature dependent value for the maximum water vapour pressure is given by Antoine's equation (Reid et al. 1987):

$$P_{v,max} = 10^{\left(A - \frac{B}{C+T}\right)} \quad (7.1)$$

Where  $P_{v,max}$  is the maximum water vapour pressure,  $T$  is the temperature, and  $A$ ,  $B$  and  $C$  are constants. For water between a temperature range of 1 and 100°C,  $P_{v,max}$  in mmHg and  $T$  in °C,  $A = 8.07131$ ,  $B = 1730.63$  and  $C = 233.426$  (Dortmund Data Bank, [www.ddbst.com](http://www.ddbst.com)).

### 7.1.9 High Precision Output Times (TIMES record)

Higher precision times allows for more accurate output times, particularly for times greater than 25 k years. Higher precision times (5E15.10) in the standard TOUGH2 TIMES input record is invoked by setting the number of times (ITI) negative.

### 7.1.10 Output Files

Binary output files, revised COFT/FOFT formats, and COFT/FOFT path for MP are invoked with the FILES keyword, as described in Table 7-8.

**Table 7-8: FILES Input Records**

| Line | Variables  | Format |
|------|--|--------|
| 1    | FILES keyword  | A5     |
| 2    | IBINOUT - if greater than zero, binary output files are produced<br>IFCOFT – if greater than zero, writes revised FOFC/COFT output<br>IGFDOUT – if greater than zero, writes diffusion output in binary format to DOUT | 3I5    |
| 3    | IPATHOUT - if set to non-zero, MP FOFT and COFT output is written to a separate file by each processor.  | I5     |
| 4    | GFPATH - output path if IFPATH is non-zero   | A200   |

## 7.2 GGM

GGM consists of a set of FORTRAN 77 subroutines that are compiled with TOUGH2. In order to drive the GGM module, in addition to configuring TOUGH2 to provide the necessary run-time information via subroutine arguments, files containing all input and solution control parameters must be prepared. Example input files are provided with the source code containing input data that is consistent with the relevant Data report (Quintessa and Geofirma 2011b). A description of each of the input parameters is given in Table 7-12 and Table 7-13. GGM sends its output to various FORTRAN units with the format described in the Design Description. This output can be directed to file and analyzed as appropriate. Note that for extremely long runs very large output files (several gigabytes in size) may be produced if output is requested at every internal time step. The LOGTR input parameter can be used to control how often GGM sends output to the output file unit.

GGM can also be compiled and run in standalone mode for testing purposes. Compilation scripts that can be run in a Linux environment or on Windows using Cygwin are provided with the source code for this purpose. Further details can be found with the README file provided with the software.

## 7.2.1 Input Files

GGM requires two types of input file:

1. A single global input file defining global parameters and GGM configuration options (read from unit IGGMINPT); and
2. A per compartment input file defining compartment specific input parameters (read from unit IGGMINCO).

The general format employed by these fields is given in Table 7-9, with italicized text denoting user input. Here *filetype* is GLOBAL or COMPARTMENT, *value* is the data value, *name* is an alphanumeric code and *comment* is arbitrary text that is ignored by the GGM but which can be used to store information such as required units.

**Table 7-9: General Format for Input Files**

| Line       | Contents                              |
|------------|---------------------------------------|
| 1          | # GGM_INPUT_FILE_FORMAT 1             |
| 2          | # GGM_INPUT_FILE_TYPE <i>filetype</i> |
| subsequent | <i>value name comment</i>             |

The data required for the global and compartmental input files are given in Table 7-12 and Table 7-13, respectively.

The values used for these parameters in the postclosure safety assessment for OPG's proposed DGR for L&ILW are given in Quintessa and Geofirma (2011b). The name, description and units of each parameter are output to the console before it is read in. All input is echoed to file by GGM so that it can be checked that it has been read in and correctly converted to internal units. Note that GGM accepts as input the initial masses of the organic substrates (PIMORG1, PIMORG2 and PIMORG3) and effective molar masses (PMORG1, PMORG2, PMORG3) that define the mass per mole of the relevant functional group. This allows the total number of moles of each of the relevant functional groups to be calculated by GGM. GGM output file variables are listed in Table 7-14.

## 7.2.2 Output Files

GGM generates three types of output file:

1. A single global output file providing summed inventories and rates across all compartments (written to unit IGGMCALC);
2. A single output file containing compartment specific outputs (written to unit IGGMOUCO); and
3. Files with the input file format presented in Section 7.2.1 that can be used when restarting T2GGM.

### 7.2.2.1 Global Output File

The format of the global output file is given in Table 7-10 with italicized text denoting user input. The columns are formatted in a fixed width, space separated column format. Each column contains data padded with spaces to a width of 26 characters. All units and names fields are

quoted so that, should any of these fields contain spaces, the file can still be read in to common packages as a space separated file format.

The global output file contains data summed or averaged over all compartments. The specific data output, together with units and method with which compartment data are processed to get the 'global' value are given in Table 7-14.

**Table 7-10: Global Output File Format**

| Line       | Contents  |
|------------|---|
| 1          | # GGM_OUTPUT_FILE_FORMAT 1  |
| 2          | # GGM_OUTPUT_FILE_TYPE GLOBAL   |
| 3          | # <i>array_index</i> <i>array_index</i> <i>array_index</i> ...                |
| 4          | # "( <i>units</i> )"      "( <i>units</i> )"      "( <i>units</i> )"      ... |
| 5          | " <i>name</i> "      " <i>name</i> "      " <i>name</i> "      ...            |
| subsequent | <i>value</i> <i>value</i> <i>value</i> ...                                    |

#### 7.2.2.1.1 Compartment Output File

The file format used for the output file containing all compartment-based data is given in Table 7-11. The data to be output are the same as those specified in Table 7-14.

**Table 7-11: Compartment Output File Format**

| Line  | Contents  |
|-------|---|
| 1     | GEOFIRMA FOFT 1   |
| 2     | <i>number of data types (d)</i>   |
|       | Then one line per data type:  |
| 3     | <i>name#1 units#1</i>   |
| 4     | <i>name#2 units#2</i>   |
| ...   | ...   |
| d+2   | <i>name#d units#d</i>   |
| d+3   | <i>number of compartments (c)</i>   |
|       | Then one line per compartment:  |
| d+4   | <i>comp_id#1</i>  |
| d+5   | <i>comp_id#2</i>  |
| ...   | ...   |
| c+d+3 | <i>compartment_id#c</i>   |
|       | Then one block per time step:   |
| c+d+4 | Time  |
|       | Within a time block include one line per compartment containing all data for that compartment |
| c+d+5 | <i>comp#1 value#1, comp #1 value#2, ....</i>  |
|       | <i>comp#2 value#1, comp #2 value#2, ....</i>  |
|       | ...   |

#### 7.2.2.1.2 Restart Output Files

As part of the restart facility, the code is required to generate output files that allow the code to be restarted. Only the compartment-based input files contain time dependent inventory data and so data in the same format but with up-to-date inventory data are written to file for each compartment on demand. The restart data are written to and read from files with the filestem GGMRES. The file format for the restart files is identical to that presented in Section 7.2.1.

Table 7-12: Specification of GGM Global Input Data

| Name   | Description/Category   | Input Units                           | Internal Units                       |
|--------|--|---------------------------------------|--------------------------------------|
|        | <b>Biomass Decay</b>   |                                       |                                      |
| PD     | Biomass decay rate   | a <sup>-1</sup>                       | s <sup>-1</sup>                      |
|        | <b>Solubility constants</b>  |                                       |                                      |
| PKC02  | CO <sub>2</sub>  | mol L <sup>-1</sup> MPa <sup>-1</sup> | mol m <sup>-3</sup> Pa <sup>-1</sup> |
| PKH2   | H <sub>2</sub>   | mol L <sup>-1</sup> MPa <sup>-1</sup> | mol m <sup>-3</sup> Pa <sup>-1</sup> |
| PKH2S  | H <sub>2</sub> S   | mol L <sup>-1</sup> MPa <sup>-1</sup> | mol m <sup>-3</sup> Pa <sup>-1</sup> |
| PKCH4  | CH <sub>4</sub>  | mol L <sup>-1</sup> MPa <sup>-1</sup> | mol m <sup>-3</sup> Pa <sup>-1</sup> |
| PKO2   | O <sub>2</sub>   | mol L <sup>-1</sup> MPa <sup>-1</sup> | mol m <sup>-3</sup> Pa <sup>-1</sup> |
| PKN2   | N <sub>2</sub>   | mol L <sup>-1</sup> MPa <sup>-1</sup> | mol m <sup>-3</sup> Pa <sup>-1</sup> |
|        | <b>Effective molar mass of metals</b>  |                                       |                                      |
| PM1    | Mass of carbon and galvanized steel per mole of equivalent iron.                     | kg mol <sup>-1</sup>                  | kg mol <sup>-1</sup>                 |
| PM2    | Mass of passivated carbon steel per mole of equivalent iron.                         | kg mol <sup>-1</sup>                  | kg mol <sup>-1</sup>                 |
| PM3    | Mass of stainless steel and Ni-based alloys per mole of equivalent iron.             | kg mol <sup>-1</sup>                  | kg mol <sup>-1</sup>                 |
| PM4    | Mass of zirconium alloys per mole of equivalent zirconium.                           | kg mol <sup>-1</sup>                  | kg mol <sup>-1</sup>                 |
|        | <b>CO<sub>2</sub> Enhanced corrosion</b>   |                                       |                                      |
| PPRC02 | Reference partial pressure of CO <sub>2</sub> for enhancement of corrosion           | MPa                                   | Pa                                   |
| PE     | Exponent for the enhancement of corrosion by CO <sub>2</sub>                         | -                                     | -                                    |
|        | <b>L&amp;ILW Corrosion rates</b>   |                                       |                                      |
| PR111  | carbon and galvanized steel corrosion rate aerobic conditions unsaturated conditions | μm a <sup>-1</sup>                    | m s <sup>-1</sup>                    |
| PR112  | carbon and galvanized steel corrosion rate aerobic conditions saturated conditions   | μm a <sup>-1</sup>                    | m s <sup>-1</sup>                    |

| Name  | Description/Category   | Input Units            | Internal Units      |
|-------|--|------------------------|---------------------|
| PR121 | carbon and galvanized steel corrosion rate anaerobic conditions unsaturated conditions         | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR122 | carbon and galvanized steel corrosion rate anaerobic conditions saturated conditions           | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR211 | passivated carbon steel corrosion rate aerobic conditions unsaturated conditions               | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR212 | passivated carbon steel corrosion rate aerobic conditions saturated conditions                 | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR221 | passivated carbon steel corrosion rate anaerobic conditions unsaturated conditions             | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR222 | passivated carbon steel corrosion rate anaerobic conditions saturated conditions               | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR311 | stainless steel and Ni-based alloys corrosion rate aerobic conditions unsaturated conditions   | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR312 | stainless steel and Ni-based alloys corrosion rate aerobic conditions saturated conditions     | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR321 | stainless steel and Ni-based alloys corrosion rate anaerobic conditions unsaturated conditions | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR322 | stainless steel and Ni-based alloys corrosion rate anaerobic conditions saturated conditions   | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR411 | Zr alloys corrosion rate aerobic conditions unsaturated conditions                             | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR412 | Zr alloys corrosion rate aerobic conditions saturated conditions                               | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR421 | Zr alloys corrosion rate anaerobic conditions unsaturated conditions                           | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PR422 | Zr alloys corrosion rate anaerobic conditions saturated conditions                             | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
|       | <b>Used Fuel Corrosion Rates</b>   |                        |                     |
| PD1   | Basic rate of corrosion of carbon steel during Phase 1   | $\mu\text{m a}^{-1/2}$ | $\text{m s}^{-1/2}$ |
| PD2   | Basic rate of corrosion of carbon steel during Phase 2   | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PD3   | Basic rate of corrosion of carbon steel during Phase 3   | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |
| PD4   | Basic rate of corrosion of carbon steel during Phase 4   | $\mu\text{m a}^{-1}$   | $\text{m s}^{-1}$   |

| Name   | Description/Category   | Input Units         | Internal Units      |
|--------|--|---------------------|---------------------|
|        | <b>Used Fuel Molar Activation Energies</b>                             |                     |                     |
| PE1    | Activation energy of corrosion of carbon steel reaction during Phase 1 | $\text{J mol}^{-1}$ | $\text{J mol}^{-1}$ |
| PE2    | Activation energy of corrosion of carbon steel reaction during Phase 2 | $\text{J mol}^{-1}$ | $\text{J mol}^{-1}$ |
| PE3    | Activation energy of corrosion of carbon steel reaction during Phase 3 | $\text{J mol}^{-1}$ | $\text{J mol}^{-1}$ |
| PE4    | Activation energy of corrosion of carbon steel reaction during Phase 4 | $\text{J mol}^{-1}$ | $\text{J mol}^{-1}$ |
|        | <b>Rate constants for organic degradation</b>                          |                     |                     |
| PVCA   | cellulose under aerobic degradation                                    | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVCB   | cellulose under denitrification  | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVCC   | cellulose under ferric-ion reduction                                   | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVCD   | cellulose under sulphate reduction                                     | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVCE   | cellulose under methanogenesis   | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVRA   | IX resins under aerobic degradation                                    | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVRB   | IX resins under denitrification  | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVRC   | IX resins under ferric-ion reduction                                   | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVRD   | IX resins under sulphate reduction                                     | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVRE   | IX resins under methanogenesis   | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVPA   | plastics and rubbers under aerobic degradation                         | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVPB   | plastics and rubbers under denitrification                             | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVPC   | plastics and rubbers under ferric-ion reduction                        | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVPD   | plastics and rubbers under sulphate reduction                          | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVPE   | plastics and rubbers under methanogenesis                              | $\text{a}^{-1}$     | $\text{s}^{-1}$     |
| PVFES  | Rate constant for the precipitation of FeS                             | $\text{s}^{-1}$     | $\text{s}^{-1}$     |
| PVFE00 | Rate constant for the reductive dissolution of FeOOH                   | $\text{s}^{-1}$     | $\text{s}^{-1}$     |

| Name    | Description/Category   | Input Units          | Internal Units       |
|---------|--|----------------------|----------------------|
| PVMG0   | Rate constant for the conversion of Magnesium Oxide to Magnesium Carbonate | s <sup>-1</sup>      | s <sup>-1</sup>      |
|         | <b>Rate constants for hydrogen kinetic reactions</b>                       |                      |                      |
| PVH1    | Microbial oxidation of H <sub>2</sub> via iron reduction                   | a <sup>-1</sup>      | s <sup>-1</sup>      |
| PVH2    | Microbial oxidation of H <sub>2</sub> via sulphate reduction               | a <sup>-1</sup>      | s <sup>-1</sup>      |
| PVH3    | Microbial generation of methane  | a <sup>-1</sup>      | s <sup>-1</sup>      |
|         | <b>Biomass yield coefficients</b>  |                      |                      |
| PYA     | aerobic degradation  | -                    | -                    |
| PYB     | Denitrification  | -                    | -                    |
| PYC     | ferric-ion reduction   | -                    | -                    |
| PYD     | sulphate reduction   | -                    | -                    |
| PYE     | Methanogenesis   | -                    | -                    |
|         | <b>Biomass recycling</b>   |                      |                      |
| PKR     | Fraction of dead biomass recycled as cellulose                             | -                    | -                    |
|         | <b>Densities of metals</b>   |                      |                      |
| PRO1    | carbon and galvanized steel  | kg m <sup>-3</sup>   | kg m <sup>-3</sup>   |
| PRO2    | passivated carbon steel  | kg m <sup>-3</sup>   | kg m <sup>-3</sup>   |
| PRO3    | stainless steel and Ni-based alloys  | kg m <sup>-3</sup>   | kg m <sup>-3</sup>   |
| PRO4    | Zr alloys  | kg m <sup>-3</sup>   | kg m <sup>-3</sup>   |
|         | <b>Miscellaneous</b>   |                      |                      |
| PRLIQ   | Density of the water (saline) in the repository as modelled by GGM         | kg m <sup>-3</sup>   | kg m <sup>-3</sup>   |
| PMLIQ   | Molar mass of the water (saline) in the repository as modelled by GGM      | kg mol <sup>-1</sup> | kg mol <sup>-1</sup> |
| PRLIQT2 | Density of the geosphere water (fresh)                                     | kg m <sup>-3</sup>   | kg m <sup>-3</sup>   |
| PMLIQT2 | Molar mass of the geosphere water (fresh)                                  | kg mol <sup>-1</sup> | kg mol <sup>-1</sup> |

| Name   | Description/Category  | Input Units          | Internal Units       |
|--------|---|----------------------|----------------------|
|        | <b>Effective molar mass of the organic substrates</b>   |                      |                      |
| PMORG1 | Mass of actual cellulose substrate per mole equivalent cellulose  | kg mol <sup>-1</sup> | kg mol <sup>-1</sup> |
| PMORG2 | Mass of actual IX resins substrate per mole of equivalent styrene monomer.  | kg mol <sup>-1</sup> | kg mol <sup>-1</sup> |
| PMORG3 | Mass of actual plastics and rubbers substrate per mole of equivalent styrene monomer.   | kg mol <sup>-1</sup> | kg mol <sup>-1</sup> |
|        | <b>Relative Humidity Dependence</b>   |                      |                      |
| PHUM   | T or F. (True or false) Specifies whether relative humidity dependent behaviour is enabled. When set to F it is assumed that the relative humidity is sufficiently high to allow all vapour phase processes to proceed.   | -                    | -                    |
| PRHMIN | Relative Humidity value (fractional) below which all vapour phase corrosion and microbial reactions are modelled as having ceased   | -                    | -                    |
| PRHMAX | Relative Humidity value (fractional) above which all vapour phase corrosion and microbial reactions are modelled as fully active.   | -                    | -                    |
| PHTYPE | Type of relative humidity modulation function to use. An integer. Can currently be 1 = linear ramp, or 2 = smoothed linear ramp.  | -                    | -                    |
|        | <b>Temperature Dependence</b>   |                      |                      |
| PTMODE | The temperature mode to use. An integer. Can be 1 = isothermal, or 2 = non-isothermal. When non-isothermal, the temperature is taken from TOUGH2. When isothermal, each compartment can be given an independent temperature that is read in from the compartmental input files. | -                    | -                    |

| Name    | Description/Category  | Input Units | Internal Units |
|---------|---|-------------|----------------|
|         | <b>Time step and output control</b>   |             |                |
| PEPS    | Specifies the maximum fractional change allowed in a differential variable per time step. Controls the maximum time step reported to TOUGH2.  | -           | -              |
| PEPSC   | Cut-off value below which differential variables are not used to control the suggested timestep.  | mixed       | mixed          |
| PEPSR   | Cut-off value below which the rate of a differential variable is not used to control the suggested time step.   | mixed       | mixed          |
| LOGTR   | Log base 10 of the ratio of times of subsequent writes to the output file. The next output time occurs at approximately (last output time)*10 <sup>(LOGTR)</sup> , and allows output to be generated with a resolution suitable for plotting on a logarithmic scale, consistent with the way it is usually displayed. | -           | -              |
| PMINSAT | Saturation below which the water consuming reactions are controlled to prevent them from drawing water into the volume.   | -           | -              |

**Table 7-13: Specification of GGM Compartment Specific Input Data**

| <b>Name</b> | <b>Description</b>                                     | <b>Input Units</b>  | <b>Internal Units</b> |
|-------------|--|---------------------|-----------------------|
|             | <b>Surface areas of metals</b>                         |                     |                       |
| PA1         | carbon and galvanized steel                            | m <sup>2</sup>      | m <sup>2</sup>        |
| PA2         | passivated carbon steel                                | m <sup>2</sup>      | m <sup>2</sup>        |
| PA3         | stainless steel and Ni-based alloys                    | m <sup>2</sup>      | m <sup>2</sup>        |
| PA4         | Zr alloys  | m <sup>2</sup>      | m <sup>2</sup>        |
|             | <b>Initial concentrations</b>                          |                     |                       |
| PIQNO3      | Initial quantity of nitrates in volume                 | kg                  | mol                   |
| PICSO4      | Initial concentration of sulphates in repository water | kg m <sup>-3</sup>  | mol m <sup>-3</sup>   |
| PICFE0      | Initial concentration of Fe(III) in repository water   | mol m <sup>-3</sup> | mol m <sup>-3</sup>   |
|             | <b>Initial gas partial pressures</b>                   |                     |                       |
| PIPO2       | O <sub>2</sub>   | MPa                 | Pa                    |
| PIPCO2      | CO <sub>2</sub>  | MPa                 | Pa                    |
| PIPNO2      | N <sub>2</sub>   | MPa                 | Pa                    |
| PIPH2       | H <sub>2</sub>   | MPa                 | Pa                    |
| PIPH2S      | H <sub>2</sub> S                                       | MPa                 | Pa                    |
| PIPCH4      | CH <sub>4</sub>  | MPa                 | Pa                    |
|             | <b>Initial masses of organic substrates</b>            |                     |                       |
| PIMORG1     | Cellulose  | kg                  | kg                    |
| PIMORG2     | IX resins (dry)  | kg                  | kg                    |
| PIMORG3     | Plastics and rubbers                                   | kg                  | kg                    |

| Name    | Description  | Input Units | Internal Units |
|---------|--|-------------|----------------|
|         | <b>Initial quantities of metallic materials</b>                                    |             |                |
| PIQ1    | Carbon and galvanized steel  | kg          | mol            |
| PIQ2    | Passivated carbon steel  | kg          | mol            |
| PIQ3    | Stainless steel and Ni-based alloys  | kg          | mol            |
| PIQ4    | Zr alloys  | kg          | mol            |
|         | <b>Initial amounts of biomass species</b>  |             |                |
| PIXA    | Aerobes  | mol         | mol            |
| PIXB    | Denitrifiers   | mol         | mol            |
| PIXC    | Iron reducers  | mol         | mol            |
| PIXD    | Sulphate reducers  | mol         | mol            |
| PIXE    | Methanogens  | mol         | mol            |
| PIXDIED | Total amount of biomass that has died  | mol         | mol            |
| PIXDEAD | Total amount of dead (dehydrated) and non-recyclable biomass                       | mol         | mol            |
|         | <b>Properties used for tracking system across restarts</b>                         |             |                |
| PIIC02  | Amount of CO <sub>2</sub> that has left the volume                                 | mol         | mol            |
| PIIH2   | Amount of H <sub>2</sub> that has left the volume                                  | mol         | mol            |
| PIIH2S  | Amount of H <sub>2</sub> S that has left the volume                                | mol         | mol            |
| PIICH4  | Amount of CH <sub>4</sub> that has left the volume                                 | mol         | mol            |
| PIIO2   | Amount of O <sub>2</sub> that has left the volume                                  | mol         | mol            |
| PIIN2   | Amount of N <sub>2</sub> that has left the volume                                  | mol         | mol            |
| PINGH2O | Cumulative amount of water that has been generated by the gas generation reactions | mol         | mol            |

| Name    | Description  | Input Units | Internal Units |
|---------|--|-------------|----------------|
|         | <b>Initial amounts of other materials</b>  |             |                |
| PIQFEC  | FeCO <sub>3</sub>  | mol         | mol            |
| PIQFE3  | Fe <sub>3</sub> O <sub>4</sub>   | mol         | mol            |
| PIQFES  | FeS  | mol         | mol            |
| PIQMGO  | MgO  | mol         | mol            |
| PIQFE2  | Fe <sub>2</sub> O <sub>3</sub>   | mol         | mol            |
| PIQC03  | CO <sub>3</sub> <sup>2-</sup> (The amount of carbonate ions available for corrosion. This can be set to a very large number – larger than the total number of moles Fe present – if this is assumed to be effectively infinite.)   | mol         | mol            |
| PIQZR02 | Total amount of ZrO <sub>2</sub>   |             |                |
|         | <b>Temperature Dependence</b>  |             |                |
| PT      | Compartment temperature. Only used if the current temperature mode (PTMODE) is isothermal.   | °C          | K              |
| PTORIG  | The time at which temperature dependent corrosion starts (the waste emplacement time). This is the time origin, t <sub>1</sub> , for the Phase 1 corrosion rate.   | y           | s              |
|         | <b>Compartment Dimensions</b>  |             |                |
| PBTS    | The ratio of the expected bentonite wet-zone thickness to the ratio of the thickness of the compartment as measured away from the container wall. Alternatively, this can be thought of as the saturation above which water breaks through to the container wall. (Break-Through Saturation) | -           | -              |

**Table 7-14: Specification for GGM Global Output Data**

| Name   | Description  | Processing over compartments      | Units               |
|--------|--|-----------------------------------|---------------------|
| TIME   | Time   | None                              | s                   |
| DELTAT | The elapsed time since the last TOUGH2 time step.  | None                              | s                   |
| QAIR   | The rate of generation of bulk gas.  | Sum                               | kg s <sup>-1</sup>  |
| QLIQ   | The rate of generation of geosphere water.   | Sum                               | kg s <sup>-1</sup>  |
| DAIR   | The discrepancy between the amount of gas generated by T2 and GGM over the last time step.         | Sum                               | mol                 |
| DLIQ   | The discrepancy between the amount of water generated by T2 and GGM over the last time step.       | Sum                               | mol                 |
| IAS    | Water saturation   | Void volume weighted average      | -                   |
| IAGWV  | Saturated void volume  | Sum                               | m <sup>3</sup>      |
| IAVAV  | Unsaturated void volume  | Sum                               | m <sup>3</sup>      |
| IATEAS | Terminal electron acceptor stage   | Maximum                           | -                   |
| IACFEO | The effective concentration of FeOOH were it to be dissolved in the aqueous phase                  | Saturated volume weighted average | mol m <sup>-3</sup> |
| IAPCO2 | Partial pressure of CO <sub>2</sub>  | Gas volume weighted average       | Pa                  |
| IAPH2  | Partial pressure of H <sub>2</sub>   | Gas volume weighted average       | Pa                  |
| IAPH2S | Partial pressure of H <sub>2</sub> S   | Gas volume weighted average       | Pa                  |
| IAPCH4 | Partial pressure of CH <sub>4</sub>  | Gas volume weighted average       | Pa                  |
| IAP02  | Partial pressure of O <sub>2</sub>   | Gas volume weighted average       | Pa                  |
| IAPN2  | Partial pressure of N <sub>2</sub>   | Gas volume weighted average       | Pa                  |
| IAPGAS | Total gas pressure   | Gas volume weighted average       | Pa                  |
| IANGAS | Quantity of gas in the unsaturated phase (Sum of the number of moles of all the individual gases.) | Sum                               | mol                 |

| Name   | Description   | Processing over compartments      | Units               |
|--------|---|-----------------------------------|---------------------|
| IAMAIR | Mass of bulk gas (IANGAS * the molar mass of bulk gas)                                | Sum                               | kg                  |
| IACCO2 | Concentration of CO <sub>2</sub> in repository water                                  | Saturated volume weighted average | mol m <sup>-3</sup> |
| IACH2  | Concentration of H <sub>2</sub> in repository water                                   | Saturated volume weighted average | mol m <sup>-3</sup> |
| IACH2S | Concentration of H <sub>2</sub> S in repository water                                 | Saturated volume weighted average | mol m <sup>-3</sup> |
| IACCH4 | Concentration of CH <sub>4</sub> in repository water                                  | Saturated volume weighted average | mol m <sup>-3</sup> |
| IACO2  | Concentration of O <sub>2</sub> in repository water                                   | Saturated volume weighted average | mol m <sup>-3</sup> |
| IACN2  | Concentration of N <sub>2</sub> in repository water                                   | Saturated volume weighted average | mol m <sup>-3</sup> |
| IANCO2 | Total number of moles of CO <sub>2</sub> in the unsaturated phase                     | Sum                               | mol                 |
| IANH2  | Total number of moles of H <sub>2</sub> in the unsaturated phase                      | Sum                               | mol                 |
| IANH2S | Total number of moles of H <sub>2</sub> S in the unsaturated phase                    | Sum                               | mol                 |
| IANCH4 | Total number of moles of CH <sub>4</sub> in the unsaturated phase                     | Sum                               | mol                 |
| IANO2  | Total number of moles of O <sub>2</sub> in the unsaturated phase                      | Sum                               | mol                 |
| IANN2  | Total number of moles of N <sub>2</sub> in the unsaturated phase                      | Sum                               | mol                 |
| IAQGAS | Gas generation rate (Rate of increase of number of moles of gas in the vapour phase.) | Sum                               | mol s <sup>-1</sup> |
| IAQAIR | Bulk gas generation rate. (IAQGAS * the molar mass of bulk gas.)                      | Sum                               | kg s <sup>-1</sup>  |

| Name   | Description   | Processing over compartments | Units               |
|--------|---|------------------------------|---------------------|
| IAA11  | Surface area of carbon and galvanized steel under unsaturated conditions                  | Sum                          | m <sup>2</sup>      |
| IAA21  | Surface area of passivated carbon steel under unsaturated conditions                      | Sum                          | m <sup>2</sup>      |
| IAA31  | Surface area of stainless steel and Ni-based alloys under unsaturated conditions          | Sum                          | m <sup>2</sup>      |
| IAA41  | Surface area of Amount of Zr alloys under unsaturated conditions                          | Sum                          | m <sup>2</sup>      |
| IAA12  | Surface area of carbon and galvanized steel under saturated conditions                    | Sum                          | m <sup>2</sup>      |
| IAA22  | Surface area of passivated carbon steel under saturated conditions                        | Sum                          | m <sup>2</sup>      |
| IAA32  | Surface area of stainless steel and Ni-based alloys under saturated conditions            | Sum                          | m <sup>2</sup>      |
| IAA42  | Surface area of Zr alloys under saturated conditions                                      | Sum                          | m <sup>2</sup>      |
| IARH2O | Rate of generation of H <sub>2</sub> O within the volume due to gas generation processes. | Sum                          | mol s <sup>-1</sup> |
| IAQH2O | Amount of H <sub>2</sub> O  | Sum                          | mol                 |
| IAQLIQ | The water generation rate. (IARH2O times the molar mass of water.)                        | Sum                          | kg s <sup>-1</sup>  |
| IAGPSF | Gas pressure scaling factor.  | Maximum                      | kg kg <sup>-1</sup> |
| IARCDV | Rate controlling differential variable number   | Zero                         | -                   |
| IARH   | Relative humidity (fractional)  | Gas volume weighted average  | -                   |
| IAH    | Relative humidity modulation factor h( RH ) at the current relative humidity              | h( gas volume weighted RH)   | -                   |
| IAXTOT | Amount of live (hydrated) biomass   | Sum                          | mol                 |

| Name     | Description   | Processing over compartments      | Units               |
|----------|---|-----------------------------------|---------------------|
| IAWATEPS | Water consuming reaction rate scaling factor  | Maximum                           | -                   |
| IADWDT   | Rate of increase of amount of water   | Sum                               | mol s <sup>-1</sup> |
| IADCDT   | Rate of consumption of water due to saturated phase reactions   | Sum                               | mol s <sup>-1</sup> |
| IADDDT   | Rate of generation of water due to other reactions  | Sum                               | mol s <sup>-1</sup> |
| IADIDT   | Rate at which water is entering   | Sum                               | mol s <sup>-1</sup> |
| IATEMP   | The current temperature   | Maximum                           | K                   |
| IADELTA  | The saturation breakthrough factor (delta), which increases from 0 to 1 as the water saturation increases from the break-through saturation to 1. | Maximum                           | -                   |
| IAPHI1   | The Phase 1 carbon steel consumption rate. This is defined as $\Phi_1$ in Section 3.4.5.1.  | Sum                               | mol s <sup>-1</sup> |
| IAPHI2   | The Phase 2 carbon steel consumption rate. This is defined as $\Phi_2$ in Section 3.4.5.1.  | Sum                               | mol s <sup>-1</sup> |
| IAPHI3   | The Phase 3 carbon steel consumption rate. This is defined as $\Phi_3$ in Section 3.4.5.2.  | Sum                               | mol s <sup>-1</sup> |
| IAPHI4   | The Phase 4 carbon steel consumption rate. This is defined as $\Phi_4$ in Section 3.4.5.2.  | Sum                               | mol s <sup>-1</sup> |
| IDCN03   | Concentration of NO <sub>3</sub>  | Saturated volume weighted average | mol m <sup>-3</sup> |
| IDQFE0   | Amount of FeOOH   | Sum                               | mol                 |
| IDCS04   | Concentration of SO <sub>4</sub>  | Saturated volume weighted average | mol m <sup>-3</sup> |
| IDQC     | Amount of cellulose monomer   | Sum                               | mol                 |
| IDQR     | Amount of styrene monomer   | Sum                               | mol                 |

| Name   | Description  | Processing over compartments | Units |
|--------|--|------------------------------|-------|
| IDQP   | Amount of styrene monomer from plastics and rubber | Sum                          | mol   |
| IDQ1   | Amount of carbon and galvanized steel              | Sum                          | mol   |
| IDQ2   | Amount of passivated carbon steel                  | Sum                          | mol   |
| IDQ3   | Amount of stainless steel and Ni-based alloys      | Sum                          | mol   |
| IDQ4   | Amount of Zr alloys                                | Sum                          | mol   |
| IDXA   | Amount of aerobes                                  | Sum                          | mol   |
| IDXB   | Amount of denitrifiers                             | Sum                          | mol   |
| IDXC   | Amount of iron reducers                            | Sum                          | mol   |
| IDXD   | Amount of sulphate reducers                        | Sum                          | mol   |
| IDXE   | Amount of methanogens                              | Sum                          | mol   |
| IDQFEC | Amount of $\text{FeCO}_3$                          | Sum                          | mol   |
| IDQFE3 | Amount of $\text{Fe}_3\text{O}_4$                  | Sum                          | mol   |
| IDQFES | Amount of $\text{FeS}$                             | Sum                          | mol   |
| IDQMG0 | Amount of $\text{MgO}$                             | Sum                          | mol   |
| IDNCO2 | Total number of moles of $\text{CO}_2$             | Sum                          | mol   |
| IDNH2  | Total number of moles of $\text{H}_2$              | Sum                          | mol   |
| IDNH2S | Total number of moles of $\text{H}_2\text{S}$      | Sum                          | mol   |
| IDNCH4 | Total number of moles of $\text{CH}_4$             | Sum                          | mol   |
| IDNO2  | Total number of moles of $\text{O}_2$              | Sum                          | mol   |

| Name    | Description  | Processing over compartments | Units |
|---------|--|------------------------------|-------|
| IDNN2   | Total number of moles of N <sub>2</sub>  | Sum                          | mol   |
| IDXDIED | Total amount of biomass that has died  | Sum                          | mol   |
| IDXDEAD | Total amount of dead (dehydrated) and non-recyclable biomass                       | Sum                          | mol   |
| IDIC02  | Amount of CO <sub>2</sub> that has left the volume                                 | Sum                          | mol   |
| IDIH2   | Amount of H <sub>2</sub> that has left the volume                                  | Sum                          | mol   |
| IDIH2S  | Amount of H <sub>2</sub> S that has left the volume                                | Sum                          | mol   |
| IDICH4  | Amount of CH <sub>4</sub> that has left the volume                                 | Sum                          | mol   |
| IDIO2   | Amount of O <sub>2</sub> that has left the volume                                  | Sum                          | mol   |
| IDIN2   | Amount of N <sub>2</sub> that has left the volume                                  | Sum                          | mol   |
| IDNGH2O | Cumulative amount of water that has been generated by the gas generation reactions | Sum                          | mol   |
| IDQZRO2 | Total amount of ZrO <sub>2</sub>   | Sum                          | mol   |
| IDQFE2  | Amount of Fe <sub>2</sub> O <sub>3</sub>   | Sum                          | mol   |
| IDQC03  | The amount of CO <sub>3</sub> <sup>2-</sup>  | Sum                          | mol   |

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**ABBREVIATIONS AND ACRONYMS**

|        |                                       |
|--------|---------------------------------------|
| DGR    | Deep Geologic Repository              |
| EDZ    | Excavated Damage Zone                 |
| EOS    | Equation-of-State                     |
| GGE    | Gas Generation Experiment             |
| GGM    | Gas Generation Model                  |
| IFD    | Integral Finite Difference            |
| IX     | Ion-Exchange                          |
| LBL    | Lawrence Berkeley National Laboratory |
| L&ILW  | Low and Intermediate Level Waste      |
| NE     | Normal Evolution Scenario             |
| NE-RC  | Reference Case                        |
| NE-SBC | Simplified Base Case                  |
| NWL    | Non-Water Limited                     |
| NWMO   | Nuclear Waste Management Organization |
| OPG    | Ontario Power Generation              |
| RH     | Relative Humidity                     |
| TEA    | Terminal Electron Acceptor            |
| UFC    | Used Fuel Container                   |
| WI     | Work Instruction                      |
| WIPP   | Waste Isolation Pilot Plant           |
| WL     | Water Limited                         |