Durability of High Level Waste and Spent Fuel Disposal Containers – an overview of the combined effect of chemical and mechanical degradation mechanisms

Appendix D1: Integration of Container Failure Modes

Fraser King
## DOCUMENT ISSUE RECORD

<table>
<thead>
<tr>
<th>Issue</th>
<th>Description</th>
<th>Author</th>
<th>Checker</th>
<th>Approver</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draft 1</td>
<td>Draft Issue 1 for comment</td>
<td>Fraser King</td>
<td>Sarah Watson</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Issue 1</td>
<td>Review comments addressed</td>
<td>Fraser King</td>
<td>Gráinne Carpenter</td>
<td>Gráinne Carpenter</td>
<td>12th July 2013</td>
</tr>
<tr>
<td>Issue 1.2</td>
<td>Updated terminology etc to reflect change</td>
<td>Sarah Watson</td>
<td></td>
<td></td>
<td>October 2015</td>
</tr>
<tr>
<td></td>
<td>to Durability report</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Issue 2</td>
<td>Addressed comments from C Padovani</td>
<td>Sarah Watson</td>
<td>Fraser King</td>
<td></td>
<td>December 2016</td>
</tr>
</tbody>
</table>

Previous issues of this document shall be destroyed or marked **SUPERSEDED**

©Amec Foster Wheeler Nuclear UK Limited 2016

This report was prepared exclusively for RWM by Amec Foster Wheeler Nuclear UK Limited. The quality of information, conclusions and estimates contained herein is consistent with the level of effort involved in Amec Foster Wheeler’s services and based on: i) information available at the time of preparation, ii) data supplied by outside sources and iii) the assumptions, conditions and qualifications set forth in this report. This report is intended to be used by RWM only, subject to the terms and conditions of its contract with Amec Foster Wheeler. Any other use of, or reliance on, this report by any third party is at that party’s sole risk.
CONTENTS

D1.1 Introduction.......................................................................................................................... 6
D1.2 General approaches to integration of mechanical and corrosion failure modes ............ 8
D1.3 Examples from national programmes .................................................................................. 11
  D1.3.1 Japan (RWMC).............................................................................................................. 11
  D1.3.2 Switzerland (Nagra)..................................................................................................... 13
  D1.3.3 USA (DOE).................................................................................................................. 15
D1.4 Summary ............................................................................................................................. 20
D1.5 References .......................................................................................................................... 21
FIGURES AND TABLES

Figure D1.1: Schematic illustration of the mechanical and material-related factors leading to container failure and their relationship to various failure modes. .................................................. 7
Figure D1.2: Overall approach to container integrity followed by Asano et al. (2005, 2006a,b, 2011). ........................................................................................................................................ 12
Figure D1.3: Overall methodology for assessing container integrity developed by Asano et al. (2006b). .................................................................................................................................. 13
Figure D1.4: Overall container design approach adopted by Nagra (Patel et al. 2012). ...... 14
Figure D1.5: Effect of fracture toughness of carbon steel on the propensity to brittle fracture illustrated using a Failure Assessment Diagram (Patel et al. 2012). ........................................ 15
Figure D1.6: Flow chart illustrating inter-relationships between various processes and models for the nominal scenario for the Yucca Mountain Project (DOE 2008). .................... 16
Figure D1.7: Structure of models for the seismic disruptive event scenario (DOE 2008) ..... 18
Figure D1.8: Structure of models for the igneous disruptive event scenarios (DOE 2008) .... 19

Table D1.1: Summary of the extent of integration of mechanical and corrosion failure mechanisms in the overall assessment of container failure in various international HLW/SF programmes.................................................................................................................. 9
## GLOSSARY OF TERMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBS</td>
<td>Engineered Barrier System</td>
</tr>
<tr>
<td>RWMC</td>
<td>Radioactive Waste Management Center (Japan)</td>
</tr>
<tr>
<td>SCC</td>
<td>Stress Corrosion Cracking</td>
</tr>
<tr>
<td>YMP</td>
<td>Yucca Mountain Project</td>
</tr>
</tbody>
</table>
D1.1 Introduction

Component failure may result from either purely mechanical or material-related factors or a combination of the two. Mechanical factors include loads due to hydrostatic or lithostatic pressures or damage resulting from accidents, rockfall, or seismic activity. Material-related factors include various forms of corrosion, degradation of material properties, and non-corrosion processes such as creep. If failure is a result of a single mechanical or material-related factor then estimation of the component failure time can be based simply on the appropriate “damage function”, be that an expression for the rate of localised corrosion, for example, or an analysis of the structural integrity as a result of a time-dependent external load. More commonly, however, component failure is a result of a combination of mechanical and material-related factors and it is then appropriate to use an integrated approach to predicting the time-dependent degradation of the container.

Figure D1.1 defines failure modes considered possible for waste containers for high level waste and spent fuel, as well as a number of possible mechanical and material-related factors that could result in failure. This summary is not exhaustive and other factors and definitions of failure could be imagined. The five failure modes defined here are:

- Plastic collapse as a result of the loss of wall thickness and/or an increase in the total stress (applied plus residual);
- Brittle fracture as a result of crack growth and/or an increase in the total stress (applied plus residual);
- A through-wall penetration without the loss of overall structural integrity (i.e., the container continues to act as a significant mass-transport barrier);
- Plastic collapse and/or brittle fracture as a result of the degradation of the properties of the container material;
- Brittle fracture due to cyclic loading (fatigue).

Failure as a result of degradation of the properties of the container material is highlighted here because this is a clear case of where there is an interaction between mechanical and material-related factors. Failure due to cyclic loading is also separately identified because this failure mode is a consequence of specific mechanical loading conditions. However, this type of loading is not expected in a disposal facility (with the possible exception of its transport period) so is generally excluded from consideration.

Figure D1.1 also shows how the various mechanical and material-related processes may, or may not, lead to one or more potential container failure modes. Some processes have multiple consequences for the integrity of the container. For example, the applied stress resulting from the hydrostatic load may lead to either plastic collapse or brittle fracture. Similarly, localised corrosion could lead to container failure by plastic collapse if the area of corrosion is extensive or through-wall penetration in the case of isolated pits or, indirectly, to brittle fracture or degradation of the material properties if pits lead to crack initiation or the absorption of hydrogen, respectively. In other cases, the processes may only impact specific failure modes, a good example being the failure by fatigue due to cyclic loading during transport.

The exact nature of the mechanical and material-related factors and the extent of their interactions will depend on the specific combination of container material and GDF design. Nevertheless, integration of the effects of the various mechanical and material-related factors is important for developing robust container failure predictions, and becomes more important as the number of contributing factors and their degree of interaction increases.
Figure D1.1: Schematic illustration of the mechanical and material-related factors leading to container failure and their relationship to various failure modes.
D1.2 General approaches to integration of mechanical and corrosion failure modes

In nuclear waste disposal programmes, the assessment of the impacts of mechanical factors and material-related processes on the integrity of the container has generally been performed separately. Thus, structural analyses would be performed under static conditions to determine whether a particular container design (possibly with a reduced wall thickness to account for a certain degree of general corrosion) would be stable under the expected external loads. Similarly, the time-dependent penetration of the container wall by various forms of corrosion would be assessed using suitable mechanistically-based or empirical corrosion models. This approach lead to the adoption in many programmes of separate mechanical and corrosion “allowances” (ANDRA, 2005; JNC, 2000; Johnson et al. 1994). In some programmes, a small fraction (generally 1 in $10^4$ to 1 in $10^5$) of containers would be assumed to either contain an undetected through-wall defect at the time of emplacement or to fail soon after closure of a GDF (ANDRA, 2005; DOE, 2008; Johnson et al., 1994), in part as a means of accounting for premature failures due to fabrication defects.

More recently, a number of national programmes have developed integrated approaches to container integrity, in which the effects of both mechanical and material-related degradation processes are taken into account. The integration of mechanical and material-related factors leading to container failure is generally not performed using a single model or code. Instead, a series of models are used, with the output of one being used as input for another, either directly or, more usually, in some abstracted form.

Table D1.1 summarises the approaches for the assessment of container integrity in some past and current nuclear waste disposal programmes. A more detailed discussion of the integrated approaches used, or being developed, for container integrity assessment in Japan, Switzerland, and the U.S. is given in the next section.
Table D1.1: Summary of the extent of integration of mechanical and corrosion failure mechanisms in the overall assessment of container failure in various international HLW/SF programmes

<table>
<thead>
<tr>
<th>Country</th>
<th>Programme and/or GDF or container concept</th>
<th>Approach to container integrity assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
<td>AECL (titanium containers)</td>
<td>Mechanical and corrosion failures of Ti Grade-2 containers treated separately through the use of separate corrosion and structural allowances (Johnson et al. 1994). Structural allowance based on static load requirements due to hydrostatic and buffer swelling pressures. Failure by corrosion was deemed to have occurred by crevice corrosion after consumption of the corrosion allowance or hydrogen-induced cracking once the threshold absorbed hydrogen concentration was exceeded.</td>
</tr>
<tr>
<td></td>
<td>NWMO (copper-clad containers)</td>
<td>Copper-clad container design currently under development. Example of integration of mechanical and material-related factors during design process. Use of Cu cladding instead of dual-wall copper-insert design eliminates issue of the creep and stress corrosion cracking of copper. Corrosion allowance for copper clad has been defined (Kwong, 2011), but no formal container integrity assessment has been published.</td>
</tr>
<tr>
<td>Japan</td>
<td>JNC (carbon steel containers)</td>
<td>Defined wall thicknesses requirements for corrosion (40 mm) and combination of structural strength and radiation shielding (150 mm), but no overall container integrity assessment (JNC, 2000).</td>
</tr>
<tr>
<td></td>
<td>RWMC (carbon steel containers)</td>
<td>Development of an integrated approach to the integrity of the container closure weld based on fitness-for-purpose principles (Asano and Aritomi, 2005, 2010; Asano and Ito, 2008; Asano et al. 2005, 2006a,b, 2011; Kobayashi et al. 2011). Approach involves (i) definition of closure weld and inspection requirements, (ii) design of closure weld, (iii) development of various welding procedures, (iv) measurement of residual stress distributions, (v) assessment of weld corrosion properties, (vi) development and trials of weld non-destructive examination methodology, (vii) overall weld integrity assessment, including definition of critical flaw size and suitable safety factor.</td>
</tr>
<tr>
<td>Belgium</td>
<td>ONDRAF-NIRAS (stainless steel containers)</td>
<td>Preliminary assessment based on available corrosion data (ONDRAF/NIRAS, 2001).</td>
</tr>
<tr>
<td></td>
<td>ONDRAF-NIRAS (carbon steel containers)</td>
<td>Integrated assessment of the possibility of over-pressurisation of the stainless steel envelope due to ( \text{H}_2 ) generated by anaerobic corrosion of the C-steel overpack in the presence of the concrete</td>
</tr>
<tr>
<td>Country</td>
<td>Programme and/or GDF or container concept</td>
<td>Approach to container integrity assessment</td>
</tr>
<tr>
<td>----------------</td>
<td>-------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Switzerland</td>
<td>‘supercontainers’) buffer material (Macdonald et al., 2011).</td>
<td><strong>Switzerland</strong> Nagra (a variety of container types) Integrated approach involving (i) container design and fabrication, (ii) material selection, (iii) weld design and inspection, (vi) structural analyses for different load scenarios for pristine and degraded container, (vii) engineering critical assessment of consequences of weld flaws, (viii) distribution of residual stresses, (ix) feasibility of thermal heat treatment, and (x) integrated integrity assessment through use of Failure Assessment Diagrams (Patel et al., 2012).</td>
</tr>
<tr>
<td>United States</td>
<td>DOE (nickel alloy containers)</td>
<td><strong>United States</strong> DOE (nickel alloy containers) Detailed integrated assessment of container integrity for nominal and disruptive (seismic and igneous) scenarios. Hierarchy of process, abstracted, and total system performance assessment level models (DOE, 2008).</td>
</tr>
<tr>
<td>France</td>
<td>ANDRA (carbon steel containers)</td>
<td><strong>France</strong> ANDRA (carbon steel containers) Separate analyses of wall thickness required to provide mechanical integrity and corrosion allowance for isolation period for both HLW (required containment period of the order of 100’s of years) and SF (required containment period of the order of 1000’s of years) (ANDRA, 2005).</td>
</tr>
<tr>
<td>Sweden/Finland</td>
<td>SKB/Posiva (copper containers)</td>
<td><strong>Sweden/Finland</strong> SKB/Posiva (copper containers) Separate consideration of mechanical (creep, uniform and non-uniform loading due to external load for hydrostatic and buffer swelling pressures, shear loading due to seismic activity) and corrosion (general and localised corrosion) factors impacting corrosion integrity (SKB, 2010, 2011). Separate analyses for copper corrosion barrier and cast iron insert.</td>
</tr>
</tbody>
</table>
D1.3 Examples from National Programmes

D1.3.1 Japan (RWMC)

In Japan, Asano and co-workers (Asano and Aritomi 2005, 2010; Asano and Ito 2008; Asano et al. 2005, 2006a,b, 2011; Kobayashi et al. 2011) of the Radioactive Waste Management Funding and Research Center (RWMC) have developed an approach for the assessment of container integrity based on fitness-for-service principles for nuclear power plants. This approach, which has been applied to the development of a suitable procedure for the final closure weld for a thick-walled C-steel container, is generally applicable for any combination of container material, GDF design, and host rock type.

The overall approach followed by Asano and co-workers to establishing the integrity of the container is outlined in Figure D1.2. The starting point was the container design outlined in the JNC H-12 report (JNC, 2000). In that report, a container wall thickness of 190 mm was defined, comprising a 40-mm corrosion allowance and an allowance of 150 mm to withstand the external hydrostatic and lithostatic loads and to ensure sufficient radiation shielding. The next step in the process was to define the welding and inspection requirements for the final closure weld, paying particular attention to the need to weld and inspect thick sections. Definition of the various requirements is an important step in the whole process. These requirements may be derived from the safety functions for the container (both pre-closure and post-closure) or by operational requirements defined by the overall programme. One of the requirements should relate to the applicable code or standard to be used, in this case a standard taken from the Japanese code for the manufacturer of nuclear power plant components.

Having established the requirements and applicable standard, the next stage was to develop suitable welding and inspection procedures. Various degradation modes were also investigated, including the general and localised corrosion behaviour of the weld, heat affected zone, and parent material, the susceptibility to stress corrosion cracking (SCC), and the potential for radiation embrittlement of the container material due to the fast neutron flux. The magnitude and distribution of residual stresses were measured for the various prototype welds.

Based on the collected information, an overall approach to container integrity was then developed, the basis for which is illustrated in Figure D1.3. Failure is assumed to occur when a flaw grows to a critical length or at such time that the wall thickness has been reduced sufficiently by general corrosion. The critical crack length is defined by engineering critical assessment and may involve detailed finite-element structural analysis or simpler fracture mechanics calculations based on an accepted method (e.g., BS 7910). Asano et al. (2006b) estimated a critical crack length (depth) for the expected loading conditions of 56 mm or 72 mm, depending upon the assumed shape and location of the defect.
Figure D1.2: Overall approach to container integrity followed by Asano et al. (2005, 2006a,b, 2011).
Appendix D1: Integration of Container Failure Modes

Figure D1.3: Overall methodology for assessing container integrity developed by Asano et al. (2006b).

The maximum tolerable flaw size is then that critical flaw size divided by a suitable safety factor. Asano et al. (2006b) used a safety factor of 10 based on general practice in the Japanese nuclear industry. Smaller safety factors might be appropriate (Patel et al. 2012), although it can be argued that a value of 10 is appropriate since the HLW/SF container cannot be inspected after disposal. Based on a safety factor of 10, the maximum tolerable flaw size is then 5.6 mm or 7.2 mm. The size of the initial defect was assumed to be equal to the non-destructive examination detection limit of 2 mm.

Thus, the time to container failure as a consequence of both mechanical and corrosion processes is defined as the time required for the flaw to grow from 2 mm to 5.6 or 7.2 mm.

Certain assumptions were made in developing this approach, or were confirmed experimentally or analytically during the course of the work, including:

- No crack growth (due to fatigue) during earthquakes;
- No crack growth by SCC;
- No neutron embrittlement of the container material;
- No degradation in material properties due to hydrogen absorption.

Regardless of the details of the analyses or of the specific assumptions made, the general approach laid out by Asano and co-workers is broadly applicable to a range of container material and GDF designs.

**D1.3.2 Switzerland (Nagra)**

Nagra has recently completed a comprehensive design exercise for a C-steel container involving a number of different aspects, including (Patel et al. 2012):

- Basic container design;
Appendix D1: Integration of Container Failure Modes

- Material specification;
- Consideration of container corrosion processes;
- Weld design;
- Development of a weld procedure;
- Assessment of residual stress and its mitigation by heat treatment;
- Structural analysis of a defect-free container;
- Engineering critical assessment (ECA) of flaws;
- Inspection methodologies and detection limits;
- Manufacturing routes.

The overall structure of the program is illustrated in Figure D1.4.

![Diagram of container design approach](image)

**Figure D1.4: Overall container design approach adopted by Nagra (Patel et al. 2012).**

As in the RWMC work, an important first step was to define a list of container requirements relating to factors as diverse as the minimum container lifetime, mitigation of residual stress, container production, the need for unique marking/identification, criticality, and many others.

Having defined the container requirements, a preliminary container design was developed based on expert knowledge and past experience. Since most subsequent tasks were dependent to some degree on the nature of the material, the next step was to define the material composition and properties. The expected corrosion behaviour of the container in a Nagra-style repository located in Opalinus Clay host rock was then defined, with special attention to possible crack growth mechanisms or processes that could lead to degradation of the container or material properties, such as the reduction in wall thickness due to container corrosion and the degradation of the fracture toughness due to hydrogen absorption during the anaerobic phase.

Design of the weld geometry and of the detailed weld procedure was then performed. An important consideration in the design process was to try to minimise residual stress and the possibility of internal hydrogen-induced cracking, as identified by Turnbull (2009). Residual weld stresses were computed and the efficacy of thermal heat treatment assessed, bearing in mind the requirement not to exceed the upper temperature limit for SF or HLW.
Structural analyses were performed for defect-free containers of varying wall thickness (to simulate both a pristine container and a container after a period of general corrosion) and engineering critical assessments (ECA) were done for various defects and loading scenarios. It was also recognised that absorption of hydrogen by the container material would reduce the toughness.

The results of the ECA were illustrated using a Failure Assessment Diagram (see also Appendix D3). Figure D1.5 shows the results for a flaw height (depth) of 30 mm subject to asymmetrical lithostatic loading, a hydrostatic pressure, and weld residual stress for various assumed toughness values between 100 MPa m$^{1/2}$ and 300 MPa m$^{1/2}$ as a result of hydrogen absorption. As can be seen on the figure, for these assumed conditions, the container would not fail, although more-detailed analyses would be required in the case of the lowest assumed toughness.

![Figure D1.5: Effect of fracture toughness of carbon steel on the propensity to brittle fracture illustrated using a Failure Assessment Diagram (Patel et al. 2012).](image)

**D1.3.3 USA (DOE)**

The effects of various mechanical and corrosion processes on container integrity were considered in the Yucca Mountain Project (YMP) (DOE, 2008). In the YMP license application, DOE (2008) considered a nominal scenario and various disruptive event scenarios, including seismic and igneous activity. Figure D1.6 illustrates the inter-relationships between various processes and the corresponding models for the nominal scenario for the YMP. The waste package and drip shield degradation module has as inputs information related to localised corrosion initiation and propagation modules as well as from the engineered barrier system (EBS) thermal-hydrologic environment module, the latter determining the temperature and relative humidity in the disposal drift. Because the YMP drifts were not backfilled and the repository lay above the water table, there was minimal input from mechanical degradation models for the nominal scenario, although the DOE did take into account thermal and limited seismic degradation of the drifts resulting in rockfall.
Appendix D1: Integration of Container Failure Modes

Figure D1.6: Flow chart illustrating inter-relationships between various processes and models for the nominal scenario for the Yucca Mountain Project (DOE 2008).

More significant mechanical effects were incorporated into the container integrity assessments for the seismic and igneous disruptive events. Figure D1.7 shows the hierarchy of models that were developed to address various issues arising from the consideration of seismic events (DOE, 2008; Sandia, 2007). This hierarchical approach, starting from basic data and progressing through detailed process-level models to abstracted Total System Performance Assessment models, is typical of the approach taken in many programmes for assessing a wide range of processes. Seismic activity may result in both degradation of the disposal drifts (by inducing rockfall and partial drift collapse) and impact of the waste package and drip shield with each other as well as the drift walls and other components of the EBS. In this particular case, the mechanical loads on the container as a result of seismic activity include:
• Damage (including plastic deformation and induced residual stress) to the waste package and drip shield as a result of ground motion;
• Displacement of the drip shield components;
• Impact damage as a result of rockfall on the drip shield;
• Impact damage as a result of rockfall on the waste package underneath a failed or displaced drip shield;
• Increased static load on the drip shield and/or waste package as a result of the accumulation of rubble from drift degradation.

In each case, detailed dynamic and static structural analyses were performed in order to understand the extent of damage (in the form of plastic strain and induced residual stress) on the waste package and drip shield. This information was then used to determine the consequences for SCC of the EBS components, subject to other requirements for SCC being met, such as the presence of a suitable cracking environment.

Additional mechanical and corrosion processes were involved in the assessment of the igneous disruptive event. Two types of igneous event were considered, one in which a magma-filled dyke intersects a drift and molten magma contacts the waste package but does not reach the surface of the mountain (the so-called “igneous intrusion” case), and a second in which one or more packages are impacted by flowing magma which then reaches the surface and is ejected from the mountain as a plume of ash (the so-called “volcanic eruption” case) (Figure D1.7). Waste packages contacted by magma are clearly subject to elevated temperatures, which may cause over-pressurisation and rupture, as well as damage due to high-temperature interaction between the molten magma and the Alloy 22. Again, as in the seismic scenario, detailed structural analyses were performed in an attempt to quantify the consequences of these various mechanical loads and additional corrosion processes.

Although some of the scenarios considered by DOE (2008) in the YMP may appear extreme in the context of a GDF located under the water table in stable host rock, the general principles involved for incorporating the effects of mechanical loads and their interaction with corrosion processes on overall container integrity are broadly applicable.
Figure D1.7: Structure of models for the seismic disruptive event scenario (DOE, 2008).
Figure D1.8: Structure of models for the igneous disruptive event scenarios (DOE, 2008).
D1.4 Summary

Integrated approaches to assessing HLW/SF container integrity have been developed in several international nuclear waste management programmes. To date, these integrated assessments have been primarily conducted for C-steel containers, but there is no fundamental reason why the same sort of approach cannot be used for any material or container design. The essential components of such an integrated approach should include the following:

- An assessment of the potential container failures modes and of the mechanical and material-related factors and processes leading to failure and their interactions;
- The definition of the container requirements, based on the container safety functions, regulatory requirements, the design of the GDF, programmatic requirements, etc.;
- The development of suitable detailed or abstracted models for assessing the various identified mechanical and material-related processes, either individually or involving multiple processes in a single model;
- The definition of an appropriate safety factor;
- A method for representing the inter-relationship between mechanical and material-related processes and their impact on container integrity, such as the Failure Assessment Diagram or the approach developed by RWM C.
Appendix D1: Integration of Container Failure Modes

D1.5 References


