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# Technical Report 12-06

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# Abstract

As part of its long-term plans for development of a repository for spent fuel (SF) and high level waste (HLW), Nagra is exploring various options for the selection of materials and design concepts for disposal canisters. The selection of suitable canister options is driven by a series of requirements, one of the most important of which is providing a minimum 1'000 year lifetime without breach of containment. One candidate material is carbon steel, because of its relatively low corrosion rate under repository conditions and because of the advanced state of overall technical maturity related to construction and fabrication. Other materials and design options are being pursued in parallel studies.

The objective of the present study was to develop conceptual designs for carbon steel SF and HLW canisters along with supporting justification. The design process and outcomes result in design concepts that deal with all key aspects of canister fabrication, welding and inspection, short-term performance (handling and emplacement) and long-term performance (corrosion and structural behaviour after disposal). A further objective of the study is to use the design process to identify the future work that is required to develop detailed designs.

The development of canister designs began with the elaboration of a number of design requirements that are derived from the need to satisfy the long-term safety requirements (minimum 1'000 year lifetime without breaching) and the operational safety requirements (robustness needed for safe handling during emplacement and potential retrieval). It has been assumed based on radiation shielding calculations that the radiation dose rate at the canister surfaces will be at a level that prohibits manual handling, and therefore a hot cell and remote handling will be needed for filling the canisters and for final welding operations. The most important canister requirements were structured hierarchically and set in the context of an overall design methodology. Conceptual designs for SF canisters, with a BWR fuel canister selected as a reference, and HLW canisters, based on two vitrified HLW containers per canister, were then developed. Corrosion, degradation, failure mechanisms, tolerance to fabrication flaws and other structural performance issues have been investigated in the context of proposed weld designs, inspection and manufacturing. Different ways of achieving compliance with the canister requirements have been explored.

The resulting design concepts provide a description of geometric shape, dimensions, material, welding and fabrication and inspection options for the canisters, including the internal supporting structures. The corrosion, material degradation, structural performance, weld design, inspection and manufacturing issues of each option are discussed, and it is shown how the proposed designs meet the canister requirements.

One of the benefits of the study is that the design development and analysis of performance led to the identification of the specific work needed to develop detailed design concepts and prototype canisters. The most important aspects are developing the weld design, weld method and approach to post-weld stress relief, as well as the determination of the maximum allowable defect size and safety factor in relation to crack growth probability.

## Zusammenfassung

Die Nagra untersucht im Rahmen ihrer langfristigen Planung zur Realisierung eines geologischen Tiefenlagers für die Entsorgung abgebrannter Brennelemente (BE) und hochaktiver Abfälle (HAA) verschiedene Optionen bei der Auswahl von Materialien und Auslegungskonzepten für die Endlagerbehälter. Die Auswahl geeigneter Behälterauslegungen wird bestimmt durch eine Anzahl Anforderungen, wobei die wichtigste die Gewährleistung einer Mindestlebensdauer von 1'000 Jahren ohne Versagen des Einschlusses ist. Ein mögliches Material ist dabei Karbonstahl, dies aufgrund seiner vergleichsweise geringen Korrosionsrate unter tiefenlagerrelevanten Bedingungen sowie seines hohen technischen Entwicklungsstands hinsichtlich Konstruktion und Herstellung. Weitere Materialien und Auslegungsvarianten werden in Parallelstudien untersucht.

Das Ziel des vorliegenden Berichts ist die Entwicklung von Auslegungskonzepten für BE- und HAA-Endlagerbehälter aus Karbonstahl und ihre Begründung. Bei diesem Prozess werden sämtliche wichtigen Aspekte hinsichtlich Herstellung, Schweissnähte und Abnahmeprüfung sowie Funktionsfähigkeit, d. h. Kurzeit- (Handhabung und Einlagerung) und Langzeitverhalten (Korrosion und Strukturverhalten nach der Einlagerung) der Behälter behandelt. Ein weiteres Ziel des vorliegenden Berichts ist die Anwendung des Auslegungsprozesses zur Identifikation künftiger Arbeiten, die für die Entwicklung detaillierter Auslegungen erforderlich sind.

Die Entwicklung von Behälterauslegungen begann mit der Aufstellung einer Anzahl Auslegungsanforderungen, die aus dem Bedürfnis entstanden, die Langzeitanforderungen (mindestens 1'000 Jahre Lebensdauer ohne Behälterversagen) und die Betriebssicherheitsanforderungen (erforderliche Robustheit für die sichere Handhabung während der Einlagerung und potenziellen Rückholung der Behälter) zu erfüllen. Basierend auf Berechnungen zur Abschirmung radioaktiver Strahlung wurde angenommen, dass die Rate der Strahlendosis an den Behälteroberflächen auf einem Niveau sein wird, das keine manuelle Handhabung mehr erlaubt. Daher werden eine "heisse Zelle" und Fernbedienung bei der Befüllung der Endlagerbehälter und der Erstellung der abschliessenden Schweissnähte notwendig. Die wichtigsten Behälteranforderungen werden hierarchisch gegliedert und in den Kontext der Gesamtmethodologie gestellt. Es wurden konzeptuelle Auslegungen für BE-Behälter mit einem SWR- (Siedewasserreaktor) Brennstoffbehälter als Referenz und HAA-Behälter basierend auf zwei verglasten HAA-Kokillen pro Endlagerbehälter entwickelt. Korrosion, Abbau, Versagensmechanismen, Toleranz gegenüber Fabrikationsfehlern und weitere strukturelle Leistungsdefizite wurden in Zusammenhang mit vorgeschlagenen Auslegungen, Prüfkonzepten und Herstellung von Schweissnähten geprüft. Dabei wurden verschiedene Wege zur Erfüllung der Behälteranforderungen untersucht.

Die resultierenden Auslegungskonzepte liefern eine Beschreibung von geometrischer Form, Dimensionierung, Material, Schweissnaht sowie Herstellungs- und Überprüfungsoptionen für die Behälter einschliesslich ihrer internen Struktur. Korrosion, Materialabbau, strukturelle Funktion, Schweissnahtauslegung, Überprüfungs- und Fabrikationsfragestellungen jeder Option werden diskutiert. Ausserdem wird gezeigt, wie die vorgeschlagenen Auslegungen die Behälteranforderungen erfüllen.

Ein Vorteil dieser Studie ist, dass die Entwicklung der Behälterauslegungen und die Funktionsanalyse zur Identifizierung spezifischer Arbeitsgebiete führte, die zur Entwicklung detaillierter Auslegungskonzepte und Behälterprototypen erforderlich werden. Die wichtigsten Aspekte sind dabei die Entwicklung der Schweissnahtauslegung, der Schweissmethode und der zu verwendende Ansatz zum Spannungsabbau nach erfolgtem Schweissen sowie die Bestimmung der maximal tolerierbaren Grösse von Defekten und des entsprechenden Sicherheitsfaktors in Zusammenhang mit der Rissbildungswahrscheinlichkeit.

## Résumé

Dans le cadre de la planification à long terme d'un stockage pour éléments combustibles irradiés (ECI) et déchets de haute activité (DHA), la Nagra passe actuellement en revue différentes options relatives au choix des matériaux et à la conception des conteneurs utilisés pour le stockage. La solution finalement retenue devra respecter un certain nombre d'exigences, parmi lesquelles la nécessité d'assurer un confinement sans perte d'intégrité sur un minimum de 1000 ans. L'un des matériaux envisagés pour les conteneurs est l'acier au carbone, du fait de son taux de corrosion relativement bas dans les conditions du stockage, mais aussi en raison du niveau de maturité avancé des techniques de construction et de fabrication. D'autres matériaux et concepts font l'objet d'études parallèles.

La présente étude avait pour objectif la conception de conteneurs en acier au carbone pour ECI et DHA et la présentation des arguments relatifs à chacune des options. Les concepts obtenus abordent l'ensemble des principaux aspects de la fabrication des conteneurs, du soudage et des inspections, la performance à court terme (manutention et opérations de stockage) et à long terme (corrosion et comportement structurel à l'issue des opérations de stockage). Cette étude visait également à utiliser le processus de conception pour identifier les lacunes à combler avant la mise au point de concepts plus détaillés.

En premier lieu, une série d'exigences de conception a été établie sur la base des exigences de sûreté à long terme (un confinement sans perte d'intégrité assuré sur un minimum de 1000 ans) et des exigences relatives à la sûreté en exploitation (une conception robuste nécessaire pour la sécurité des manipulations lors des opérations de stockage et de récupération éventuelle). Sur la base du calcul du blindage contre les rayonnements, on a posé comme hypothèse que le débit de dose à la surface des conteneurs serait trop élevé pour autoriser une manutention directe, et qu'il faudrait par conséquent recourir à une cellule de haute activité et à une manipulation à distance pour remplir les conteneurs et procéder au scellement final. Les principales exigences relatives aux conteneurs ont été hiérarchisées et placées dans le contexte d'une méthodologie de conception globale. On a ensuite élaboré des concepts de conteneurs, d'une part pour ECI, en prenant pour référence un conteneur de combustible pour REB, et d'autre part pour DHA, en postulant deux colis de déchets de haute activité vitrifiés par conteneur. Les processus de corrosion et de dégradation, les mécanismes de défaillance, la tolérance aux erreurs de fabrication, ainsi que d'autres questions relatives à la performance structurelle ont été étudiés au regard des conceptions de soudage proposées, des possibilités d'inspection et des procédés de fabrication. Différentes solutions ont été envisagées pour respecter les exigences fixées pour les conteneurs.

Les concepts qui résultent de cette étude comprennent une description de la forme géométrique, des dimensions, des matériaux, des options disponibles pour le soudage, la fabrication et l'inspection des conteneurs et des structures internes. La corrosion, la dégradation des matériaux, la performance structurelle, de même que les questionnements liés au soudage, aux inspections et à la fabrication sont détaillés pour chacune des options envisagées et il est démontré comment les différents concepts répondent aux exigences fixées pour les conteneurs.

L'un des avantages de l'étude a été que le processus de conception et l'analyse des performances ont permis de définir dans quels domaines des travaux seront nécessaires en préalable à l'élaboration de concepts détaillés et de prototypes de conteneurs. Les thématiques à traiter en priorité sont la conception du scellement, le procédé de soudage, l'approche utilisée pour le détensionnement après soudage, ainsi que la taille de défaut maximale admissible et le facteur de sûreté relatif à la probabilité de propagation des fissures.

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# Abbreviations

| | |
|---|---|
| ANSI | American National Standards Institute |
| ASME | American Society of Mechanical Engineers |
| ASTM | ASTM International (Originally American Society for Testing Materials) |
| BSI | British Standards Institute |
| BWR | Boiling water reactor |
| CEN | European Committee for Standardisation |
| CTOD | Crack tip opening displacement |
| DAC | Distance amplitude correction (standard calibration method for ultrasonic testing) |
| dB | Decibel |
| DIN | Deutsches Institut für Normung (German Institute for Standardization) |
| DNV | Det Norske Veritas (Norway) |
| EB | Electron beam |
| EC | European Commission |
| ECA | Engineering critical assessment |
| ENIQ | European Network for Inspection Qualification |
| ENSI | Swiss Federal Nuclear Safety Inspectorate |
| ET | Eddy current testing |
| FAD | Failure assessment diagram |
| FE | Finite element |
| FMEA | Failure Modes and Effects Analysis |
| Gy | Gray |
| HAZ | Heat affected zone |
| HIC | Hydrogen induced cracking |
| HLW | High level waste |
| HSE | Health and Safety Executive (UK) |
| HZ | Hitachi Zosen |
| IAEA | International Atomic Energy Authority |
| ICC | Integrity Corrosion Consulting Ltd |
| ISI | In-service inspection |
| ISO | International Organisation for Standardisation |
| JISC | Japanese Industrial Standards Committee |
| MPI | Magnetic particle inspection |
| NDA | Nuclear Decommissioning Authority (UK) |

| | |
|---|---|
| NDT | Non-destructive testing |
| NG | Narrow gap |
| NG-GTAW | Narrow gap gas tungsten arc welding |
| NTB | Nagra Technischer Bericht (Nagra Technical Report) |
| ORNL | Oak Ridge National Laboratories |
| PAUT | Phased array ultrasonic testing |
| PCB | Printed circuit board |
| PT | Liquid penetrant testing |
| PWHT | Postweld heat treatment |
| PWR | Pressurised water reactor |
| Ra | Roughness average (standard measure of surface finish) |
| RDS | Rate determining step |
| RQ | Requirement |
| RT | Radiographic testing |
| RWMC | Radioactive Waste Management Funding and Research Centre, Tokyo, Japan |
| SCC | Stress corrosion cracking |
| SDH | Side-drilled hole (standard calibration reflector for ultrasonic testing) |
| SF | Spent fuel |
| SNV | Swiss Association for Standardisation |
| TJ | Technical justification |
| TOFD | Time-of-flight diffraction technique |
| TÜV | Technische Überwachungsvereine (Technical Inspections Organisations) |
| TWE | Through-wall extent |
| UT | Ultrasonic testing |
| WPS | Welding procedure specification |

# 1 Introduction

## 1.1 Background

Nagra is the Swiss national cooperative responsible for the disposal of all types of radioactive waste produced in Switzerland. As part of Nagra's long term strategy, it is planning to build a repository for final disposal of the spent nuclear fuel and high level nuclear waste. By about 2020, Nagra intends to have applied for a site licence for the repository. This will require documentary evidence that all factors relating to the construction, operation and maintenance of the repository have been considered.

In 2010 Nagra commissioned TWI to develop design concepts for canisters to contain spent fuel (SF) and high level waste (HLW) arising from nuclear power production in Switzerland that would be placed in the repository. Prior work in Switzerland on this topic goes back to 1985, when a first design concept was developed for a HLW canister (Steag & Motor-Columbus 1985). Corrosion aspects related to the long-term performance for a carbon steel SF canister were discussed in work by Johnson & King (2003) and in more detail in Landolt et al. (2009).

The provisional timeframe for design development, construction and emplacement of canisters in the repository is:

| | |
|---|---|
| 2009 – 2013 | Technology assessment studies for carbon steel, development of design concepts for steel SF and HLW canisters and alternative materials studies, to support the general licence application. |
| 2015 – 2025 | Design and materials studies. |
| 2025 | Final selection of canister material. |
| 2025 – 2035 | Optimisation and detailed design studies. |
| 2035 – 2045 | Canister prototype production. |
| 2050 – | Emplacement of canisters in disposal repository. |

## 1.2 Disposal concept

The disposal concept envisaged by Nagra is to emplace the canisters containing the SF and HLW in underground caverns which are subsequently completely backfilled with bentonite clay and left without anticipated intervention for thousands of years. The minimum lifetime requirement for disposal canisters for SF and HLW is to provide sealed containment of the waste for a period of at least 1'000 years. Various options have already been explored with respect to selection of materials and design concepts for SF and HLW disposal canisters (Johnson & King 2003, Landolt et al. 2009).

Given the long time until canister emplacement in the repository, there is the potential to take advantage of developments in materials understanding and technology development, thus no decisions have yet been made regarding the choice of the material or the specifics of the design. Nonetheless, two materials stand out as strong possibilities because of their expected good corrosion performance under the environmental conditions foreseen and because the welding and other key technologies relevant to full-scale production have already been convincingly demonstrated. These materials are carbon steel and copper.

A canister design using copper as the outer corrosion barrier with cast iron as a structural member has been selected by SKB (2010) and Posiva (Nolvi 2009). More than fifty prototype copper / cast iron canisters for disposal of SF have been constructed.

In the case of carbon steel, the full-scale production of prototype SF canisters has been limited. However, the principal technology aspects relevant to their production have long been used in many industrial applications and some studies of canister production and welding aspects have been performed (Asano et al. 2005, 2006 and Pike et al. 2010). Nagra has indicated its interest in further exploring the option of using carbon steel in order to identify the work needed to develop a canister prototype such that the basic feasibility aspects would ultimately be demonstrated, but has not excluded the possibility of using other materials for canisters.

## 1.3 Scope of this report

The objectives and general approach to developing concepts for the canister design(s) are discussed in Section 2. Section 3 describes the basis for the requirements that the canister design has to meet in relation to the resistance to internal and external loading and forces, production welding and mechanical handling, and to the long-term safety requirement of providing sealed containment for a minimum of 1'000 years. The approach to generating the design concept and preliminary design analysis work is presented in Section 4. Possible size, geometry and form of the canister design(s) are discussed in Section 5.

The canister design concepts are supported by detailed discussions with respect to material, corrosion, structural performance, weld design, inspection and manufacturing issues, which are presented in Sections 6 to 12. This work is summarised in Section 13 where a review of the canister design concepts is provided including a summary of how the design concepts satisfy the requirements. This is followed by overall conclusions and recommendations in Section 14.

## 1.4 Project team

This report has been produced by a project team led by TWI. It has had input from a wide range of engineering, technical and scientific disciplines at TWI, Nagra, Integrity Corrosion Consulting Ltd and Hitachi Zosen. The latter company designs and manufactures nuclear transportation and storage containers, while TWI provides the expertise in materials, welding and structural integrity. The design concepts for the disposal canister with supporting documentation presented within this report have been developed through a series of meetings and discussions between the project team and Nagra.

# 2 Objective and Canister Requirements

## 2.1 Introduction

The objective of the current work is to develop suitable design concepts for SF and HLW canisters that would be capable of meeting the basic requirements for the canisters. Nagra had proposed that the design concepts should be based on using a grade of carbon steel selected for being proven for welded fabrication and with properties potentially capable of achieving the minimum 1'000 year lifetime required by the Swiss Federal Nuclear Safety Inspectorate (ENSI). The design concepts should be based on existing technology. To meet this objective, the work comprises the following tasks:

- Definition of canister requirements,
- Development of design concepts for SF and HLW canisters,
- Canister design and manufacturing.

The objective of this report is to present conceptual designs for HLW and SF (PWR and BWR) canisters. The canister design concepts outline design descriptions for the HLW and SF canisters, including possible welding and handling features, together with options for the internal supporting structures for the HLW flasks and PWR/BWR fuel assemblies. The report provides a supporting discussion of material, corrosion, structural performance, weld design, inspection and manufacturing issues associated with the design concepts and helps to define the work needed to advance to a prototype design.

TWI and Nagra have developed and defined thirty basic requirements (RQ1 to RQ30) that a canister design has to meet or exceed. These are discussed below. Many of these requirements use the phrase "adequate margin" in relation to the avoidance of "failure" of the canister. Both "adequate margin" and "failure" require some explanation.

In this report the term "failure of the canister" should be interpreted as any loss of containment through the existence of a leak path between the inside and the outside. This definition can cover various failure modes from a through wall crack to a more widespread structural failure. Deformation, degradation or instability of the canister are not necessarily failure modes if the containment remains intact.

An "adequate margin" should be determined by a process designed so that the canister can tolerate without failure a degree of deviations from design expectation in terms of loading, inaccuracies in analysis methods, quality lapses in materials, lack of knowledge of material performance and environment, uncertainties and potential defects in construction. There is inevitably a level of engineering judgement implicit within this process that will involve an exchange of views between the project and regulators as to what is acceptable so that the risk of failure is reduced to as low as reasonably practicable. Decisions will be based on the limit of current knowledge and experience, with an acknowledgement of where gaps in knowledge and experience exist, which might be filled in the course of time.

The process for determining an adequate margin should be based on current good practice for the construction of nuclear containment. Practices defined by relevant international standards should be applied where these are appropriate since these set criteria for what is judged acceptable practice by industry standards committees and through public comment. Design standards contain 'margins' and practices that are judged 'adequate' on this basis.

Standards for unfired pressure vessels are relevant to the canister since their purpose is to construct a vessel that maintains its containment when subject to pressure and other loads. These standards provide margins on strength and deformation over and above those required to sustain design loads. For example, Section III of the ASME Boiler and Pressure Vessel Code (ASME 2010a) specifies a minimum factor of 3 between primary membrane stress intensity based on maximum shear stress theory of failure and ultimate tensile strength, while the European pressure vessel standard EN 13445 (BSI 2002 – 2011) uses a factor of 2.4 for the same.

Both ASME and EN 13445 allow a modern design-by-analysis plastic limit load approach. Design margins are contained in partial safety factors on loading and material properties. This allows more of the load carrying capacity of the structure to be utilised at the expense of undertaking a more sophisticated analysis.

Additional margins may be required to enable the canister specification to tolerate degradation by mechanisms that are not specifically covered in unfired pressure vessel standards. These mechanisms include stress corrosion cracking and hydrogen induced cracking. This topic is discussed further in Section 5.3.

## 2.2 Hierarchy of requirements

The thirty RQs are discussed in this section. Their relationships to the disposal concept and canister fabrication, handling, loading, integrity and long term performance are discussed in Section 3.

The requirements that provide the basis for structural design are shown in Figure 2.1. The approach involves stating the highest level requirements at the top of the figure and then providing the lower level requirements that are necessary to achieve the higher level requirements. The numbers in the boxes refer to the canister requirements described in Table 2.1 In addition to the requirements, Nagra has specified certain boundary conditions to be assumed for the study. These are also shown in Figure 2.1 as boundary conditions **A** and **B**. It is noted in the Design approach (Section 4.2), that the design of the canister is predominantly based on achieving the structural performance requirements within the boundary conditions and for the evaluated wall thickness loss due to corrosion.

Boundary condition **A**: The canisters to be designed are to be made of carbon steel. This provides important constraints to **RQ 2, 3, 5** and **6**.

Boundary condition **B**: The canister handling concept includes a shielding overpack (see Section 3.3), which provides radiological safety prior to canister emplacement. The surface dose rate on the disposal canister itself is determined by the waste loading and the thickness of the carbon steel used for the canister. Calculations of canister surface dose rates for various thickness values indicate that thicknesses of 140 mm (HLW) and 120 mm (SF) are required to give surface dose rate below 1'000 mSv/hr (See App. A). A maximum of 1'000 mSv/hr provides sufficient shielding to preclude radiation-induced corrosion[1].

Table 2.1 describes the requirements and in some cases their context in relation to the work performed.

[1] This is not an essential requirement, but it avoids having to develop a detailed understanding of the process.

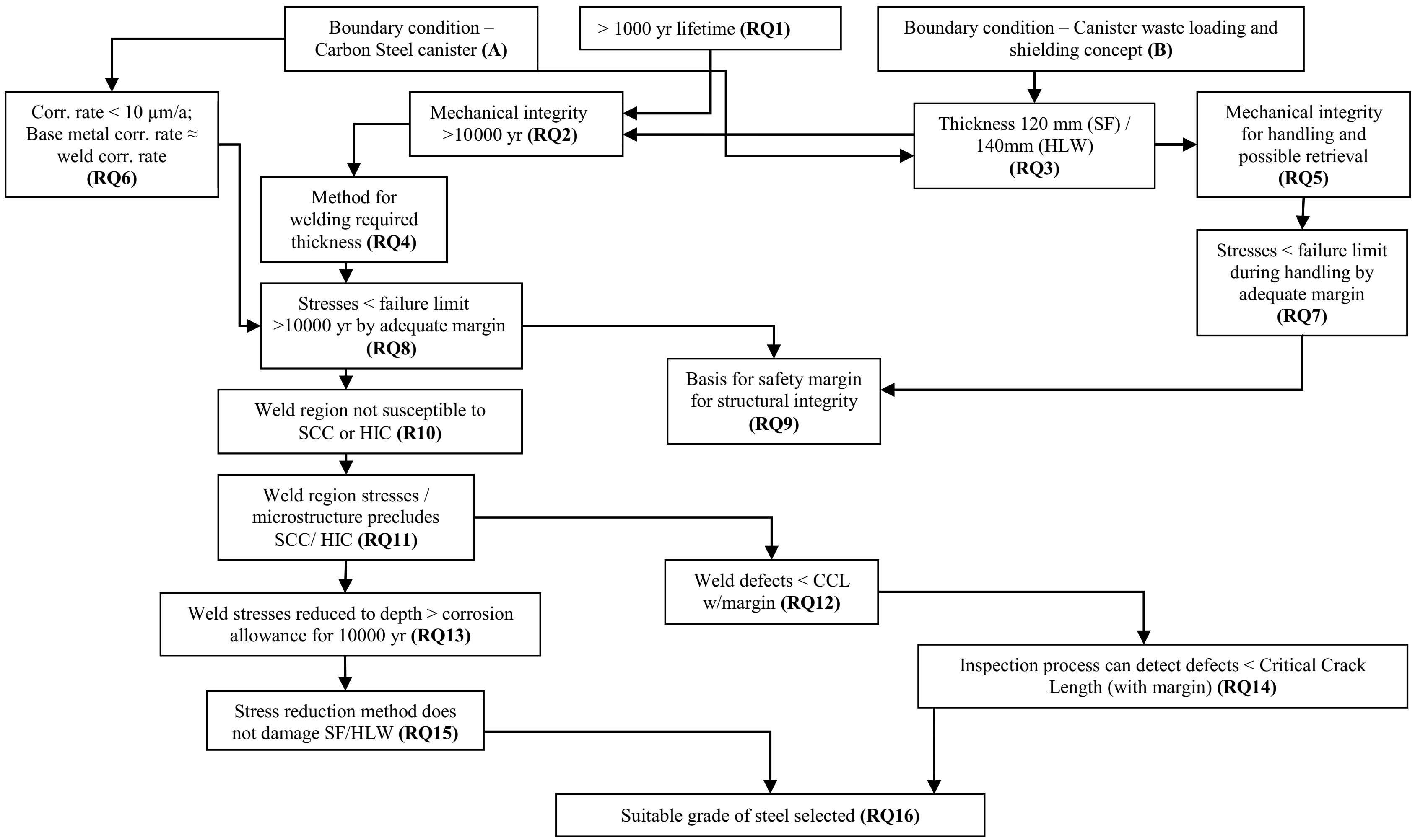


Fig. 2.1: Hierarchy of requirements.

Tab. 2.1: Disposal canister requirements.

| No. | Title | Requirement |
|---|---|---|
| RQ1 | Canister lifetime | There is a regulatory requirement of a minimum lifetime (no breach of containment) of 1'000 years for SF and HLW canisters. |
| RQ2 | Long term integrity | Nagra proposes a lifetime requirement of 10'000 years for SF and HLW canisters for the present study. This is to provide a significant margin of safety with respect to the RQ1 target and to examine structural performance over a time frame significantly exceeding 1'000 years. About 20 mm of the wall thicknesses proposed (see RQ3) would be consumed by corrosion within 10'000 years. |
| RQ3 | Canister wall thickness | The canister waste loading and shielding concept provide the basis for the shielding calculation and derived wall thickness. The wall thickness should ensure long-term structural integrity and that the radiation dose rate at the canister outer surface is < 1'000 mSv/hr in order to preclude radiation-induced corrosion; see RQ24.<br><br>The HLW canister in the shielding calculations is assumed to contain two AREVA flasks. For a 140 mm wall thickness, the surface ($\gamma$ + n) dose rate is about 130 mSv/hr. The dose rate is comparable to the total surface dose rate of 135 mSv/hr for a spent fuel canister with a wall thickness of 120 mm. |
| RQ4 | Closure welding process | There must be a satisfactory method for welding steel that has a thickness in the range in question. The weld depth need not be equal to the entire wall thickness if the requirements related to the structural integrity of the weld are met. The welding method must be suitable for remote operation, given the radiation field (ca. 130 mSv/hr). |
| RQ5 | Structural integrity (handling incidents pre-emplacement) | The canister must remain structurally sound without breach of containment during normal handling and incidents that might occur during handling. Because the canister will have to be surrounded by a heavy thick-walled transfer/shielding overpack while in the encapsulation facility and during transfer underground, it is not considered in this condition vulnerable to impacts from handling. A canister handling scheme has been identified, but the details clearly may be changed in future, thus a simplified horizontal flat drop is assumed as a general test of robustness. For this purpose a 5 m drop onto a concrete floor is proposed. |
| RQ6 | General and localised wall thickness loss as a result of corrosion | A requirement for the maximum rate of gas production in the SF/HLW repository in Opalinus Clay corresponds to a corrosion rate of steel under anaerobic conditions less than 10 µm/year. The expected rate based on present understanding is 1 – 2 µm/year. |
| RQ7 | Structural integrity - Retrieval | The stresses in the canister as a result of a handling incident should be less than values that would indicate a possibility of breaching determined on the basis of conservative assumptions and analyses. This should also include stresses from handling during possible retrieval (engaging with the lifting feature and pulling out) during the operational phase. |
| RQ8 | Structural integrity - Long term | The stresses in the canister wall, lid and base, including the weld region should not give rise to structural failure causing breach of containment for at least 10'000 years as demonstrated by compliance with an appropriate design standard. However, it should be stated that deformation beyond the elastic limit is not necessarily of concern provided the canister remains sealed. |

| No. | Title | Requirement |
|---|---|---|
| RQ9 | Structural integrity - Safety margin | A suitable basis for the safety margin for structural integrity should be proposed as part of the design study. *The repository environment may lead to a maximum load on the canister of 29 MPa horizontal and 22 MPa vertical (900 m depth).* |
| RQ10 | Weld integrity – SCC/HIC | The weld region should not be susceptible to SCC or HIC. This should also consider the possibility of HIC occurring from the inside.Fuel will have been in dry storage for 40 years prior to loading into disposal canisters, thus it can be assumed that no moisture will be released from any defective fuel after the disposal canister is sealed. Fission gas and helium release from radioactive decay within a sealed canister has been calculated to be small (Johnson & King 2003). |
| RQ11 | Residual stress mitigation/ control | The stresses in the weld region and HAZ should be low enough to preclude the occurrence of stress-assisted failure processes such as SCC and HIC. The reason for this requirement is that, given the long time frame in question, it is considered inappropriate to rely solely on the argument that the environment is one in which susceptibility to stress-assisted failure is very low. Instead, the stresses should be reduced so as to prevent any possibility of propagation. The stresses in the weld region and HAZ should be low enough to reduce the probability of stress-assisted failure processes such as SCC and HIC. |
| RQ12 | Critical flaw size | The weld procedure should ensure any defects remaining in the canister after manufacture are smaller than the critical crack length by a suitable margin. |
| RQ13 | Residual stress reduction | The weld stresses should be reduced to a depth exceeding the 20 mm corrosion allowance by an adequate margin. |
| RQ14 | Inspection and testing | The inspection process should be able to detect defects that are smaller than the critical crack length by an adequate margin. The inspection method proposed must be suitable for remote operation, given the radiation field. |
| RQ15 | Integrity of waste – residual stress reduction | The stress reduction method for a fully loaded and welded SF or HLW canister should not damage the spent fuel or HLW. The guidelines used in the present study, which may be revised depending on other studies, are SF temperature less than 400°C and HLW temperature less than 450°C. |
| RQ16 | Material properties | The selected grade of carbon steel should meet all higher level requirements. |
| RQ17 | Inner lid | An inner lid should be installed in the canister after loading of the SF or HLW. The inner lid has a temporary containment function and should have an air-tight seal to ensure the next stage of operation (placing on lid and final welding) poses no risk of spread of contamination. |
| RQ18 | Lifting/handling feature | The canister should have a lifting feature to allow handling, including possible retrieval during the operational phase. |
| RQ19 | Post-weld surface treatment | The canister weld region should be cleaned (machined) to remove residual weld material or scale resulting from heat treatment. |
| RQ20 | Production rate | It should be possible, using the preferred welding/heat treatment and inspection processes, to complete closure welding of 1 – 2 canisters per day in the encapsulation facility. |
| RQ21 | Marking / Identification | A method of physically marking canisters should be proposed. The method should able to withstand several mm of oxic corrosion that might occur prior to any retrieval operation that might be required. |

| No. | Title | Requirement |
|---|---|---|
| RQ22 | Internal structure | An internal structure (e.g. basket) should be proposed to allow 9 or 4 SF assemblies to be placed in the canisters. There should be adequate clearance (defined in Appendix A) between the structure and the fuel assemblies. The basket should be constructed from steel. |
| RQ23 | Waste sub-criticality | The loaded SF canisters should be subcritical when the void spaces are water-filled. Criticality analysis being performed outside the present study covers the arrangement of the fuel assemblies in the canister and canister geometry presented in the present study as well as other canister concepts. The criticality analysis studies are examining the credit that may be taken from burn-up. If burn-up credit is an accepted approach and sufficient burn-up of the fuel can be confirmed, (Kühl et al. 2012, Agrenius 2010), then spent fuel in the canisters will be sub-critical over the very long-term even if the canister is breached and water filled and even in the case of fuel assembly degradation. There are no specific constraints imposed on the canister design for the present study. |
| RQ24 | Surface dose rate | The radiation dose at the canister surface after loading and sealing of the canister should be < 1'000 mSv/hr, so as to avoid radiation-induced corrosion. This is not necessarily a limiting requirement, but is assumed to be for this study. It may be possible to use a smaller wall thickness than 120 mm and thus a higher surface dose rate if the corrosion data show that the effects of radiation on corrosion rate are minimal in the context of the 20 mm corrosion allowance. *This would be considered only in future optimisation studies.* |
| RQ25 | Retrievability | The canister must satisfy the requirement for retrievability during the operational phase. This implies that it must be possible to grapple the canister with the lifting ring and pull it out into a shielding unit. For this operation it is assumed that the surrounding bentonite pellets have been removed, thus there is limited friction involved in pulling the canister. |
| RQ26 | Re-packaging | There should be a method defined for repackaging in case of significant damage to a canister during a handling incident. (*This should be considered in a future iteration of the encapsulation facility design*). |
| RQ27 | Costs | Issue of materials availability, raw material cost, canister development costs, prototype costs, unit production costs, possible production methods and diversity of possible producers should be documented. |
| RQ28 | Manufacturing best practice | Best available present day technology should be adopted for the production, fabrication and welding concept. |
| RQ29 | Codes and standards | Codes and standards relevant to design, construction, structural analysis etc. for the canister should be proposed. |
| RQ30 | Dimensions | The canister should be of adequate dimensions to accommodate SF and HLW according to the proposed SF and HLW waste loadings. |

# 3 Canister Requirements in Context of the Disposal Concept

## 3.1 Canister requirements

In the first task of the design study the requirements for the SF and HLW canister designs were documented, including their origins. The way in which the canister requirements are derived from the repository concept in relation to the long-term containment requirement and the waste loading, sealing and handling are discussed here. The requirements were developed in the first stage of the project and are listed in Table 2.1. The requirements that drive the basic design are listed below by number in shortened form in the context of the description of the disposal system.

## 3.2 Repository concept – barrier system

The overall safety requirements for geologic disposal of SF and HLW are based on ENSI (2009). A key requirement in this document is that of ensuring a minimum of 1'000 years containment of the waste.

The basic repository concept for disposal of SF and HLW is based on emplacement of final disposal canisters in a repository in the Opalinus Clay, a low permeability Jurassic claystone with a thickness of about 110 m. The carbon steel canisters would be emplaced horizontally in excavated tunnels (diameter about 2.5m) and the voids around and between canisters filled with a combination of compacted bentonite blocks (on which the canisters would be initially placed) and a granular bentonite mixture prepared from dense bentonite pellets (Figure 3.1). The bentonite would gradually take up water from the host rock, swell and form a low permeability barrier around the canisters.

Key requirements related mainly to long-term safety are given in Box 3.1.

**Box 3.1 Key Requirements related principally to long-term safety**

RQ1: Minimum lifetime of 1'000 years.

RQ2: Lifetime design target of 10'000 years, to exceed RQ1 by a suitable margin.

RQ3, 30: Wall thickness (with assumed waste loading).

RQ4: Welding method that satisfies RQ2.

RQ6: General corrosion rate that satisfies gas production rate limit for rock and RQ2.

RQ8, 9, 10, 11, 12, 13, 14, 15, 16, 19: Structural integrity, weld integrity, residual stress, inspection, material properties.

RQ23: Sub-criticality.

RQ24: Surface dose rate.

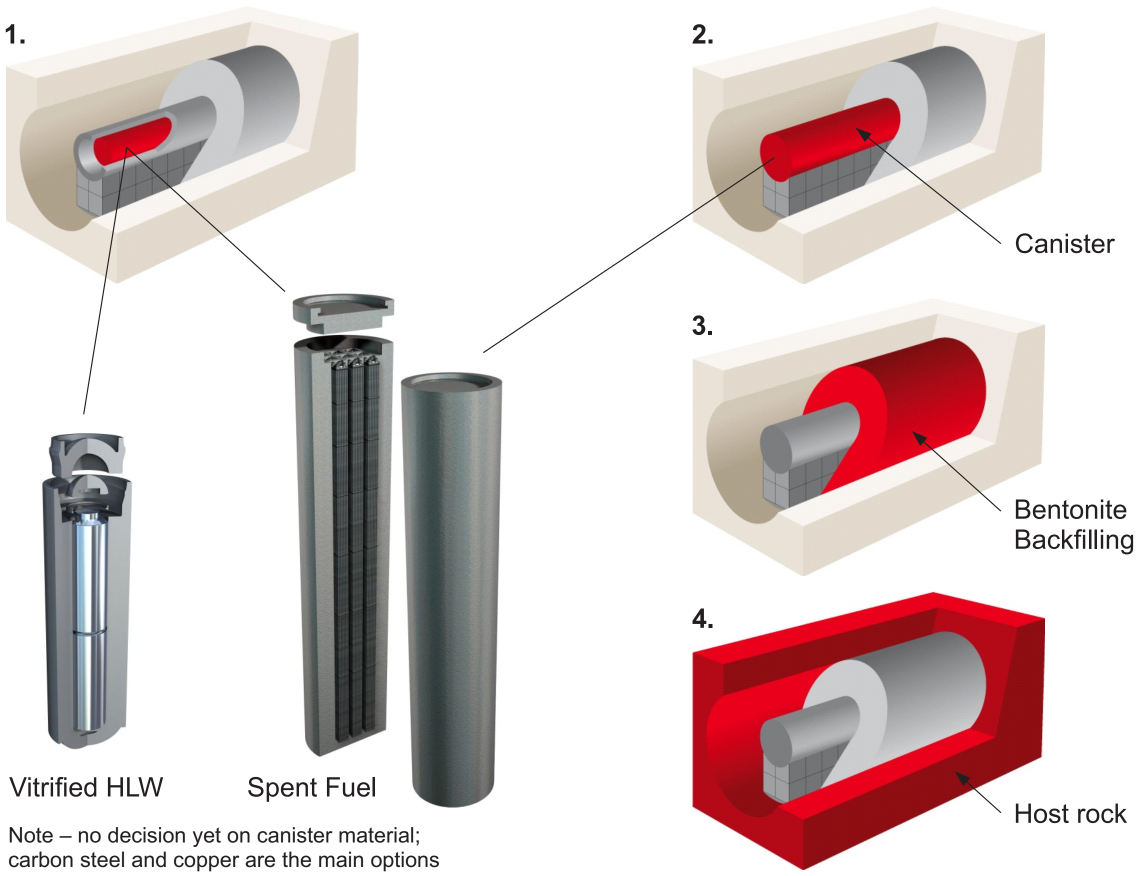


Fig. 3.1: Repository concept – barrier system.

### 3.3 Canister handling scheme

Regulations and radiation protection practices demand a handling concept that ensures operational safety. It is not practical to design a canister with a wall thickness that would permit contact handling by personnel (< 2 mSv/hr on contact)[2]. As the surface neutron dose will considerably exceed this value, the handling scheme developed involves surrounding the canister with a shielding overpack while it is loaded into the encapsulation facility (Figure 3.2).

It is an objective that the welding cell is kept free from radioactive contamination from dust or other particles. As the spent fuel has potential contamination, the SF canister will be fitted with an inner lid while it is still in the loading cell after the fuel has been loaded and sealed either by welding or by means of a seal. The canister will then move to a welding cell for welding the closure lid. (Note that the surfaces of the HLW flasks inside the HLW canister are contamination free and hence an inner lid is not required for the HLW canister).

Following final closure welding and inspection, the canister is transported in a shielding over-pack to a transfer position. It is then removed from its transport and shielding over-pack using remote handling equipment and transferred to an emplacement trolley that moves the canister to its final position. The space surrounding the canister is backfilled with bentonite granulate (Figure 3.3).

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[2] Additional steel wall thickness relative to the thicknesses selected in the present study would provide no significant reduction in the neutron dose rate of ~ 35 mSv/hr for the spent fuel canister.

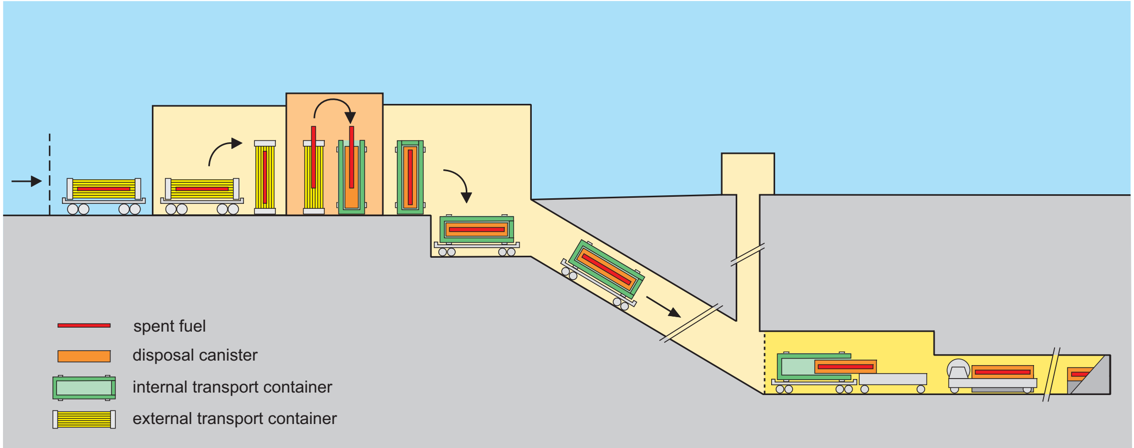



Fig. 3.2: Handling scheme.

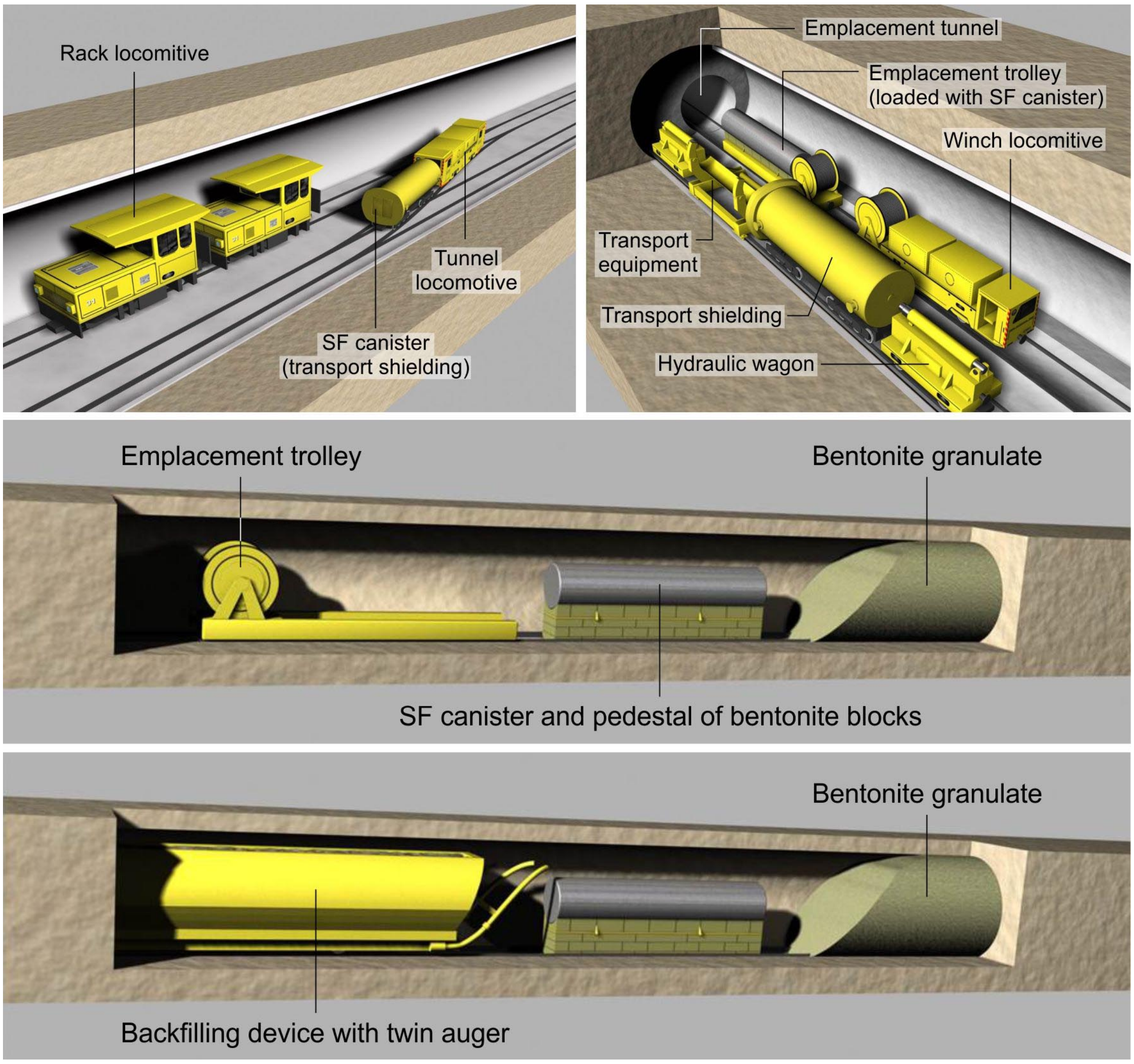



Fig. 3.3: Repository concept – operation.

As the wall thickness is therefore not set directly by radiation protection requirements related to shielding, the canister wall thickness is set to comply with requirements related to long-term corrosion performance in terms of the thickness required to reduce the canister surface dose rate below 1 Sv/hr, the threshold for radiolysis enhanced corrosion (RQ3 and RQ24), which leads to an assumed wall thickness as starting point for the design approach of 120 mm for the SF canister and 140 mm for the HLW canister.

Key requirements related mainly to the handling concept and basic manufacturing are given in Box 3.2.

**Box 3.2 Requirements related to the handling concept and manufacturing**

RQ5, RQ7, RQ25: Maintain integrity for handling incidents and possible retrieval.

RQ17: Inner lid.

RQ18: Handling feature.

RQ20: Production rate.

RQ21: Canister ID.

RQ22: Internal structure.

RQ27: Costs.

RQ28, 29: Manufacturing; codes and standards.

## 3.4 Canister loading conditions

### 3.4.1 Steady state in-situ conditions

The loading conditions imposed on the SF and HLW disposal canisters when situated within the repository are described within this section. The basis for the analysis cases for the loads experienced by SF/HLW canisters is described here.

A repository for SF and HLW may be at a depth of 400 to 900 m. At 900 m, the rock stress and hydrostatic pressure are as follows:

- Maximum principal stress ($\sigma_{max}$) is horizontal and is 29 MPa.
- Minimum horizontal stress ($\sigma_{min}$) is 22 MPa.
- Vertical stress ($\sigma_v$) is 22 MPa.
- Hydrostatic pressure is 9 MPa.

The canisters will be surrounded by bentonite with a swelling pressure of about 4 MPa. The emplacement tunnels would be oriented parallel to the maximum principal stress ($\sigma_{max}$) to minimize excavation damage. In this case, the stress condition in the rock at 900 m in relation to the tunnel orientation would be isotropic with a horizontal stress of 22 MPa and a vertical stress of 22 MPa.

### 3.4.2 Modelling of the behaviour of the bentonite and rock

A soil mechanics model for bentonite and a rock mechanics model for Opalinus Clay were used to gain insights into possible evolution of the stress in the rock-bentonite-canister system. The behaviours represent limiting cases and the real situation may be intermediate. Nonetheless, as the purpose is to identify possible maximum stresses and stress ratios, the approach is considered pragmatic.

The models were used to estimate possible loads on the canister based on worst case tunnel orientation (emplacement tunnels aligned perpendicular to $\sigma_{max}$). In these models the Opalinus Clay rock is stiffer than the bentonite. The models are used to calculate convergence of the rock, swelling of the bentonite and stress transfer to the bentonite and canister. The calculations are illustrative and were performed only for a repository depth of 400 m. An example case for 400 m depth was calculated ($\sigma_{max}$ = 12.5 MPa, $\sigma_v$ = 9 MPa) using data for a bentonite with a swelling pressure of 8 MPa. Convergence of the rock before the bentonite swells transfers a small load onto the canister (~ 1.8 MPa vertical and ~ 1.6 MPa horizontal).

In the subsequent period of saturation of the bentonite (about 100 years, according to hydraulic calculations by Senger and Ewing 2008), the full swelling pressure would develop in the bentonite. In such a condition, if the rock remains stiff and acts as a stress buffer, the stress at the canister/bentonite interface would be isotropic and equal to the sum of the swelling stress and the hydrostatic stress, despite the higher stresses in the rock. This is similar to the situation in a repository in crystalline rock. In essence the much stiffer rock carries the stress.

In order to test this result, a calculation was performed of the stress change transmitted to the canister when the vertical stress was reduced by 2.41 MPa. In this case, the stress at the canister surface is reduced by 0.15 MPa (about 6 %), i.e. very little of the rock stress change is transmitted to the canister. It can be inferred from this that for a depth of 900 m and anisotropic stresses in the rock ($\sigma_{max}$ = 29 MPa and $\sigma_v$ = 22 MPa) and a swelling pressure of 4 MPa, the expected stress on the canister is isotropic and is approximately equal to the bentonite swelling pressure of 4 MPa plus the hydrostatic pressure of 9 MPa.

The analysis is, however, based on a constitutive model for the rock that has intrinsic uncertainties that are difficult to quantify. It is possible to calculate a worst reasonable case stress scenario, in which the emplacement tunnels are aligned with $\sigma_{max}$ and the bentonite is considered to have the same mechanical properties as the rock (no stress buffering by the rock). In this case at a depth of 900 m the stress on the canister would be isotropic and equal to 22 MPa. If the tunnels are instead mistakenly aligned perpendicular to $\sigma_{max}$ and if the bentonite has the same mechanical properties of the rock, i.e. the bentonite retains no plasticity and is unable to homogenize the stresses, the loading would be 29 MPa (horizontal) and 22 MPa (vertical). The structural analyses performed on the disposal canisters when located within the repository are largely based on this extreme bounding case stress scenario. It is worth noting that the anisotropic stresses in the rock reflect effects of slow rock deformation (alpine uplift).

### 3.4.3 Qualitative picture of evolution of the load on the canister

Based on insights from the modelling calculations, the possible evolutions of the stress condition on the canister are illustrated in Figure 3.4 for a repository at a maximum depth of 900m. The situation can be briefly summarized in a time-dependent context as follows:

Rapid initial tunnel convergence (prior to saturation): ~ 2 MPa vertical and ~ 1.8 MPa horizontal if tunnels are aligned perpendicular to $\sigma_{max}$ (black line in Figure 3.4).

Full stress buffering by stiff rock: The full buffer swelling pressure of 4 MPa develops as result of hydration after about 100 years and the stress on the canister gradually increases by an additional 9 MPa (brown line in Figure 3.4) leading to an approximately isotropic stress of 13 MPa after complete recovery of hydrostatic pressure (brown diamond in Figure 3.4).

Gradual deformation of the rock and compaction of bentonite: The rock deforms gradually (time frame uncertain) and compacts the bentonite (red line in Figure 3.4). Because it should be possible to align the tunnels with $\sigma_{max}$ and because the bentonite is expected to remain more plastic than the rock, the resultant stress on the canister of 22 MPa is expected to be isotropic (lower red diamond in Figure 3.4). This represents the <u>maximum expected stress case</u>.

Gradual deformation of rock, tunnels aligned perpendicular to $\sigma_{max}$ and the bentonite is equally as stiff as the rock: The resultant stress is 29 MPa (horizontal) and 22 MPa (vertical). This represents the <u>extreme bounding stress case</u> (both red diamonds in Figure 3.4). The time dependency of deformation of the rock is at present not possible to quantify.

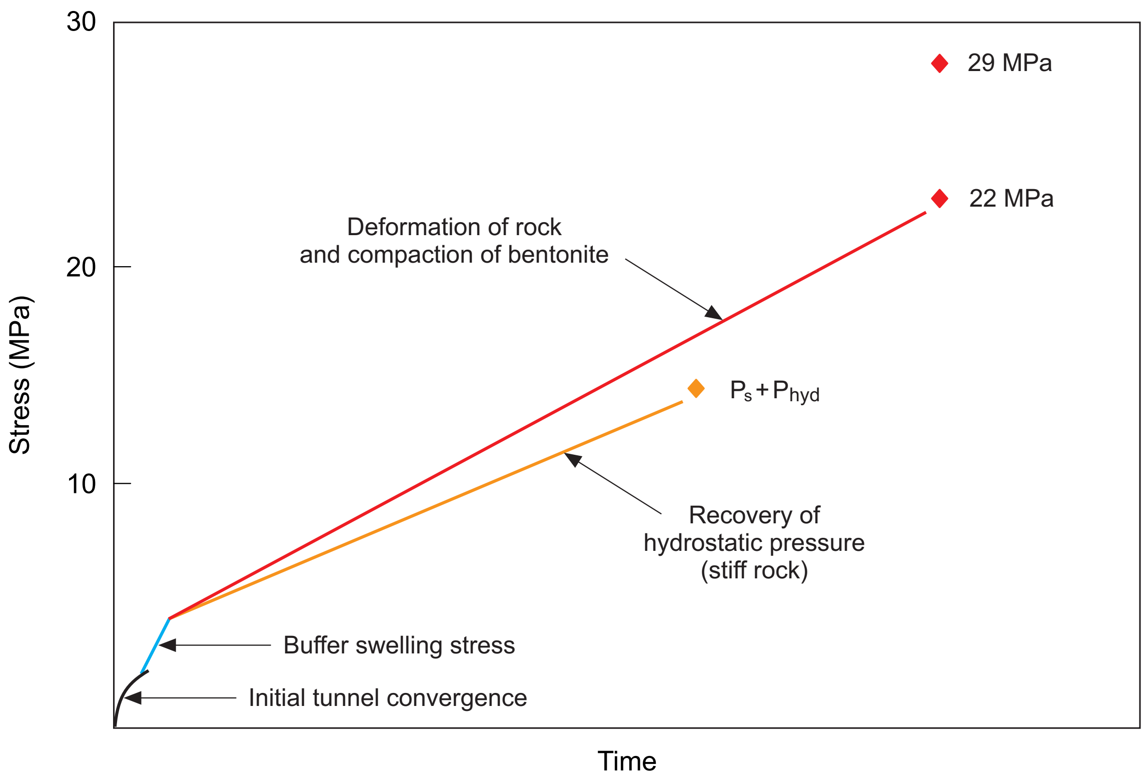



Fig. 3.4: Possible evolution of stresses experienced by a canister inside a bentonite barrier in a repository in Opalinus Clay at 900 m.

The two stress evolution paths represent two alternative possibilities, depending on the mechanical properties of the rock. The maximum conceivable stress at 900 m is 29 MPa horizontal and 22 MPa vertical.

### 3.4.4 Transient loading conditions

Transient structural loading of the canister after emplacement and backfilling could occur only through seismic disturbances. Over long periods of time strong earthquakes in the region of the repository cannot be ruled out. Nonetheless, provided the emplacement tunnels do not intersect fractures that might experience shear during a major earthquake, the accelerations experienced by the canister surrounded by bentonite would be so small that they would be of no significance in relation to canister integrity. As a result, the impacts of seismic loadings have not been assessed within this report.

Transient structural loadings arising from a potential handling incident (5 m drop) during the canister handling operations are treated in Chapter 10.

# 4 Design Methodology

## 4.1 Introduction

To meet the objective of this report, conceptual designs have been prepared for the BWR SF, PWR SF and HLW canisters. Concepts were developed initially for the SF canister with different internal structures, to accommodate the PWR and BWR fuel assemblies, and then for the HLW canister. The conceptual designs considered materials, corrosion, structural performance, weld design, inspection and manufacturing issues. The work has been performed in collaboration with Hitachi Zosen Corporation (Hitachi Zosen) and Integrity Corrosion Consulting Ltd (ICCL).

To start the design concept, specific work packages were prepared for the main areas of consideration to ensure the canister requirements were met. The canister requirements form the basis of the conceptual design and the work package explains how these requirements are met or exceeded. In the early stages of the design concept, it was important to develop a design methodology.

Section 4.2 describes the approach for the disposal canister. Here, the approach for the design focuses principally on the requirements that are associated with the structural performance. Because of uncertainty in the structural loading and environmental factors affecting the canister, how best to treat these uncertainties was considered and this is discussed in the reliability based design section (Section 4.3). Finally, due to multidisciplinary nature of the project it was important to understand the flow of work to be performed and this is explained within Section 4.4.

## 4.2 Design approach

This section describes the approach adopted for the design of the SF and HLW disposal canisters. The work first considered the SF canister and then the HLW canister. The basic design approach for the SF disposal canister is shown in Figure 4.1. Assuming an initial canister wall thickness of 140 mm, the wall thicknesses after 1'000 and 10'000 years are predicted to be 138 mm and 120 mm, respectively.

The disposal canister design starts from the boundary conditions set by Nagra and optimising corrosion resistance through material selection. The boundary conditions relate to the practical limitation on canister wall thickness, type of waste and internal dimensions. The basic design focuses principally on meeting the requirements that are associated with maintaining structural integrity throughout the timescale being considered. Specification of a particular material composition minimises the probability of stress-assisted failure processes such as SCC and HIC. The basic design is therefore based on the structural performance requirements, boundary conditions and evaluation of general corrosion.

An initial canister design was proposed, based on previous experience and knowledge gathered during the preparation of the canister requirements. The canister design was then evaluated to determine whether or not the requirements were met. If the requirements were not met, then the canister design was modified accordingly. The process was repeated iteratively until all the canister requirements were satisfied. Appropriate evidence was then provided and documented. This process is shown in Figure 4.2.

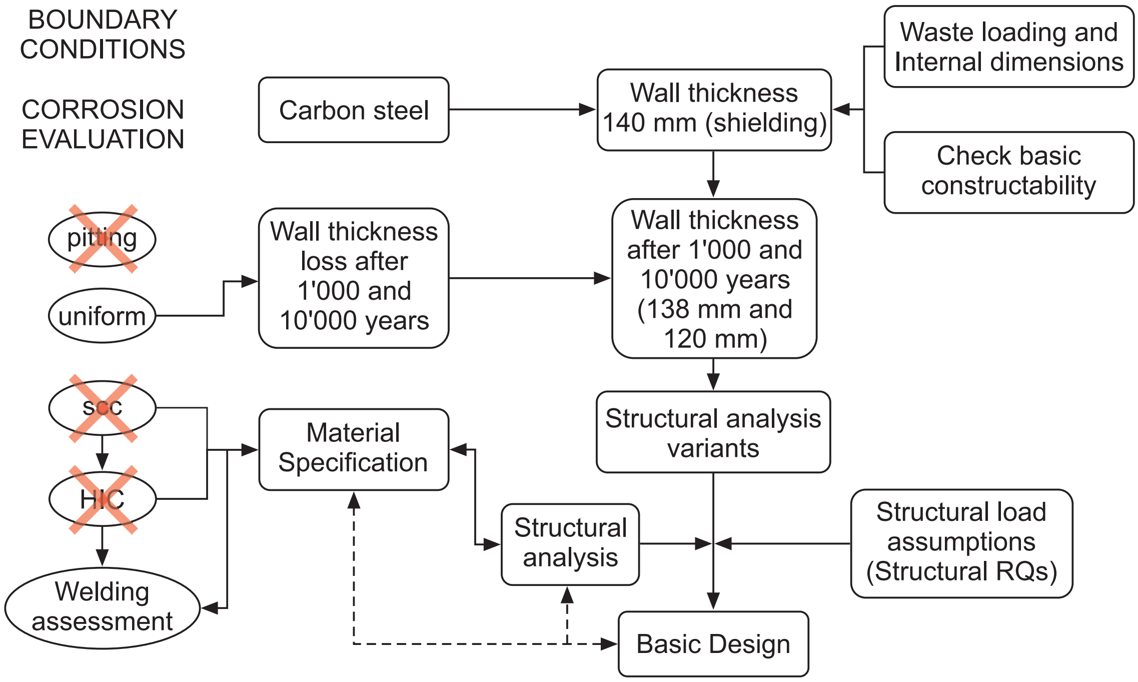



Fig. 4.1: The basic design approach for the carbon steel SF canister.

Note that the failure processes SCC and HIC are considered improbable if a suitable material specification is established and a satisfactory welding and stress remediation approach is developed. Pitting makes a small contribution to corrosion as it is relevant only during a short oxic phase (see Section 7).

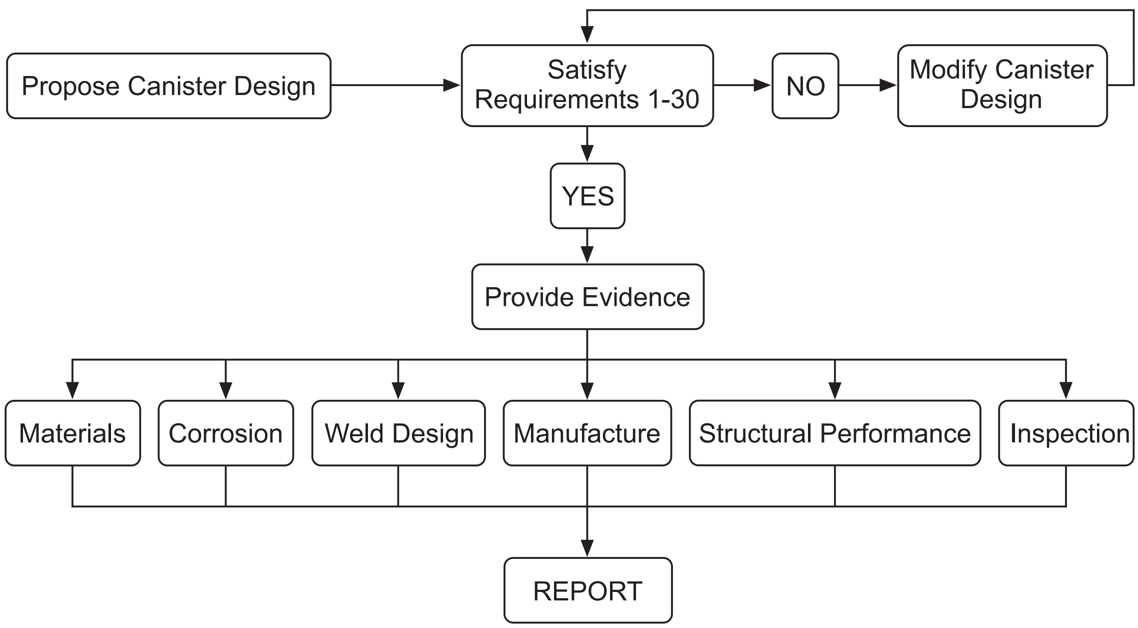



Fig. 4.2: Disposal canister design process.

At the beginning of the study it was recognised that the level of post-weld residual stress for the final closure weld is one of the most important issues for the design and development of the disposal canister. Previous studies at Nagra (Attinger & Duijvestijn 1994; Pike et al. 2010) and industrial experience of welding material of the thickness of the canister indicate that elevated residual stresses increase the probability of stress-related cracking, such as SCC. There are different methods to reduce residual stress as a result of welding and these methods are discussed within this report.

Post-weld residual stresses relate to several of the canister requirements. This report considers the effect of residual stress in the context of materials selection, welding, corrosion, structural performance and inspection. In particular, an important requirement, RQ15, is that any stress reduction method for a fully loaded and welded SF or HLW canister should not damage the spent fuel or HLW; in this case the constraint is for the SF temperature to remain less than 400°C. This has implications on the method and level of residual stress reduction that is achievable, which is discussed within this report.

## 4.3 Reliability based design

There is inevitably uncertainty in predicting the loading and environment conditions acting on the canister and changes in its materials properties over a period of 10'000 years, although the extreme bounding stress case discussed in Section 3.4.2 can be reliably assessed. Conservative estimates may be made based on current knowledge, but if the extremes of all the factors are taken this may result in a design that is unreasonable when the balance of risks is considered.

The main uncertainties in any disposal canister design are the level of external pressure loading and the corrosion rate after long periods of time. There is also uncertainty regarding the generation and uptake of hydrogen and the resulting fracture toughness of the canister materials. In order to treat these uncertainties and make a reasonable judgement, a possible engineering approach is to define upper and lower bound and best estimate values and to do a sensitivity analysis.

A more sophisticated approach would be to define probability distributions to describe the uncertainties with a best estimate and standard deviation. It would then be possible to undertake a probabilistic analysis to determine the probability of a limit state being reached and to specify the acceptability of the design on the basis of a limiting probability value. Another approach is to apply partial safety factors on the best estimate values.

The approach to conceptual design taken in this report has been based on conservative estimates of the through-life loading, environment and material properties. While there would be advantage in applying reliability based design approaches at a subsequent detailed design stage, at present it is not possible to give any variation of load but a maximum load estimate. If this approach is practicable then it is an obvious way to demonstrate achievement of stringent targets for the improbability of a breach of containment over 10'000 years.

## 4.4 Work flow diagram

Due to the multidisciplinary nature of the project it was important to prioritise the order of work to be performed and hence a work flow diagram was developed, shown in Figure 4.3. The work flow diagram helps to understand the flow of work and shows the interdependent nature of the work. It also provides some rationale as to when the variables become fixed. For example, one of the first variables to fix was the material composition and properties. Depending on the susceptibility to corrosion and structural performance results, the material composition and or properties may need to be changed. An iterative process was therefore employed.

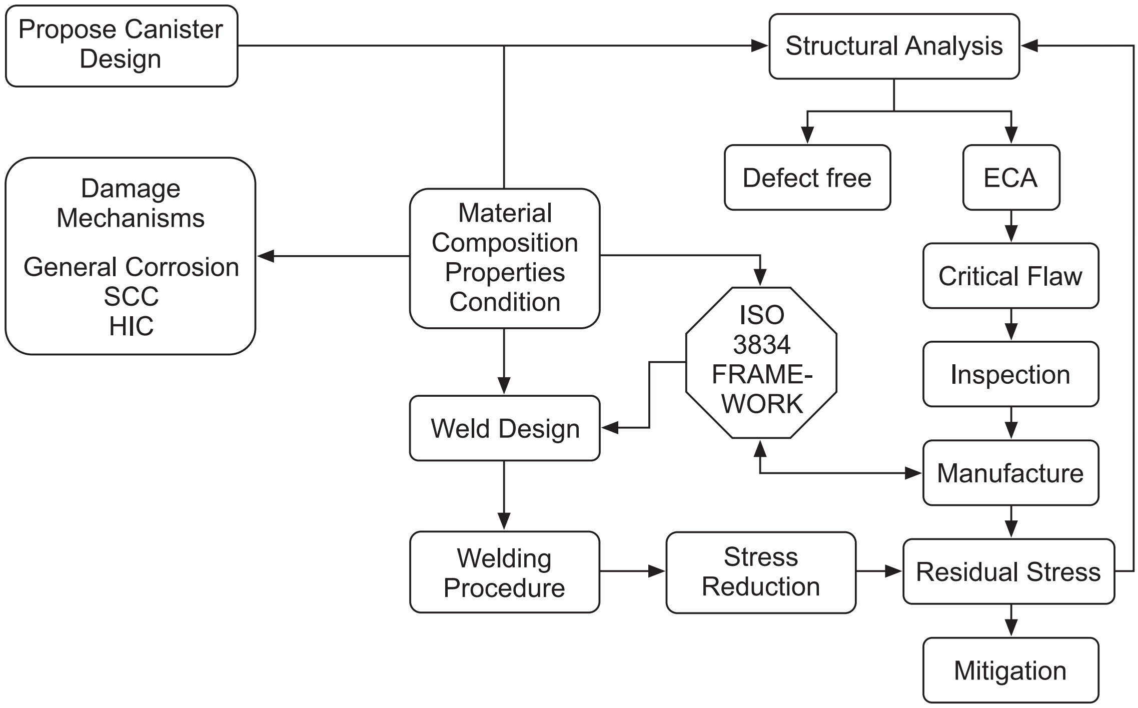



Fig. 4.3: Work flow diagram.

One can see that the welding procedure that is chosen is dependent on the design of the weld and that the welding procedure will induce residual stresses which may require some form of stress reduction. The level and extent of residual stress will have an effect on the integrity of the disposal canister and hence would need to be taken into account in the structural analysis. The structural analysis will demonstrate the integrity of the canister and will also enable critical flaw sizes to be evaluated. It will then be necessary to demonstrate that the inspection process is able to detect defects that are smaller than the critical flaw size by an adequate margin. This will affect the manufacturing route which is also dependent on the chosen material.

The work flow diagram does not show all of the interdependencies, of which there are many, but does provide some rationale to the order of work to be performed and an understanding of how the main factors are related to one another, thus ensuring that the design work is carried out effectively.

# 5 Design Considerations

## 5.1 Introduction

The conceptual design of the canister focuses principally on meeting the requirements that are associated with its structural performance and integrity. These aspects are addressed in Section 10 of the report. At the beginning of the design study it was recognized that a number of constraints to the design were already determined or at least dictated by other dominant design considerations. These are discussed below.

## 5.2 Design and construction code

The usual approach to achieving a quality of construction that is fit-for-purpose is to ensure that the design, materials and manufacturing method conform to recognised and appropriate codes and standards. Codes and standards specify a consistent set of rules and criteria covering materials, design, fabrication, inspection and testing, and quality assurance. Design standards for pressure vessels relevant to the canister are considered in Section 5.3.

The period of service of at least 1'000 years required for the canisters and the long term effect of corrosion on the material fracture toughness properties due to hydrogen uptake are beyond the applications for which current standards are intended. Additional analyses have therefore been undertaken to specify an initial build quality in terms of fabrication defects, as assured by non-destructive testing, and the level of residual stress that will ensure that failure of the canister in service remains a remote possibility.

These fracture analyses are to be used to inform whether or not post-weld heat treatment of the welds is necessary to reduce residual stress, and to indicate the size of defects that the non-destructive testing would need to detect under these circumstances. Section 10.4 presents a fracture mechanics assessment of limiting flaw sizes in the SF canister closure weld based on the stresses calculated under long term repository loading conditions by finite element analysis. It is thought that the results can be conservatively used for the HLW canister, as the latter would experience lower stresses due to its shorter length.

Most codes and standards are intended for static equipment. Integrity of disposal canisters is required when they are being handled after filling, during emplacement and during retrieval, if necessary where the possibility of a dropped load has to be considered. Dynamic impact loads of this sort are outside the scope of these codes and standards.

Additional scoping analyses have been undertaken to assess the integrity of the canisters under a dropped load scenario. These analyses are presented in Sections 10.5 and 10.6. Issues relating to elastic instability and buckling are discussed in Section 10.7. Finally, an FE analysis for the HLW canister design in the repository (in situ) is presented in Section 10.8, and results may be compared with those shown in Section 10.3 for the SF canister. A summary describing the implications of the results of the various analyses for the canister is provided within Section 10.9.

## 5.3 Design specification

International nuclear safety principles recommend the specification of recognised codes and standards for the design, materials and construction of nuclear components important to safety. Where there are no established codes and standards for the component in question, then codes and standards for equipment performing a similar role with similar safety significance may be applied. Where necessary, codes and standards should be supplemented and modified commensurate with the safety function of the component.

Beyond the specification of high-level requirements, there are no national or international standards for the design and construction of nuclear waste disposal canisters or guidance on how these high-level requirements can be achieved and demonstrated. It can be noted that nuclear waste disposal canisters are required to be high-integrity sealed leak-tight containment subject to internal and external pressure loadings. Therefore to base their design and construction on the intent of codes and standards for high-integrity unfired pressure vessels would seem to be a reasonable approach in the first instance.

Additional design considerations in terms of the loading on the canisters during handling, changes of properties in-service and the lack of access for any in-service inspection or monitoring may need special provision. It will also be necessary to specify appropriate standards for materials, welding and NDT and the acceptability of manufacturing flaws. These standards are discussed elsewhere in this report.

A summary of some relevant codes and standards applicable to unfired pressure vessels is shown in Table 5.1. These include ASME BPV Code Sections III (ASME 2010a) and VIII (ASME 2010c), the European harmonised standard EN 13445 (BSI 2002 – 2011), British Standards Published Document 5500 (BSI 2009a) and the French RCC-M standard (AFCEN 2007). The choice of standard should be determined on the basis of technical relevance and applicability, familiarity and prior experience, and national policy.

Tab. 5.1: Summary of relevant unfired pressure vessel standards.

| Standard | Recommended practice |
|---|---|
| EN 13445 (BSI 2002 – 2011) | Modern general purpose pressure vessel code written with the needs of the European chemicals and process industries in mind with significant German input. There is a presumption of conformity with the European Pressure Equipment Directive. |
| ASME BPV Code Section III (ASME 2010a) | Code managed by the American Society of Mechanical Engineers for nuclear reactor plant made largely of low alloy and austenitic steels. |
| BS PD 5500 (2009a) | British Standard Published Document for unfired pressure vessels. Does not have full standard status and may not be supported over the full timescale of the disposal project. |
| AFCEN (2007) | French code for nuclear reactor vessels. It is based largely on French materials and practices and is not widely applied outside France. |

Section III of the ASME code is well established and recognised worldwide as providing a safe basis for design of nuclear components. It offers design-by-analysis approaches based on either stress classification or limit load. The ASME III code produces conservative designs that are consistent with US regulations, construction practice and quality standards.

For the purposes of the design, construction and assessment of the canisters, the project team recommends the European Harmonised Standard for Unfired Pressure Vessels EN 13445-2010. This is a modern standard, first introduced in 2002, and has been accepted by standards' bodies in the major European countries as a sound basis for meeting international obligations and achieving essential safety requirements for pressure vessels.

EN 13445 allows the use of advanced methods to achieve an optimised design. There is a presumption of the use of qualified materials, suppliers and manufacturing methods, third party approval of NDT and welding procedures, including the use of automated welding and NDT, to give a product of high build quality. EN 13445 allows the use of elastic–plastic finite element based design-by-analysis to assess the design based on the plastic limit load. This allows designs with less material than would be needed in more conventional approaches since stress redistribution utilises more of the load carrying capacity of the structure.

In selecting a pressure vessel standard, it has to be accepted that there will be aspects with which it will not be possible to comply. For example, it would be normal to undertake a pressure test, but this is clearly not going to be feasible. EN 13445 allows exemption from pressure testing where there is appropriate NDT.

Many other aspects of EN 13445 would appear to be relevant to nuclear waste disposal canisters. These include the quality control over materials supply, tolerances and fit-up, welding and welder qualification, the qualification of NDT personnel, and the control and access of records. Where there are exemptions from EN 13445 requirements these will have to be noted and justified on a case-by-case basis.

## 5.4 Geometric shape

Based on the experience of other nuclear waste programmes and common engineering practice it was considered initially that the proposed SF and HLW canisters should be cylindrical in form with the fuel or waste loaded from one end with the canister in a vertical position. However, it was recognised that this assumption was largely due to convention rather than consideration of all of the factors affecting manufacture, operation and performance. Therefore a review of the design premises and assessment of alternatives was undertaken briefly and radical departures from the cylindrical design options considered.

One option considered was a square section hollow container. This suggestion was based on the logic that the fuel itself is in square bundles and arranged in a rectangular array. It was postulated that a horizontal box with the uppermost end removed could be loaded with spent fuel and the closure achieved by welding the end in place.

The perceived advantages of a square section container were in the simple manufacture of square cases from steel plate and in later handling of the canister for horizontal emplacement. Although some advantages are apparent, there are difficulties with closure welding a square section and uncertainties with structural performance given the stress concentration of the internal corners and the buckling susceptibility of a non-cylindrical section vessel. Therefore, this option was not investigated further.

Different geometries for the ends for a cylindrical canister were considered. The preferred geometry for the ends of a pressure vessel, especially one subjected to an external load, is a hemi-spherical or tori-spherical head. However, in view of the need to eliminate complexity in the fit-up for welding and concerns with the cost of manufacture it was proposed that a flat base and lid be investigated first. It is also anticipated that a better inspection resolution would be achieved in a cylindrical canister, because the ranges needed for a 0° UT inspection from a flat lid for flaws parallel to the inner half of the weld centre-line (including the root area), would be smaller than for the corresponding high angle probes needed to inspect a dished head.

## 5.5 Size

The size and number of SF fuel assemblies or HLW flasks to be encapsulated in each individual canister is defined in McGinnes (2002) with requirements for clearances. Further information on the data for SF and HLW can be found in Appendix A. This data in turn dictates the minimum internal diameter of the SF and HLW canisters. It was considered beneficial at the design stage to standardise the internal diameter to accommodate both the BWR and PWR fuel types. As a consequence of this, and an assumed initial minimum wall thickness based on a requirement for shielding to eliminate the risk of enhanced corrosion due to radiolysis at the surface, the basic length and outside diameter of the disposal canisters were defined.

## 5.6 Construction

Following the consideration of the geometric options and proposed emplacement method the use of a blank flat-ended cylinder with welded flat closure head was defined as a starting point for analysis. The flat base of the cylinder could be formed or welded. The cylinder would be an integral structure, although the possibility of having two concentric cylinders each of lesser thickness was briefly considered, but discounted on grounds of complexity.

The possibility of having an external cladding or coating to provide corrosion protection early in life was considered. However, the use of a thin coating was discounted because of the risk that thin coatings might be easily damaged. This could lead to enhanced localized corrosion (including accelerated hydrogen generation) through crevice or galvanic effects. The application of a cathodic protection system using some form of sacrificial anodes has also been dismissed at this stage, as the hydrogen generated is likely to be detrimental. Developments in cladding and coating technology should be kept under review.

No coating is required internally. An internal structure is required to support the SF assemblies, but no internal structure is required for the HLW which is already in flasks. However, provision should be made for a radial gap to be maintained between the canister walls and the HLW flasks to minimise heat transfer during PWHT or thermal stress relief.

## 5.7 Evolution of canister properties and environmental conditions during life

A schematic showing the expected evolution of the loading, environment and canister parameters and properties with time up to 10'000 years is presented in Figure 5.1. Each of these, described below, has influenced the conceptual design of the disposal canister. It has been presumed that the canister material is carbon steel.

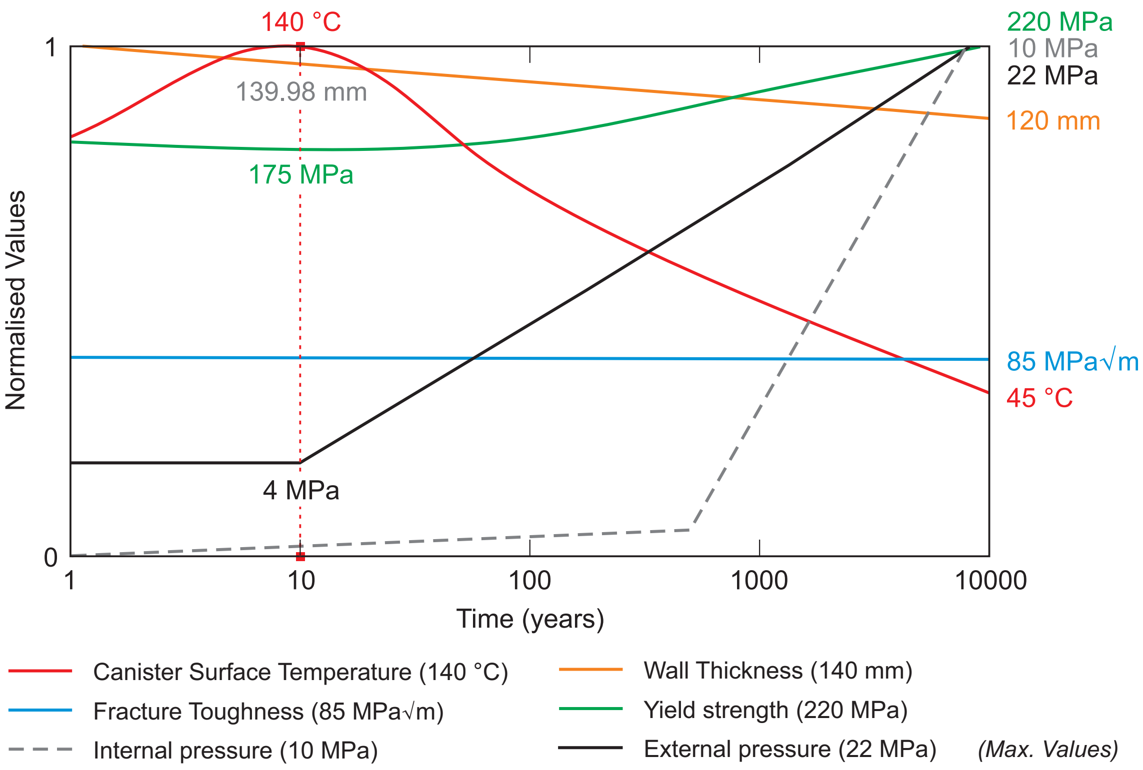



Fig. 5.1: Schematic showing expected evolution of canister material and environmental conditions.

### (a) Canister surface temperature

The canister surface temperature (Landolt et al. 2009) after 10 years is expected to increase from ambient (20°C) to reach a maximum value of 140°C and drop to a value of ~ 45°C after 10'000 years.

### (b) Canister internal pressure

After ca. 500 years the internal pressure within the disposal canister is expected to rise to a maximum of about 10 MPa at 8'000 years from nominally zero due to hydrogen diffusing into the canister from the corrosion processes occurring on the external surface (Turnbull 2009).

### (c) External pressure

Due to the external conditions, as described above, the external pressure is expected to rise from an isotropic load of 4 MPa, after 10 years, and may reach a maximum expected stress of 22 MPa. Note that an extreme bounding stress case has also been identified (see Fig. 3.4).

### (d) Yield strength

The variation of the canister bulk metal temperature has a direct influence on the material yield strength. Assuming the material is plain carbon steel with a nominal room temperature yield strength of 220 MPa, the yield strength is predicted to decrease to 175 MPa after 10 years when the temperature has risen to 140°C and to rise towards 220 MPa after 10'000 years, when the temperature will have fallen to 45°C.

### (e) Fracture toughness

The average hydrogen concentration in the thick section carbon steel forgings proposed for the canisters after manufacture has been specified to be less than 1 ppm (0.9 ml/100 g), but can vary depending on the manufacturing process. The hydrogen from manufacture will combine with any hydrogen arising from closure welding or absorbed from corrosion. Hydrogen diffuses to the regions of high strain where it concentrates resulting in a variable distribution of hydrogen throughout the material.

Humphries et al. (2009) have observed that the fracture toughness of a C-steel and associated weldments reduces with increased hydrogen absorption (see Section 6.2.8.3). Concentrations of hydrogen as low as 1 ml/100 g can significantly reduce the fracture toughness in steel and weld metal. Even if the bulk level of hydrogen is low, local concentrations of hydrogen at regions of high strain can have a significant embrittling effect.

The level of fracture toughness assumed in the canister must account for the anticipated temperature of the canister and the effect of hydrogen embrittlement at various stages of the canister life. The effect of hydrogen on fracture toughness depends on the particular steel. Ideally it needs to be established by testing hydrogen charged specimens.

The exact level and distribution of hydrogen in the canister body at any given time is difficult to predict, as hydrogen diffuses around and out of the iron lattice structure easily. As such, the local conditions (temperature, which encourages hydrogen diffusion, and initial hydrogen concentration, along with the generation of hydrogen from corrosion) all affect the level of fracture toughness that can be assumed. Owing to this uncertainty, it is assumed for the time being that the fracture toughness will be at a minimum value (of the order of 85 MPa$\sqrt{m}$) for much of the canister lifetime.

It is worth noting that the neutron flux experienced by a spent fuel canister is approximately three orders of magnitude below that which is conservatively predicted to cause radiation embrittlement of the steel (King et al. 2012). Therefore brittle fracture from radiation embrittlement of a carbon steel canister in a repository in Opalinus Clay is a remote possibility. Even after 10'000 years, there is a significant safety margin with respect to radiation embrittlement.

### (f) Canister wall thickness

Assuming an average corrosion rate of 2 µm/a (Landolt et al. 2010) it is predicted that 20 mm of material thickness will be lost uniformly due to general corrosion after 10'000 years. Localised corrosion (pitting) is not expected to be significant (King 2008, Johnson & King 2003).

# 6 Materials

## 6.1 Introduction

The selection of the optimum parent material is a crucial aspect in achieving the requirements for the canister. Previous work carried out by Nagra has identified that for this work it wishes to consider a ferritic material, nominally cast iron or steel. On this basis, this study has focussed on identifying appropriate compositions and mechanical properties.

The key requirements for the selection of an appropriate material are to obtain a low corrosion rate over long term exposure to the repository environment, have sufficient strength, toughness and ductility to resist the in-service forces, and be readily weldable, for the sealing of the canister. It is also a pre-requisite that the material is available in an appropriate product form for the intended application and defined within a recognised standard specification.

The selection of the appropriate grade of material will depend upon the manufacturing route selected for the canister as the standards relating to forgings, plate and castings differ. Irrespective of the selected grade of material, more stringent restrictions will be needed on a number of factors. These restrictions are required to limit the variation that can be anticipated in canister composition and properties, and to reduce the risk of stress corrosion cracking. Material ordered to a standard grade generally has much less stringent restrictions, which can have repercussions for weldability and service.

The chemical compositions of cast iron and steel are very different, largely defined in terms of the carbon content. Appropriate alloying and processing can be selected to give similar mechanical properties and corrosion performance for both materials, so the main concern for the materials initially relates to weldability. The most weldable grade of cast iron is nodular graphite cast iron, and the most easily weldable grades of steel are those with low alloy content. The advantages and disadvantages of these two material types with respect to weldability and associated processes are discussed in the following sections.

The selection of parent material addresses the requirements listed in Box 6.1.

**Box 6.1 Requirements related to the materials selection.**

RQ1, 2, 6, 8 Long term integrity, particularly corrosion properties.

RQ11, 15 Residual stress mitigation/control.

RQ3 Wall thickness requirements.

RQ4, 10 Weldability for the required service.

RQ5, 7, 8, 12 Structural integrity – dependent upon the developed material properties.

RQ16 Material properties.

RQ28 Current best practice manufacturing.

RQ29 The use of relevant codes and standards.

## 6.2 Steel

### 6.2.1 Composition

Initially, Nagra had suggested ASTM A516 Grade 70 as a reference material, a C-Mn steel. Earlier work (Pike et al. 2010), and consideration of the detailed requirements in the current programme indicate that a plain-carbon steel is preferable. This arises from the requirement to avoid failure from hydrogen related corrosion in the presence of a tensile residual stress whilst maintaining a similar general corrosion performance over the lifetime of the canister. The selection of plain-carbon steel has certain additional benefits with respect to weldability.

The composition of the plain-carbon steel must have enough carbon to obtain the required strength, but be suitably restricted to reduce the hardenability of the steel and also to result in better corrosion performance. Owing to the combination of load, geometry and thickness, it is anticipated that strengthening via other alloying additions will not be required. Adoption of a plain carbon steel will also provide confidence in the stability of properties from closure welding through the life of the canister. Plain-carbon steels contain impurities and production-related alloy additions that affect corrosion properties and weldability. These will be restricted as discussed in detail below.

### 6.2.2 Mechanical properties (strength, ductility)

These requirements arise from the anticipated service condition of the canisters, and are influenced by the active degradation mechanisms, such as hydrogen embrittlement, acting over the lifetime of the canisters. As such long term data (1'000 years) is not readily available, existing mechanical property data will be used, and the degradation projected to the design life.

The minimum requirements of ASTM A516 Grade 55 in terms of mechanical properties will be taken as the baseline to begin with, with additional testing requirements (Charpy toughness etc.) specified if these are not given in the standard.

It is generally held that the susceptibility of steels to stress corrosion and hydrogen induced cracking increases with yield strength. Therefore to minimise the risk of failure of the canister through an environmentally assisted cracking mechanism over its intended life span, it is proposed that the strength level of the steel is specified to be as low as reasonably practicable, whilst meeting the minimum static strength requirement for the canister. Also, an upper limit to yield strength is required.

For some industries, the ratio of yield to tensile strength is important, as it is used to ensure a certain amount of plasticity in high yield strength materials. For the low strength materials being considered, the yield to tensile strength ratio should be substantially lower than the limit of 0.9 often quoted in the pipeline industry. This will ensure that the material shows significant yielding (plasticity) before failure.

### 6.2.3 Impurity content

The impurity content of the steel influences the mechanical properties and corrosion behaviour, along with the weldability and susceptibility to long term cracking mechanisms. Maximum levels of critical elements (P, S) to avoid any increased susceptibility to degradation are suggested. Steel should be sourced from manufacturers who employ good steelmaking practice, to limit other impurity elements (such as Cu, Pb, Sn, As) to tolerable levels. It is recommended that for material of the thickness under consideration that vacuum degassing and a hydrogen release treatment is specified.

The influence of sulphur on susceptibility to sour corrosion, and the effect of phosphorous on the risk of certain fabrication cracking mechanisms are known (Shida et al. 1984, Cotton 1986). ISO 15156 (BSI 2009b) specifies a maximum limit on sulphur of 0.003 % for flat rolled products, 0.01 % for seamless products and 0.025 % for conventional forgings. Phosphorous is limited to avoid both the formation of low melting point constituents in weld metal (leading to solidification cracking) and to avoid problems with hydrogen pressure induced cracking (also known as step-wise cracking or blister cracking) in sour service. The phosphorous level is often limited to 0.015 % maximum for these benefits.

### 6.2.4 Weldability

Many factors may be taken into account in an assessment of weldability, from the original composition (carbon content or carbon equivalent) of the steel, to the developed microstructures in the heat affected zone, as well as the strength and appearance of the joint after welding and any post processing.

The weld zone microstructures for both of the candidate welding processes, and advantages and disadvantages of both processes with respect to microstructure are discussed in Section 8.6.

### 6.2.5 Microstructure, grain size, heat treatment

The microstructure and grain size of the parent material arises from the composition and processing route. The processing routes are considered in Section 12.2.2 as this influences the specification selected. The potential for different processing routes, and their relative benefits or disadvantages are also given in Section 12.2.2. The need for post-weld heat treatment of the closure weld, along with the restrictions on temperature of the contents of the canister, is considered in Section 9.

ISO 15156 (BSI 2009b) specifies a number of heat treatments that are acceptable, and these are limited to annealed, hot-rolled, normalised, normalised and tempered, austenitised, quenched and tempered and normalised, austenitised quenched and tempered. It is recommended that the canister body is supplied in a normalised condition, as this is a process that can be applied to any manufacturing route to result in a low-stress canister body prior to the closure weld. If the manufacturing method for the canister body requires it to be welded, the weld metal used must be suitable for normalising.

### 6.2.6 Production method

Consideration needs to be given to the likely method(s) for production of the material i.e. casting, forging, rolled plate, etc. The method(s) selected will have an impact on the integrity and homogeneity of properties, composition and microstructure achieved.

### 6.2.7 Surface finish

The surface finish should ideally be better than 3.2 μm Ra to facilitate inspection during manufacture and non-destructive testing of the closure weld (Section 11 and 12). This requirement needs to be kept in mind so that the manufacturing route is capable of achieving this surface finish. Forged or cast components are more likely to require machining to achieve this level of surface finish than a rolled plate.

The welded repair of defects found in the canister during manufacture should be addressed. Ideally, avoidance of weld repairs is preferred, but the decision for a welded repair should consider the weld chemistry and resistance to being normalised. It is likely that some minor repairs will be required to correct geometric weld bead deficiencies. For major repairs many different possibilities could exist and each should be uniquely assessed. Ultimately, correction of a defective weld at the base of the canister could require cutting off the base and replacement.

### 6.2.8 Degradation mechanisms during service

#### 6.2.8.1 General corrosion and stress corrosion cracking

These degradation mechanisms are considered in Section 7. In general, the selection of a low strength steel material will result in good general corrosion properties and avoid developing microstructures that will result in accelerated corrosion or cracking.

#### 6.2.8.2 Degradation mechanism – elevated temperature

The early portion of the canister life is anticipated to be at elevated temperatures, which needs to be accounted for in terms of the anticipated mechanical properties and the structural analysis. The codes used to define the material selected account for this, such that the code requirements include specified elevated temperature properties, where appropriate.

#### 6.2.8.3 Degradation mechanism – hydrogen

Hydrogen arising from canister manufacture, closure welding and corrosion during the canister lifetime can diffuse into the canister material and cause hydrogen embrittlement of the structure. This is not problematic in the early stages of the canister life, as the temperature is higher, and the loading is minimal. However, hydrogen has been shown to reduce the measured toughness of many materials, including steel, to a minimum level (Pargeter & Cheaitani 2011; Humphries et al. 2009), see Figure 6.1, which shows crack tip opening displacement (CTOD) at 20°C for a number of steels. This is considered in more detail in Appendix B, and it is recommended that the toughness is considered to be at the minimum level throughout the canister life.

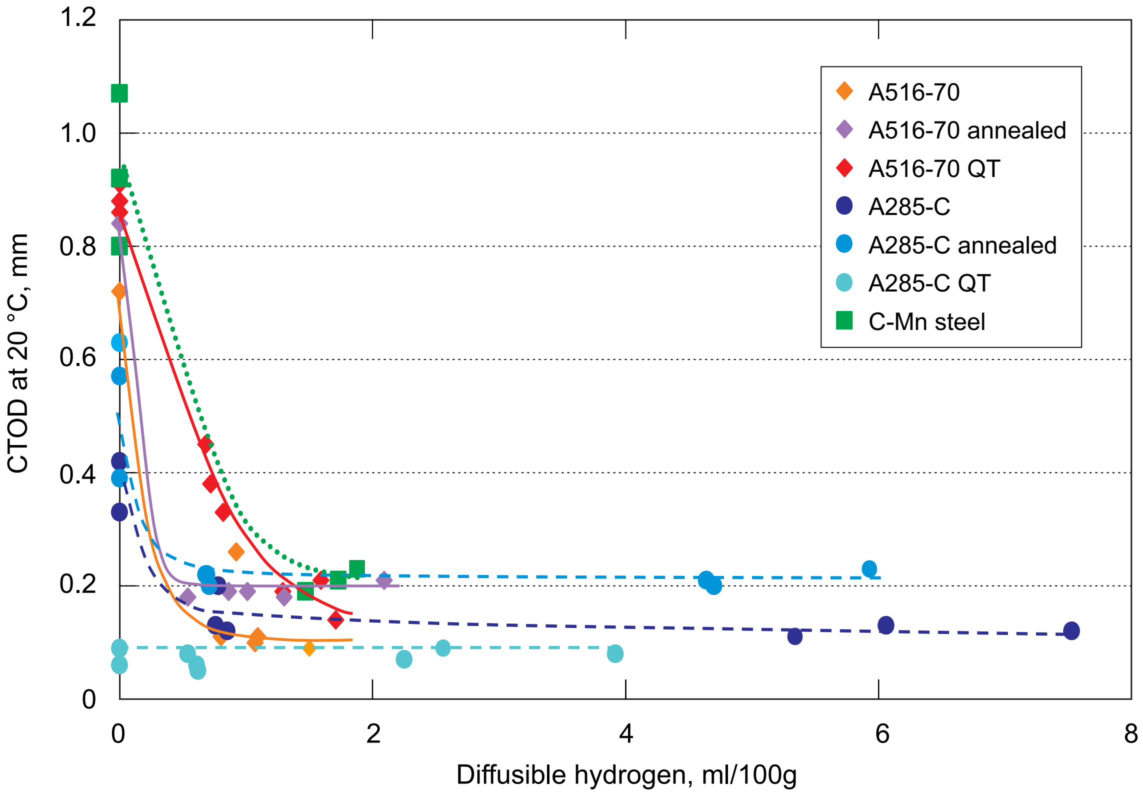



Fig. 6.1: The effect of hydrogen on the toughness of a number of steels at 20°C.

## 6.3 Materials data sheet (initial specification)

### 6.3.1 Selection of appropriate elements

The composition of the canister body should be appropriate irrespective of product form, but, as indicated for sulphur content in Section 6.2.3, some relaxation of or more stringent compositional limits may be appropriate.

As carbon is the key element in strength and hardness development, but also is the most detrimental in terms of weldability, and corrosion susceptibility, a limit of 0.12 % by weight has been suggested. Other key elements for strength, toughness and hardness development are manganese, nickel, chromium and copper. Manganese is limited to 0.8 % by weight, as, like carbon, it has a significant effect on weldability and corrosion. Nickel, chromium and copper, although all beneficial in terms of strength and corrosion resistance to some extent, are restricted to low residual levels to limit the effect on weldability and hardness. Copper is used in weathering steels to promote the formation of an adherent scale, but this is not relevant in the present application. Microalloying elements, used to enhance strength, are restricted to residual levels since it is preferable to have steel with low strength (ASM 1990).

Sulphur is limited to the level of seamless products recommended by ISO 15156 (BSI 2009b), and phosphorous to a level typically used to avoid problems with solidification cracking or hydrogen pressure induced cracking. Other elements, which can cause grain boundary embrittlement such as Pb, Sn, As, are also required to be low, to avoid having any temper embrittlement.

The degradation mechanisms considered for the canister are mainly linked to long term corrosion and hydrogen cracking. In order to minimize these risks, the material needs to be as homogeneous as possible (with minimal segregation and banding):

- The low defined C content, as well as the normalised production route, will help to reach a homogeneous material. A tempering treatment after normalising could further improve the properties and minimize the influence of long term exposure to moderate temperatures (100 – 150°C).
- The concentration of all elements which elongate the solidification path of steel also need to be minimised: besides C, the levels of the impurity elements P, S and B have an important influence. These elements could be limited further than currently specified (e.g. P below 80 ppm, S below 20 ppm).
- Similarly, the internal cleanliness of the steel will benefit from an oxygen content as low as possible (e.g. < 20 ppm should be achievable).
- HIC resistance also requires extra low sulphur and oxygen contents in order to reduce the size and number of sulfide and oxide inclusions since these inclusions are known initiation sites for HIC. Ultra-low sulphur and oxygen contents as stated above also mean that additional sulphide shape control measures, such as additional calcium treatment, are not considered necessary.

Tab. 6.1: Compositional limits recommended for the canister material.

| Element [wt %] | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **C** | **Si** | **Mn** | **P** | **S** | **Cr** | **Ni** | **Cu** | **$CE_{IIW}$** | **Notes** |
| 0.12 max | 0.3 max | 0.8 max | 0.015 max | 0.01 max* | 0.2 max | 0.2 max | 0.02 max | 0.30 max | Cr + Ni + Mo < 0.25<br>Nb + V < 0.02<br>H < 1 ppm<br>Vacuum degassed (low O, N) |

Additional requirements:

* Depends on product form – for plates 0.003 max, for forgings 0.025 max.

### 6.3.2 Mechanical properties

The mechanical properties outlined in Table 6.2 have arisen from the need to have a material strong enough for the required service, whilst being not excessively strong, which can affect the corrosion resistance of the material. The strength and hardness requirements are linked, and as such, a low hardness requirement is also needed. The toughness of the canister will vary through the lifetime, as the temperature changes and embrittlement mechanisms take effect. The specification refers to the material on its arrival at the repository. To avoid having variation in the material, it is recommended that prior to arrival at the repository, the canister body undergoes a heat treatment to relieve the stresses introduced by manufacture, and to give a soft microstructure.

The through thickness tensile properties of the canister body should have sufficient elongation in the through thickness direction to avoid problems with lamellar tearing.

Tab. 6.2: Mechanical properties.

| Property | Notes |
|---|---|
| Strength | As low as possible, low yield to tensile ratio of below 0.8.<br>220 N/mm² yield strength at room temperature |
| Elongation | 17 % minimum (axial)<br>15 % minimum reduction in area (through-thickness) |
| Hardness | In line with ISO 15156 (BSI 2009b), 250 HV max, other than for forgings, for which 200 HV max |
| Toughness | Above lower shelf for all normal processing and operation<br>27 J at room temperature |
| Heat treatment | Consistent with ISO 15156 (BSI 2009b), similar microstructure irrespective of processing route<br>Normalised |

All the standard grades suggested in Table 6.3 can be supplied in the normalised condition, and restrictions on composition can be made to the levels given in Table 6.1.

Tab. 6.3: Examples of materials grades that could be specified, with additional restrictions as per Table 6.1.

Room temperature properties unless specified.

| Form | Grade | σY [MPa] | σUTS [MPa] | Elongation [%] | CVN |
|---|---|---|---|---|---|
| Forging | BS EN 10250-2 S235J2G3 (BSI 2000a) | 175 | 340 | 23 (long)<br>17 (trans) | 20 J @ -20°C (trans)<br>30 J @ -20°C (long) |
| | BS EN 10222-2 P245GH (BSI 2000b) | 220 | 410 – 530 | 25 (long)<br>23 (trans) | 27 J @ 0°C (trans)<br>32 J @ 0°C (long) |
| Casting | BS EN 10293 GE200 (BSI 2005c) | 200 | 380 – 530 | 25 | 27 J @ +20°C |
| Plate | BS EN 10028-2 P235GH (BSI 2009e) | 185 | 350 – 480 | 24 | 27 J @ -20°C |

### 6.3.3 Physical properties

To begin assessment of the design concepts proposed, an initial set of properties were required for the purposes of modelling. For the purposes of this analysis a forged steel specification was selected, and assumed to have the physical properties given in Table 6.4. The properties are based generally upon BS EN 10222 P245GH (BSI 2000b), a forged steel, which has specified elevated temperature properties.

Tab. 6.4: Physical properties.

| **Temperature** <br><br> **[°C]** | **Property** | | | |
|---|---|---|---|---|
| | **Thermal conductivity [W/mm/K]** | **Specific heat capacity [J/kg/K]** | **Density** <br><br> **[kg/mm³]** | **Yield strength** <br><br> **[N/mm²]** |
| 25 | 0.054 | | $7.86 \times 10^{-6}$ | 220 |
| 26.85 | | 447.76 | | |
| 100 | | 481 | | 180 |
| 125 | 0.051 | | | |
| 150 | | 519 | | 175 |
| 200 | | 536 | | 165 |
| 225 | 0.047 | | | |

## 6.4 Cast iron

Despite the higher carbon content in cast irons compared to mild steel, there is no appreciable difference in strength or corrosion performance. However, cast irons are considered to be very difficult to weld successfully, and usually require high levels of preheat and significant postweld heat treatment in order to obtain acceptable ductility and toughness in the HAZ of the weld (ASM 1990). Specifically, the preheat required for welding ferritic nodular cast irons (the most weldable grades), may be up to 600°C or above, depending on the welding process used. This high preheat is applied to retard the cooling rate in the weld region, specifically in the HAZ, where large grain size martensitic microstructures may be formed. Details of the required post-weld heat treatments for nodular cast irons are given in Appendix B.

A further drawback of cast materials, in general, is a tendency towards poorer surface finish due to gas pores, which could impact the inspection as well as the corrosion performance of the canister (see also Section 6.2.7). It can be difficult in practice to establish how much of the surface layer needs to be machined away to ensure a pore-free surface. Furthermore, the significant attenuation of the ultrasonic waves in cast iron, and the large grain sizes within the weld HAZ that is likely to aggravate the attenuation, presents a problem with detection and sizing of any weld zone flaws. Further details on the effectiveness of ultrasonic inspection in nodular cast irons are included in Appendix B.

The limitations on the weldability, and particularly the heat treatment requirements being in excess of the temperature restrictions on the fuel, along with the limitations associated with inspection have eliminated cast iron as a suitable material for the canister body.

## 6.5 Summary

A bespoke steel composition has been suggested that will have low hardenability. A low hardenability steel will be weldable by many processes and also will have a low susceptibility to stress corrosion cracking. This feature addresses RQ1, RQ2, RQ6, RQ10, RQ16 and RQ28. The low hardenability and relatively low strength of this material in the normalised condition also address the concerns relating to RQ11 and RQ15, as the developed residual stresses will be relatively low.

The relatively low strength of the steel is beneficial for corrosion, and is sufficient for the integrity of the disposal canister throughout its lifetime. This addresses RQ5, RQ7 and RQ8. The effect of hydrogen on toughness in steels is known, and irrespective of the initial toughness, the embrittlement of hydrogen results in a low fracture toughness value. This influences the critical flaw size, and addresses RQ12.

The bespoke composition can be achieved within a number of national and international standards, allowing for thicknesses up to 180 mm. This addresses RQ3 and RQ29.

# 7 Corrosion Issues

## 7.1 Introduction

Corrosion is one process that could lead to a breach in containment of the canister prior to the design target lifetime of 10'000 years (RQ2, Table 2.1). The interaction between the design and corrosion behaviour of the canister needs to be taken into account in the development of a suitable canister design. Here, the implications of the corrosion behaviour of carbon steel on the design of the canister are considered.

The corrosion behaviour of carbon steel canisters in a HLW/SF repository in Opalinus Clay has been described in detail elsewhere (Johnson & King 2003, 2008). Only brief details of the corrosive environment are described here, with a focus on those parameters of most importance for the design, namely the canister temperature and the applied and residual stress levels. In addition, a brief overview of the corrosion behaviour of the canister is provided.

The issues discussed below address the requirements listed in Box 7.1.

**Box 7.1 Requirements relating to corrosion**

RQ2 Long term integrity.

RQ6 General and localised corrosion.

RQ10 Weld integrity – SCC/HIC.

## 7.2 The corrosion environment

Details of the repository design (Chapter 3) and of the near-field environment (Johnson & King 2003, 2008; Landolt et al. 2009) are given elsewhere. An important aspect of the corrosive environment is that it evolves with time (Figure 7.1), primarily in response to the decrease in canister temperature as the radionuclides in the SF/HLW decay and as a result of the increase in the degree of saturation of the bentonite sealing materials. In addition, the environment becomes increasingly anaerobic as the initially trapped $O_2$ is consumed by various processes, including corrosion of the canister.

The temperature affects the rates of various chemical and electrochemical processes, as well as the properties of the canister itself and of the sealing materials and host rock. After reaching a maximum of 130 – 140°C approximately 10 years after emplacement, the canister surface temperature will decrease with time reaching a value of 40 – 50°C after 10'000 years (Figure 7.1).

The other important environmental parameter with respect to the canister design is the magnitude of the applied stress. (The sum of the applied and residual stresses affects the structural performance of the canister, as well as the susceptibility to environmentally-assisted cracking). As the repository saturates, the compacted bentonite develops a swelling pressure of 2 – 4 MPa (Johnson & King 2003). In the long term, a maximum isotropic pressure (lithostatic) on the canister of 22 MPa is expected for 900 m depth and a bounding maximum load case may also involve a horizontal stress of 29 MPa. Full details of the loading and structural analyses are presented in Section 10 (Structural Performance Section).

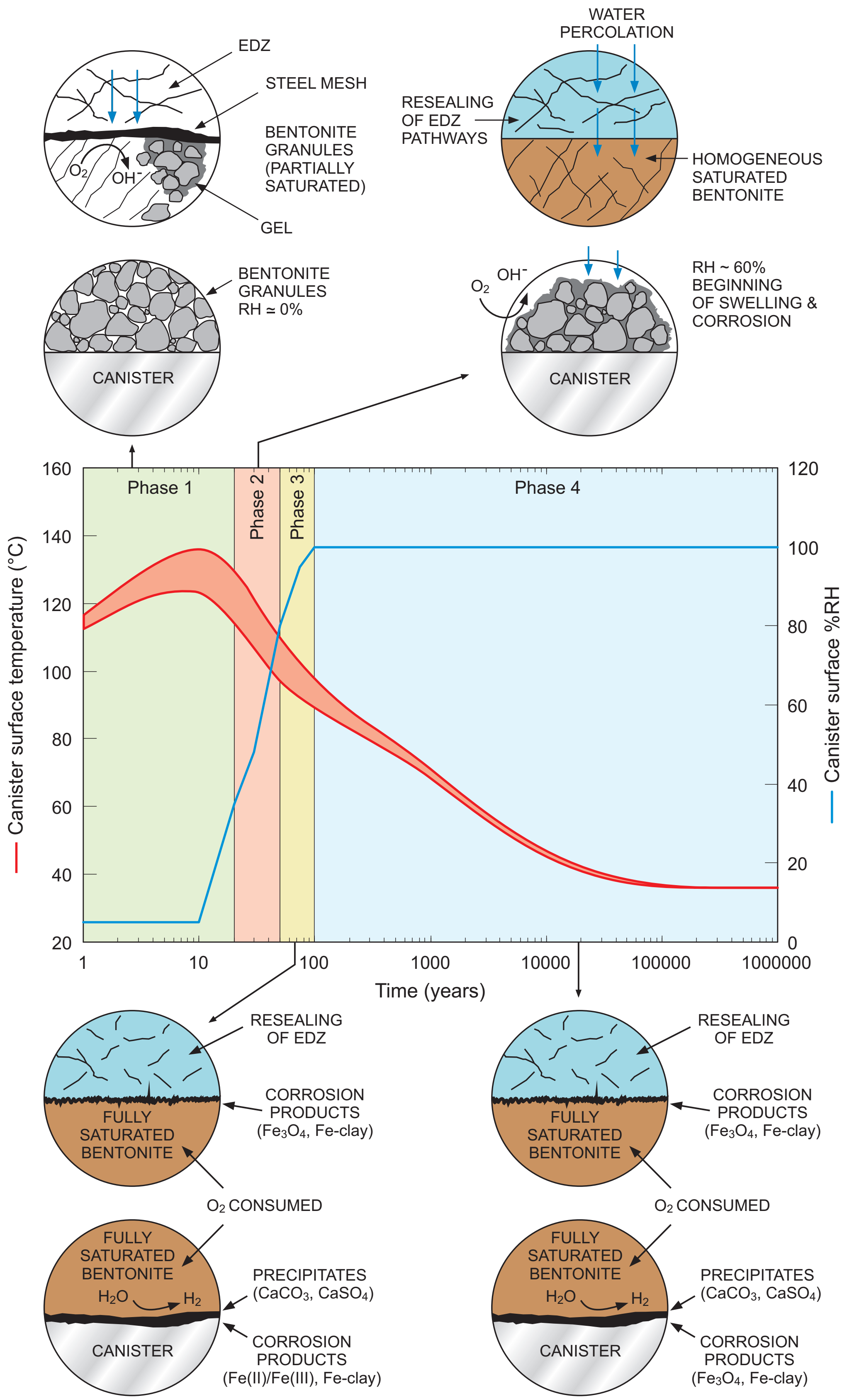



Fig. 7.1: Schematic Illustration of the Evolution of the Repository Environment and the Impact on the Corrosion Behaviour of the Canister (Landolt et al. 2009).

## 7.3 Overview of the corrosion behaviour of carbon steel canisters

The canister may be subject to the following corrosion processes (Johnson & King 2003, 2008):

- Uniform corrosion – the canister will corrode uniformly, initially under aerobic conditions due to the initially trapped $O_2$ and subsequently under anaerobic conditions accompanied by the evolution of $H_2$. The aerobic phase is likely to last for only a few tens of years. During the long-term anaerobic phase, the corrosion rate of carbon steel in compacted bentonite will be of the order of 1 – 2 µm/year (King 2008).
- Localised corrosion – localised corrosion in the form of discrete pitting is unlikely to persist for any length of time, although the surface of the canister will be subject to a certain degree of uneven corrosion or roughening.
- Hydrogen-related damage – carbon steels can be susceptible to various forms of hydrogen-related degradation, particularly in severe environments (e.g. those containing $H_2S$) and for higher-strength grades (Turnbull 2009). As discussed in more detail below, hydrogen-related failure of the canister is considered unlikely, primarily because of the proposed use of a low-strength material and because of the benign nature of the repository environment (Johnson & King 2003, 2008).
- Stress corrosion cracking (SCC) – carbon steels are known to be susceptible to SCC in a number of environments when subject to specific types of mechanical loading. Failure of a canister by SCC is considered unlikely, however, in part because of the general absence of specific SCC agents in the repository environment and because of the lack of cyclic loading (Johnson & King 2003, 2008).
- Microbiologically influenced corrosion (MIC) – in common with many structural alloys, carbon steel is susceptible to MIC in the presence of active microbes. However, it is generally assumed that the repository environment is not conducive to microbial activity (King 2009), primarily because of the low water activity in compacted bentonite. Consequently, MIC will only result if corrosive metabolic by-products of microbial activity in the Opalinus Clay host rock reach the canister surface, a process that will be transported limited and unlikely to cause extensive corrosion of the canister (Johnson & King 2003, 2008). Nonetheless, in situ studies should be pursued to determine if these assumptions are valid.

The corrosion behaviour of the canister will change with time as the environment evolves, with different corrosion processes occurring at different stages during this evolution. Although the canister will be subject to uniform corrosion at all times, the susceptibility to environmentally assisted cracking (either SCC or hydrogen-related damage) changes with time.

## 7.4 Implications of the corrosion behaviour of carbon steel for the canister design

### 7.4.1 Overview

The potential for failure of the canister by corrosion is often considered separately from failure by purely mechanical factors. Failure by corrosion alone (for example, as the result of a small through-wall pit) is unlikely for carbon steel canisters and the most likely cause of failure is through a combination of corrosion and mechanical factors (for example, due to overload following wall thinning due to uniform corrosion or as a result of environmentally assisted cracking under a combined applied and residual stress). Consequently, it is important to consider the implications of the corrosion behaviour of the material of construction in the design of the canister.

### 7.4.2 General wall loss

A number of the requirements in Table 2.1 are related to the canister wall thickness, not least the requirement to maintain structural integrity for at least 10'000 years (RQ8). If all of the atmospheric $O_2$ initially trapped in the repository is conservatively assumed to cause uniform corrosion of the canister, the maximum wall loss during the aerobic phase will be of the order of 0.1 – 0.2 mm, depending upon the exact design of the repository and the properties of the sealing materials. Following the aerobic phase, the rate of uniform corrosion under anaerobic conditions can be assumed to be in the range 1 – 2 µm/year (King 2009). Therefore, the maximum reduction in wall thickness as a function of time is approximately:

- 0.2 mm after 10 – 100 years (the estimated duration of the aerobic phase).
- 2.2 mm after 1'000 years (the sum of the aerobic corrosion and approximately 1'000 years of anaerobic corrosion at a rate of 2 µm/year).
- 20 mm after 10'000 years.

### 7.4.3 Environmentally assisted cracking

#### 7.4.3.1 Stress corrosion cracking

Stress corrosion cracking requires the presence of both a suitable environment and the necessary mechanical loading conditions. Carbon steel is susceptible to SCC in various environments (King 2010), a number of which are not relevant for the expected repository environment (e.g. high-temperature water at temperatures > 200°C, concentrated phosphate or caustic solutions). Of the environments in which cracking has been observed, the only ones possible in the repository are concentrated and dilute carbonate solutions (which are associated with the so-called high-pH and near-neutral pH forms of cracking of pipeline steels) and concentrated nitrate solution. The concentrated solutions could form during Phase 2 in Figure 7.1 due to the deliquescence of suitable salt contaminants on the canister surface as the bentonite saturates. The formation of a dilute, near-neutral pH carbonate solution is possible during Phase 3 and, especially, Phase 4.

In addition to a suitable chemical environment, the electrochemical potential of the carbon steel must be in the appropriate range for cracking. The intergranular SCC observed in concentrated carbonate and nitrate solutions is believed to be the result of a slip-dissolution mechanism (King 2010), which requires that the potential be sufficiently positive to support crack advance by dissolution. As a consequence, these forms of cracking are only possible during Phases 2 and 3 and then only if both a suitable chemical environment <u>and</u> the necessary tensile loading conditions are present. Transgranular cracking in dilute, near-neutral pH carbonate solutions occurs at the corrosion potential under anaerobic conditions and, therefore, would be limited to Phase 4, again assuming that a suitable environment and tensile load were present.

When considering the required mechanical loading conditions for SCC, it is useful to distinguish between crack initiation and crack propagation (King 2010). Initiation of a crack on a planar surface requires some degree of plastic deformation so that the level of tensile stress on the surface must be of the order of the yield stress. Under static loading conditions, the threshold stress for a range of pipeline steels in concentrated carbonate solutions has been found to be approximately equal to the yield strength (King 2010). The threshold stress for crack initiation is lower, however, in the presence of cyclic loading.

The threshold conditions for the growth of an initiated crack or other crack-like defect is a function of both the loading conditions and the size of the crack or defect. Expressed in terms of the threshold stress intensity factor for SCC ($K_{ISCC}$), the threshold for crack growth for carbon steel in concentrated carbonate solution is of the order of 20 MPa·m$^{1/2}$ (King 2010). By way of illustration, the stress intensity factor a 2 – 3 mm deep edge crack for a surface tensile stress of the order of the yield strength of the parent material (say, 220 MPa) would be in the range 20-24 MPa·m$^{1/2}$. Cracking is promoted by cyclic loading, as is encountered on pipelines and some other structures, and the transgranular form of cracking in dilute bicarbonate solution at near-neutral pH is thought to be a form of corrosion fatigue. In this latter environment, the threshold stress intensity range for cracking ($\Delta K_{SCC}$) is of the order of 10 – 15 MPa·m$^{1/2}$ (King 2010).

Because of the evolution of the repository environment and the environmental and loading requirements for SCC, cracking is only possible for a limited period of time, if at all. Table 7.1 summarises the nature of the mechanical loading and environmental conditions for each of the four phases identified in Figure 7.1. The most likely period for SCC is during the early aerobic phase when the surface could be wetted by (small volumes of) concentrated electrolyte formed from the deliquescence of salt deposits (Phase 2 and the initial part of Phase 3, corresponding to the first 100 years or less following closure of the repository).

#### 7.4.3.2 Hydrogen-related degradation

Carbon steels are susceptible to a range of H-related damage mechanisms (Turnbull 2009). The most likely forms of damage are hydrogen-induced cracking (HIC) and, in the presence of residual or applied stress, stress-oriented hydrogen-induced cracking (SOHIC). The susceptibility to HIC and SOHIC increases with increasing strength of the material (because a stress gradient can be sustained in higher-strength materials resulting in higher local H concentrations) and with increasing corrosiveness of the environment (which leads to higher absorbed H concentrations). In general, the susceptibility of carbon steel canisters to HIC is minimal because of the use of low-strength alloys and because the repository environment is generally benign (Turnbull 2009).

Crack growth occurs above a critical stress intensity factor $K_{th}$ (Turnbull 2009). Values for $K_{th}$ have been reported for various grades and strengths of carbon steel in aggressive electrolytes and in gaseous $H_2$ atmospheres. Although the bentonite pore water is relatively benign, a $H_2$ atmosphere with a pressure of up to 8 – 10 MPa is likely to be generated at the surface of the container because dissolved $H_2$ produced by the anaerobic corrosion of carbon steel cannot diffuse away fast enough through compacted bentonite and Opalinus Clay (Johnson & King 2003, 2008). Therefore, the highest absorbed H concentration is likely to result from the exposure to a gaseous $H_2$ atmosphere. Turnbull (2009) has estimated a $K_{th}$ of > 70 – 100 MPa·m$^{1/2}$ under these conditions corresponding to a threshold crack depth (given the same assumptions regarding the crack geometry and tensile stress as those above for SCC) of > 50 mm. (Note: the critical crack size could be significantly smaller if hardened microstructures with higher potential residual stress persist, for example, in the weld region). Section 10.4 assesses the effect of residual stress on the critical flaw height.

Hydrogen-related damage is an issue only during Phase 4 in the evolution of repository conditions (Table 7.2). Little or no H will be generated during the early aerobic phases (Phases 1 – 3). Hydrogen will be generated during Phase 4 and begin to accumulate both within the steel itself and as a gaseous $H_2$ phase at the canister surface. As Turnbull (2009) notes, $H_2$ will also accumulate inside the canister as atomic H diffuses through the wall and desorbs as $H_2$ on the inner surface of the canister wall. Eventually, a $H_2$ pressure equivalent to that on the outside of the canister will be created in the internal cavity (a process that could take from a few hundred to a few thousand years). This then raises the possibility of HIC or SOHIC from the inside of the canister. This form of 'internal' HIC/SOHIC could be more likely than cracking from the external surface because it is impossible to remove or repair internal surface-breaking defects in the final closure weld or relieve the residual stress (on the assumption that thermal stress relief of the closure weld is not feasible).

Tab. 7.1: Time dependence of the requirements for SCC of carbon steel canisters during the evolution of the repository environment.

| **Phase** | **State of applied and residual stress** | **Nature of the corrosive environment** | **Likelihood of SCC** |
|---|---|---|---|
| Phase 1: dry conditions | No applied stress, residual stress only.<br>No cyclic loading component. | No surface aqueous phase. | SCC not possible because of absence of corrosion. |
| Phase 2: humid, aerobic conditions | Residual stress, development of bentonite swelling pressure possible during latter stages.<br>No cyclic loading component. | Possible deliquescence of surface salts leading to concentrated electrolytes on surface. Electrochemical potential relatively oxidising. | Formation of suitable concentrated electrolyte cannot be ruled out, although volume of solution would be small. Electrochemical potential possibly in permissive range for cracking. Absence of cyclic loading will limit extent of crack growth. |
| Phase 3: saturated aerobic-anaerobic transitional phase | Both residual and applied stresses, the latter from bentonite swelling and hydrostatic and lithostatic loading.<br>No cyclic loading component. | Salinity of surface aqueous phase decreases as bentonite saturates.<br>Electrochemical potential relatively oxidising. | Formation of suitably concentrated electrolyte unlikely as bentonite progressively saturates. Electrochemical potential possibly in permissive range for cracking. Absence of cyclic loading will limit extent of crack growth. |
| Phase 4: saturated, anaerobic conditions | Both residual and applied stresses, the latter from bentonite swelling and hydrostatic and lithostatic loading.<br>No cyclic loading component. | Bentonite pore water eventually equilibrates with Opa pore water (salinity 0.2 – 0.3 eq/L)<br>Electrochemical potential relatively reducing. | SCC in concentrated carbonate or nitrate solutions not possible because of relatively reducing potential and absence of suitable electrolyte.<br>SCC in dilute carbonate not possible because of absence of cyclic loading and of suitable electrolyte. |

Tab. 7.2: Time dependence of the requirements for hydrogen-induced cracking of carbon steel canisters during the evolution of the repository environment.

| Phase | State of applied and residual stress | Nature of the corrosive environment | Likelihood of HIC |
|---|---|---|---|
| Phase 1: dry conditions | No applied stress, residual stress only. | No surface aqueous phase. | HIC not possible because of absence of corrosion and, hence, hydrogen. |
| Phase 2: humid, aerobic conditions | Residual stress, development of bentonite swelling pressure possible during latter stages. | Possible deliquescence of surface salts leading to concentrated electrolytes on surface. Electrochemical potential relatively oxidising. | HIC not possible because no significant hydrogen is generated under the relatively oxidising conditions. |
| Phase 3: saturated aerobic-anaerobic transitional phase | Both residual and applied stresses, the latter from bentonite swelling and hydrostatic and lithostatic loading. | Salinity of surface aqueous phase decreases as bentonite saturates.<br>Electrochemical potential relatively oxidising. | HIC not possible because no significant hydrogen is generated under the relatively oxidising conditions. |
| Phase 4: saturated, anaerobic conditions | Both residual and applied stresses, the latter from bentonite swelling and hydrostatic and lithostatic loading. | Bentonite pore water eventually equilibrates with Opa pore water (salinity 0.2 – 0.3 eq/L)<br>Electrochemical potential relatively reducing. | HIC/SOHIC possible from both external and internal surfaces of the canister in the presence of sufficient tensile stress and a sufficiently large defect. |

## 7.5 Implications for canister design

In summary, there are a number of implications of the corrosion behaviour of carbon steel for the design of the canister:

- A wall loss of approximately 20 mm can be expected as a result of uniform corrosion by the end of the target design lifetime of 10'000 years. This addresses RQ2 and RQ6.
- SCC is most likely during the early aerobic phase when a suitable environment and relatively oxidising conditions may exist.
  - As a consequence, techniques for relief of the near-surface residual stress could significantly reduce the possibility of SCC.
  - Furthermore, removal of surface-breaking (or near-surface) defects would also be beneficial in reducing the probability of SCC.
- In contrast, HIC/SOHIC is possible only during the long-term anaerobic period.
  - Therefore, both surface-breaking and sub-surface weld defects can potentially act as stress concentrators for HIC/SOHIC.
  - Accumulation of gaseous $H_2$ inside the canister could result in HIC/SOHIC from the inner surface, particularly at un-repairable defects or regions of high residual stress in the closure weld. Weld design optimization might be considered as an approach to reducing the stresses at the weld root and thus lowering the likelihood of HIC/SOHIC.

The above issues relating to SCC and HIC identify mitigation strategies to satisfy RQ10.

# 8 Closure Weld Design

## 8.1 Introduction

It has been stipulated (RQ4) that welding will be used as the final closure method for both high level waste (HLW) and spent fuel (SF) canisters. Welding offers the greatest likelihood of being demonstrated to have least risk of loss of hermeticity over the intended canister life. In view of the current design requirement for 140mm thickness material and following a detailed review of welding methods (Pike et al. 2010) two processes have been selected as being appropriate for canister closure; electron beam (EB) welding and narrow gap gas tungsten arc welding (NG-GTAW). Both processes are suitable for remote operation and production of high quality welds in thick-section steel. The processes differ, however, in that EB welding is a non-contact, autogenous welding process in which heat is supplied by a high voltage electron beam and welding is completed in a single pass with no added filler metal; in contrast NG-GTAW is a multi-pass process in which heat is provided by an electric arc and filler metal is added by means of a wire to a narrow groove weld preparation. In consequence, EB welding has a rapid joint completion rate and is ideally suited to remote operation but does not benefit from multiple weld passes for microstructural refinement and inherently smaller potential flaws of the NG GTAW process.

The weld design detail is critical for the closure weld since it has to be made remotely using a robotic system. The requirements for high integrity and resistance to degradation and cracking over a 1'000 year life demand a weld of consistently high quality with low residual stress whose properties are optimised for the duty and environment. In respect to the candidate welding processes, potential closure joint designs were identified. These are reviewed and explained in the following sections.

The weld design addresses the requirements given in Box 8.1.

**Box 8.1 Requirements relating to closure weld design**

RQ4 Closure welding process.

RQ10 Weld integrity – SCC/HIC.

RQ17 Inner lid.

RQ20 Production rate.

## 8.2 NG-GTAW weld design

### 8.2.1 Technology

NG-GTAW has been proven as a reliable technology for producing high quality welds for joining of thick materials. It has found many applications on safety critical components used for power generation, such as boiler headers, steam piping, generator rotors, steam turbine rotors and nuclear pressure vessels (Pike et al. 2010). Equipment used for NG-GTAW process is widely available ranging from standard torches to bespoke tailor-made torches with integrated vision systems designed for specific operations. For the canister closure weld, an integrated system will be required to suit the remote operation and monitoring requirements in the hot cell environment (RQ4).

### 8.2.2 Welding position

For the NG-GTAW process, two welding positions can be considered. In both cases, the canister will be stood vertically. The first option is to deposit the closure weld in the flat (1G/PA) (i.e. vertical) position with either the torch or the canister rotating. For this option, the set-in lid design is adopted (Figure 8.1). From a welding point of view, this position is favourable as gravity acts down through the molten pool, which is supported by material being welded, allowing larger molten pools and faster deposition rates.

As the NG welding head is of a substantial length, a specially designed curved head will be required for welding in the flat position. This adapted NG welding head can only be used to produce canisters with a fixed diameter. As such, canisters of different diameters will require bespoke NG torches. Some development work will be required to develop the NG process for welding radial welds in the flat (1G/PA) position.

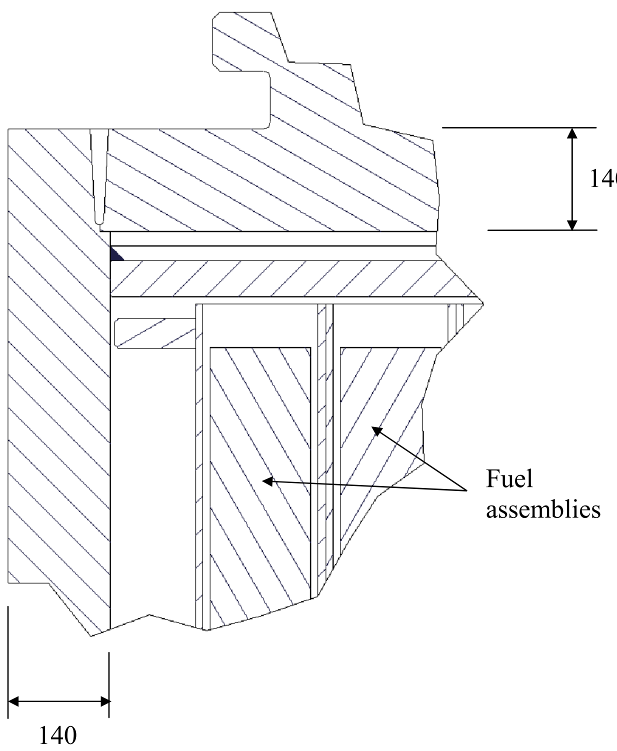



Fig. 8.1: Set-in lid design (joint detail for NG-GTAW).

The other option is to deposit the closure weld in the horizontal position (2G/PC) and either the torch or the canister is rotated. For this option, a set-on lid design is proposed (Figure 8.2). From a welding point of view, this position is less favourable than the flat (1G/PA) position because the weld pool settles towards one side of the joint under the action of gravity on the molten pool. The size of the weld deposits will be restricted to around 2.5 mm thick, compared to a larger weld deposits (around 3 mm thick) obtained in the flat (1G/PA) position. This means a slightly lower deposition rate for the horizontal (2G/PC) position than the flat (1G/PA) position.

For this particular application, in the horizontal (2G/PC) position, an off-the-shelf system for the NG head can be used. NG-GTAW is widely used in the horizontal (2G/PC) position for many existing applications such as production of thick turbine rotors. Very often customised equipment based on integrated welding and monitoring system is designed and commissioned to meet specific operational requirements. Such equipment has a proven track record for welding thick materials and can be customised to suit the canister closure weld operation.

From residual stress (transverse) point of view, it is thought to be more favourable to perform welding in the horizontal (2G/PC) position than in the flat (1G/PA) position. This is because with a set-on lid configuration, the edge of the lid has more freedom to move (bend) than the canister wall and therefore some of the weld shrinkage can be compensated by the movement of the lid. Whereas in the flat (1G/PA) position, freedom of movement for both the lid and the canister wall is more restricted, so the weld is expected to develop more extensive tensile transverse residual stress field.

Considering the pros and cons of the two welding positions, it is recommended to consider the horizontal (2G/PC) position for the closure weld due to the higher technology readiness level of the welding torch and proven track record of NG-GTAW welding for thick materials in this position. Welding in the flat (1G/PA) position with the long axis of the canister positioned horizontally will not be considered as the risk of fuel movement and damage occurring while the canister is being rotated horizontally is too high, unless a very accurate dimension can be guaranteed for the internal structure to ensure that all the fuel assemblies are tightly supported laterally by the internal structure.

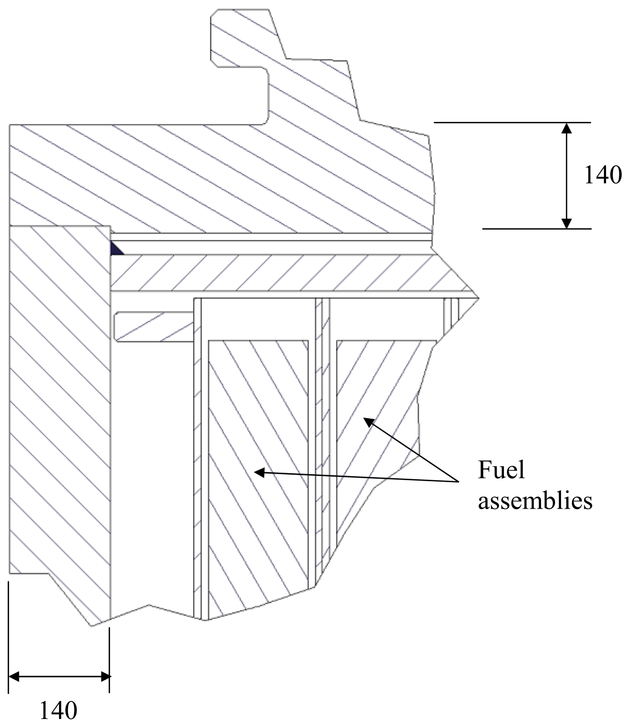



Fig. 8.2: Set-on lid design.

The inner lid is required for the SF canisters to prevent radioactive contamination of the outer lid and the welding cell. Although the fixing of the inner lid to the canister wall is yet to be decided, the inner lid could also be welded, as shown in Figure 8.1 and 8.2. Whether the inner lid sits on top of the basket or is positioned above it is a design matter to be resolved.

### 8.2.3 Profile of groove

For conventional multi-pass arc welding from single side, the edge of the parent materials are bevelled to provide a groove either in the shape of 'V' or 'U' ('single Vee' or 'single U' groove). The primary function of the groove is to provide access to the root and also to allow good fusion for the fill passes as the groove is then backfilled. Narrow gap welding has been developed to reduce the amount of weld metal and associated processing time whilst still ensuring good fusion.

For conventional butt-welds, the groove angle is primarily selected to suit the access required for the selected welding process. Since the grooves are wide in conventional butt-welds, slight changes to groove angle due to weld shrinkage has very little effect on equipment access. However, for NG welding, since the groove width is very small (typically 8 – 10 mm), any slight change in groove width due to weld shrinkage can greatly affect the access of the NG head. Therefore, depending on the shrinkage characteristics of the material to be welded, the groove angle needs to be carefully chosen to keep the width of the groove within a close range (typically 8 – 10 mm) throughout the welding operation, so that the fusion boundaries stay almost parallel after the weld is completed as shown in Figure 8.3.

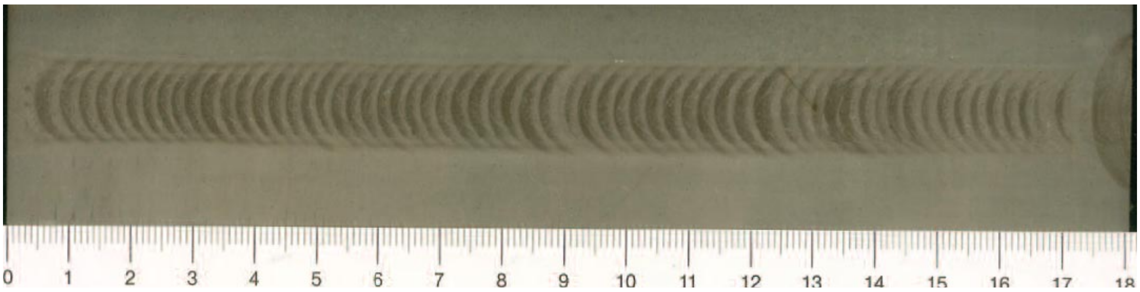



Fig. 8.3: Cross section of HW-NG-GTAW weld produced in 180 mm P91 steel.
Each striation visible on the macro indicates one pass.

In order to achieve this, a shrinkage curve needs to be generated by experimental work for each NG application, which forms an essential part of welding procedure development. For the purpose of developing the canister design concept, a preliminary groove design is proposed based on existing knowledge of NG welding of carbon and low alloy steels. The proposed design is shown in Figure 8.4. Experimental work as proposed in Section 8.8 will be required to generate the shrinkage curve required for the selected canister materials in order to finalise the groove profile.

A single bevel groove configuration (J-groove) was chosen as shown in Figure 8.4. This is because a different level of weld shrinkage is expected between the lid and the canister body. In the horizontal (2G/PC) welding position, it is envisaged that the canister body is unlikely to move to the same extent as the lid which is expected to bend in the vertical direction. This is because the lid (140 mm thick) is less stiff in the vertical direction than the canister wall. Therefore, the bevel is only required to compensate for the lid movement. Based on previous experience, a bevel angle of 2 – 3° for the first 30 mm and then 1° for the remaining thickness is proposed (Figure 8.4). It is proposed that no root gap will be required and the root face will be 2 – 3 mm, which would allow full fusion to be achieved along the root face.

With the proposed weld design for both NG-GTAW and EB welds, there is a vertical un-fused seam/land at the root of the weld (Figure 8.4). The implication of this un-fused detail is that it results in a potential stress concentration. This may be an issue, and therefore needs to be considered in future work. A potential concern is hydrogen concentration building with time at areas of stress concentration. The un-fused seam represents a stress concentration but its significance is dependent on the magnitude and distribution of welding residual stresses resulting from closure welding and any post weld treatment. Based on the rudimentary weld models reported in Sections 9.4 – 9.6, the NG-GTAW results in low tension or compressive residual stresses in the hoop direction at the root region whereas the EB weld process results in higher tensile residual stresses in the root region. However, this should be investigated via a more detailed numerical model using more accurate data to establish the true effect of stress concentration at the un-fused seam.

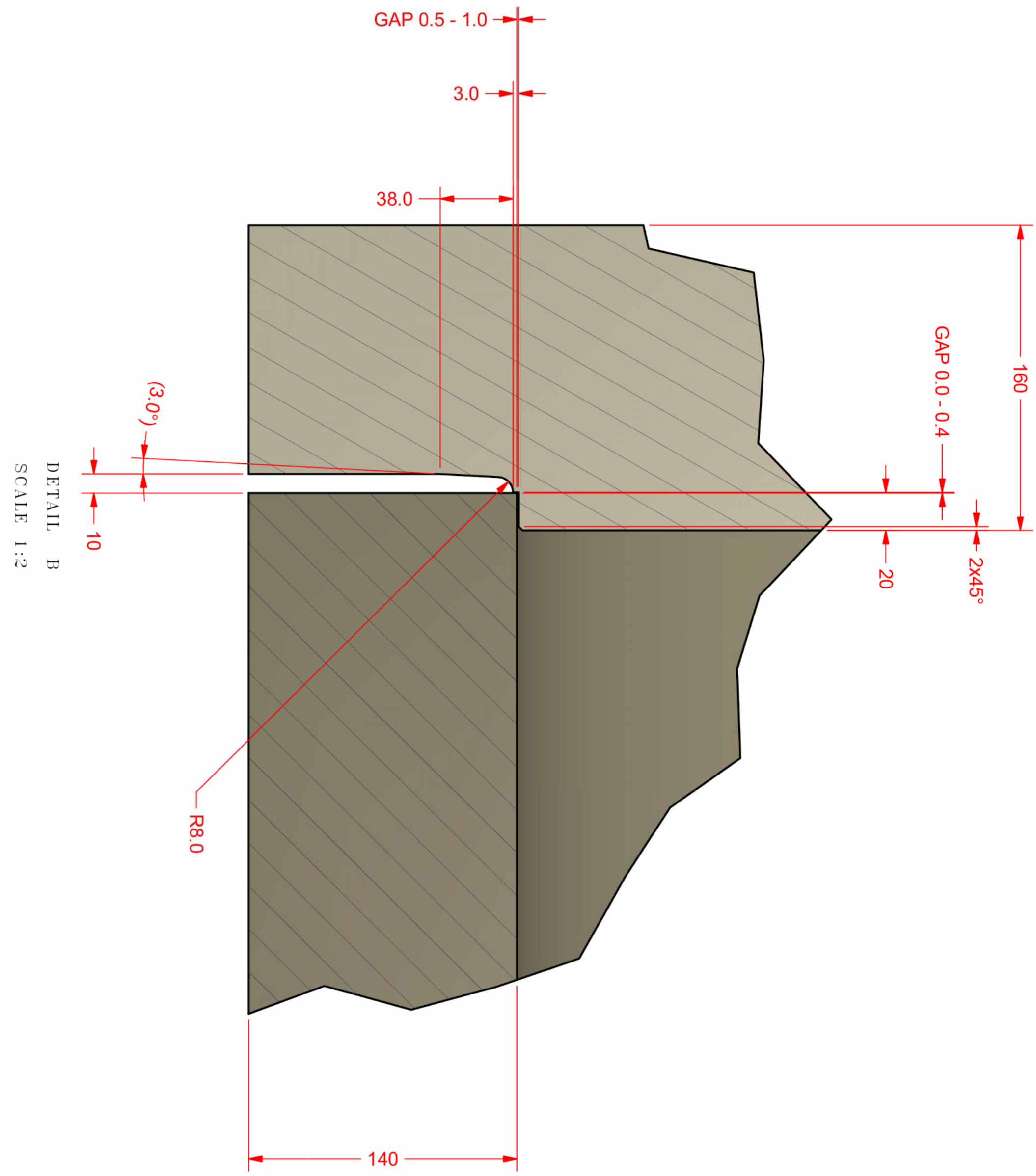



Fig. 8.4: Proposed joint design for NG-GTAW based on existing knowledge of NG welding of carbon and low alloy steels (actual design needs to be finalised after experimental work).

### 8.2.4 Process mode and fit-up tolerance

Fit-up tolerance is dependent on the width of the groove and the process mode used. The advantages and disadvantages of the three operating modes (1 layer 1 pass with electrode oscillation, 1 layer 2 pass/split pass, and 1 layer 1 pass without oscillation) are outlined by Pike et al. (2010). The oscillation mode requires complicated torch design which is not regarded as user-friendly in the hot cell environment. This is because oscillating tungsten will have a higher risk of malfunction than a fixed one. The split pass option can tolerate slightly poorer fit-up tolerance than the 1 layer 1 pass method, but productivity is halved, which will struggle to meet the productivity requirements for the hot cell operation. The 1 layer 1 pass method without oscillation is therefore recommended for the canister closure weld. It requires a tight fit-up tolerance of 0.4 mm for an 8 – 10 mm wide groove. The other disadvantages mentioned by Pike et al. (2010) such as potential for lack of sidewall fusion can be avoided by applying an optimum welding procedure developed by competent welding engineers.

## 8.3 Electron beam weld design

Electron beam welding of thick section steel is heavily influenced by gravity thus welding position is critical. Below 100 mm thickness welding can be conducted reliably in the flat or downhand position (referred to as 1G or PA by ASME and EN ISO welding codes, respectively) but without complicated beam deflection or beam pulsing it is difficult to produce welds of sufficient width to be practical and yet still achieve the required penetration depth in the 1G/PA position. As depth of weld penetration increases, the head of metal is increased which limits the maximum depth achievable to approximately 120 mm. Welding a set-in lid has the accompanying hindrance of increased restraint leading to greater risk of cracking. In the horizontal-vertical (2G/PC) position, the weld depth achievable increases with beam power for a given welding speed and are limited only by stability of the weld pool. For the proposed Nagra canister wall thickness (140 mm) the set-on lid concept, and 2G/PC welding position is preferred and thus the weld design proposed is based on this premise.

The objective in designing a joint for EB welding is to present a close fitting square butt joint to the beam with a nominally zero gap. For closure welding of the canisters under consideration it is impractical to set dimensions and tolerances for the parts to consistently achieve a constant zero gap. Therefore it is suggested that the parts are dimensioned so the joint gap is permitted to vary between zero and 1mm and remain in specification. The presence of the fuel in the container and the fact that the weld is the final closure dictates that an integral backing or beam stop is incorporated into the joint design. Also on consideration of non–destructive testing sensitivity required at the surface and long term performance requirements, it appears likely that the weld cap will need to be dressed by machining (this is also the case for NG-GTAW) and therefore some sacrificial material may be required to ensure clean up. The weld cap reinforcement can be minimised by use of a V groove feature incorporated in the joint preparation, and some provision of a weld bead support may be required although this is not always essential at this thickness.

## 8.4 Proposed welding procedure

The proposed welding procedure will need to be developed in conjunction with the stated requirements for material properties, joint design, candidate welding processes and the equipment to be developed. The specifications will also include requirements of the codes, standards and regulations and required/recommended testing regimes for validation of the procedures.

If the qualification welds are subjected to radiation and/or hydrogen conditions, the relevant non-destructive and destructive tests will be repeated afterwards to demonstrate that the required properties can be achieved using this welding procedure.

### 8.4.1 NG-GTAW

#### 8.4.1.1 Proposed WPS (Welding Procedure Specification)

**Parent materials:**

Refer to materials requirements detailed in Section 6.

**Filler metal:**

Filler metal matching or slightly overmatching the strength of the parent materials will be used. Specification of filler metal manufacturer and trade name will be based on experimental trials using several candidate products, as a recommendation for further work (Section 8.8). Chemical composition of the filler metal based on the selected manufacturers and trade name will be specified after experimental trials are conducted in further work.

**Material thickness:**

140 mm (refer to drawings).

**Joint preparation:**

Type: Single bevel narrow groove
Bevel angle: 2 – 3° for the first 30 mm, then 1° for the remaining thickness
Groove width: 8 – 10 mm
Root gap: no root gap
Root face: 2 – 3 mm
Radius: 8 mm
Fit-up (machined) tolerance: 0.4 mm.

**Welding position:**

Horizontal (2G).

**Pre-heat:**

Pre-heat: Preheat is not required due to the fact that a low hydrogen process is used. However, it is expected the steel will reach a temperature of around 50°C before NG-GTAW welding due to self-heating in the hot cell.

Interpass temperature: to be determined by future welding procedure development.

**Welding parameters:**

Current: 320 – 400 A
Voltage: 12 V
Travel speed: 80 – 100 mm/min
Heat input: 1.0 – 1.7 kJ/mm.

**Gas:**

Shielding gas: Ar-He mixture with 25 – 50 % He

Requires a torch change for the last 40 mm to provide good gas coverage.

**Technique:**

1 layer 1 pass without oscillation.

**Cleaning:**

The edge preparations are obtained by precision machining and hence the only cleaning operation required before welding will be degreasing. Grinding should not be necessary. Cleaning needs to be carried out and cleanliness inspected before entering the encapsulation facility assuming that the encapsulation facility is a controlled environment and is free from contamination of dust, grease, etc. This will be considered in more detail during future welding procedure development and encapsulation facility design.

#### 8.4.1.2 Recommendation for Welding Procedure Qualification

It is recommended that procedure qualification is carried out on the basis of a pre-production welding test in accordance with BS EN ISO 15613 (BSI 2004b) standard. This will require producing a test piece under the condition as close as possible to production welding conditions using production tooling. This means that the procedure test piece will be made remotely using the production welding equipment and monitoring systems designed for the hot cell operation. This test will be witnessed by an authorised third-party inspector. After completion, the test weld will be subject to the relevant non-destructive and destructive tests demonstrating that the required properties can be achieved using this welding procedure.

Existing experience on the manufacturing of thick components using NG-GTAW is briefly mentioned in 8.2.1 and more information on NG-GTAW is given in Pike et al. (2010).

#### 8.4.1.3 Productivity

In the preferred horizontal (2G/PC) welding position, the weld bead thickness deposited will be approximately 2.5 mm. So for a 140 mm thick groove, 56 – 58 passes including capping runs will be required to complete the joint. Welding speed is generally 80 – 100 mm/min so on average each pass can be completed in 30 minutes. This means that the joint can be completed in 29 – 30 hours with 1 narrow gap welding head. It is important that a balanced welding approach is adopted for the root pass to prevent uneven shrinkage along the joint line. This can be achieved by using multiple welding heads. For welds that are around or over 1m in diameter, usually 3-4 welding heads are used to cover 1/3 or 1/4 of the joint length. In this case, time for completion one closure weld could be significantly reduced to about 8 – 10 hours with multiple welding heads.

#### 8.4.1.4 Equipment requirements

The equipment has to be designed for remote operations and the components placed inside the hot cell will be expected to function adequately under the influence of radiation (Requirement RQ4). The total amount of radiation a piece of equipment can absorb before losing its function is measured in Gray (Gy), which is specified by the equipment manufacturer and is often marked on the equipment. Generally, electrical and electronic components such as printed circuit board (PCB) have lower Gray number than other mechanical components. Therefore, it is important that all the control systems, electrical motors and machine-to-human interface are located outside of the hot cell, and are designed to have adequate protection against radiation. Also, due to the foreseeable use of a high quantity of shielding gas and the generation of welding fumes during the closure welding operation, adequate ventilation will be necessary. The ventilation system will be specified during the detailed design of the encapsulation facility.

Torch life, water-cooled torch requirements and other equipment and maintenance considerations for NG-GTAW process for the Nagra canister application have been evaluated and discussed in detail in Pike et al. (2010).

#### 8.4.1.5 Potential issues and difficulties

The following issues and difficulties associated with NG-GTAW for the canister closure welds are identified and need to be addressed during further development work:

- The profile of the groove cannot be fixed until experimental work has been carried out to establish the shrinkage curve for this particular application.
- During the capping run in the 2G/PC position, there is a risk that the machined edge of the canister wall will be melted away. So edge protection will be required during the capping run.
- Interpass cleaning may be required after certain amount of passes depending on the amount of oxides accumulated on the weld surface. Excessive oxides form slag islands on the weld surface, which affect arc stability if large slag islands are formed. As a result, trials are required to select adequate filler wire to minimise oxides. A cleaning mechanism may be required in the hot cell to perform interpass cleaning after a certain number of passes.
- Torch change will be required for the last 40 mm of the weld thickness to provide adequate gas shielding. This will require additional torches and a torch change and associated control mechanism within the hot cell.

- Potential weld imperfections are lack of fusion at bottom edge of the groove and possible rolling pass/cold lap along the top edge of the groove if the heat input used is not adequate. With the correct welding procedure development program and electronic control in modern power sources, there is a small likelihood of occurrence for these types of imperfections.
- Blow out due to gas expansion has mainly been experienced in small sized containers or tubes. For larger containers such as the Nagra canister, the risk of blow out should be fairly low as heat can be conducted away relatively quickly with only localized heating. This should be further studied during future welding procedure development.
- The use of multiple torches as recommended in 8.4.1.3 can generate a large number of start/stop locations. The increased number of start/stop locations could potentially increase the risk of lack of fusion and other welding defects. Further work should assess the level of defects associated with start/stop locations and also carry out welding procedure optimisation to minimise the level of weld defects.

### 8.4.2 EB

#### 8.4.2.1 Proposed WPS

**Parent materials:**

The material composition specification stated in Table 6.1 takes into account the possibility of applying EB welding for the closure weld. The insistence on vacuum degassing and restrictions on impurity levels, although useful in promoting good mechanical properties in the parent steel are also pre-requisites for reliable EB welding behaviour. The materials presented for welding must also be sufficiently clean (degreased locally) and free from surface residual magnetic field levels of > 5 gauss. The surface finish of the joint faces should be specified to be better than 3.2 µm or at least to a finish good enough to allow adequate cleaning.

**Filler metal:**

No filler metal is required.

**Material thickness:**

140 mm (refer to drawings).

**Joint preparation:**

Type: Close fitting square butt with 0 – 1 mm gap.

**Welding position:**

Horizontal (2G).

**Pre-heat:**

Pre-heat: not required (a pre-heat level of approximately 50°C is expected in the steel at the time of welding due to self-heating by the SF/HLW).

**Welding parameters:**

Current: 300 mA
Voltage: 150 kV
Travel speed 100 mm/min
Heat input: ~ 35 kJ/mm.

**Gas:**

Local vacuum (reduced pressure) 0.3 to 0.1 mbar with background helium gas.

**Flow rate:**

He 0.2 l/min.

**Technique:**

Single pass 360° weld with 30° slope up and 30° slope down.

#### 8.4.2.2 Recommendation for Welding Procedure Qualification

It is recommended that weld procedure qualification is achieved by welding a representative test piece under environmental conditions simulating the canister temperature, joint fit –up and remote access constraints that are anticipated to be present in the closure welding activity, excepting the background radiation conditions. Weld assessment and testing will subsequently be performed according to the selected weld procedure qualification code.

#### 8.4.2.3 Productivity

The cycle time for EB welding is largely dictated by the system design and mode of operation. For a bespoke system designed to accommodate the SF and HLW canisters, it is envisaged that a local vacuum arrangement would be preferred. Operating at reduced pressure, it is likely that a weld chamber evacuation time of the order of 10 minutes would be readily achievable. After a period of ~ 20 minutes for fitting the lid, joint finding and tack welding, the full current weld cycle is estimated to take ~ 40 minutes leading to a complete cycle time of 70 minutes. It would be preferable for the canister to be rotated in front of a laterally fixed welding head but it is also possible for a moving welding head to be applied in this application and configuration.

#### 8.4.2.4 Equipment requirements

Electron beam welding equipment has been designed already for application to closure welding of spent fuel canisters and a number of systems already exist in prototype form e.g. at SKB in Oskarshamn (Claesson & Ronneteg 2003). The process itself generates high energy X-rays and consideration has been given to the anticipated radiation flux which in Nagra's case would be dealt with in the requirements for the shielded cell. The remote operation constraints are generally always present for EB welding as the requirements for biological shielding to deal with the X-rays generated by the welding process are similar to those for hot cell operation and joint tracking and viewing is readily achieved through the use of radiation hard cameras and back scattered electron imaging. Best practice suggests that where possible electronics and digital control systems are distanced from the weld head and operated through remote interfaces. The process is entirely non-contact and requires no consumables thus the system has low maintenance requirements excepting a scheduled cathode change after 500 kWhrs of operation (i.e. after ~10 canister closure welds).

The key remaining question surrounds the method for achieving a vacuum (or reduced pressure helium) environment. The lid will have to be fitted remotely and it is possible that the inner canister will be evacuated and backfilled with inert gas. These aspects will be taken into consideration when developing an equipment configuration and operating strategy for the closure welding cell. It is possible that the inner lid can be engineered to provide an adequate vacuum seal and thereby limit the internal volume to be evacuated for EB welding. Use of local sealing and pumping for the external surface also will result in a minimal pumped volume leading to rapid process cycle time and tolerance.

#### 8.4.2.5 Potential issues and difficulties

The following issues and difficulties associated with applying EB welding for the canister closure welds are identified and need to be addressed during further development work:

- The absence of successive thermal passes inherent in multi–pass welds may result in lower weld metal impact toughness properties than specified (although 27 J @ 20°C should be achievable).
- The requirements for sealing the inner lid and evacuation of canister need to be considered in the method of application and configuration of the equipment.
- The weld cap reinforcement and the method for dressing the weld cap for reliable inspection need to be considered in the final operating schedule and sequence.
- The requirement for an inert or low pressure atmosphere inside the closed canister will have implications in the operation of the closure welding facility and applied load in structural performance analysis.
- The completion of the weld by a slope-down operation needs to be assessed carefully and a method developed for avoidance of significant flaws.
- It is not anticipated that severe loss of alloy content will occur as a result of EB welding under vacuum. Experience suggests that a small reduction in manganese content will occur and reduction in residual gasses. It is recommended that the degree of elemental loss is determined by experiment.

## 8.5 Minimisation of hydrogen-induced cracking

Two H-induced cracking issues need to be considered, one being the long-term integrity issue (Section 7.4.3.2) and the other being fabrication-related hydrogen-induced cracking.

The weld design needs to minimize the probability of H-induced cracking initiating from the inner side of the closure weld (see Turnbull 2009, NTB 09-04). The main methods for avoiding such cracking during fabrication relate to the control of the factors that influence cracking. These include: (a) the concentration of hydrogen introduced to the weld region (consumable hydrogen content) (b) the diffusion of hydrogen away from the weld region (preheat and interpass temperature) and (c) the development of HAZ microstructures (dependent upon the composition of the parent material) and the residual stress. NG-GTAW is a low hydrogen process, and the canister is likely to be above 50°C at the start of the welding operation, giving some self-preheating. The HAZ microstructures developed are not likely to be susceptible to cracking as the carbon and alloy content of the parent material is low (Section 6), and the retarding of cooling rate associated with the self-preheating is also beneficial. The residual stress developed cannot be reduced without some form of stress relief, but with controls on the other three factors, the likelihood of fabrication hydrogen cracking is very low.

The likelihood of H-induced cracking from the inner side of the closure weld is reduced by the use of an unfused land to eliminate the possibility of generating weld spatter or other undesirable surface features to act as additional stress raisers on the internal surface of the canister. Additionally, for a NG-GTAW weld, the stresses at the root of the weld are anticipated to be compressive (Section 9).

During the canister lifetime, the surface condition and the absence of surface breaking and sub-surface flaws are important in avoiding SCC/HIC (Section 7.5). The removal of the weld cap also is beneficial for inspection (Section 11). Service-related cracking will also depend on avoiding susceptible weld zone microstructures. This can be achieved by the application of the hardness limits given in ISO 15156 (i.e. below 250 HV; BSI 2009b).

The EB welding process is inherently unlikely to generate additional hydrogen during welding. The only concern relates to the residual hydrogen in the forged canister parts which will be restricted in the material composition specification.

## 8.6 Weld zone microstructure

### 8.6.1 NG-GTAW weld

The use of a multipass weld can be beneficial in providing an effective tempering effect, modifying the microstructure associated with earlier weld passes by the heating arising from subsequent passes. This can be beneficial in terms of reducing the hardness of the weld zone, and modifying the developed microstructure from a rapidly cooled martensitic or bainitic microstructure to a tempered microstructure.

The cooling rates associated with NG-GTAW are likely to generate isolated regions of martensite within the HAZ. The refinement and tempering associated with subsequent passes, and the design of a weld procedure that does not make the final pass of the weld on to the parent material also can be beneficial in reducing the proportion of microstructure susceptible to SCC available. This final bead is then machined off to facilitate inspection, so leaving a favourable microstructure. A well refined and tempered microstructure would also tend to have improved toughness compared to a single pass as-deposited microstructure.

From a microstructural perspective, PWHT would not be necessary for modification of the microstructure in a multipass NG-GTAW weld, providing the weld sequence has been suitably qualified and shown to result in well refined and tempered weld and HAZ microstructures. This will not address the development of residual stress and its associated reduction, and this is considered further in Section 9.

### 8.6.2 EB weld

As EB is a single pass process, there is limited opportunity for refinement of the weld and HAZ microstructures. However, EB welding results in a relatively slow cooling rate, which is more likely to give a bainitic (softer) microstructure in the HAZ initially. The slow cooling rate associated with EB welds can also give some measure of auto tempering, which leads to an improvement in the developed properties.

EB welds are generally associated with poor low temperature toughness, but this can be altered by the development of weld microstructures containing high proportions of acicular ferrite. This is largely associated with having an aluminium to oxygen ratio that is below unity in the weld metal. This can be achieved by the starting composition, but is affected strongly by the loss of oxygen as a result of EB welding (Francis-Scrutton 1995). The use of titanium to offset this may also assist in acicular ferrite formation. Aluminium is not specified in Table 6.1, but studies on the optimum levels of aluminium and oxygen for EB weld toughness in the candidate material, alongside restricting the oxygen content to avoid degassing during welding should be carried out.

Microstructurally, if the weld zone composition can be designed to give acicular ferrite, the slow cooling rate and autotempering may also be sufficient to avoid developing undesirable microstructures. As such, PWHT would not be necessary to modify the developed microstructure. As with NG-GTAW welds, the residual stress developed may still need to be modified, and is considered in Section 9.

## 8.7 Welding investigations and future development work

### 8.7.1 General considerations

In the long term canister development plan there are a number of activities that are recommended to reinforce the observations discussed and to confirm the proposed selection of the two alternative welding processes. In particular, it is advisable that the resistance to general corrosion, SCC and HIC is demonstrated for both welding processes using representative welding procedures, base metal and consumables.

### 8.7.2 NG-GTAW

The following laboratory experimental work is recommended prior to implementation of this method for canister closure welds:

- Generate shrinkage curve for the required canister material.
- Determine filler metal specifications using standard NG-GTAW equipment.
- Produce a mock-up weld using standard NG-GTAW equipment and check properties achieved.

### 8.7.3 EB welding

The successful application of EB welding in this application is reliant on establishing a reliable weld procedure that produces a consistent weld cap which can be easily dressed for inspection and a reliable weld termination procedure for completion of the circumferential weld pass. The requirements for weld properties should be readily achievable. However, as an autogenous process sensitivity of properties to variations within the canister/lid material composition specification should be examined. The key issue is that an experimental demonstration of resistance to localised preferential corrosion and SCC should be made to verify that the predictions for this are correct, prior to implementation of this as a method for canister closure welding.

### 8.7.4 Repair strategy

Ideally, avoidance of weld repairs would be preferred, but it is likely that some minor repairs will be required to correct geometric weld bead deficiencies. For major repairs many different possibilities exist and each should be uniquely assessed. Ultimately, correction of a defective weld could require cutting off the lid and re-packaging the SF/HLW.

Due to the nature of remote operation and the large thickness of the closure weld, it will be challenging to repair in-situ any large buried volumetric defects detected by the relevant inspection techniques. For multi-pass welding, a staged inspection (once every 1/3 of the weld thickness) can be used so that any defects found in the early stage of the weld can be addressed before completing the whole weld. Detailed repair philosophy and specific repair procedure will be developed in a subsequent study.

## 8.8 Summary

Both EB and NG-GTAW weld designs discussed are possible options for the closure weld design. As both are suitable for remote operation, and weld parameters can be selected to achieve the required properties, this satisfies RQ4.

The main issues associated with SCC and HIC (RQ10) in the weld zone relate to the surface condition, the presence of flaws and residual stresses. The inspection of the weld is likely to require surface dressing (see Section 11), which will give a good surface finish and reduce surface discontinuities. The residual stresses developed in the weld region and mitigation methods are further discussed in Section 9.

# 9 Post Weld Stress Relief

## 9.1 Introduction

Welding of thick section steel using a fusion based welding process invariably results in tensile residual stresses in the weld region. The maximum residual stress typically reaches the yield strength of the material. In view of the intended application, and the requirement to minimise the risk of failure of the canister over the repository lifetime, high tensile residual stresses, particularly those close to the outer surface, are undesirable. Firstly, it is recognised that the threshold stress for initiation of SCC in steel approximates to the yield strength of the material. Secondly, the resistance to brittle fracture and tolerance to flaws can be significantly reduced by the presence of tensile residual stresses if the toughness is low. Reduction of tensile residual stresses to, say, half or two thirds of the parent material yield strength could strengthen the safety case by reinforcing the argument that SCC and brittle fracture will not occur. Therefore the application of a stress relieving method is being considered in the weld process and lid welding methodology.

Post weld heat treatment (PWHT) is generally used for stress relief of welded thick steel structures. In order to avoid risking damage to the fuel cladding Nagra has limited the temperature of the canister contents to 400°C for the SF, and 450˚C to minimise risk of damage to the vitrified waste in the HLW canister, thus imposing a restriction on the soaking temperature and time for any stress relief PWHT. Codes for fabrication generally allow for longer duration PWHT if a reduction in the soak temperature is considered as stress relief is a time/temperature dependant phenomenon. The increase in soak time for reduced temperatures can be calculated based on formulae such as Holloman-Jaffe or Larson-Miller parameters. These can be considered in conjunction with the proposed level of stress relief required, material properties including fracture toughness and microstructure to give guidance on relevant PWHT temperature and duration. (It is possible that low temperature PWHT will be sufficient to reduce the level of tensile residual stress, particularly in the weld region close to the surface). This needs to be determined by a combination of weld modelling and experiment in the context of future development work.

Alternatively, there is a possibility that surface stress modification techniques such as laser shock peening could be employed to change the surface residual stress state from tensile to compressive in the region of the final closure welds or to carry out stress balancing through the use of the EBW process to cause a change in the residual stress distribution and reduce tensile surface stresses to tolerable levels. One key question remains as to whether tensile stresses are tolerable at the weld root and inside surfaces of the canister.

The level of tensile stress necessary to induce hydrogen cracking in the selected material will need to be evaluated. If the magnitude of the predicted residual stresses, resulting from closure welding or the applied stresses from loading, exceed this level then remedial action will be required. The threshold stress for HIC will be determined for the selected welding process and specific canister material composition in the proposed development study following the basic concept design phase.

The post weld stress mitigation addresses the requirements given in Box 9.1.

**Box 9.1 Requirements relating to closure weld design**

RQ10 Weld integrity – SCC/HIC.

RQ11 Residual stress mitigation and control.

RQ12 Critical flaw size.

RQ13 Surface residual stress reduction.

RQ15 Integrity of waste – residual stress reduction.

## 9.2 Weld process modelling for prediction of residual stresses

Key to the selection of the closure welding process and definition of the need for post weld mitigation of residual stresses is the understanding of the magnitude and distribution of residual stresses arising from the weld processes when applied in conjunction with the proposed canister lid and weld joint details.

To provide a basis for predicting residual stresses arising from welding, FE weld modelling was carried out to examine the consequences of the closure lid weld on the PWR spent fuel canister design using a lid with an integral lifting feature. Both EB and NG-GTAW welding processes were analysed. For each case, the 2G welding position and set-on lid geometry were analysed.

## 9.3 Modelling method

All geometry was created in ABAQUS CAE (Dassault Systèmes 2010) and the analyses were carried out using the ABAQUS/STANDARD (Dassault Systèmes 2010) solver. The weld modelling procedure involves a heat transfer analysis followed by a mechanical analysis. The results of the heat transfer analysis were used as a thermal load in the mechanical models, in which the residual stresses were calculated. A suitable FE mesh was generated for the EB and NG-GTAW models. Figure 9.1 presents the FE mesh used for the EB model, which shows a concentration of elements in the region of the weld. The figure shows a representation of the SF canister, which has a wall thickness of 140 mm (the thickness ultimately selected, see Section 10.2) and a lid thickness of 160 mm.

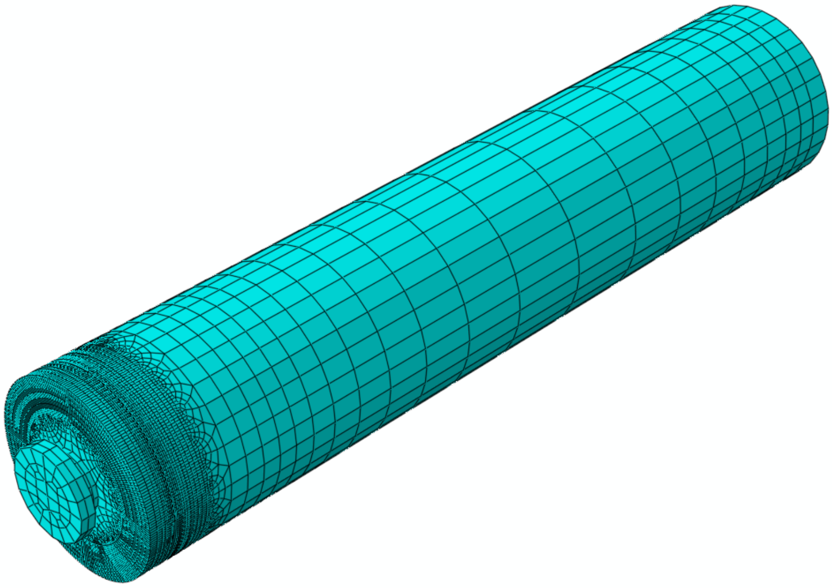


Fig. 9.1: FE mesh, showing a concentration of elements in the region of the weld.

## 9.4 Electron beam welding

The EB welding parameters used in the heat transfer analysis are shown in Table 9.1 and represent typical welding conditions for welding carbon steel of 140 mm thickness. Figure 9.2 presents the predicted temperature distribution during welding, showing the extent of the weld fusion zone and heat affected zone. For this analysis, room temperature conditions were assumed inside and outside of the canister.

Tab. 9.1: Welding parameters used in the EB weld model analysis.

| **Voltage [kV]** | **Current [mA]** | **Welding speed [mm/min]** |
|---|---|---|
| 150 | 300 | 100 |

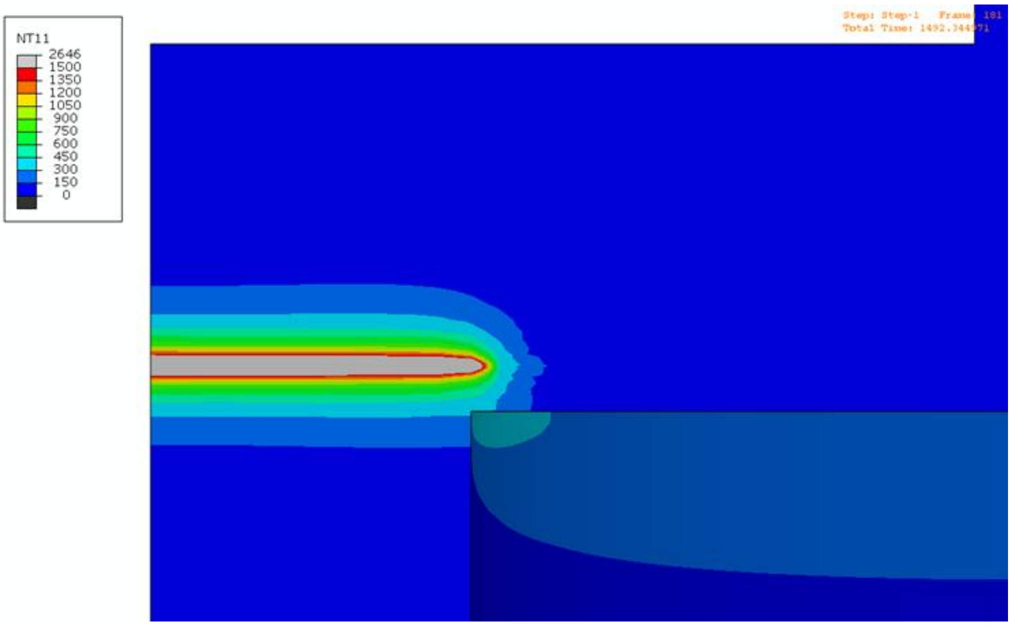



Fig. 9.2: Instantaneous temperature distribution during EB welding of the closure weld, at steady state, showing the extent of the weld fusion zone (grey colour).

Units in degrees Celsius.

A Von Mises stress plot of the welded canister on cooling to ambient temperature is shown in Figure 9.3. At the weld regions the material has a residual stress of near yield magnitude. The stress pattern also illustrates the effect of the start and finish of the weld. Figures 9.4 and 9.5 present the axial, longitudinal and through-thickness stresses on the surface and in a cross-sectional view of the weld respectively.

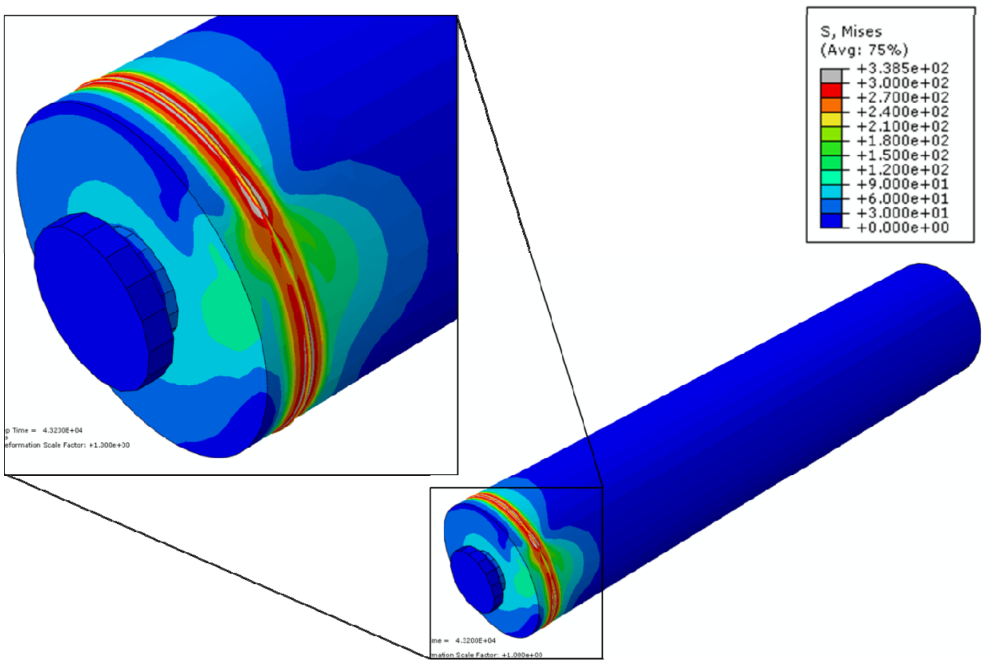
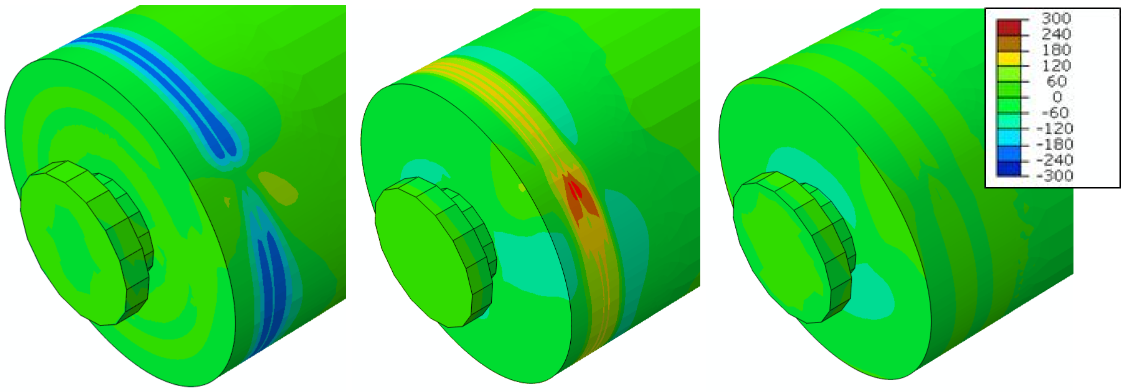
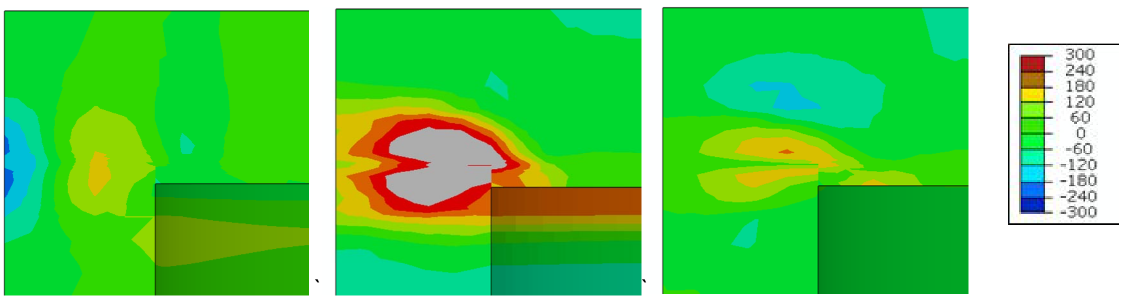



Fig. 9.3: Prediction of Von Mises residual stress after EB welding of the closure weld.




a) b) c)

Fig. 9.4: Prediction of residual stresses (Units in MPa) on the surface of the closure weld after EB welding, showing: a) Axial stress; b) Hoop stress; c) Through-thickness stress.




a) b) c)

Fig. 9.5: Prediction of residual stresses (Units in MPa) in a section of the closure weld after EB welding, showing: a) Axial stress; b) Hoop stress; c) Through-thickness stress.

The analyses do not take into account the metallurgical changes as a result of melting, cooling rates and effects of phase transformation density changes, which could influence the final residual stress distribution.

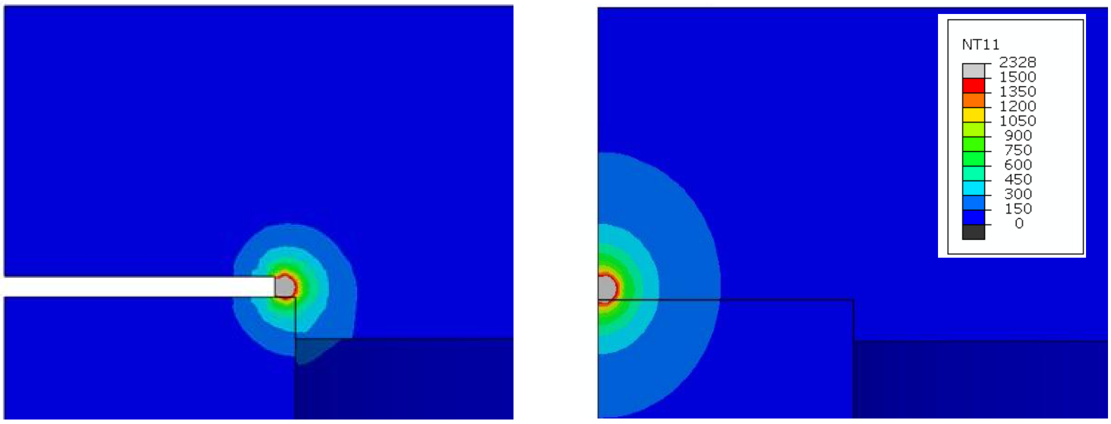
## 9.5 Narrow gap TIG welding

Table 9.2 shows the welding parameters used in the NG-GTAW model.

Tab. 9.2: Welding parameters used in the NG-GTAW weld model analysis.

| **Voltage [V]** | **Current [A]** | **Welding speed [mm/min]** |
|---|---|---|
| 12 | 360 | 90 |

The number of weld passes required to complete the joint was estimated to be 56. In the model, however, to reduce the time required to converge to a solution, 14 weld passes were modelled. Therefore, in the model four weld passes were assumed to be welded as one amalgamated weld pass. In Figure 9.6 the temperature distribution during the first amalgamated pass and during the final amalgamated weld pass are shown. For this analysis, room temperature conditions were assumed inside and outside of the canister.




a) b)

Fig. 9.6: Temperature distribution (Units in degrees Celsius) during NG-GTAW welding of the closure weld, showing the extent of the weld fusion zone (grey colour) at: a) The 1st weld pass; b) The last weld pass.

The resulting Von Mises stress plot, Figure 9.7, shows yield magnitude stresses to have developed in the weld region. The distribution of residual stress, however, is much longer range in comparison with the stress field calculated in the EB model. Figures 9.8 and 9.9 present the axial, longitudinal and through-thickness stresses on the surface and in a cross-sectional view of the weld respectively.

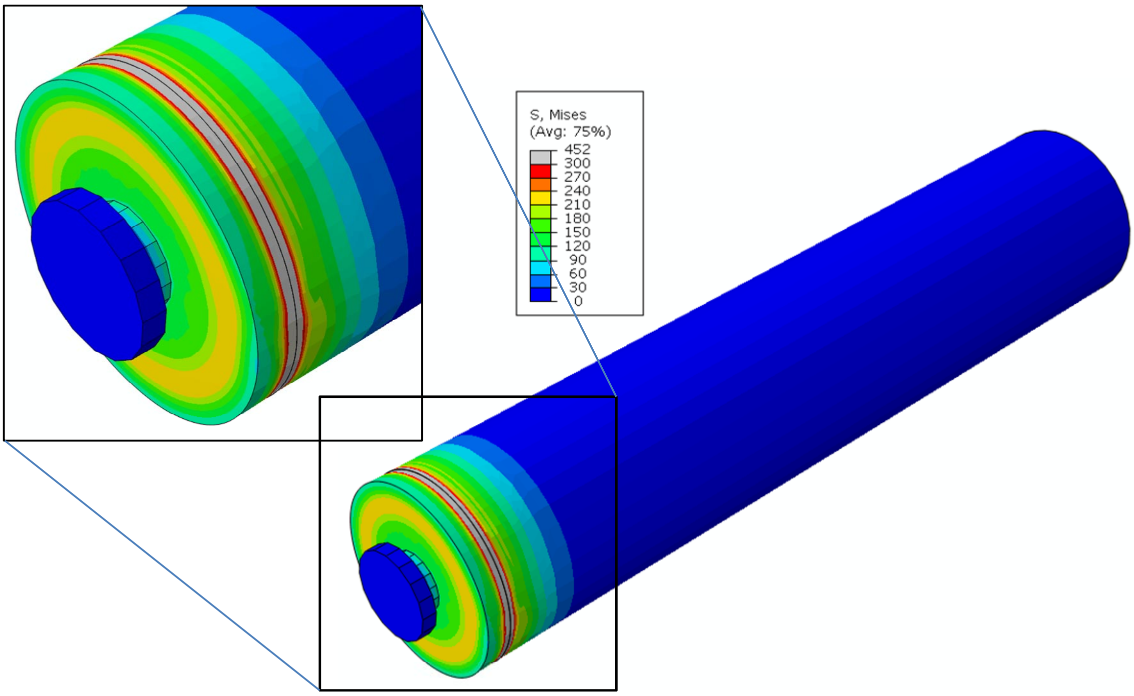



Fig. 9.7: Prediction of Von Mises residual stress (Units in MPa) after NG-GTAW welding of the closure weld.

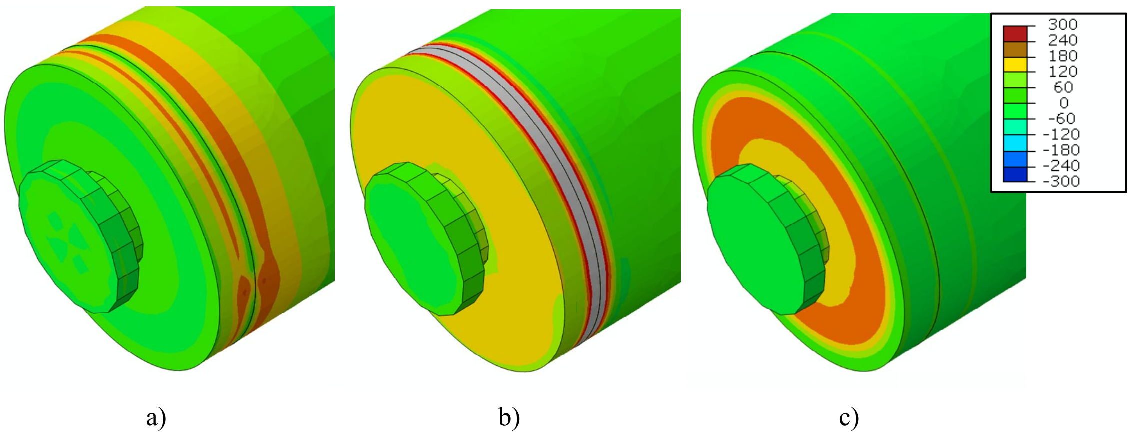



Fig. 9.8: Prediction of residual stresses (Units in MPa) on the surface of the closure weld after NG-GTAW welding, showing: a) Axial stress; b) Hoop stress; c) Through-thickness stress.

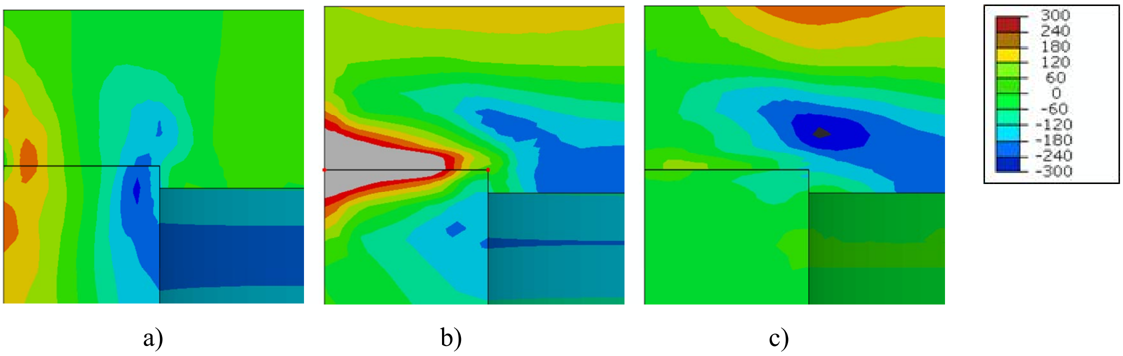



Fig. 9.9: Prediction of residual stresses (units in MPa) in a section of the closure weld after NG-GTAW welding, showing: a) Axial stress; b) Hoop stress; c) Through-thickness stress.

## 9.6 Discussion of results

The analyses described above although not entirely rigorous due to assumptions on weld procedure, pre-heat levels etc. give a good indication of the magnitude, distribution and range of residual stresses likely to occur as a result of performing the closure of a PWR spent fuel canister using EB and NG-GTAW welding.

The key observation is that both processes result in yield magnitude residual stresses developing in the weld region but that the distribution and range are quite different. Both methods cause high tensile stresses to develop in the hoop direction. The NG-GTAW process results in high surface stresses extending to ¾ weld depth but with low tension or compressive stresses at the root whereas the EB stresses are highest at mid depth and in tension at the weld root. Notably the use of NG-GTAW welding has resulted in the development of long range tensile stresses on the outer surface of the lid and the EB process causes compressive stress to develop at the outer weld surface in the axial (transverse) direction. The consequence of these observations is that the preferred options for mitigation or stress relief may be different as discussed below in Section 9.8.

## 9.7 Model of PWHT (full thickness)

A thermal, steady-state finite element analysis was carried out in order to determine the temperature of the HLW when local PWHT is applied to the closure weld (temperature between 550 and 600°C in the region of the closure weld). The analysis did not take into account the PWHT cycle, but determined the maximum temperatures assuming the soak period was under steady state conditions as this represented the worst case condition. The analyses were performed using ABAQUS v11-2 assuming properties of carbon steel for the canister, stainless steel for the flask and using properties provided by Nagra for the HLW.

A 5mm gap between the canister and the flask was assumed. The simplest case of heat transfer was considered using only infra-red radiation on the basis that if this resulted in a HLW temperature above the allowable 450°C there would be no need to consider a more complex model. This is because the additional heat transfer mechanisms would cause the temperature of the HLW to increase even further. Thus, it was assumed that there was no convection or radiation within the flask, only radiation between the canister and the flask. Also, no conduction was modelled between the canister and the flask. A best-case scenario was assumed such that the flask producing less heat (AREVA at 606 W) was placed at the top and the flask producing more heat (Sellafield Ltd. at 660 W) was placed at the bottom, away from the heat source. The inner lid was not modelled. Adding this component would cause a heat sink that may cause the temperature gradient to be more severe than recommended by the codes of practice. Hence, a thermal stress analysis would need to be performed in order to determine the effect of this temperature distribution on the residual stress after local PWHT.

The results showed that when local PWHT is applied (temperature between 550 and 600°C in the region of the closure weld) the temperature experienced by the top of the vitrified HLW was well above 450°C. Reducing the area over which the heat source was applied reduced the temperature in the HLW significantly from 517 to 464°C, not including the heat generation from the HLW. When the heat generation was included, the maximum temperature in the HLW increased to 473°C. The temperature distribution is even across the width of the canister and in the top of the HLW, with a fairly small region of HLW above 450°C as shown in Figure 9.10.

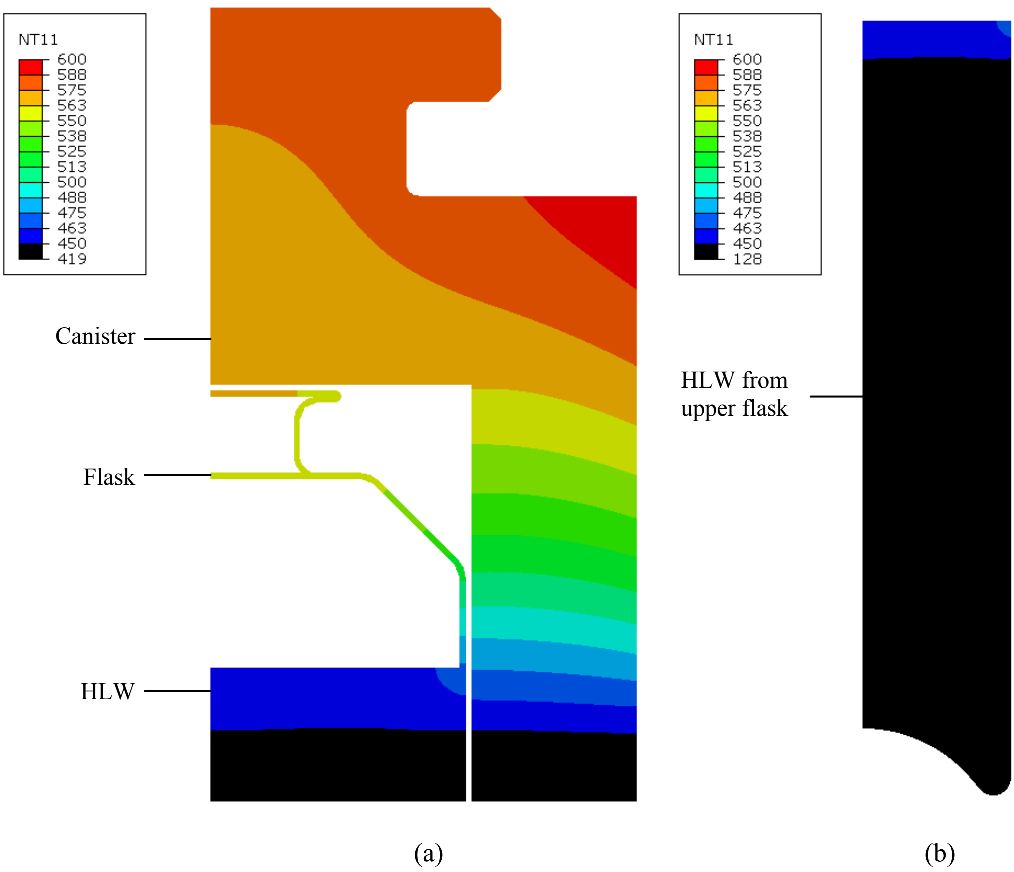



Fig. 9.10: (a) Temperature distribution in top of model including heat generation,
(b) Temperature distribution in HLW including heat generation.

The predicted temperature of the HLW is 23°C above the limit and so further design modifications need to be made. It is recommended that changes to the PWHT process or design modifications to the canister are made and further analyses conducted. Also, since non-standard heating in the PWHT is being applied, a stress analysis is recommended using these thermal loads as data input to calculate the resulting residual stresses to ensure that they are acceptable.

A more detailed description of the PWHT FE analysis of the HLW canister is given in Appendix F, including a sensitivity study showing the insignificant effect of the emissivity parameter. It is worth noting that a PWHT FE analysis of the SF canister has not been performed. The HLW canister was analysed first because the geometry of the flasks containing the high level waste is axisymmetric, whereas modelling the spent fuel assemblies would be much more complex.

## 9.8 Alternative residual stress mitigation methods

Application of a local thermal stress relief to the closure weld at 550 – 600°C may be possible and has the advantage of providing stress relaxation to a significant depth thereby minimising the risk of SCC from the outer surface of the canister and HIC from the root of the weld (particularly for the EB process where tensile residual stresses are developed). The secondary benefits exist also in eliminating the risk of localised regions of high hardness in the as-deposited closure welds through the tempering effect of heat treatment in this temperature range. In addition, the beneficial effect of reduced tensile residual stresses on tolerance to flaws has been demonstrated and discussed later in Section 10.

The disadvantages of applying this method of stress relief are, as noted above in Section 9.7, that there is a risk that the HLW or spent fuel assemblies could be heated beyond a safe temperature. Also the implications on throughput and surface finish may be unacceptable. However, it appears possible that, with development, a strategy could be adopted whereby a thermal stress relieving heat treatment could be optimised, in terms of time at temperature, to achieve a sufficient reduction in tensile residual stress through the weld thickness. It is not practical to achieve zero or compressive residual stresses by any local method and it could be that a restricted temperature thermal treatment (applied for example by induction heating which generates sub-surface heating) could be applied without risk of damaging the HLW or fuel and achieve a sufficient reduction in tensile residual stress to say 2/3rds of the yield strength of the material.

If this level of tensile residual stress is considered tolerable then other options exist for mitigation of closure welding stresses. It has been shown both for EB welding and TIG welding that by heating regions adjacent to the weld region, where balancing compressive residual stresses are predicted, only to a relatively low temperature (< 400°C), significant reduction in the weld residual stresses can be achieved even some distance (~ 50 mm) from the surface (Punshon et al. 2009). This heating method can be applied using a simple radiant or induction heat source or, as in the tests conducted to date, using the welding beam in the case of EB welding.

Similarly, considering the NG-GTAW case, as–deposited the stress state at the weld root is satisfactory and with application of either local heating to the weld or a surface treatment such as laser shock peening or low plasticity burnishing it will be possible to reduce tensile residual stresses in the outer 10 – 20 mm to a low level. Nevertheless this approach will inevitably leave a region of yield magnitude tensile residual stress in the hoop direction of the weld buried well away from the surface.

In order to define the best strategy it is necessary to consider the practical implications against the performance risks. It appears likely that for the canister design proposed, reduction in tensile residual stresses to less than 2/3rds of the specified yield strength of the material will be possible for both of the welding processes examined. If this requirement is necessary for the weld root detail then NG-GTAW welding must be used or else a thermal stress relief capable of achieving stress relaxation at the root without the risk of thermal damage to the fuel must be applied if EB welding is deployed. If tensile residual stress can be tolerated at the weld root then EB welding can be applied with stress balancing treatment or surface stress relief of sufficient depth. Because of the issue of potential HIC if the weld root retains tensile stress, it would be necessary to obtain further material fracture toughness data that accounts for hydrogen diffusion ($K_{IH}$) for parent and weld material in order to define the best strategy for residual stress mitigation.

It is recommended that the FE model is refined and the postulates for low temperature stress relieving heat treatment are verified by experiment on representative structures.

# 10 Structural Performance

## 10.1 Introduction

The conceptual design of the canister focuses principally on meeting the requirements that are associated with its structural performance and integrity. These aspects are addressed in this section of the report. The work within this section aims to demonstrate that the conceptual design would be likely to be capable of meeting the requirements in Box 10.1.

**Box 10.1 Requirements relating to structural performance**

RQ5 Structural integrity – handling incidents pre-emplacement.

RQ7 Structural integrity – retrieval.

RQ8 Structural integrity – long term.

RQ9 Structural integrity – safety margin.

RQ12 Critical flaw size.

RQ25 Retrievability.

RQ29 Codes and standards.

## 10.2 Design by analysis

The assessment of design using design-by-analysis is contained in Annex B of EN 13445-3 (BSI 2009d). This provides acceptance criteria for different limit states based on the results of an elastic-plastic finite element analysis of the structure subject to the relevant loadings and yield conditions containing partial safety factors and safety margins. The advantage of the design-by-analysis approach is that it covers geometric and loadings configurations for which there are no design formulae, such as the circumferentially distributed pressure that applies on the canister.

Annex B contains provisions for the limit states that are relevant to the canister:

- Ductile collapse (unstable gross plastic yielding).
- Excessive local plastic strain (ductility exhaustion).
- Fracture (brittle/ductile).
- Instability (buckling).

In its acceptance criteria, EN 13445-3 (BSI 2009d) makes a distinction between normal and design loads and exceptional loads with regard to the safety factor. Normal and design loads are reasonably foreseeable extreme values and include permanent actions (e.g. self-weight, sustained geological conditions, subsidence), applied pressure and loads as a result of temperature differences and gradients. Exceptional actions are not considered to occur under reasonably foreseeable circumstances, such as extreme earthquake or ground movement, and can have a reduced factor of safety for acceptability compared with normal and design loads. Such conditions should be considered in future studies.

Analyses consider the early and long-term pressure (Figure 10.1) as design loads, although it should be noted that the time frame of evolution of pressure is difficult to estimate. Thus analyses are performed for 4 MPa (short-term) and 29 MPa (horizontal) and 22 MPa (vertical) in the long-term, with the latter anisotropic case being considered the extreme bounding case (see Section 3.4). In this latter case 20 mm thickness of the 140 mm design wall thickness are removed to represent the corrosion loss over 10'000 years. The SF canister modelled in the FE analyses assumes a wall thickness of 140 mm. It is worth mentioning that a design wall thickness of 120 mm for the SF canister was also modelled, but because the results suggested a low safety margin this case was not considered any further. Also, having a wall thickness of 140 mm fulfils the necessary requirements for the inner lid attachment structure.

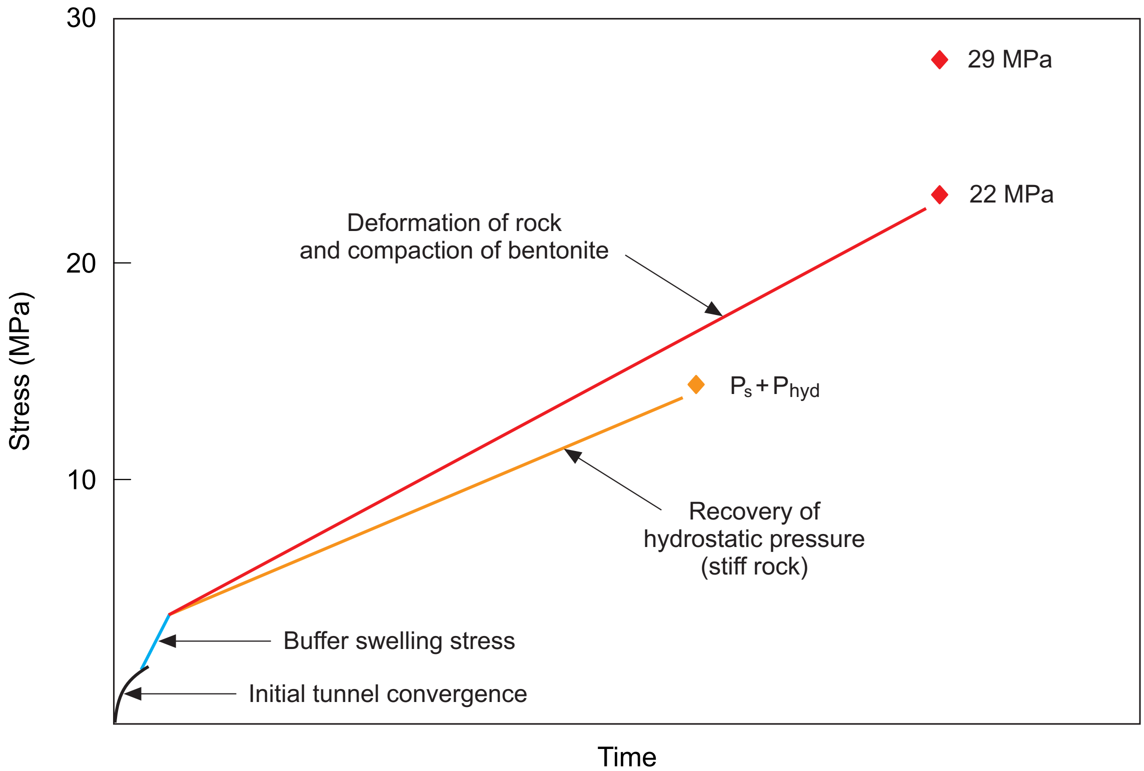



Fig. 10.1: Possible evolution of stresses experienced by a canister inside a bentonite barrier in a repository in Opalinus Clay at 900 m.

The two stress evolution paths represent two alternative possibilities, depending on the mechanical properties of the rock. The maximum conceivable stress at 900 m is 29 MPa horizontal and 22 MPa vertical.

The elastic-plastic finite element analysis should be based on a linear elastic perfectly plastic material property law. The law is based on the specified Young's modulus and minimum yield strength for the parent or weld metal factored down by a partial safety factor of 1.2. Either a Tresca or Von Mises yield condition may be applied, but if Von Mises is used the yield strength is multiplied by a factor of √3/2 (0.866). (Note, the Von Mises criterion is a yield criterion that combines the 3 principal stresses into an equivalent stress, which is then compared to the yield stress of the material to assess whether yielding has occurred).

The acceptance criteria for gross plastic deformation uses the finite element analysis to determine the loading at the lower bound limit state where the analysis becomes unstable. The acceptance criteria are that design loadings must not exceed the loading at the lower bound limit state, subject to the maximum absolute value of plastic strain anywhere in the structure being less than 5 %.

An elastic plastic finite element stress analysis of the canister and determination of the plastic limit load and the comparison of the FEA results against its acceptance criteria in relation to design basis loading are described in the sections below.

## 10.3 Stress analysis of SF canister designs in repository (in-situ)

### 10.3.1 Trial canister designs and dimensions

Three trial designs were investigated, all based on the BWR SF canister dimensions. The first design (Design 1) shows the initial concept where a shoulder is machined into the internal wall of the body of canister to support and screw down the inner lid. This has the effect of locally reducing the wall thickness and creating a groove below the closure weld.

In the second design (Design 2), lifting features were added to the closure lid at each end of the canister. The shoulder in the wall incorporated in Design 1 was removed in order to estimate the effect of the groove on the stress and strain fields in this region. The third design (Design 3) also has the shoulder removed and does not have lifting features. Design 3 was chosen to compare the results from the two earlier designs with the results obtained from a more basic geometry.

For each of the models analysed, the body and closure lids of the canister were modelled as one part only, assuming that the stress transfer from the lid to the body would be perfect. A number of different lid thicknesses were modelled with each basic design. The internal lid and waste were not included to the models. The geometries of the three designs are shown in Figures 10.2, 10.3 and 10.4. Appendix G shows drawings (including dimensions) of Design 1 and Design 2 that were used to generate the FE models. Design 3 is the same as Design 1, but without the notch.

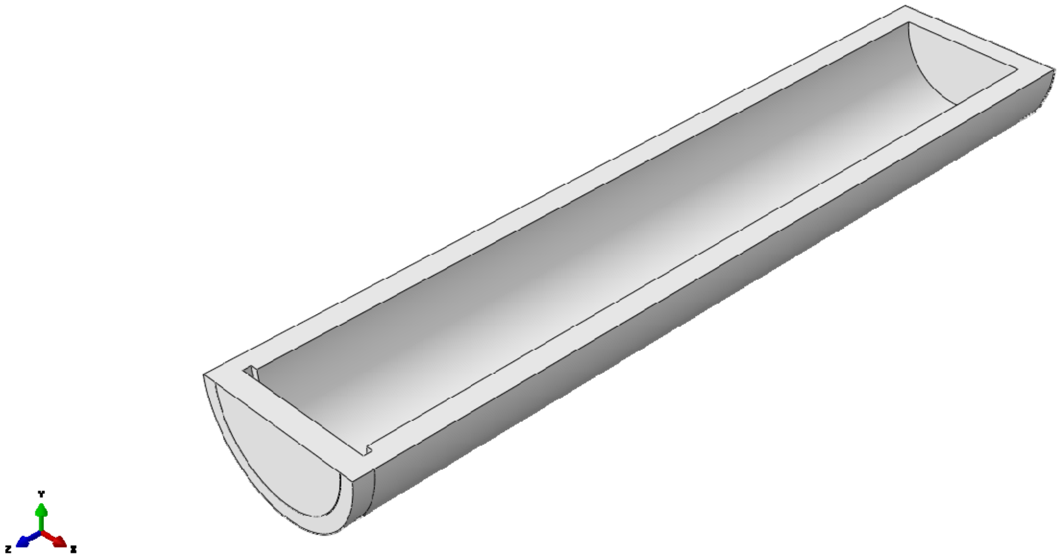


Fig. 10.2: SF canister geometry for Design 1 with a wall thickness of 140 mm and a lid thickness of 140 mm showing the shoulder in the wall below the closure lid.

### 10.3.2 Effect of corrosion on wall thickness

Each of the initial canister geometries listed above were also analysed assuming that the outer surface had been eroded by corrosion. For this purpose, 20 or 40 mm of the original 140 mm thickness was removed from the outer surface of the canister. Figure 10.3 shows the effect of thickness reduction on the Design 2 geometry.

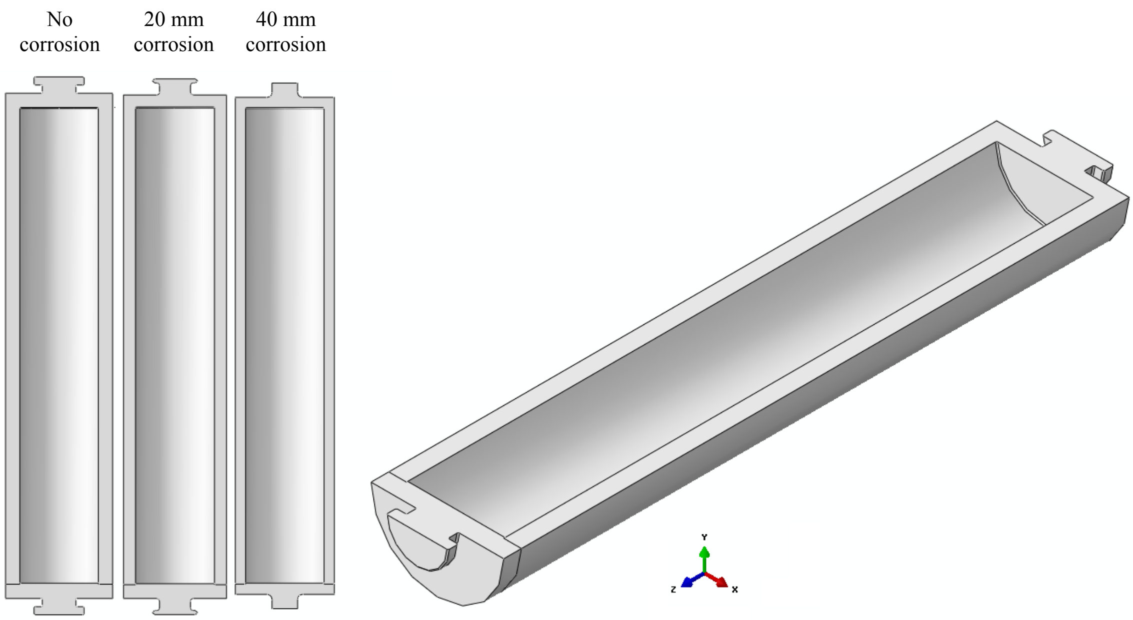



Fig. 10.3: SF canister geometry for Design 2 with an initial wall thickness of 140 mm and a lid thickness of 150 mm.

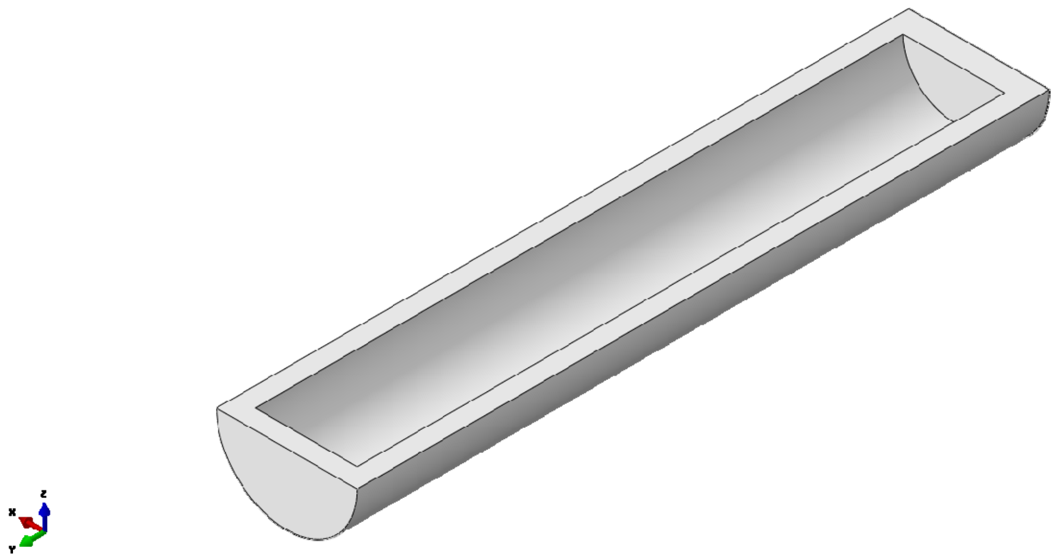



Fig. 10.4: SF canister geometry for Design 3 with a wall thickness of 140 mm and lid thickness of 180 mm.

### 10.3.3 Material properties

The forging grade steel modelled in the finite element analyses is BS EN 10222 P245GH (BSI 2000b). The data used for modelling this material are the minimum specified data from the standard. These data are reported in Table 10.1.

Tab. 10.1: Elastic and perfectly plastic material data for short term analyses at 150ºC and long term analyses at room temperature (RT).

| E [MPa] | Poisson's ratio | $\sigma_y$ at RT [MPa] | $\sigma_y$ at 150ºC [MPa] |
|---|---|---|---|
| 207'000 | 0.3 | 220 | 175 |

For each design and condition (short term or long term), two different analyses were performed: an elastic analysis to obtain the stress distribution in service condition, and an elastic-plastic analysis to determine what would be the limit load before plastic yielding becomes too significant. In this case, the behaviour was assumed to be elastic-perfectly plastic. Assuming an elastic-perfectly plastic behaviour will produce a conservative estimate of the collapse load, since in reality the material will work harden and be resistant to a greater load.

### 10.3.4 Stress analysis results for time, pressure and temperature conditions analysed

#### (a) Short term

The short term conditions were chosen to be those experienced early in life when the canister reaches its maximum predicted temperature. This maximum temperature is predicted to be 130 – 140°C and to be reached at approximately 10 years after emplacement.

The loading is assumed to be buffer swelling pressure of 4 MPa applied uniformly on all the external surfaces of the canister. This value was applied for the elastic analysis of the short term conditions. The pressure at which the plastic limit load is reached at this temperature was determined using an elastic-plastic analysis from which a safety factor was derived.

**(b) Long term**

These analyses assume conditions that would be valid when the canister has been in the repository for 1'000 years or longer. After 10'000 years, the temperature of the canister is expected to drop to a value of ~ 45°C. In these analyses room temperature material data were used, which would have the effect of making the limit load calculations slightly non-conservative, because of the slightly lower yield strength at 45°C.

In the long term, displacement of rocks and compaction of clay may lead to much higher pressure being applied to the outer faces of the canisters. In the elastic analysis performed to predict the stress long term in service, the pressure applied to the cylindrical surface of the canister was taken to follow a sine function around the circumference from 22 MPa in the vertical plane to 29 MPa in the horizontal plane as shown in Figure 10.5. The pressure on the ends was taken to be 22 MPa. For estimating the limit load, elastic-perfectly plastic analyses were performed where these pressures were increased proportionally.

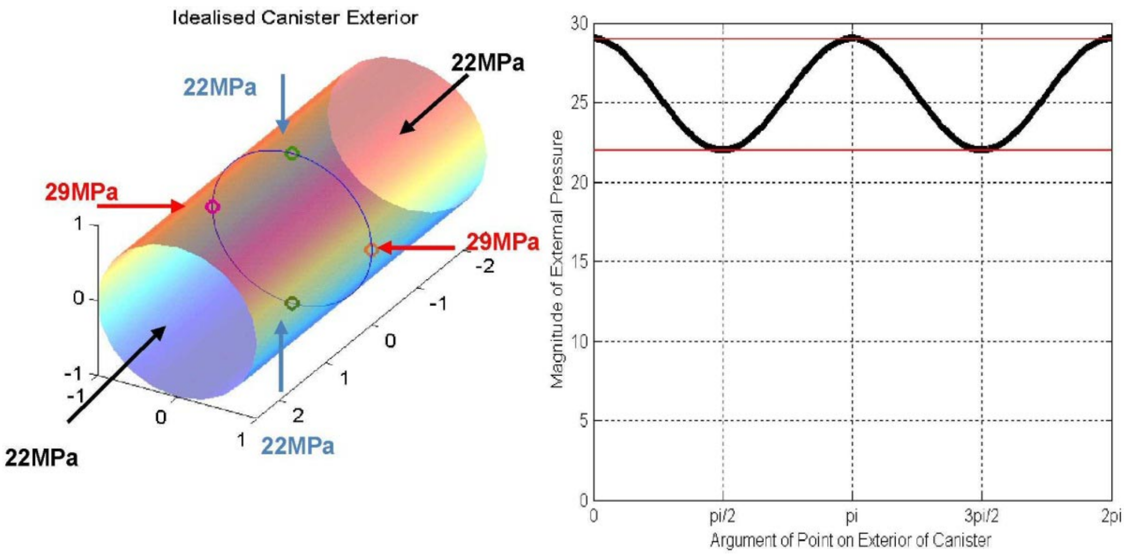



Fig. 10.5: External pressure distribution for in-situ long term conditions.

In order to analyse the effect of more realistic pressure distribution than that above, another case was analysed where the pressure is isotropic and equal to 22 MPa.

### 10.3.5 Model constraints

For both the short and long term stress analysis conditions, the models were constrained to avoid rigid body displacement.

### 10.3.6 Results

#### (a) Short term conditions

Figures 10.6 and 10.7 show the Von Mises stress contour plots for Design 1 and Design 2 in short term conditions. These figures show that the predicted Von Mises stress values are low in general and do not exceed 35 MPa in the case of Design 1 with the 140 mm thick lid. However, the stress rises in the internal groove of Design 1, and at the internal edge between the lid and the body in Design 2. This stress rise is due to the geometrical singularity, but also to the reduction of cross section area caused by the groove in the case of Design 1.

Note that the maximum predicted stress values are higher for Design 2 (135 MPa) than for Design 1 (105 MPa), but these values cannot be strictly compared because results at singularities obtained from elastic analyses are very dependent on the mesh refinement. Figures 10.8, 10.9 and 10.10 show the Von Mises stress distribution along the external face of the canister, the internal face, and through the lid thickness. The results demonstrate that in the short term the stresses are not critical in any of the 3 designs analysed.

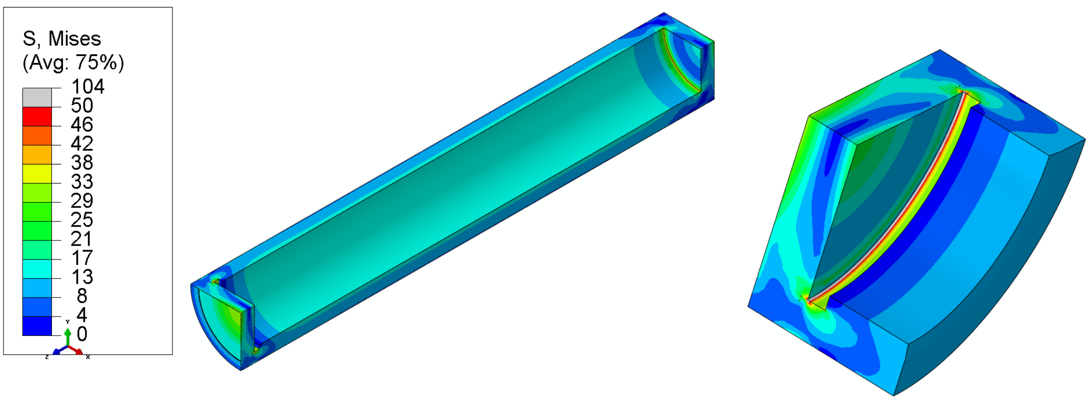



Fig. 10.6: Von Mises stress predicted in SF Design 1 for in-situ short term conditions.

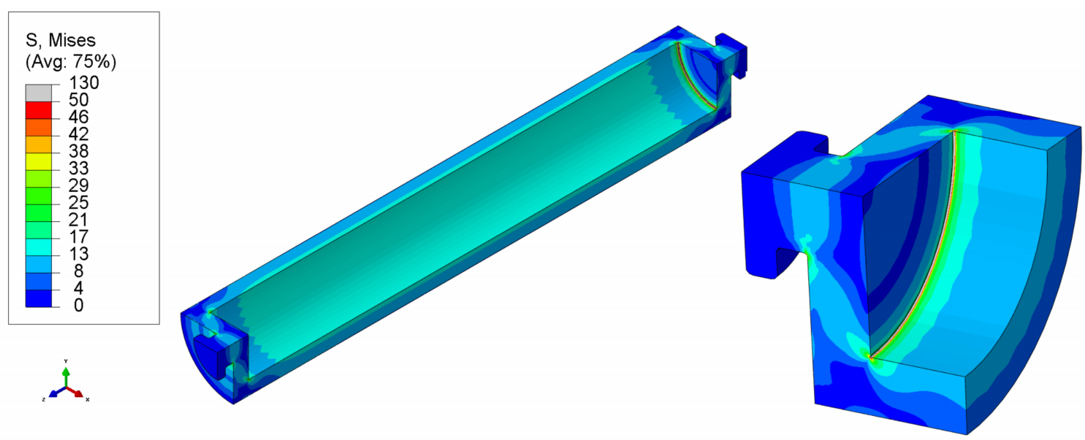
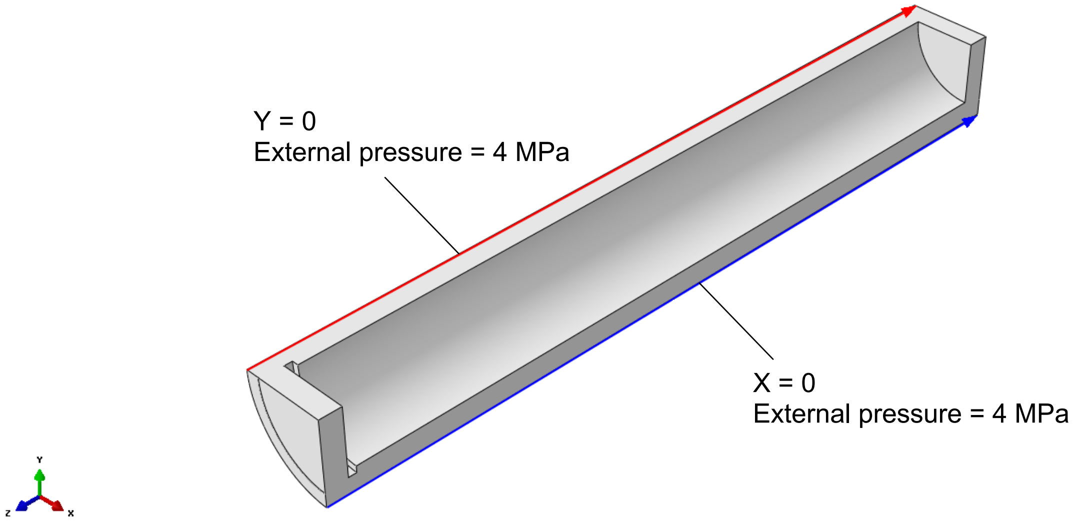



Fig. 10.7: Von Mises stress predicted in SF Design 2 for in-situ short term conditions.



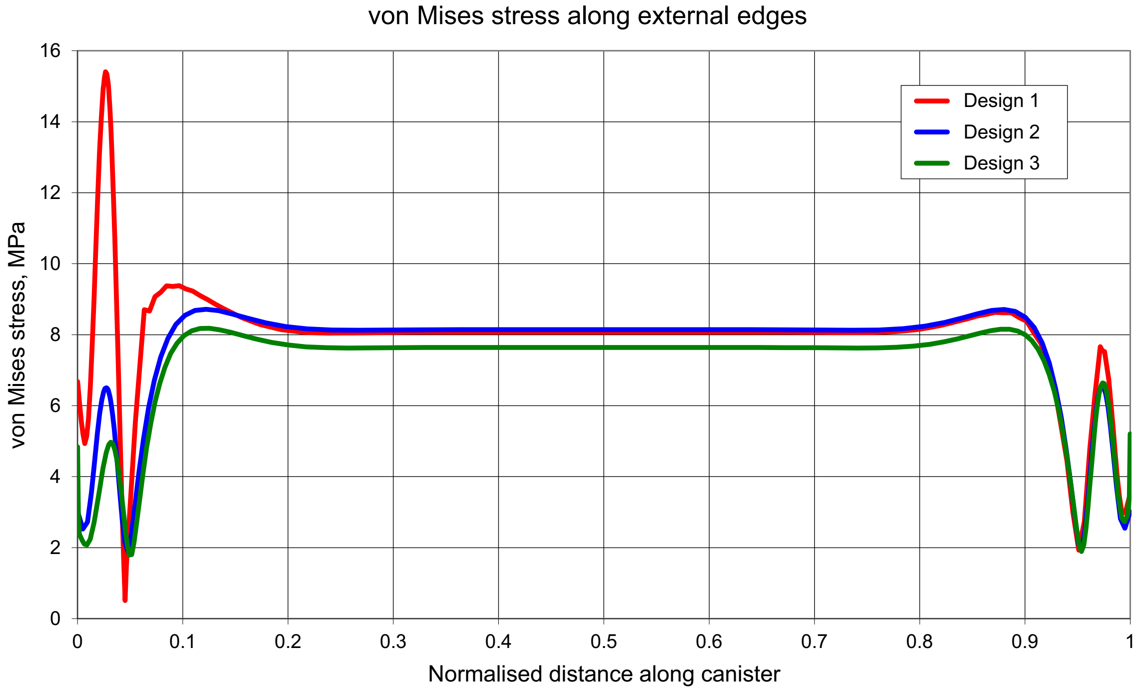
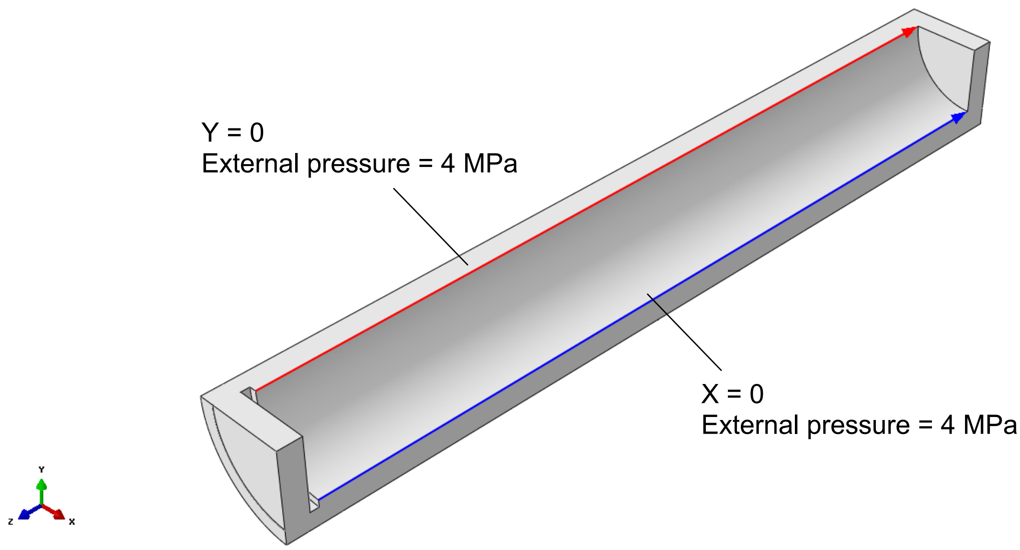




Fig. 10.8: Von Mises stress along the external edges predicted from analyses of Designs 1, 2, and 3, using in-situ short term conditions.



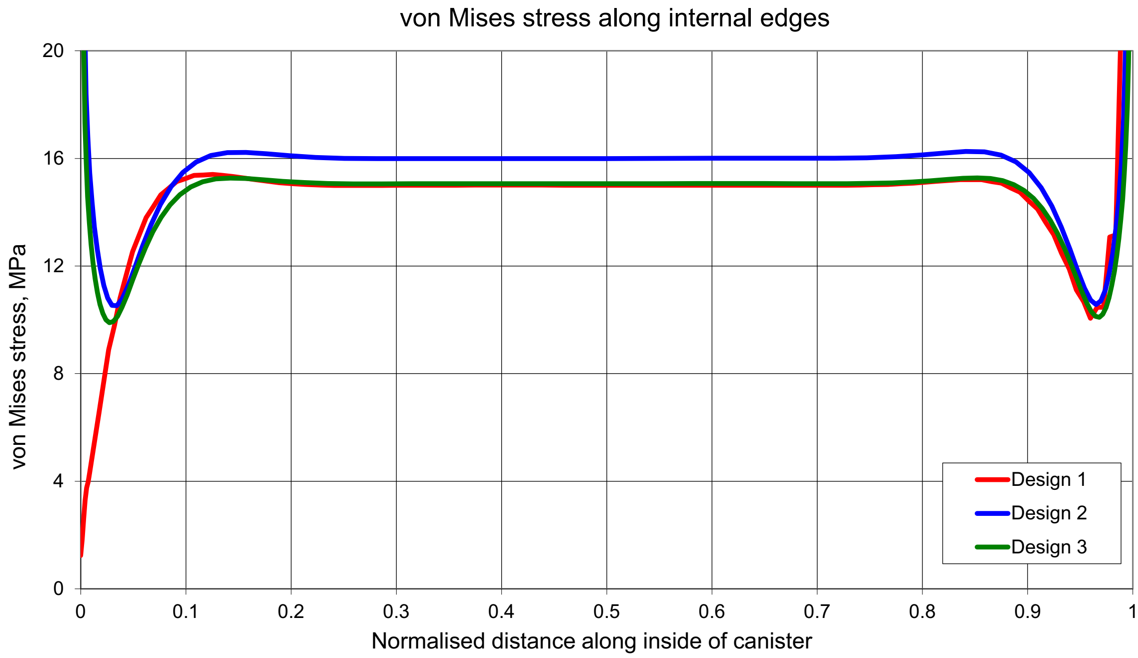
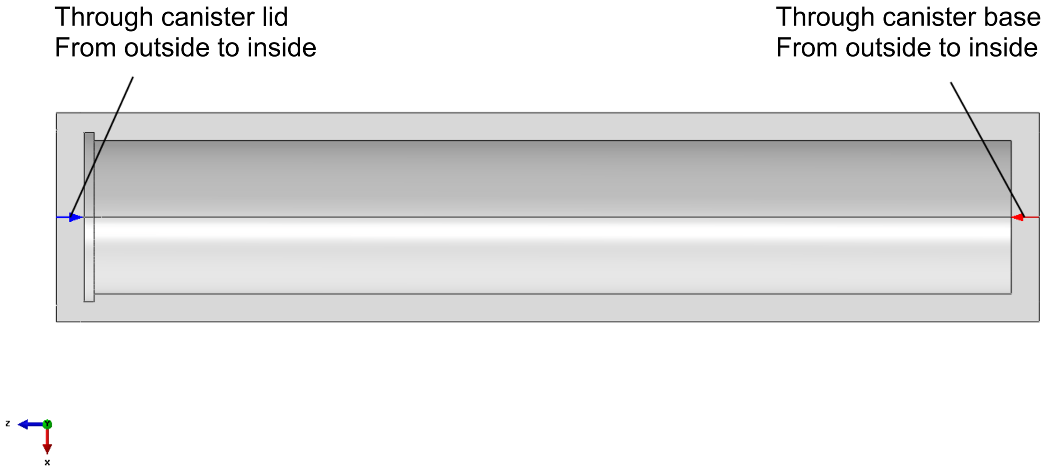




Fig. 10.9: Von Mises stress along the internal edges predicted from analyses of Designs 1, 2, and 3, using in-situ short term conditions.



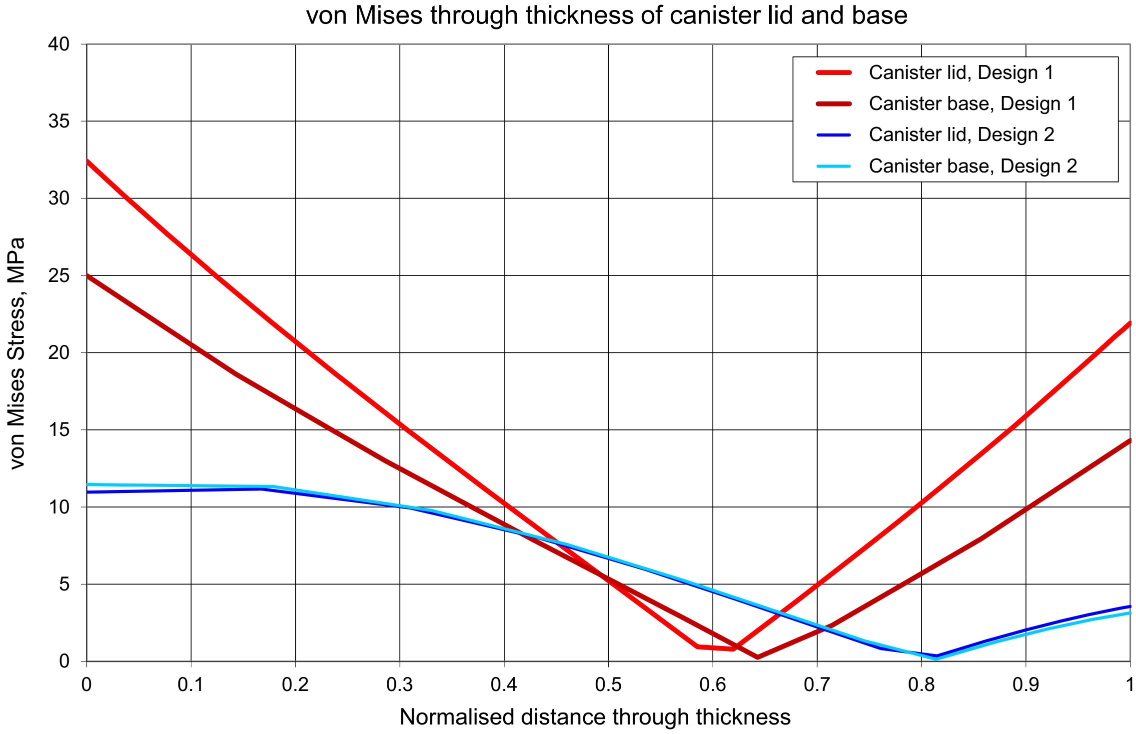




Fig. 10.10: Von Mises stress across the lid thickness predicted from analyses of Designs 1, 2, and 3, using in-situ short term conditions.

**(b) Long term conditions with anisotropic pressure (22 MPa/29 MPa)**

Figures 10.11 and 10.12 show the Von Mises stress contour plots obtained for Design 1 and Design 2 assuming the long term conditions. The Von Mises stresses produced under long term loading conditions are significantly higher than those under short term conditions. This is due to the larger external pressure applied, and also the reduced thickness of the canister due to corrosion in the long term condition.

Figures 10.13, 10.14 and 10.15 show the Von Mises stress profiles along the external faces, internal faces, and through the lid thickness. The Von Mises stress exceeds the yield stress in significantly large regions of the designs. The long term condition may therefore be close to the plastic limit load of the structure.

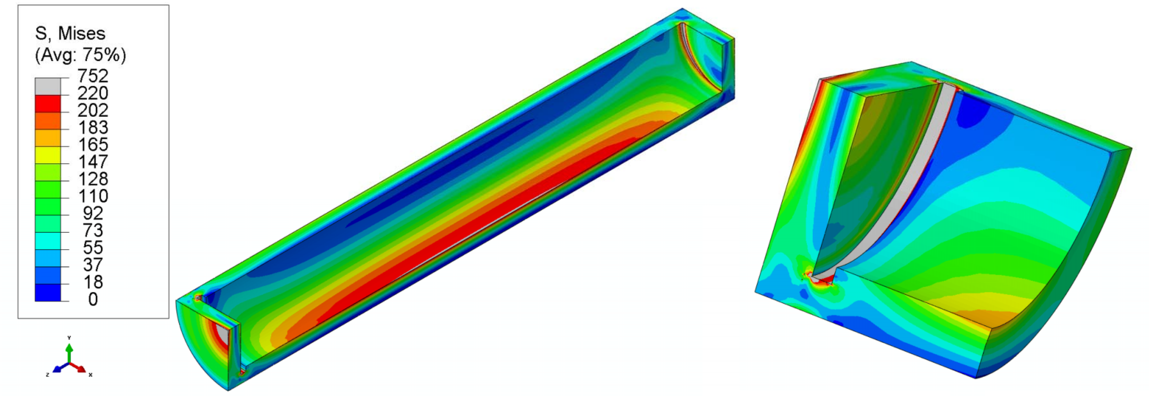



Fig. 10.11: Von Mises stress predicted in SF Design 1 for in-situ long term conditions.
Stress contour shown on undeformed configuration.

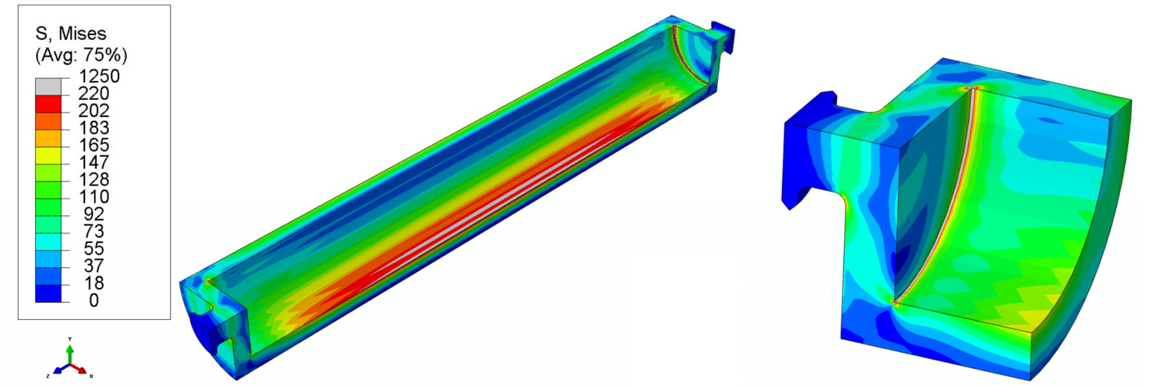



Fig. 10.12: Von Mises stress predicted in SF Design 2 for in-situ long term conditions.
Stress contour shown on undeformed configuration.

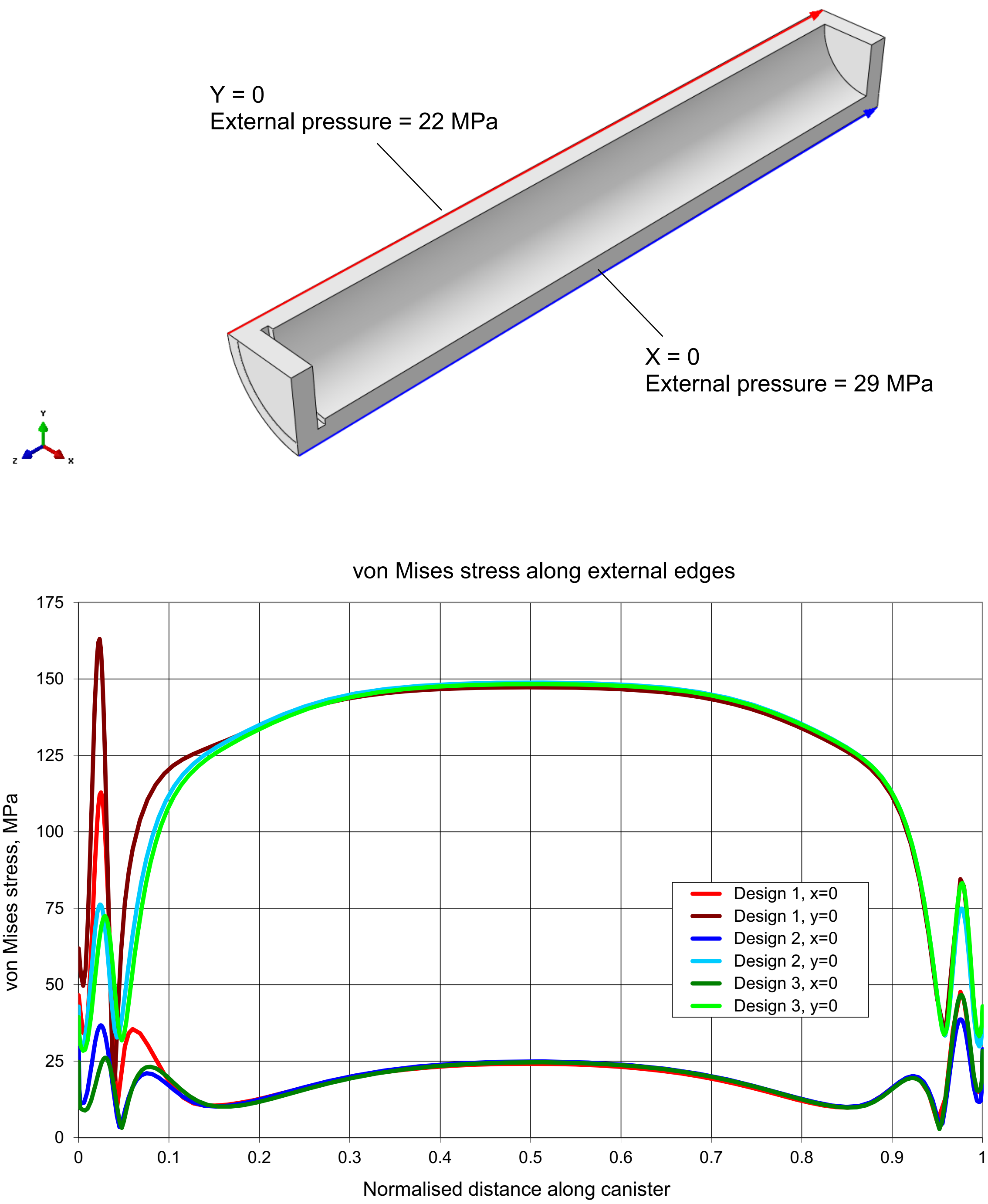
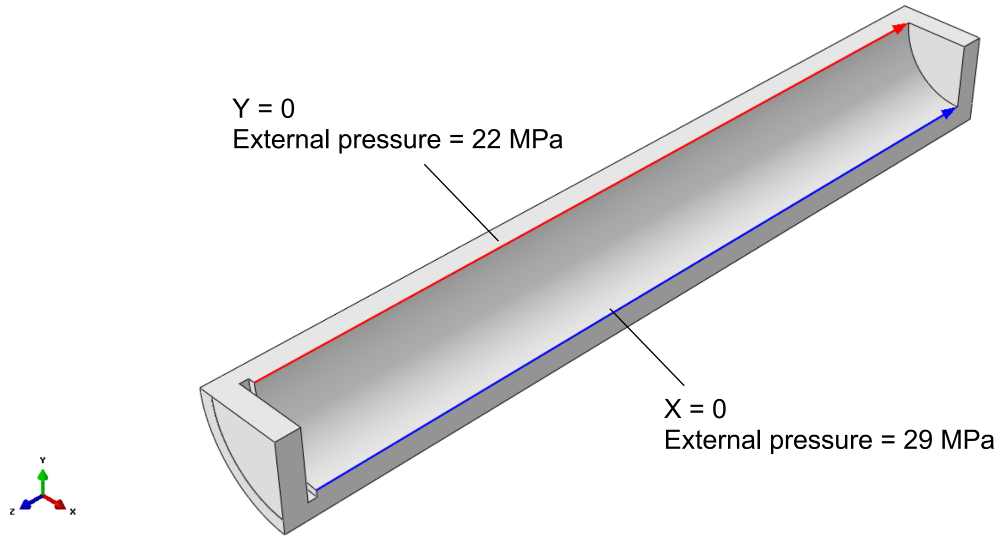



Fig. 10.13: Von Mises stress along the external edges predicted from analyses of Design 1, 2, and 3, using long term in-situ conditions.



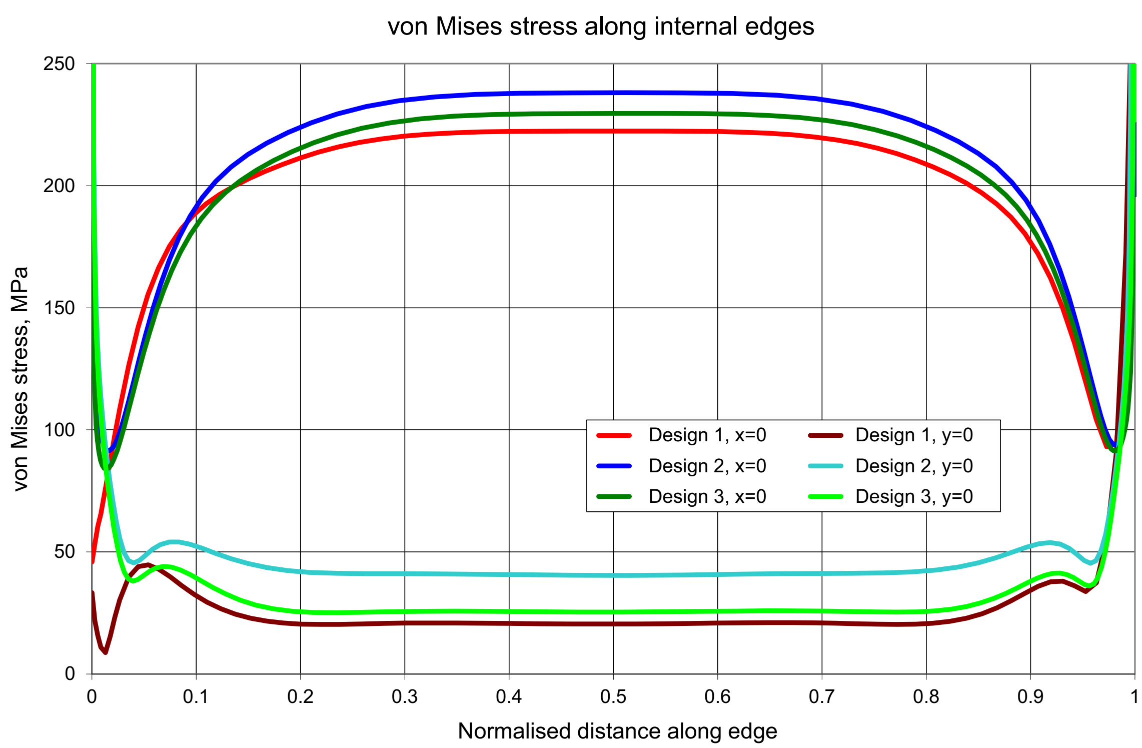
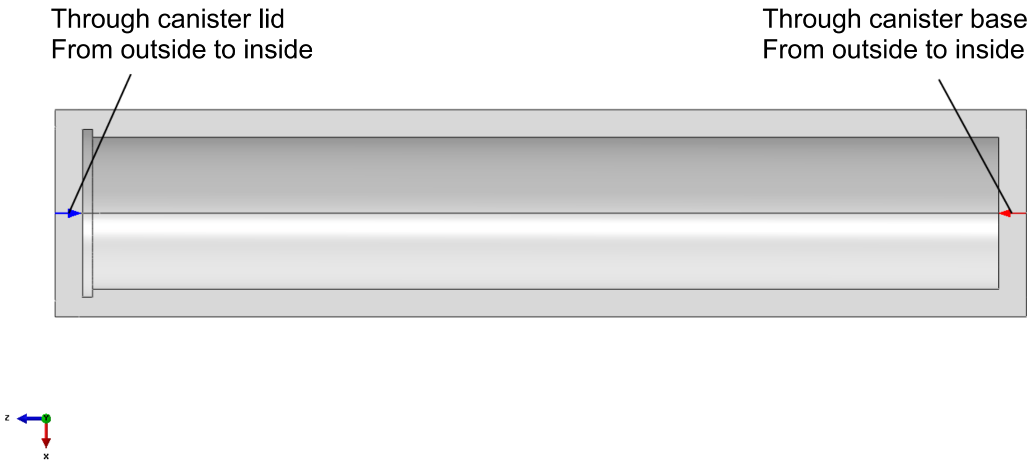




Fig. 10.14: Von Mises stress along the internal edges predicted from analyses of Designs 1, 2, and 3, using in-situ long term conditions.



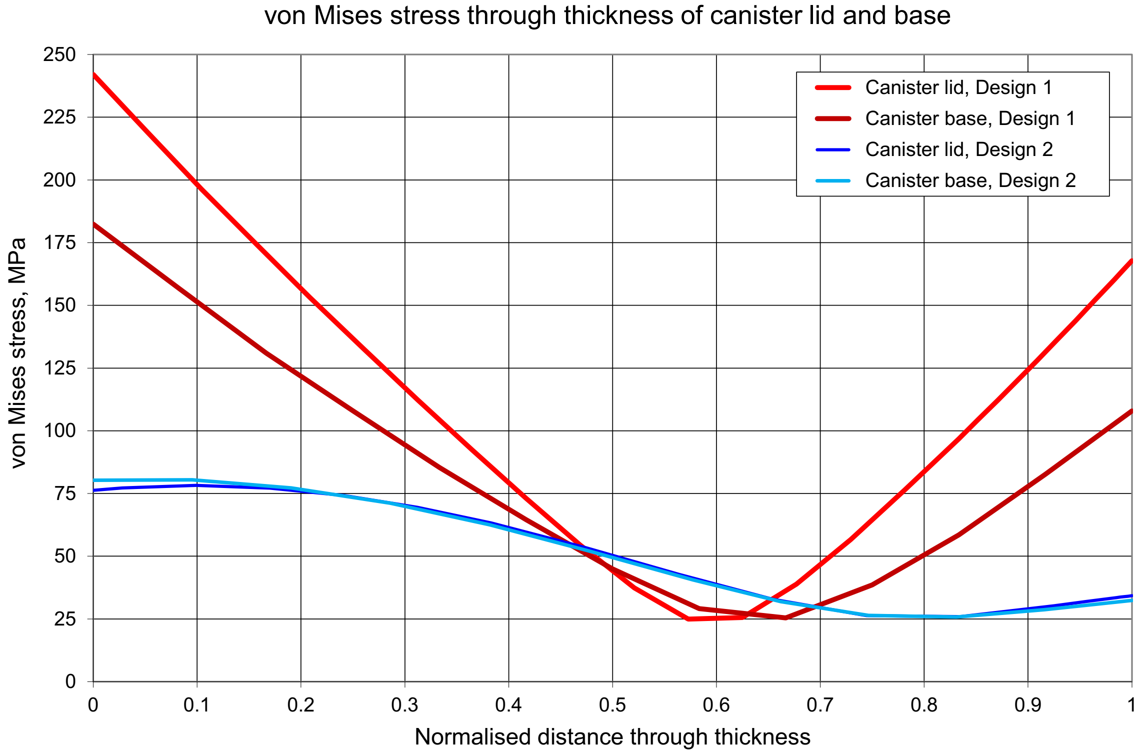




Fig. 10.15: Von Mises stress across the lid thickness predicted from analyses of Designs 1 and 2, using in-situ long term conditions.

### (c) Long term conditions with isotropic pressure (22 MPa)

The result from the long term in-situ analysis, where the pressure is hydrostatic and equal to 22 MPa is shown in Figure 10.16. The graph shows that the Von Mises stress is significantly lower than predicted in the case of anisotropic pressure (Figures 10.13 and 10.14).

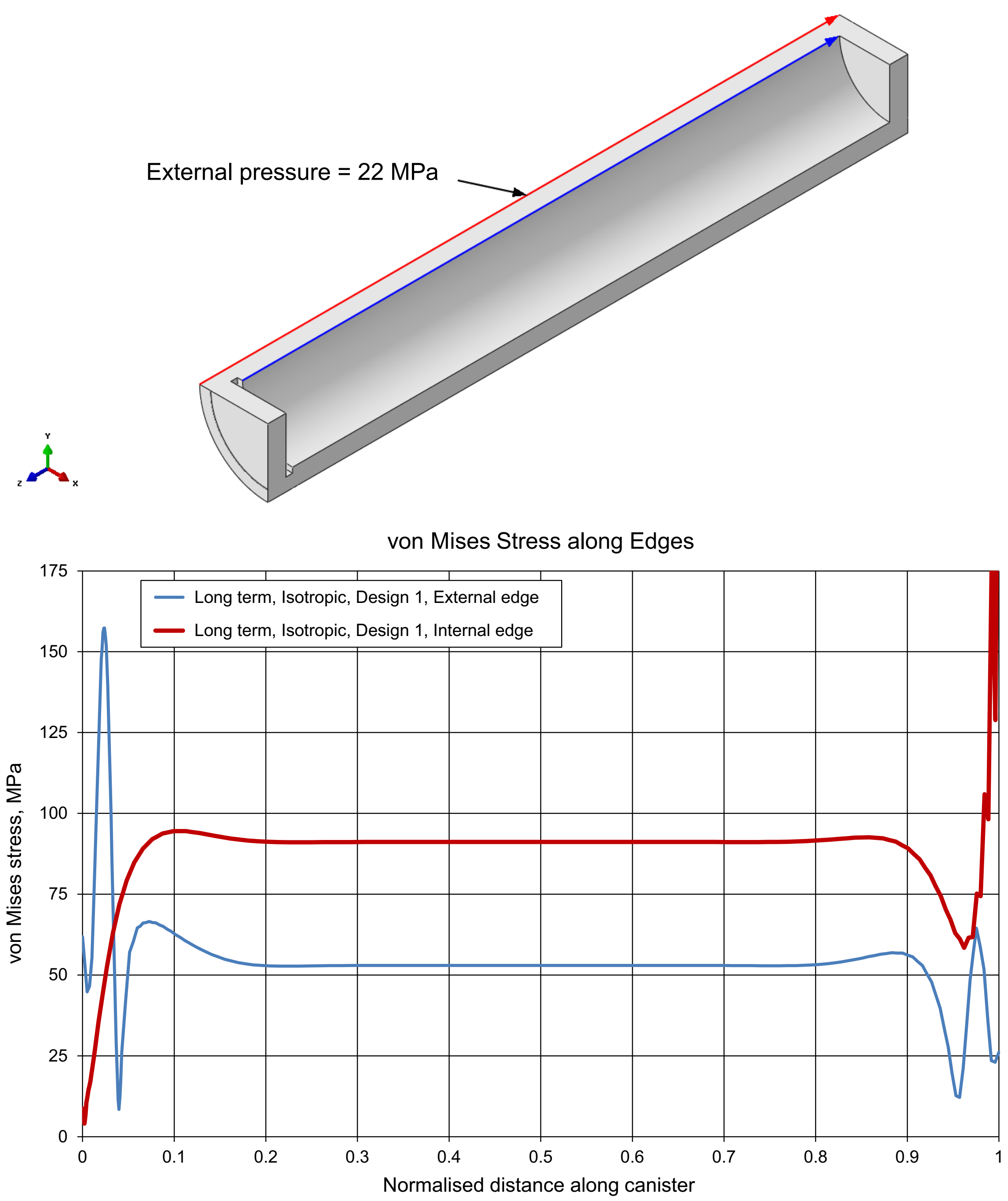



Fig. 10.16: Von Mises stress profile along the internal and external edges.

The results shown in this section regard mainly the equivalent plastic strain. This is because this parameter is used for determination of the limit load. The canister is considered to be in a high risk of failing when either plastic yielding occurs through the entire cross section of the wall or lid thickness, or when the plastic strain reaches a value equal to 5 % at any point of the canister. Some deformation (local yielding) of the canister is considered to be acceptable as long as it does not extend through the wall thickness and that the plastic strain remains below 5 %. Figure 10.17, obtained at collapse when isotropic pressure is applied, shows that the local plastic strain in Design 1 is very close to 5 % when the ligament between the groove and the external surface is beyond yield.

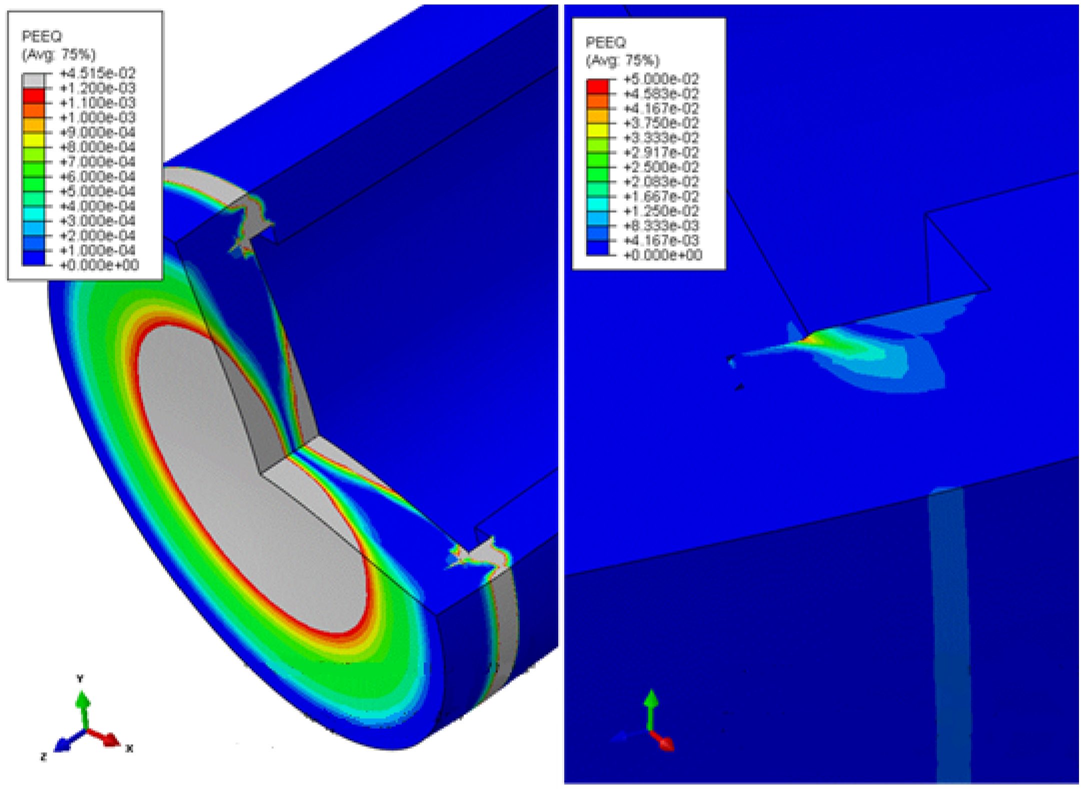



Fig. 10.17: View of the plastic strain in Design 1 at collapse load.

Yielding in the ligament occurs at a load when 5 % plastic strain is nearly reached (EN 13445-3 (BSI 2009d) criterion for collapse).

### 10.3-7 Discussion of limit loads and comparison of the designs and loading cases

Limit loads were determined from combinations of design, lid thickness, loading and corrosion analysed and given in Table 10.2 as a scale factor on the design basis load.

Tab. 10.2: Limit loads as a scale factor on the design basis load.

| Design | Original Lid Thickness [mm] | Design basis load, (horizontal: vertical) [MPa] | Corrosion [mm] | Limit Load Scale Factor |
|---|---|---|---|---|
| 1 | 140 | 4:4 | 0 | 10.1 |
| 1 | 140 | 22:22 | 20 | 1.5 |
| 1 | 140 | 29:22 | 20 | 1.4 |
| 1 | 180 | 29:22 | 20 | 1.7 |
| 2 | 150 | 4:4 | 0 | 12.2 |
| 2 | 150 | 29:22 | 20 | 1.8 |
| 2 | 150 | 29:22 | 40 | 1.5 |
| 3 | 180 | 4:4 | 0 | 14.0 |
| 3 | 180 | 29:22 | 20 | 1.8 |

It can be seen that the limit load scale factor exceeds 1.4 in all cases. It should be noted that this analysis was based on a yield strength of 220 MPa. A limit load analysis according to BN13445-3 (BSI 2009d) Appendix B using von Mises strain should be based on a factored lower value of yield strength (see Section 10.2). of $\sigma_y' = \frac{\sigma_y}{1.2} \times 0.866 = 0.721\,\sigma_y = \sigma_y/1.4$. However, the current results suggest that the basic design thickness should be satisfactory.

In all cases the limit load is determined by the plastic hinge formed at the canister body/closure lid intersection. For the 29/22 MPa loading with 20 mm corrosion, the results for Design 1 show that thickening the closure lid from 140 mm to 180 mm results in a significant improvement in limit load scale factor from 1.4 to 1.7 as bending at the intersection is restricted. Removal of the shoulder and groove and the addition of a lifting feature with a small increase in lid thickness in Design 2 also results in a significant improvement of limit load scale factor from 1.4 to 1.8.

The results for Design 3 compared with Design 1 show that when the lid thickness is 180 mm, the removal of the shoulder and groove has a minimal effect (1.7 to 1.8). In Design 2, increasing corrosion from 20 mm to 40 mm reduces the scale factor from 1.8 to 1.5. Comparing Designs 2 and 3, the lifting feature in the centre of the lid appears to have the same effect as an increase in general lid thickness of 30 mm.

Thus from these results it can be seen that removal of the shoulder and groove and inclusion of a lifting feature are both beneficial. If these measures are adopted there is no advantage in increasing the lid thickness above 150 mm. More detailed design improvements in areas of stress concentration may be required.

## 10.4 Fracture mechanics assessment of SF canister design in repository (in situ)

Within this section, fracture mechanics, employing a standard Engineering Critical Assessment (ECA) approach, is used to determine the critical heights of welding and other flaws postulated at various locations in the canister. Any flaws present greater than this size would create an unacceptable risk of a propagating fracture during life. The critical flaw heights provide a means for determining the performance required of non-destructive testing to detect a level of smaller flaws that can be qualified with high confidence. They are also for evaluating whether any flaws detected are allowable or should be repaired.

As the level of welding residual stress that remains in the canister is an important input to the calculation of critical flaw heights, the ECA is a means to determine whether or not welding residual stresses need to be reduced by post weld heat treatment (PWHT) in order that demands on the NDT and the number of repairs required are not too great.

The work presented within this section uses the ECA approach to address this problem. The level and pattern of residual stress from NG-GTAW and EB welding process are different, but for the purpose of this scoping assessment, the residual stress is conservatively assumed to be of a constant value through the wall-thickness.

The work presented within this section considers the SF disposal canister, as an example case, in the worst case long term conditions of 29/22 MPa orthogonal external pressure. The effect of residual stress and fracture toughness on flaw tolerance is examined and critical flaw heights are evaluated for different values of residual stress and fracture toughness. Since the external pressures acting on the canister in the short term are lower (of the order of magnitude of 4 MPa), the short term condition is not discussed further.

### 10.4.1 ECA methodology

The methodology to evaluate the critical flaw sizes for avoidance of fracture of the SF disposal canister uses a combination of finite element stress analyses (FEA) and the BS 7910 flaw analysis procedure. The equations of BS 7910 are codified in the TWI commercial software package, CRACKWISE®, which is used to perform ECA calculations. Stresses determined from FEA, for the long term in-situ conditions, are input into CRACKWISE®. The ECA calculations enable critical flaw heights to be evaluated for different levels of residual stress and in-service fracture toughness.

When flaws are detected during inspections, a safety factor is normally applied to the calculated critical flaw heights to derive a maximum height of flaw that is deemed allowable to remain in the component without repair. For example, the RWMC canister design work proposes a safety factor of 10 on critical flaw height based on a criterion within the ASME XI and Japanese codes for in-service inspection of nuclear power plant. (For example if a critical flaw height of 50mm is evaluated at the location being considered, then the allowable flaw height is 5mm).

The safety factor of 10 within the ASME XI code (ASME 2010c) is between the critical flaw size calculated from the stresses and temperatures under normal operating conditions and accommodating future flaw growth and the size of a flaw detected by in-service inspection that is allowed to remain without repair. The safety factor for the sentencing of detected flaws is primarily intended to provide a margin on the load (stress) to increase before a propagating fracture could occur and is in line with prevention of other failure modes.

It should be noted that these safety factors set a sentencing criterion for the repair or toleration of a real flaw detected by inspection. They do not set a size by which the capability of the inspection is to be determined or judged. This capability is characterised by another size of defect for which the inspection is qualified to detect with high confidence.

The factor by which the critical flaw sizes are reduced to set the minimum flaw sizes that the manufacturing inspections of the canisters must be qualified to detect with high confidence has yet to be established. The qualification size factor utilised should be dependent on the amount and likelihood by which the maximum load predicted on the canister during life might be exceeded and the likelihood of any crack growth during life. The expected welding quality, types of credible postulated defects, and the reliability of detection and sizing flaws also need to be taken into account.

There are grounds for considering that an inspection qualification size factor of 2 may be appropriate. This would generally be consistent with the practice for the manufacture of the primary components for the Sizewell B PWR (Edmondson 1984). Below this inspection qualification size, a further size of defect, which is within the inspection's capability to detect, is defined at each location for reporting, and also a flaw size which would be considered tolerable without repair.

Any limit imposed on the residual stress in order to achieve a reasonable critical flaw size may require post weld heat treatment (PWHT) of the canister. There is a restriction on PWHT temperature in relation to not over-heating the SF or HLW in the canister, and other advantages not to PWHT, so it is preferable not to perform the PWHT. Requirement 15 states that any application of heat treatment for the benefit of the weldment must not compromise the canister contents; the spent fuel must be kept below 400°C.

### 10.4.2 Geometry and location of flaw

For the ECA calculations, the SF canister without a lifting ring is considered with an external semi-elliptical flaw through Section A-A, as shown in Figure 10.18. Allowing for 20 mm of uniform corrosion when the long term condition is reached, the wall thicknesses of the lid and cylindrical body are 160 and 120 mm, respectively.

When analysing the susceptibility to fracture, it is common practice within the nuclear industry to assume a quarter wall thickness reference flaw. Therefore, a flaw size of 30 mm (i.e. 120 mm/4) was postulated. An external semi-elliptical flaw through Section A-A was chosen since this is an area of high stress and hence considered to be a limiting location.

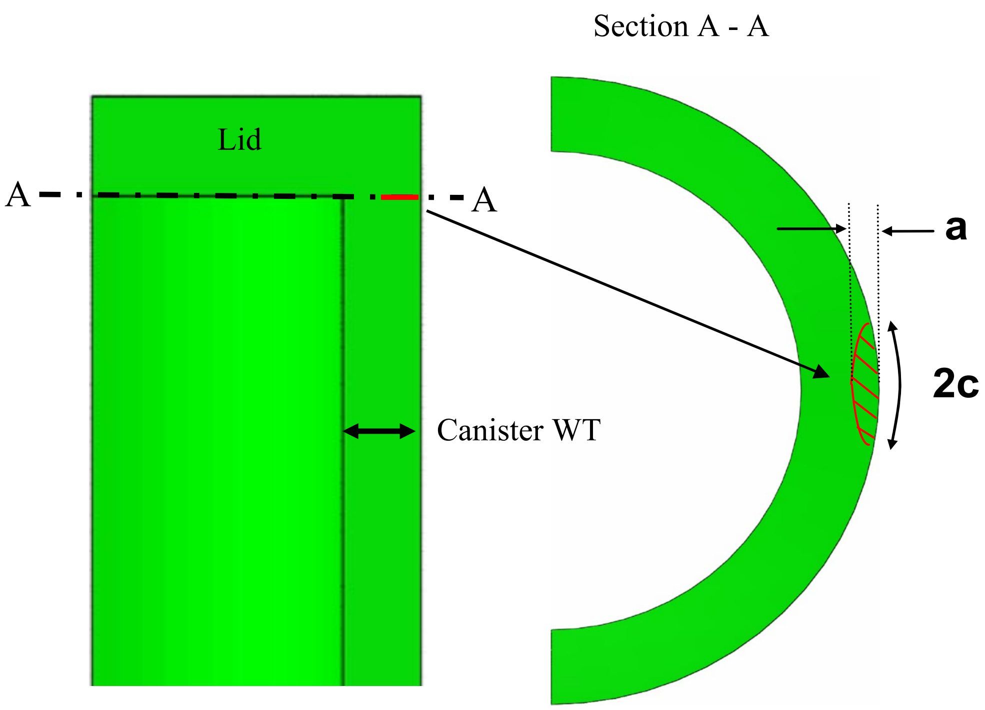



Fig. 10.18: Geometry and location of semi-elliptical flaw in SF disposal canister without lifting feature, assuming 2 c/a = 6.

Canister WT = 120 mm, Lid WT = 160 mm. 20 mm of corrosion is assumed.

Within CRACKWISE® the SF canister was idealised as an open ended cylinder with an external semi-elliptical flaw as shown in Figure 10.19.

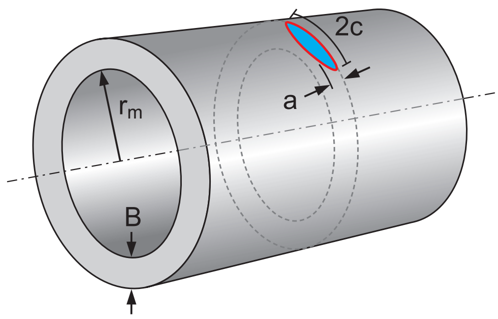



Fig. 10.19: Idealised SF canister with external semi-elliptical flaw within CRACKWISE ®.

### 10.4.3 Loading conditions

The worst case loading is considered to be compressive horizontal and vertical stresses of 29 and 22 MPa acting on the canister in the long term condition (10'000 years) when the canister surface temperature is predicted to be 45°C (Landolt et al. 2009). The yield stress at this temperature would be 220 MPa assuming best estimate material properties. The residual stress would be 220 MPa assuming the residual stress is of yield magnitude. There will be some relaxation of residual stresses during service due to the time at elevated temperature, but the extent of this is difficult to quantify without carrying out numerous simulations and associated validation. However, the sensitivity of the critical flaw height to different levels of residual stress and fracture toughness has been assessed.

Figure 10.20 shows the axial stress through the canister wall calculated using FEA along four paths, A, B, C and D. Because the weld (and hence postulated flaw) is likely to be located along path A, this stress plot was used as the input to CRACKWISE®. The stress along path A was conservatively idealised to be 46 MPa uniform across the wall thickness. This approach is often adopted to obtain an initial assessment of the critical flaw size. If a more accurate assessment is required, the actual stress profile is used.

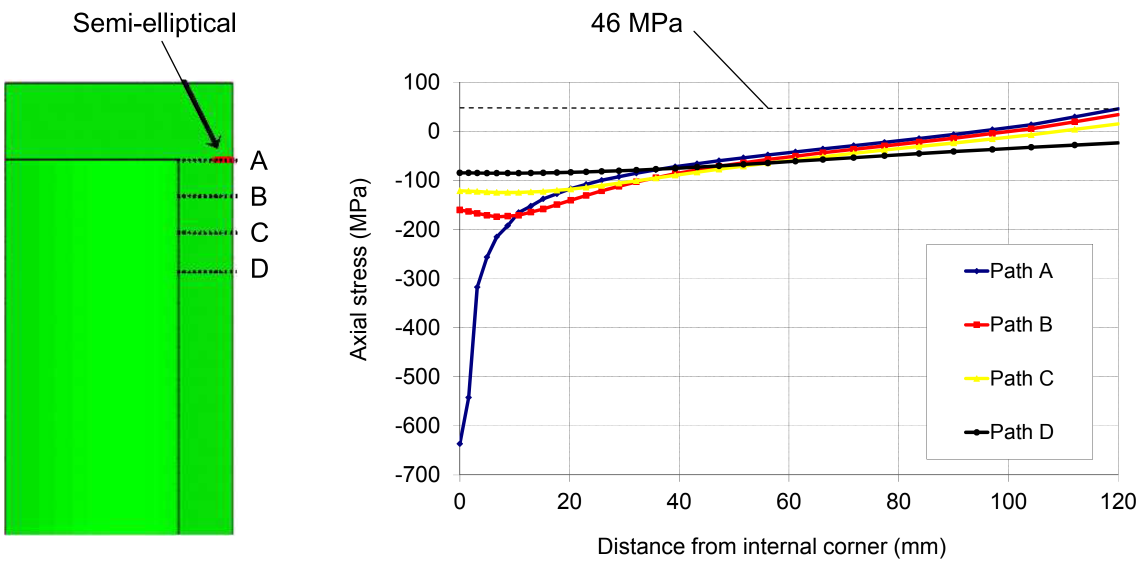



Fig. 10.20: Axial stress plot through canister wall along four paths, A, B, C and D.

### 10.4.4 ECA assessment

The ECA assessment procedure is based on the BSI (2005a; BS 7910) failure assessment diagram (FAD). The FAD approach provides a method to assess whether a flaw in a structure is acceptable or unacceptable, i.e. could lead to failure of the structure. The FAD, shown in Figure 10.21, comprises two axes, $L_r$ which is the ratio of the applied load divided by the collapse (or limit) load ($P/P_L$) and $K_r$ which is the ratio of the stress intensity factor divided by the fracture toughness value of the material ($K/K_{IC}$). $L_r$ represents the proximity to failure by plastic collapse and $K_r$ represents the proximity to failure by fracture of the structure.

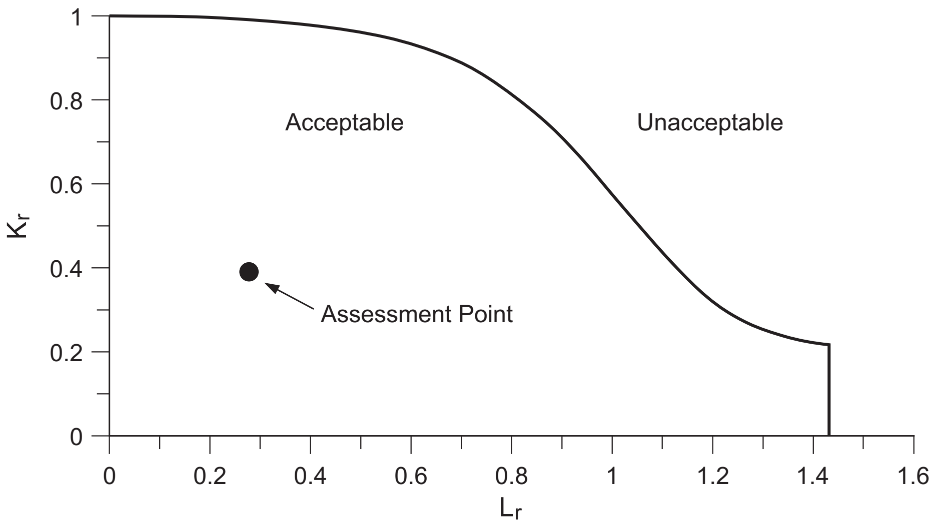



Fig. 10.21: BS 7910 Failure assessment diagram (FAD; BSI 2005a).

Values of $L_r$ and $K_r$ are evaluated making appropriately conservative assumptions according to the procedure, and an assessment point is plotted on the FAD. If the assessment point falls within the area bounded by the axes and failure assessment line, the flaw under consideration is deemed acceptable. If the assessment point falls outside the failure assessment line, the flaw is deemed unacceptable, that is it could lead to failure (though in some cases, a more refined analysis may show the flaw to be acceptable).

### 10.4.5 ECA results

For the SF canister with an external semi-elliptical flaw subject to the long term loading condition, three cases of analysis were performed. Each of the cases is described below:

Case 1: Reference flaw acceptability for a fracture toughness value ($K_{IC}$) = 220 MPa√m

Case 2: Sensitivity of reference flaw acceptability to fracture toughness (Table 10.4)

Case 3: Critical flaw height for various fracture toughness and residual stress yield values (Table 10.5).

For Case 1, the input parameters, found in Table 10.3, assume a fracture toughness of 220 MPa√m. This is a generic reference value for carbon steel at room temperature taken from API 579-1/ASME FFS-1 (API 2007). In practice the toughness of parent material and weld material may vary considerably. The assessment point, displayed in Figure 10.22, shows that a reference flaw with height of 30 mm, under a yield level residual stress of 220 MPa, would be acceptable.

Tab. 10.3: Case 1 Parameters – API 579-1/ASME FFS-1 (API 2007).

| **Parameter** | **Value** |
|---|---|
| Long term in-situ loading conditions | 29/22 MPa |
| Membrane axial stress (constant) | 46 MPa |
| Residual stress (yield level) | 220 MPa |
| Flaw height, a | 30 mm |
| Fracture toughness ($K_{IC}$) | 220 MPa√m |

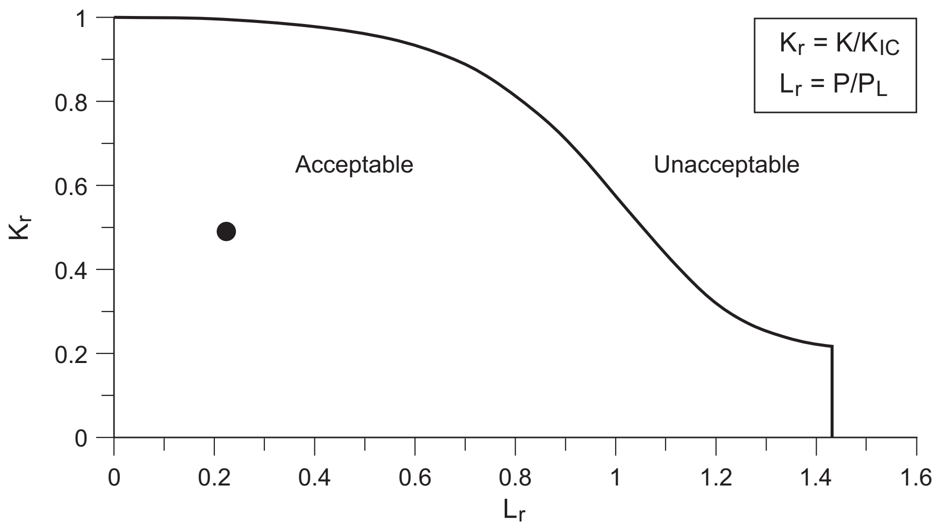



Fig. 10.22: Case 1 BS 7910 FAD results.

Long term in-situ loading conditions = 29/22 MPa, membrane axial stress = 46 MPa, residual stress = 220 MPa, flaw height = 30 mm, fracture toughness = 220 MPa√m.

Case 2 is the same as Case 1, but this time the fracture toughness value is varied between 100 and 300 MPa√m (Table 10.4). The results, in Figure 10.23, show that for all of the fracture toughness values, a flaw height of 30 mm is found to be acceptable. However, if the fracture toughness value is 100 MPa√m the assessment point falls just within the failure assessment line, suggesting that a flaw height of 30 mm is close to being limiting.

Tab. 10.4: Case 2 Parameters – Sensitivity to KIC.

| **Parameter** | **Value** |
|---|---|
| Long term in-situ loading conditions | 29/22 MPa |
| Membrane axial stress (constant) | 46 MPa |
| Residual stress (yield level) | 220 MPa |
| Flaw height, a | 30 mm |
| Fracture toughness ($K_{IC}$) | 100, 150, 200, 250, 300 MPa√m |

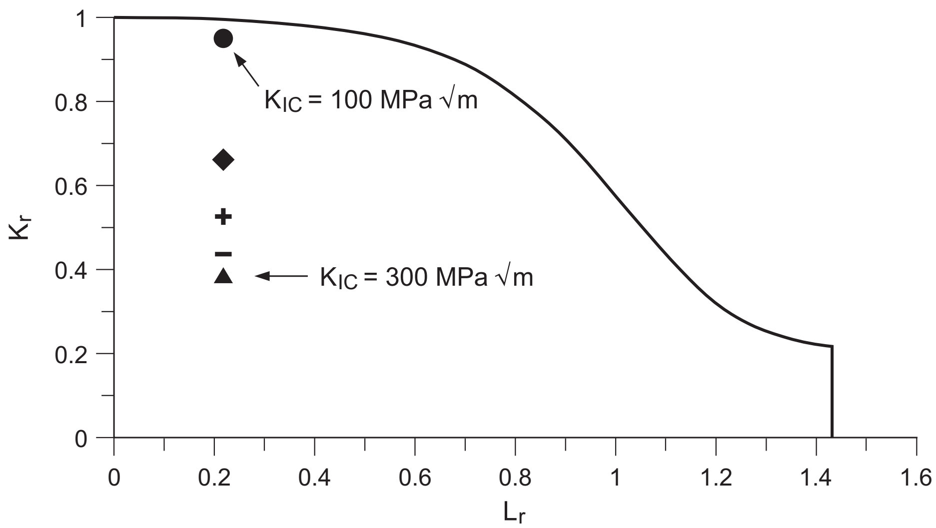



Fig. 10.23: Case 2 BS 7910 FAD results (BSI 2005a).

Long term in-situ loading conditions = 29/22 MPa, membrane axial stress = 46 MPa, residual stress = 220 MPa, flaw height = 30 mm, fracture toughness = 100, 150, 200, 250, 300 MPa√m.

Within Case 3, critical flaw heights are evaluated for different combinations of fracture toughness and residual stress. The input parameters are shown in Table 10.5. The results are presented in Table 10.6.

The critical flaw height tends to vary as the square of the fracture toughness to stress ratio ($K_{IC}$/stress)$^2$. Reducing the fracture toughness from 220 to 85 MPa√m has a significant effect on the critical flaw height, reducing it to 22 mm if 220 MPa residual stress is assumed. On the other hand reducing the residual stress to 70 and 30 % yield also has a significant effect on increasing the critical flaw height. The results show that both fracture toughness and residual stress have a large influence on the critical flaw height.

Tab. 10.5: Case 3 Parameters – critical flaw heights.

| Parameter | Value |
|---|---|
| Long term in-situ loading conditions | 29/22 MPa |
| Membrane axial stress (constant) | 46 MPa |
| Residual stress (yield level) | 220 MPa |
| Fracture toughness ($K_{IC}$) | 85*, 150, 220 MPa√m |
| Critical flaw height | $a_{cr}$ |

* 85 MPa√m ($K_{IH}$) represents a fracture toughness value that takes into account the effect of hydrogen diffusion as shown in Figure 6.1 (CTOD = 0.16 mm).

Tab. 10.6: Case 3 – critical flaw results.

| Fracture toughness [MPa√m] | Residual stress [MPa] | Critical flaw height, $a_{cr}$ [mm] |
|---|---|---|
| 220 | $\sigma_y$ | 82 |
| 150 | $\sigma_y$ | 55 |
| 85 | $\sigma_y$ | 22 |
| 85 | 70 % $\sigma_y$ | 35 |
| 85 | 30 % $\sigma_y$ | 70 |

Asano et al. (2011) propose a structural integrity evaluation model for a weld joint which considers critical flaw height, maximum tolerable flaw height without repair, and sizing limitation of NDE. A safety factor of 10 is currently proposed by RWMC as a ratio between the critical flaw height and maximum tolerable flaw height. For example if we take the SF disposal canister in in-situ long term conditions, with a yield level residual stress and fracture toughness value of 150 MPa√m, the critical flaw height is evaluated to be 55 mm. Assuming a safety factor of 10, the maximum tolerable flaw height would equal 5.5 mm.

As mentioned earlier, a factor of 2 of the critical flaw size to define a flaw height for inspection qualification would be appropriate. The flaw size used would be net of flaw growth in-service by hydrogen induced cracking or other mechanism (i.e. qualification flaw size = critical flaw size for failure – predicted in-service crack growth/2). In addition a reporting flaw height would be defined, above the sizing limitation of the NDE procedure, and any flaws detected sentenced using engineering critical assessment or good workmanship criteria. A factor of 10 between the detected flaw size and the critical flaw size (net of in-service growth) could be considered as a criterion for acceptance without repair.

### 10.4.6 Validation of CRACKWISE® solution

To ensure that the CRACKWISE® solutions are conservative, it is important that the results obtained from idealised canister geometry and stress distribution assumed within the CRACKWISE® analyses are validated with an FEA solution. The stress intensity factor ($K_1$) for a flaw height of 5 mm in long term loading conditions, assuming a zero residual stress, was evaluated in CRACKWISE ® and using FEA.

The results, in Table 10.7, show that CRACKWISE® estimates a higher stress intensity factor than that evaluated from FEA. This demonstrates that the CRACKWISE® stress intensity factor solutions provide a conservative estimate. Although these preliminary results go some way to validate CRACKWISE®, different flaw sizes and loading conditions should be analysed to provide full validation. The detailed CRACKWISE ® solutions and FEA results can be found in Appendix C.

Tab. 10.7: Validation of CRACKWISE® solution with FEA results.

| **Flaw size, a [mm]** | **Loading [MPa]** | **Residual stress [MPa]** | **$K_1$ (CRACKWISE®) [MPa√m]** | **$K_1$ (FEA) [MPa√m]** |
|---|---|---|---|---|
| 5 | 29/22 | 0 | 5.7 | 4.3 |

### 10.4.7 Fracture mechanics conclusions

An ECA approach has been used to establish a flaw acceptance criterion. Together with considerations about the capability and reliability of the non-destructive testing used in the inspection, the analyses help to establish the highest level of residual stress that results in a critical flaw size that can be readily detectable. In addition, the sensitivity to residual stress and fracture toughness has been examined, and critical flaw heights have been evaluated for different values of residual stress and fracture toughness.

In long-term conditions of 29/22 MPa, with a yield level residual stress (220 MPa) and fracture toughness value of ranging from 100 to 300 MPa√m, a 30 mm semi-elliptical external reference flaw is found to be acceptable.

In long-term conditions of 29/22 MPa, with a yield level residual stress (220 MPa) and fracture toughness value of 85 MPa√m, the critical flaw height is evaluated to be 22 mm. Reducing the residual stress to 70 and 30 % of yield increases the critical flaw height to 35 and 70 mm, respectively. The results provide an indication of the effect of residual stress and fracture toughness on the defect tolerance of the SF disposal canister.

## 10.5 SF canister handling incident

The purpose of this section is to provide evidence to show that the SF canister design meets RQ5, that is, the canister must remain structurally sound during normal handling and incidents that might occur during handling. It was considered, as stated in RQ5, that the most severe handling incident might involve a drop of maximum 5m onto a concrete floor. The canister handling details are not finalized, thus a horizontal impact was assumed, although it is not the worst configuration. The analysis is thus considered a general test of robustness and further analysis may be needed when handling details are better defined.

The sections below give a summary of the analyses and results, as well as a discussion and the details of the analyses are given in Appendix C.

### 10.5.1 Model conditions

The SF canister model, developed by Hitachi Zosen using LS-Dyna, includes the steel canister, the internals, and a solid concrete floor. Only half of the geometry was modelled and a plane symmetry was defined. The concrete and steel behaviour were assumed to be elastic-plastic, with linear hardening. The material parameters and geometry can be seen in Appendix C.

The canister was assumed to hit the floor when its axis is horizontal (0° position). Note that this is probably not the worst orientation. If the canister hits the floor at an angle, the impact load would be carried by a smaller volume of the canister, and local deformations would be more severe. The canister position was that immediately before impact, and the effect of initial height was given in term of initial velocity. The 5 m drop was modelled with velocity before impact equal to 9853.3 mm/s.

The criteria for the acceptance of the canister design were:

- No stress higher than tensile strength or strain higher than fracture strain.
- No plastic deformation on the inner surface of the canister in the circumferential direction.

Other criteria for the integrity of the internals were:

- The horizontal deceleration should not exceed 160 G for the BWR SF and 75 G for the PWR SF based on Hitachi Zosen's metal cask design Standard, "Standard for Safety Design and Inspection of Metal Casks for Spent Fuel interim Storage", AESJ-SC-F002 (Atomic Energy Society of Japan 2010), Appendix R to ensure integrity of the fuel pins.
- No contact between the internals and the canister.

### 10.5.2 Results

The highest maximum principal stress predicted in the canister was 111 MPa. The highest plastic strain value obtained was 0.09 %.

The peak of deceleration in the canister was predicted to be 500 G.

The main conclusions drawn by Hitachi Zosen from these analyses are:

- The canister is not breached during and after the drop (confinement is held).
- The fuel cladding may be breached, so that the lid re-opening process needs careful attention.

### 10.5.3 Discussion of results

The assessment performed by Hitachi-Zosen shows that the canister will not fail during a handling incident. However, it is worth noting that this assessment does not account for residual stresses in the region of the weld between the lid and the shell, and the breach criteria do not account for initial defects. Ideally, a fracture assessment should be performed, but this would require the need for predicted or experimental data.

For the final assessment of the design, dynamic fracture data obtained experimentally, and residual stress values obtained from a rigorous process model and supported by experimental validation can increase the tolerable flaw size.

The dynamic fracture analysis to assess the tolerance to defects covers brittle and ductile failure modes depending on the transition properties of the material at its lowest temperature. TWI proposes the BSI 7910 (BSI 2005a) failure assessment diagram (FAD), based on the R6 two criteria approach, which is widely accepted in the nuclear industry.

To perform the assessment a dynamic lower bound toughness value, from experimental testing, is required for the specified geometry and loading conditions. The NDT capability needs to be able to detect the critical defect height, determined from the fracture assessment, with a suitable safety margin to avoid fracture from fabrication and in-service crack-like defects.

## 10.6 SF Canister retrieval

Requirement 25 states that the disposal canister must satisfy the requirement for retrievability during the operational phase of approximately 50 years. Therefore, the disposal canister and lifting feature must remain structurally sound before, during and post-retrieval. To assess the structural integrity of the disposal canister and lifting feature during the retrieval process, an analytical calculation was performed. This calculation was based on upper bound assumptions, where the load applied to the lifting feature was assumed to be the weight of the canister (17100 kg), and the weight of the fuel assemblies (4960 kg). Under this load, the peak nominal stress in the packaging was determined to be 2.5 MPa. Even in the case of stress concentration factors being applied to account for geometry singularity, the stress from retrieval would still be extremely low, and retrieval would not affect the integrity of the canister.

## 10.7 Elastic instability and buckling

Annex B of EN 13445-3 (BSI 2009d) states that instability of the canister is an area that needs to be addressed. This analysis has not been performed within this report. However, the limit load FEA, as described above, suggests that the condition for instability of the SF canister is not likely to occur. This is because the buckling instability, if present, would also cause the numerical analysis to be unstable, and the convergence of the calculation would not be possible.

It is recommended that a quantitative buckling analysis is performed in order to determine the buckling mode of the SF canister.

## 10.8 HLW canister designs in repository (in situ)

### 10.8.1 Geometry

The geometry of the HLW canister modelled for this analysis was similar to that of Design 2 SF canister, although the dimensions are different. The internal length and diameter of the canister are 2612 and 440 mm respectively. The wall and lid thicknesses are 120 and 140 mm. These thickness values account for a 20 mm reduction due to corrosion, as the canister will be analysed in long term conditions. The joint between the body and the bottom includes an internal fillet 5 mm in radius, and a gap, 21 mm in length and 1mm in width was modelled between the lid and the body. Figure 10.24 shows views of the geometry and the mesh.

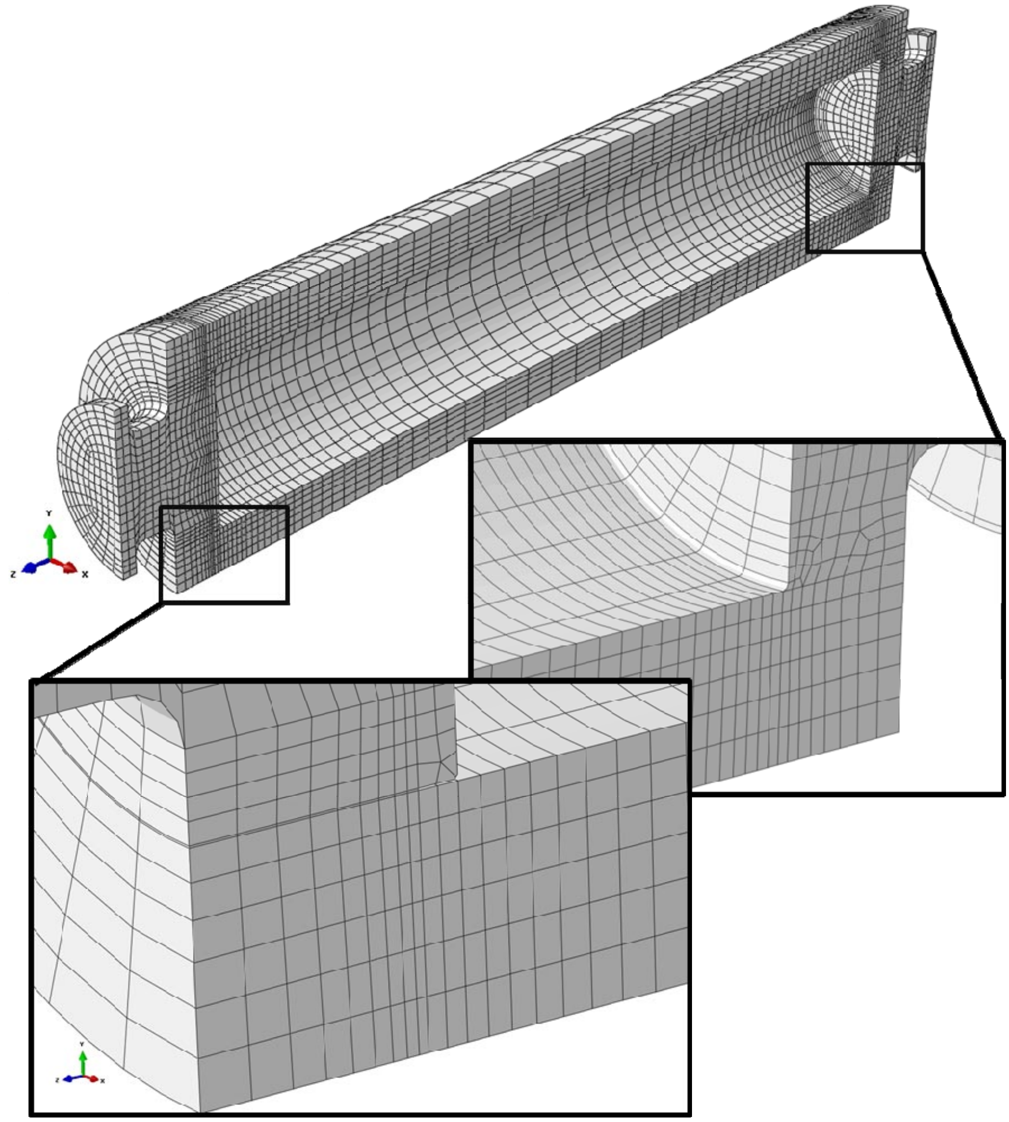


Fig. 10.24: Geometry and mesh of the model analysed for the assessment of the HLW canister.

### 10.8.2 Material properties

The material properties are the same as described in Section 10.3.3.

### 10.8.3 Loading and boundary conditions

The model assumes that the canister is in the long-term condition, which means the structure is at a temperature between 35 and 40ºC, and the pressure applied varies between 22 and 29 MPa, depending on position, as described in Section 10.3.4 and Figure 10.5. Although the temperature is about 15ºC higher, the properties used in the analyses are those at room temperature, as they are available from the material's specification, and the small difference in temperature is expected to have a little effect on the results. For estimating the limit load, the elastic-plastic analyses were performed where the pressure values applied for the long term condition were increased proportionally.

### 10.8.4 Results

Figure 10.25 shows the Von Mises stress contour plot obtained from the elastic analysis in long term condition. Figure 10.26 shows the stress profiles along longitudinal edges of the cylindrical body. The Von Mises stress values obtained are lower than those predicted from the analyses of the Design 2 SF canister which are shown in Figure 10.12.

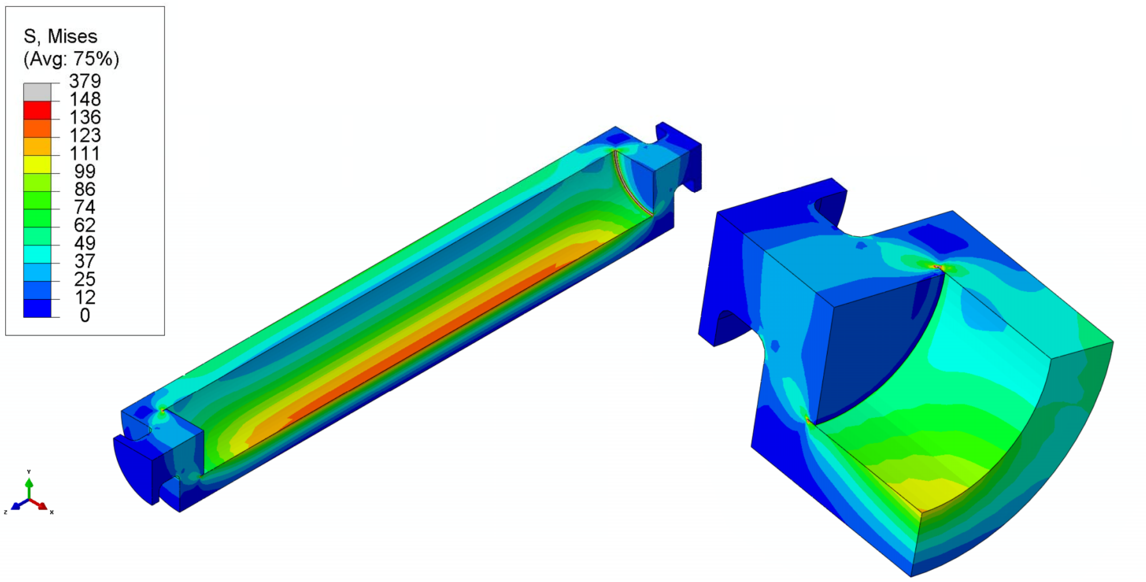



Fig. 10.25: Von Mises stress contour plot obtained in the HLW canister from an elastic analysis assuming in-situ long term condition.

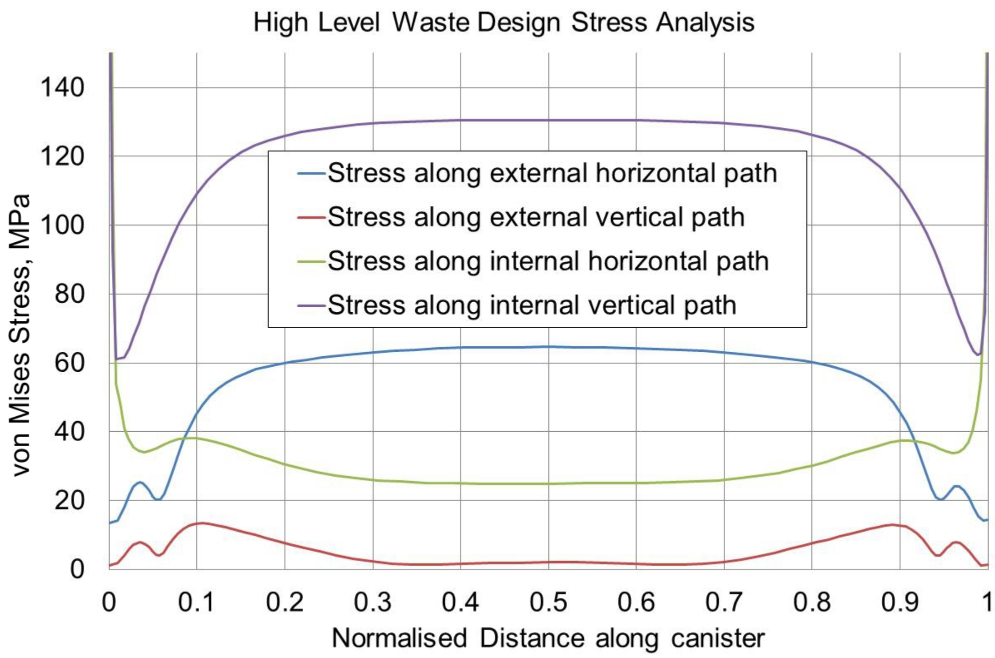



Fig. 10.26: Von Mises stress profile along longitudinal edges of the canister obtained from the elastic analysis assuming in-situ long term condition.

Figure 10.27 shows the plastic equivalent stress from the elastic-plastic model performed in order to determine the limit load. As in the case of SF Design 2, the yielding first occurs in the main wall of the body, rather than in the singular regions causing stress concentration. This limit state was obtained when the pressure applied was 2.5 times the in-situ pressure.

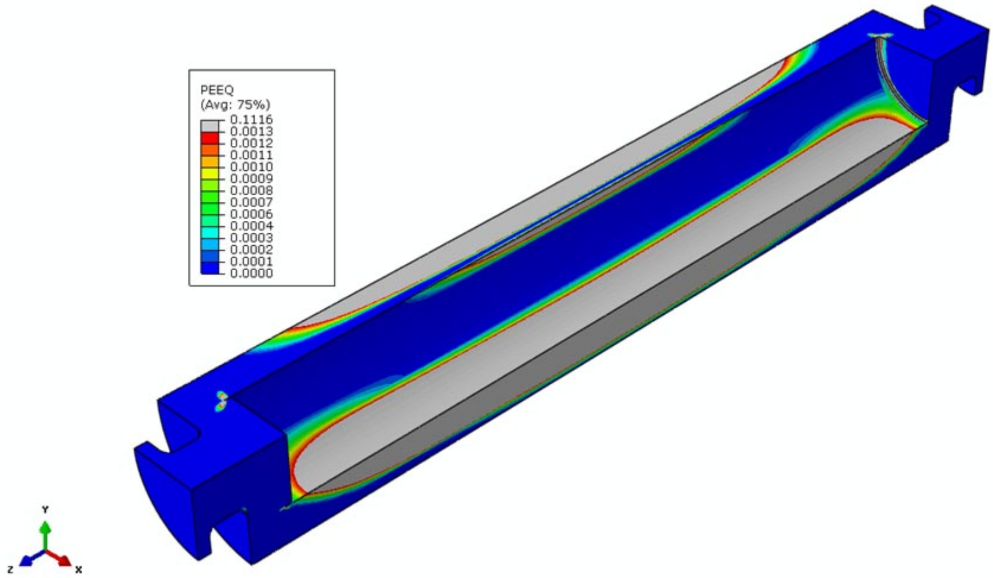



Fig. 10.27: Contour plot of the plastic equivalent strain showing yielding through the canister's side wall when the loading is 2.5 times the in-situ pressure.

## 10.9 Summary

Since the basic design focuses principally on meeting the requirements that are associated with maintaining structural integrity throughout the timescale being considered, as stated in the design approach (Section 4.2), this section forms a key part for the design of the SF and HLW disposal canister.

The safety margins presented below are factors to reach the plastic limit load on the assumed maximum loading pressure of 22 MPa (vertical) and 29 MPa (horizontal), which is a worst case condition having a very low probability. They provide an initial basis on which the integrity of the proposed canister design concept may be judged. The safety margins will need to be re-evaluated against the requirements of the relevant design code in further work taking any changes to optimise the design into account.

**In-situ conditions**

The SF and HLW canister designs are not at risk of failure by plastic collapse in the short term condition with a safety margin on pressure of approximately 10.

Plastic collapse of the SF canister does not occur under long term conditions for all 3 designs, but the safety margins are significantly reduced to the values shown below:

Design 1 safety margin = 1.4 or 1.7, if the initial lid thickness is 140 or 180 mm respectively.

Design 2 safety margin = 1.8 or 1.5, if the corrosion is respectively 20 or 40 mm.

Design 3 safety margin = 1.9.

For the SF canister in long-term conditions of 29/22 MPa, with a yield level residual stress (220 MPa) and fracture toughness value of ranging from 100 to 300 MPa√m, a 30 mm semi-elliptical external reference flaw (postulated to occur in the weld region) is found to be acceptable.

For the SF canister in long-term conditions of 29/22 MPa, with a yield level residual stress (220 MPa) and fracture toughness value of 85 MPa√m, the critical flaw height is evaluated to be 22 mm, assuming an external semi-elliptical flaw (postulated to occur in the weld region). Reducing the residual stress to 70 and 30 % of yield increases the critical flaw height to 35 and 70 mm, respectively.

Plastic collapse of the HLW canister does not occur under long term conditions. In this case the safety margin is 2.5.

### Handling incident

Dynamic stress analyses simulating a handling incident of a drop from 5 m showed that a defect-free SF canister is not breached during and after the impact. The fuel assembly deceleration is predicted to exceed the specified maxima from the acceptance standard for both BWR and PWR fuel types and therefore consideration would need to be given to safe retrieval of the canister contents following such an incident.

It should be noted that the analyses did not model the fuels, but just considered their weight. However, the purpose of this analysis was to examine the performance of the canister body in a handling incident and it is proposed that a more detailed dynamic assessment is conducted in the canister development phase to optimise the canister and internal fuel support structure. Future work should also analyse a handling incident for a case with the maximum allowable defect size, established by ECA.

### Retrieval

Analytical calculation shows that the nominal stress is 2 MPa at the highest during retrieval. Therefore the SF canister can be retrieved from the repository without affecting its integrity.

# 11 Inspection

## 11.1 Introduction

The inspection process should be able to detect defects that are smaller than the critical flaw size by an adequate margin, and the proposed inspection method(s) must be suitable for remote operation, given the radiation field (RQ14, Table 2.1). The critical flaw sizes are considered in Section 10.4. In practice, the margin between the critical flaw sizes and the flaw sizes used in the inspection qualification (discussed further in Section 11.3) will be a compromise between:

1 The required level of assurance in the structural integrity of the canister, and,

2 The practicability of the inspection, which has a potential impact on production rate and costs (RQ20 and RQ27, Table 2.1).

On this basis, it is proposed that the inspection qualification concentrate on flaws with a through-wall extent (TWE) of 3mm upwards.

The requirements given in Box 11.1 are addressed in this section.

**Box 11.1 Requirements relating to inspection**

RQ14 Inspection and testing.

RQ19 Post weld surface treatment.

RQ20 Production rate.

RQ27 Costs.

RQ29 Codes and standards.

Section 11.2 sets out the inspection objectives in further detail. Section 11.4 considers the advantages and disadvantages of various inspection methods in meeting these objectives, including the impact of temperature, radiation field and remote operation. Finally, Section 11.5 considers the effect of the proposed weld designs on the inspection, including the constraints on access. The main focus here is the inspection of the closure weld, but it is envisaged that the same inspection methods would be used to inspect the other welds. Inspection of these other welds and the parent material will, almost certainly, be less challenging, because:

- The inner surface of the canister will be accessible as well as the outer surface.
- There is no need for remote operation.

Procedures will also need to be developed for inspection of repairs, along with a corresponding qualification protocol.

ASME (2010a; III) and EN 13445-5 (BSI 2009c) include additional guidance of a general nature on inspection issues, including:

- Joint preparation testing.
- Inspection of parent material.
- Visual inspection.
- Inspection of repairs.

Visual inspection of the finished welds should be performed both before and after dressing the weld cap (and also after heat treatment, if applicable). This will need to be done remotely using camera(s) (at least for the closure weld).

## 11.2 Inspection objectives and flaw acceptance criteria

In general, weld inspections have two distinct objectives:

1 Provide assurance that the weld is structurally fit for purpose.

2 Provide quality control.

In the latter case, the results of inspection are normally assessed against 'good workmanship' or quality control acceptance criteria which are usually quite stringent, e.g. ASME (2010a; III) stipulates that all cracks, lack of fusion and incomplete penetration are unacceptable. When flaws are found which exceed these criteria, the choices are either to reject the component outright, repair the flaws, or carry out a fitness-for-purpose (FFP) assessment. In the latter case, a structurally tolerable size of flaw is calculated based on knowledge of the material properties and service loads. These flaw sizes are usually, but not always, less stringent than the quality control acceptance criteria and can provide a further decision level which may allow the flaws to be accepted.

There are two distinct categories of flaw corresponding to the two inspection objectives above:

1 High priority flaws. These are the flaws that need to be reliably detected and should therefore be considered during the inspection qualification. Their type and size will depend on the outcome of the structural assessment, and should be agreed between the parties involved, e.g. following the European methodology for inspection qualification (EC 2007).

2 Low priority flaws. These are flaws for which detection and reporting by NDT is desirable, and should therefore be considered when developing the inspection procedure and the flaw acceptance criteria. However, these flaws do not need to be specifically included within the scope of the inspection qualification.

Based on TWI's experience, the reasonably foreseeable types of flaw that could exist in the welds are those listed in Table 11.1 (roughly in priority order for inspection). Examples of these flaws are illustrated in Figures 11.1 to 11.6.

Tab. 11.1: Foreseeable welding flaws.

| **NG-GTAW welds** | **EB welds** |
|---|---|
| Lack of sidewall fusion (Figure 11.1) | Missed joint |
| Lack of root fusion / lack of penetration | Lack of penetration |
| Lack of inter-run fusion (Figure 11.2)<br>TWE unlikely to exceed 1 weld bead (3 – 5 mm) | Slope-down spiking porosity (Figure 11.3)<br>Flaw tilt within few degrees of vertical – favourably oriented for 0° UT beam |
| | Gross cavities (Figure 11.4) |
| Solidification cracking<br>Relatively unlikely<br>Flaw tilt up to 45° (relative to weld centre-line) | Solidification cracking (Figure 11.5) / cold cracking (Figure 11.6)<br>TWE could exceed 5 mm<br>Flaw tilt 0° or 90° – ideally oriented for 0° UT beam |
| Tungsten inclusions<br>Volumetric (ie. readily detected by UT)<br>Unlikely to be > 3 mm TWE | |
| Worm hole (agglomerated porosity)<br>Readily detected by 0° UT (similar response to 3 mm side-drilled hole) | |
| Clustered porosity<br>Likely to be detected by UT if gross enough to be of structural concern | |

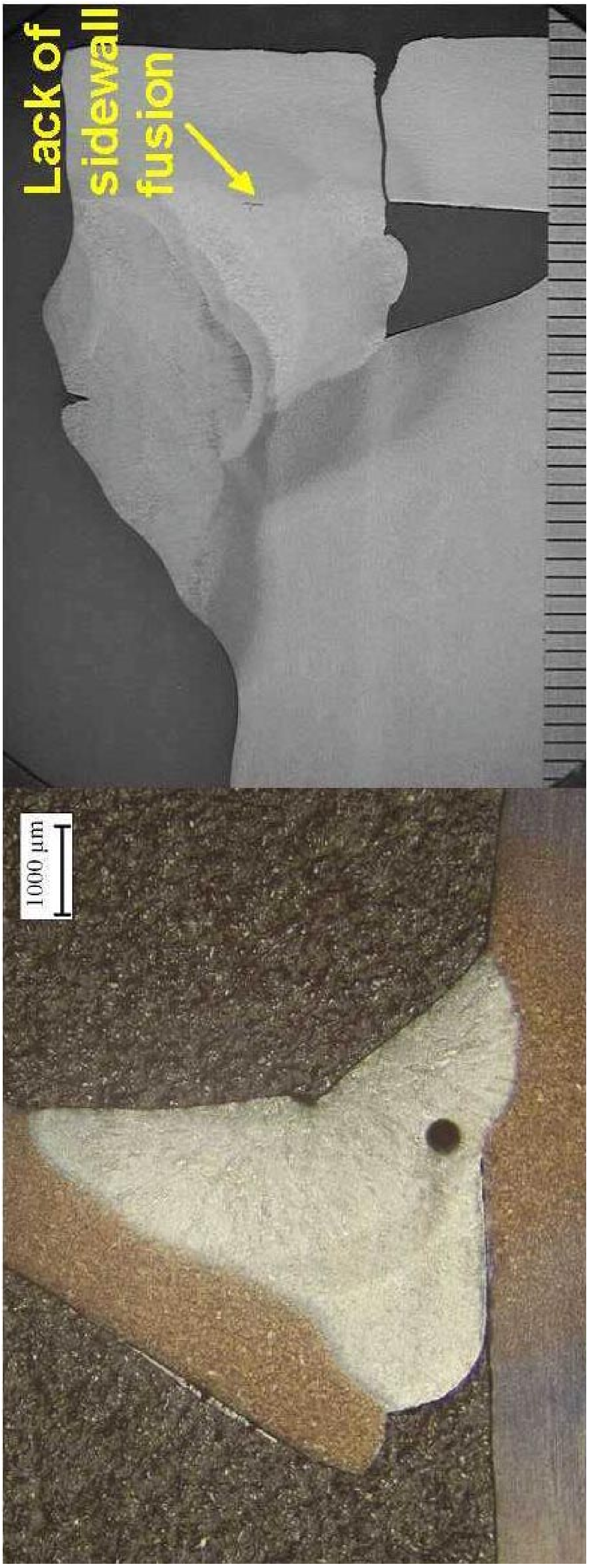



Fig. 11.1: Examples of lack of sidewall fusion flaws.

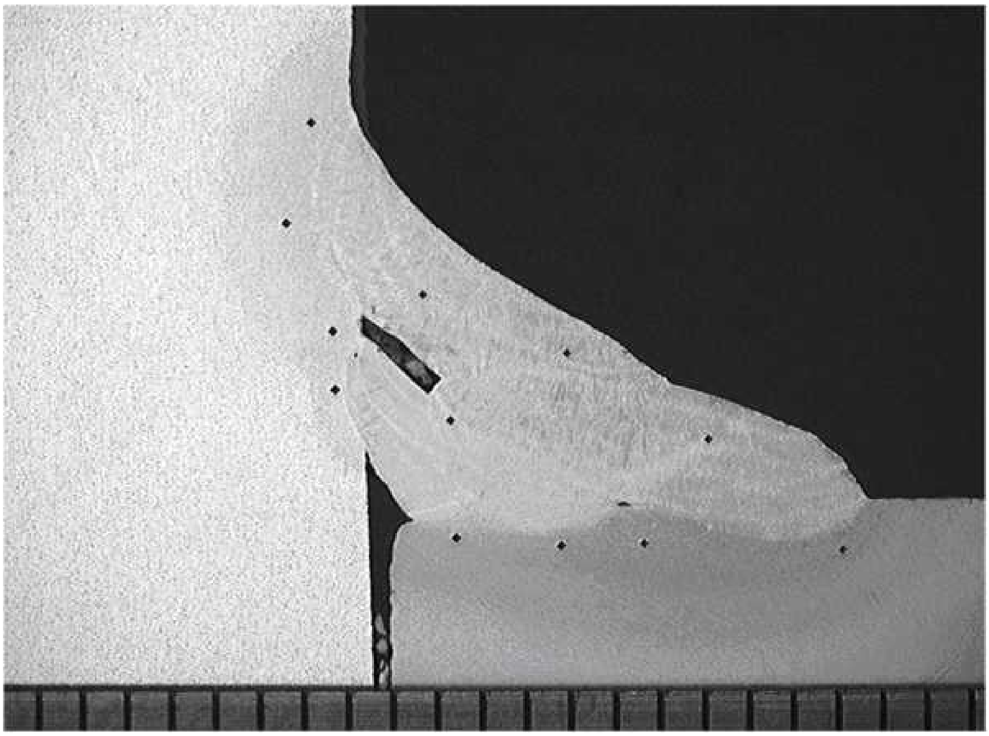


Fig. 11.2: Example of lack of inter-run fusion flaw.

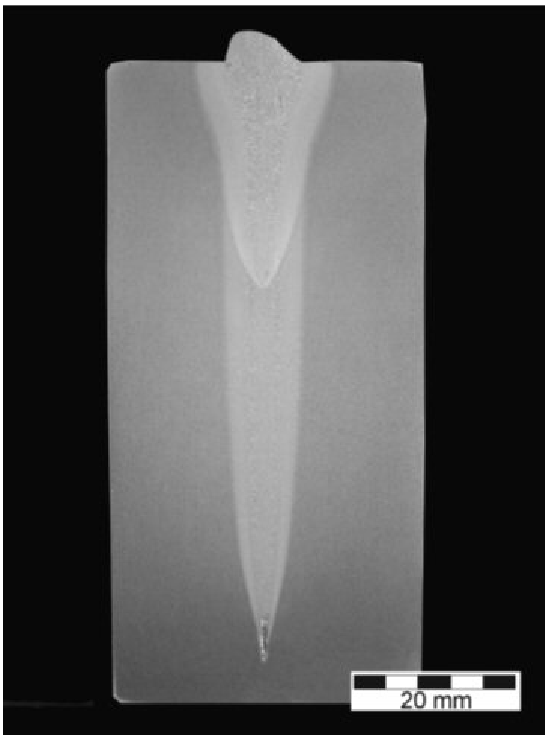



Fig. 11.3: Example of spiking porosity.

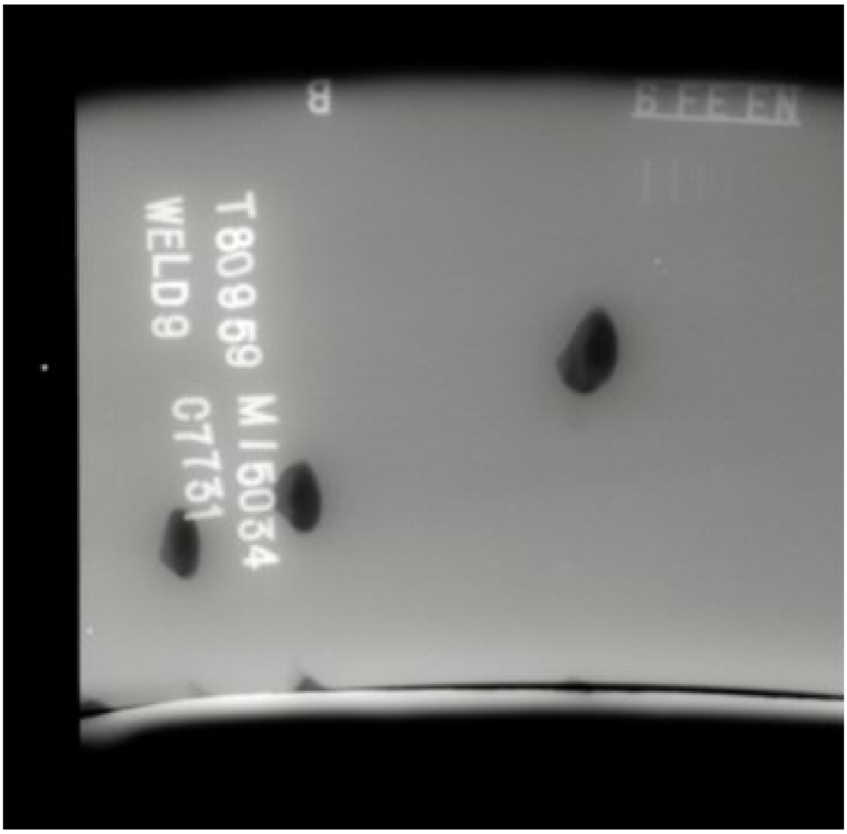



Fig. 11.4: Example of gross cavities.

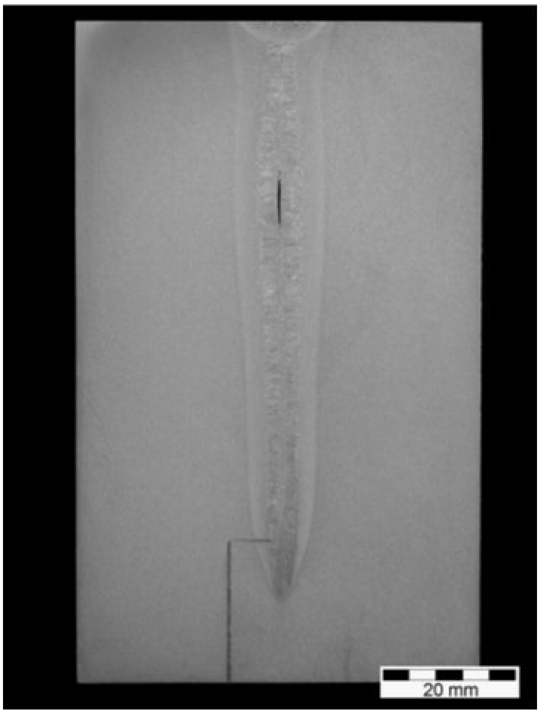



Fig. 11.5: Example of solidification cracking.

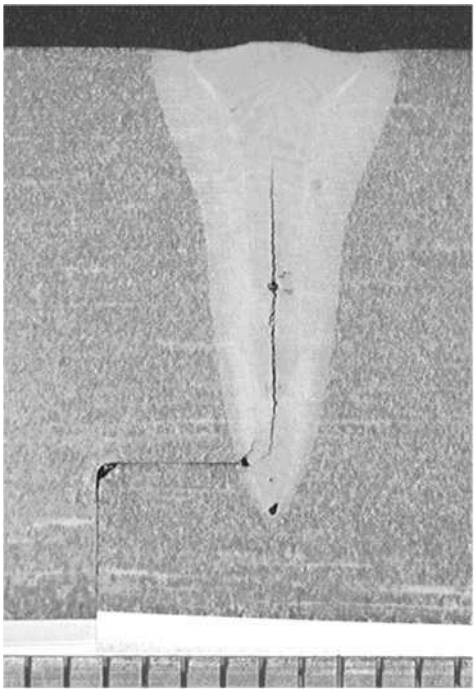


Fig. 11.6: Example of cold cracking.

Other types of welding flaws as listed below are excluded from further consideration on the grounds that they could only occur in the event of a gross failure of quality assurance of the materials to meet specification:

- Liquation cracking – < 3 mm TWE and/or to be designed out.
- Hydrogen cracking – designed out by selection of a low carbon equivalent material and low hydrogen welding processes (Section 8.5).
- Lamellar tearing – designed out by the selection of low sulphur content to reduce the presence of sulphides. Guaranteed through thickness properties are required also (Table 6.2).
- Reheat cracking – designed out by the low impurity content of this steel, limits on Pb, As, P, Sn as indicated in Section 6.3.1.
- Slag – not possible for the proposed welding processes.

This report is mainly concerned with the inspectability of the planar flaws in Table 11.1, since these are the flaws that are most likely to be of structural concern.

## 11.3 Inspection qualification

In broad terms, inspection qualification is a process followed to provide assurance that a given inspection is fit for its purpose. EN 13445-5 (BSI 2009c) requires that NDT personnel be certified to EN 473 (BSI 2008), but it does not include any provisions for the qualification of the NDT methods themselves. However, the European Network for Inspection Qualification (ENIQ) has developed a European methodology for this process, which is published by the European Commission (EC 2007). The ENIQ guidance was developed within, and is mainly used by, the nuclear industry, but it also provides general recommendations for inspection qualification.

In the ENIQ approach, the qualification methodology is defined in three tiers of document, which provide guidance at successively decreasing levels of abstraction:

- The Methodology Document (EC 2007).
- Recommended Practices (also published by the EC and available from the ENIQ website at http://safelife.jrc.ec.europa.eu/eniq/publications/complete.php).
- The Qualification Procedure, which is application-specific and is produced by the qualification body responsible for qualifying the inspection.

In the ENIQ approach, qualification is composed of some combination of one or both of the following two key aspects:

- Practical assessment, which involves blind and/or non-blind trials on simplified or representative test-pieces of the component to be inspected, and
- Technical justification (TJ), which involves assembling all evidences on the effectiveness of the test including previous experience of its application, laboratory studies, modelling, etc.

ENIQ places priority on the use of technical justification, and the practical assessment is seen as supporting evidence that is used only where necessary. The use of technical justification could minimise or remove the need for practical assessment where suitable evidence exists. This is encouraged where possible to minimise the extent of comparatively expensive practical trials. However, where a satisfactory technical justification cannot be made, an inspection can be qualified by practical assessment alone. Recommended contents for a technical justification are given in ENIQ Recommended Practice 2.

A key feature of the ENIQ methodology is the need to define the input information which includes the qualification objectives, the description of the component and the defects of interest and, most importantly, the inspection performance (in terms of detection, sizing and location) to be achieved. ENIQ was the first methodology to define the role of a 'qualification body' and to define the responsibilities of all other parties involved.

Other guidance documents on inspection qualification, which generally follow a similar approach to ENIQ and have some relevance to nuclear components, are as follows:

- PD CEN/TR 14748 (BSI 2004a) provides very similar guidance to ENIQ and states that the use of technical justification 'should reduce practical assessment exercises'.
- IAEA (1998) provides a methodology for the qualification of systems for in-service inspection (ISI) of WWER (water cooled water moderated energy reactor) power plant. This methodology is particularly used by licensees in Eastern Europe and the former Soviet Union where many WWERs are in operation. Like ENIQ, the IAEA guidelines place precedence on the technical justification over practical assessment, the latter only being used when technical justification cannot adequately qualify an ISI system.
- ASME V (ASME 2010b) Article 14 requires a TJ and contains an additional stipulation to ENIQ that the TJ must be prepared and approved by personnel certified to Level 3 in the appropriate technique(s).

ASME XI (ASME 2010d) Appendix VIII includes requirements for generic performance demonstration of ultrasonic in-service examination of certain nuclear components. Unlike the ENIQ approach, it is almost exclusively based on practical trials and does not require the production of a TJ. Whittle (2009) reviewed the ASME XI approach to inspection qualification and concluded that, compared to the ENIQ methodology, it has little technical merit and does not, in itself, provide confidence in the ability of a specific inspection to meet particular targets. Whittle (2009) argues that the ENIQ methodology, by contrast, is more flexible and provides confidence that an inspection can meet its objectives.

## 11.4 Inspection methodologies

### 11.4.1 General capabilities

The NDT methods most commonly used for the detection of welding flaws in steel components are as follows:

- Ultrasonic testing (UT), including 'advanced' techniques such as time-of-flight diffraction (TOFD), phased array ultrasonic testing (PAUT) and creeping waves.
- Radiographic testing (RT).
- Eddy current testing (ET).
- Magnetic particle inspection (MPI).
- Liquid penetrant testing (PT).

Of these methods, only UT and RT are well-suited to the detection of sub-surface flaws (at least for ferritic steel); the other techniques are essentially for surface inspection.

Tables 11.2 to 11.7 provide indicative detection capabilities for these techniques, when applied to ferritic steel welds in general, and cite reference material to support these claims. Sections 11.4.2, 11.4.3 and 11.4.4 provide further information on the impact of temperature, radiation field and remote operation respectively on the capabilities of these techniques for the canister inspections.

For RT (Table 11.4), the detection capability is quantified for pores only. The capability for planar flaws is more difficult to quantify, because it mainly depends on defect gape. It is well known that RT can miss tight flaws, especially if they are misoriented with respect to the radiographic beam. Some form of ultrasonic inspection is therefore needed to satisfy RQ14 for sub-surface flaws. RT is not feasible for the cylindrical canister designs considered in this report. The use of RT in addition to UT would require a more complex canister design without any obvious benefit, which would have an impact on costs (RQ27, Table 2.1).

Of the surface NDT methods, ET is generally the preferred method for remote deployment (see Section 11.4.4). Comparing Tables 11.5 and 11.2 suggests that ET has an advantage over conventional UT for the detection of surface-breaking welding flaws only if the weld cap is dressed. In practice, however, the two techniques are complementary and surface flaws will be detected much more reliably if both are used. In particular, ET will be more sensitive than UT wherever the surface is locally smooth.

Tab. 11.2: Indicative detection capabilities – conventional UT of ferritic steel welds.

| Defect type | Position | Defect size for reliable detection | Reference | Assumptions |
|---|---|---|---|---|
| Planar | Inspection ranges ≤ 150 mm<br>Inspection ranges > 150 mm | 3 mm (through-wall) × 15 mm (long)<br>4 × 15 mm | Chapman & Bowker (2001) | Defect skew ≤ 3°<br>Within 20° of normal incidence for at least one probe<br>High sensitivity (3 mm SDH DAC +20 dB threshold)<br>Weld thickness ≤ 120 mm (not critical)<br>Unrestricted access<br>No 'restrictions to test' such as geometric echoes at a similar range or poor weld root profile |
| Linear inclusions | Depth 3 – 25 mm<br>Depth 25 – 75 mm<br>Depth 75 – 125 mm<br>Depth > 125 mm | 1 × 4 mm<br>1.5 × 6 mm<br>2 × 6 mm<br>3 × 10 mm | ENA (1988) | Unrestricted access<br>Applies to longitudinal and transverse defects |
| Isolated point reflectors (e.g. pores) | Depth 3 – 25 mm<br>Depth 25 – 75 mm<br>Depth 75 – 125 mm<br>Depth > 125 mm | 2 mm (diameter)<br>3 mm (diameter)<br>4 mm (diameter)<br>4 × 6 mm | ENA (1988) | |
| Multiple flaws (e.g. localised porosity) | Depth 3 – 25 mm<br>Depth 25 – 75 mm<br>Depth 75 – 125 mm<br>Depth > 125 mm | 3 × 3 mm<br>4 × 4 mm<br>5 × 5 mm<br>8 × 8 mm | ENA (1988) | |

Tab. 11.3: Indicative detection capabilities – advanced UT of ferritic steel welds.

| Defect type | Position | Defect size for reliable detection | Reference | Assumptions / notes |
|---|---|---|---|---|
| Planar (longi-tudinal) | Depth ~ 3 – 80 mm | 1.5 × 10 mm | Shipp et al. (2002) | Swept beam phased array<br>Focussed beams<br>High sensitivity |
| Various | Depth 0 – 190 mm | 2 mm high | Nakamura et al. (2009) | RWMC welds (60 and 190 mm thickness)<br>TOFD / phased array / creeping wave |

Tab. 11.4: Indicative detection capabilities – radiographic testing (RT).

| Defect type | Position | Defect size for reliable detection | Reference | Assumptions |
|---|---|---|---|---|
| Volumetric flaws (e.g. pores) | Any | 3 mm (diameter) | Halmshaw (1982) p. 223 | BS EN 462-3:1997 Class A (BSI 1997)<br>Weld thickness 100 – 150 mm |

Tab. 11.5: Indicative detection capabilities – eddy currents.

| Defect type | Position | Defect size for reliable detection | Reference | Assumptions / notes |
|---|---|---|---|---|
| Planar | Accessible surface | 1 mm (through-wall) × 5 mm (long) | American Society for Metals (ASM 1989) | Preferred surface NDT method for remote deployment<br>ET at least as good as MPI (Chapman & Bowker 2001)<br>Machined/ground surface |
| | | 3 × 15 mm | Visser (2002)<br>Crutzen et al. (1999) | Undressed weld cap<br>Rough material / excessive weld beads removed by grinding |

Tab. 11.6: Indicative detection capabilities – MPI.

| **Defect type** | **Position** | **Condition of test surface** | **Defect size for reliable detection** | **Reference** | **Assumptions** |
|---|---|---|---|---|---|
| Crack-like | Accessible surface | Machined / ground to 3.2 µm Ra | 1 mm (through-wall) × 5 mm (long) | Chapman & Bowker (2001) | Flux density B ≥ 1 T<br>Relative permeability ≥ 240 at a flux density of B = 0.72 T<br>Plane of defect normal to the direction of magnetisation |
| | | Local dressing of weld cap | 2 × 10mm | | |

Tab. 11.7: Indicative detection capabilities – liquid penetrant testing.

| **Defect type** | **Position** | **Defect size for reliable detection** | **Reference** | **Assumptions** |
|---|---|---|---|---|
| Linear flaws | Accessible surface | 1mm (through-wall) × 5 mm (long) × 0.25 mm (gape) | ENA (1989) | 'Medium' sensitivity<br>Cleaned and descaled<br>Rough material / excessive weld beads removed by grinding<br>Surface finish 1.6 – 6.4 µm roughness |
| Rounded flaws | | 1 mm (through-wall) × 2 mm (diameter) | | |

### 11.4.2 Temperature constraints

Wet MPI typically has an upper temperature limit of ~ 50°C (see, for instance, http://www.magnafluxindia.com/2410.pdf). Higher temperatures require dry powder methods, which will give poorer performance. Standard penetrants have a similar upper temperature limit on temperature. Thus, above ~ 50°C it is necessary to use special high temperature penetrants, which give a slightly poorer performance than standard penetrants.

By contrast, standard eddy current testing can generally be performed up to ~ 70°C. Higher temperature testing is also possible by cooling the probes. The vendor assessment for the Yucca Mountain project (INEEL 2003) confirms that eddy current equipment already exists that would withstand a temperature of 350°F (177°C).

The British and European standard for ultrasonic testing of welds (BSI 2010) stipulates that testing outside the range 0 to 60ºC 'can only be used when defined by specification' and requires that the temperature during the test be within ± 15°C of that during range and sensitivity setting. The ASME V (ASME 2010b) code contains a similar requirement, stating that the temperature difference between the component under test and the calibration block must be within ± 14°C. In addition, BS EN 583-1 (BSI 1999) states: *'The consequences of temperature differences between examination object, probes and reference blocks shall be considered and compared to the requirements for the accuracy of the examination. If necessary the reference blocks shall be maintained within the specified temperature range during the examination'.*

Temperature affects ultrasonic velocity, as shown in Table 11.8.

Tab. 11.8: Change in ultrasonic velocity over the range 25 to 40°C.

| **Material** | **Nominal velocity at 25ºC [m sec$^{-1}$]** | **Temperature dependence [m sec$^{-1}$ per ºC]** | **Source** |
|---|---|---|---|
| Steel, longitudinal wave | 5900 | −0.57 | R/D Tech (2004) Figure 2.12 |
| Steel, shear wave | 3230 | −0.40 | R/D Tech (2004) Figure 2.13 |
| *PMMA | 2690 | −2.20 | R/D Tech (2004) Figure 10 |
| *Rexolite™ | 2285 | −0.68 | Imasonic (Figure 10.7 of this report) |

* PMMA (polymethyl methacrylate, also known by the trade names Perspex™ and Lucite™) and Rexolite™, a cross-linked polystyrene, are common probe shoe materials.

The change in velocity with temperature will result in a change in beam angle. This can be illustrated most simply by calculating the change in angle for a single crystal conventional probe producing a 60º beam at 25ºC. At 40ºC the beam angle will change to 60.3º using a Rexolite™ shoe and to 61.1º using a PMMA shoe. These figures are both within normal experimental error for beam angle although they do illustrate the benefit of using Rexolite™ as a shoe material. Fortunately, this is the most common material used for shoes in phased array systems. Even at temperatures up to 60ºC, Figure 11.7 suggests that the changes in beam angle for a ± 14ºC change in temperature would still be negligible (~ ± 0.4º) for a Rexolite™ shoe. These figures support the ± 14ºC criterion (ASME 2010b; ASME V) for Rexolite™ shoes, as long as the temperatures during both inspection and calibration remain below ~ 60ºC. However, a tighter tolerance on temperature may be needed if PMMA shoes were used.

It should be noted that Rexolite™ has more than one manufacturer and its properties vary between manufacturers. In general, the relationship between velocity and temperature cannot be assumed to be linear for the temperatures at which the canisters will be inspected (as illustrated for the particular material illustrated in Figure 11.7). Although the properties of Rexolite™ vary, the variation of velocity with temperature is, in each case, less pronounced than for PMMA.

Clearly, water-based couplants cannot be used above 100°C. However, high temperature angled UT probes and TOFD equipment have been successfully deployed at temperatures up to ~ 170°C, using silicon oil based couplants, and achieving a similar performance as at room temperature (Bowker 1999). The procedures must be adapted to take account of changes in velocities, and hence beam angles, with temperature. As a result, it may be necessary to recalibrate the equipment if the temperature of the scanning surface changes by more than ~ 10°C.

If necessary, the use of couplants might be avoided through the use of wheel probes. INEEL (2003) reported that some (but not all) vendors could supply wheel probes that could tolerate temperatures of 200°F (93°C). At least one vendor (http://www.sigmatx.com/abstact.htm), on request, supplies wheel probes that are claimed to withstand temperatures up to 350°F (177°C).

Finally, it should be noted that the UT flaw detector may have a different temperature limit to the transducer itself. Maximum operating temperatures are typically between 40 and 60°C for commercially available conventional flaw detectors, or between 35 and 50°C for phased array flaw detectors, depending on specification (see, for example, http://www.olympus-ims.com/en/omniscan-mx2/). However, it should, in principle, be possible to place the flaw detector in a cooler environment than the transducers. This approach has been successfully demonstrated in other high temperature applications, by attaching the probes to the flaw detector with long cables (Bowker 1999).

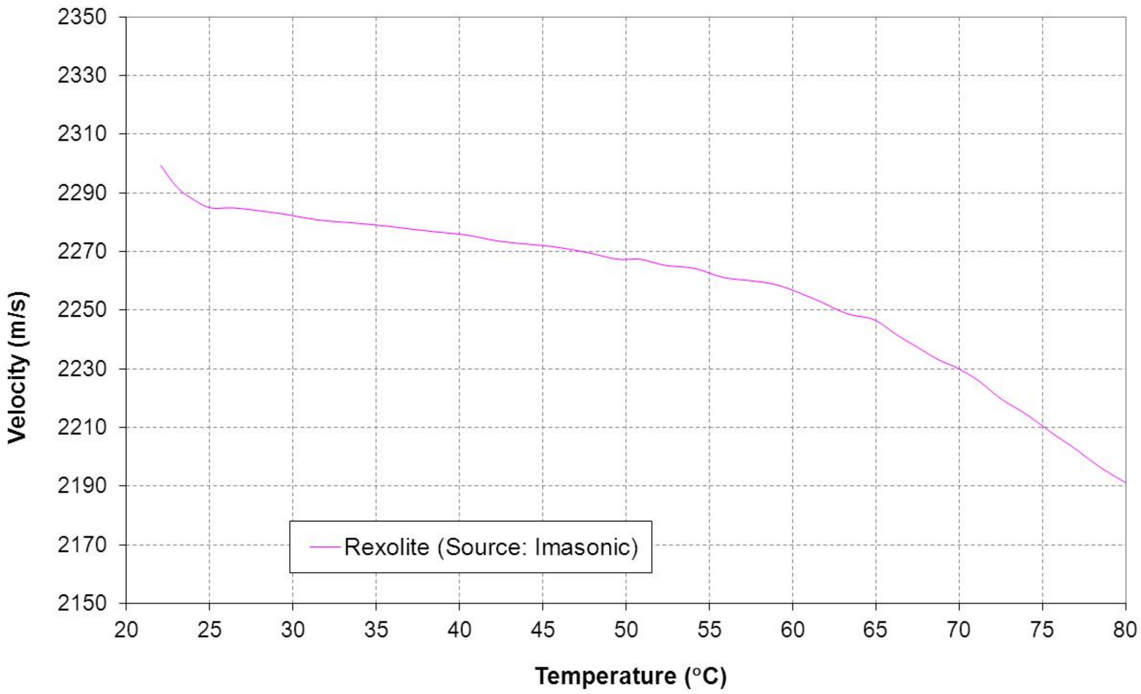



Fig. 11.7: Effect of temperature on ultrasonic velocity in Rexolite.

### 11.4.3 Radiation effects

Ultrasonic techniques have been successfully used in radiation environments but test times have been short. As a result, the vendor assessment for Yucca Mountain (INEEL 2003) concluded that UT systems could withstand a radiation exposure of 160 Roentgens/hr (equivalent to a dose rate of ~ 1600 mSv/hr for gamma rays; cf. FEMA 2008), but that the long-term durability of the transducers and associated cabling in high radiation fields was unknown. This level of exposure is much larger than that expected at the surface of either the HLW or SF canister; for a HLW canister of wall thickness 140 mm, the total surface dose rate would be ~ 130 mSv/hr (based on RQ3 and Appendix 1). The radiation exposure for the SF canister will be even lower than this.

Nevertheless, given the uncertainties over the long-term effects, the UT procedures would need to include periodic checks for such effects. A stock of spare equipment would also need to be maintained in case these equipment checks uncover any long-term deterioration.

INEEL (2003) reported that existing ET equipment would withstand a radiation exposure of 423 Roentgens/hr (i.e. ~ 4'200 mSv/hr for gamma rays). This is well above the radiation levels required for inspection of a 140 mm thick canister.

RT would be potentially hampered by fogging of the film because the radioactive products in the canister generate strong gamma radiation, which is not coherent. Nevertheless, this problem was successfully addressed for the SKB canister project (Pitkänen 2010) by using a very high energy X-ray source (9 MeV).

### 11.4.4 Suitability for remote operation

Remote deployment of both automated UT and digital radiography systems have been successfully demonstrated for other canister projects (e.g. Ronneteg et al. 2009). Eddy current testing is essentially a non-contact inspection method and is therefore inherently more adaptable for remote deployment than MPI or PT (Watkins et al. 2006); ET techniques have also been verified for other canister projects (Stępiński 2003). On this basis, MPI and PT are rejected in favour of ET.

UT and ET systems could both be based on existing technology, but some probe development and system integration would be required (INEEL 2003).

### 11.4.5 Time required for inspection

It should be possible, through the use of multiple phased array / TOFD probe pairs, to design a mechanised UT system that can inspect the full volume of the closure weld in a single pass. Scanning speeds of 50 mm/s are typical for the mechanised systems used for zonal AUT of pipeline girth welds (de Raad & Dijkstra 1997). The Japan Atomic Energy Agency database (JAEA 2011) cites similar scanning speeds of between 10 mm/s and 80 mm/s. Based on TWI's experience, a scanning speed towards the lower end of this range (~ 10 mm/s) would be appropriate for swept beam phased array inspection of the 120 mm thick canister welds (assuming that a separate phased array probe is used for each focal 'group'). On this basis, the UT data collection time for a 1'050 mm diameter weld would be 4 – 5 minutes, which is consistent with the total data collection times in JAEA (2011). In principle, ET is capable of a faster inspection speed, because it is based on a contactless sensor and direct use of an electrical signal (JAEA 2011). Thus, the addition of an eddy current array to the inspection head would allow ET data to be collected at the same time (with negligible impact on the data collection time).

INEEL (2003) reported that the use of phased array probes would allow data collection times to be reduced by a factor of between 10 and 40, as compared with a raster scan using a single probe. On this basis, it is estimated that raster scanning of conventional UT/ET probes would increase the data collection time to between 1 and 3 hours per weld. It is not anticipated that a raster scanning system will be needed, but even if it were, it would have relatively little impact on production costs (RQ27) or on the required production rate of 1 – 2 canisters per day (RQ20).

For both UT and ET, automated data collection offers higher reliability and traceability, and allows data analysis to be performed 'off-line' so that there is less of a time constraint on the data analysis. In practice, the time required for data analysis would depend on the number of indications found. JAEA (2011) estimates total inspection times (including data analysis) of 1 – 2 hours for PAUT and 30 minutes for TOFD. These inspection times are for a canister lid weld that is 2.6 m long and 190 mm thick, so they would be very similar for the weld considered in this report. As above, the addition of an inspection using an eddy current array would have a relatively minor impact on the overall inspection time, especially if the ET and UT data were analysed by different operators.

In summary, it is very unlikely that the time taken to analyse the inspection data would affect productivity unless there were a systematic failure in the control of the welding process, in which case production would presumably be suspended pending corrective action.

## 11.5 Effect of weld design on inspectability

### 11.5.1 Unfused land

The flaws of greatest concern in Table 11.1 (e.g. lack of sidewall fusion, missed joint) are planar and are essentially oriented in the through-wall direction. If, in a partial penetration weld, the unfused land at the weld root lies in the same direction, then the only way of distinguishing a planar root flaw from the unfused land may be from the difference in position of the tip of the flaw and the nominal location of the root. In this situation, a UT operator's accept/reject decision requires the sizing of the observed reflector rather than simply detecting it. This has the following disadvantages:

- Greater operator skill required.
- Increased time required for the analysis of the inspection data, with a potential impact on production rate and costs (RQ20 and RQ27, Table 2.1).
- Reduced sensitivity to flaws; through-wall sizing errors for conventional UT could be ~ ± 5 mm (ENA 1988), so a flaw might need to be 10 mm in size before it could be reliably distinguished from the unfused land (impacting on RQ14, Table 2.1).

For these reasons, the unfused land in the proposed weld designs (Figures 8.1 and 8.2) is perpendicular to the weld centre-line. Note that none of the planar flaws in Table 11.1 would result in an extension of the unfused land in a direction perpendicular to the weld centre-line.

### 11.5.2 Access constraints

The weld design should ideally allow access to the whole weld section, from both sides of the weld, equivalent to half-skip UT of an in-line butt weld by beam angles θ up to 60° (see Figure 11.8), a level of access categorised as 'unrestricted' in ENA (1988). To achieve this, ENA (1988) recommends that the following length of surface be available for scanning from each side of the weld:

$$S_i > 2\,t_i + 20mm$$

where:

$t_i$ is the relevant wall thickness

$S_i$ is measured from the weld centre-line

$i$ = 1, 2 denotes the two sides of the weld.

For the proposed weld design, $t_i$ = 140 mm, giving $S_i$ > 300 mm. This constraint is satisfied by the set-on lid design (Figure 11.9), but not by the set-in lid design (Figure 11.10). For the set-in lid design, the lifting ring restricts the effective beam angle to θ ⩽ 45° from one side of the weld. This is likely to result in a slight loss of sizing accuracy for flaws near the fusion face on that side of the weld (ENA 1988). The set-on design is therefore marginally preferable for inspection purposes.

If the set-in lid design were adopted, the access for UT could, in principle, be improved by reducing the size of the lifting feature. However, the resulting marginal improvement in access for UT must be set against the reduction in the strength of the lid. Although this has not been specifically analysed, the structural effect of a lifting feature is examined in Section 10 of this report.

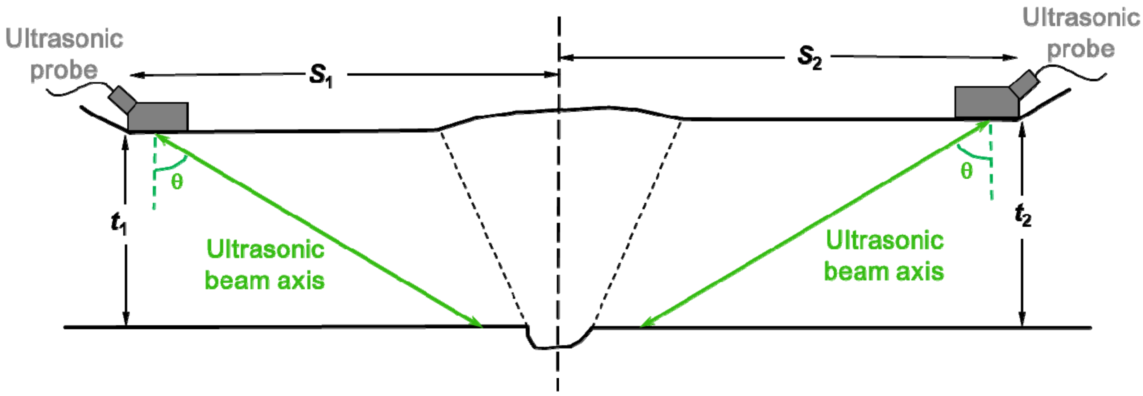



Fig. 11.8: Nomenclature used to define 'unrestricted' access for in-line butt welds (cf. ENA 1988).

## 11.6 Summary

- Some form of automated ultrasonic inspection is needed to satisfy requirement RQ14 for sub-surface flaws.
- The use of RT in addition to UT would require a more complex canister design without any obvious benefit. This would have a negative impact on costs (RQ27).
- UT and digital radiography systems have both been successfully deployed remotely for other canister projects.
- Conventional UT procedures can be designed to reliably detect a high proportion of foreseeable planar flaws of size 4 mm (TWE) × 15 mm (length).
- Advanced UT procedures can be designed to reliably detect a high proportion of foreseeable planar flaws of TWE 2 mm.
- ET is well-suited to the canister environment (i.e. remote deployment and temperatures above ~ 50°C) relative to the alternative surface methods of MPI or PT.
- ET and remote visual testing should be used to supplement UT to enhance the reliability of detection of flaws at the outer surface of the welds.
- For ET (and other surface NDT methods), dressing of the weld cap would allow much smaller flaws to be detected (RQ19).
- ET procedures can be designed to reliably detect flaws of size 1 mm (TWE) × 5 mm (length) at the outer surface as long as the surface is machined or ground smooth.
- The NDT procedures should be qualified to confirm that they are fit for purpose.

- The set-on lid design (Figure 11.9) is marginally preferable to the set-in design (Figure 11.10) for inspection purposes.
- The geometry of the unfused land in both of the proposed designs has been selected to aid inspectability.
- ASME III (ASME 2010a) and EN 13445-5 (BSI 2009a) provide appropriate guidance on other inspection issues, e.g. inspection of parent material and repairs.

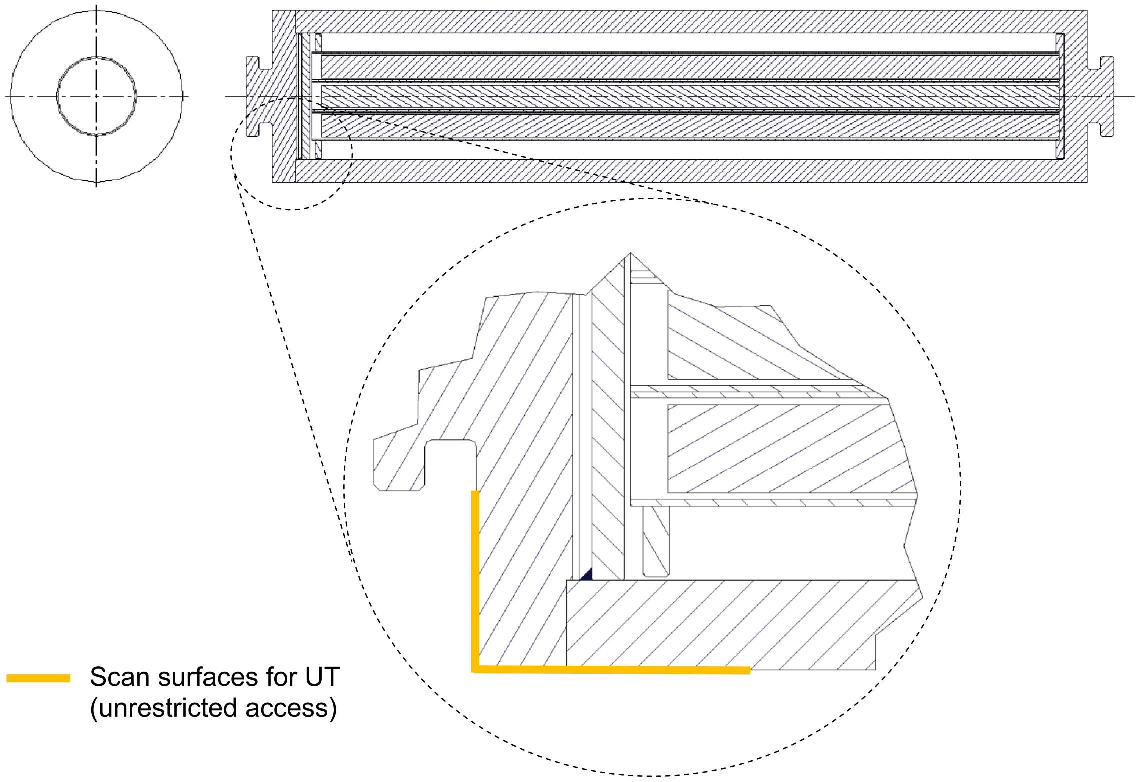



Fig. 11.9: Scanning surfaces for UT of set 'on' design (unrestricted access).

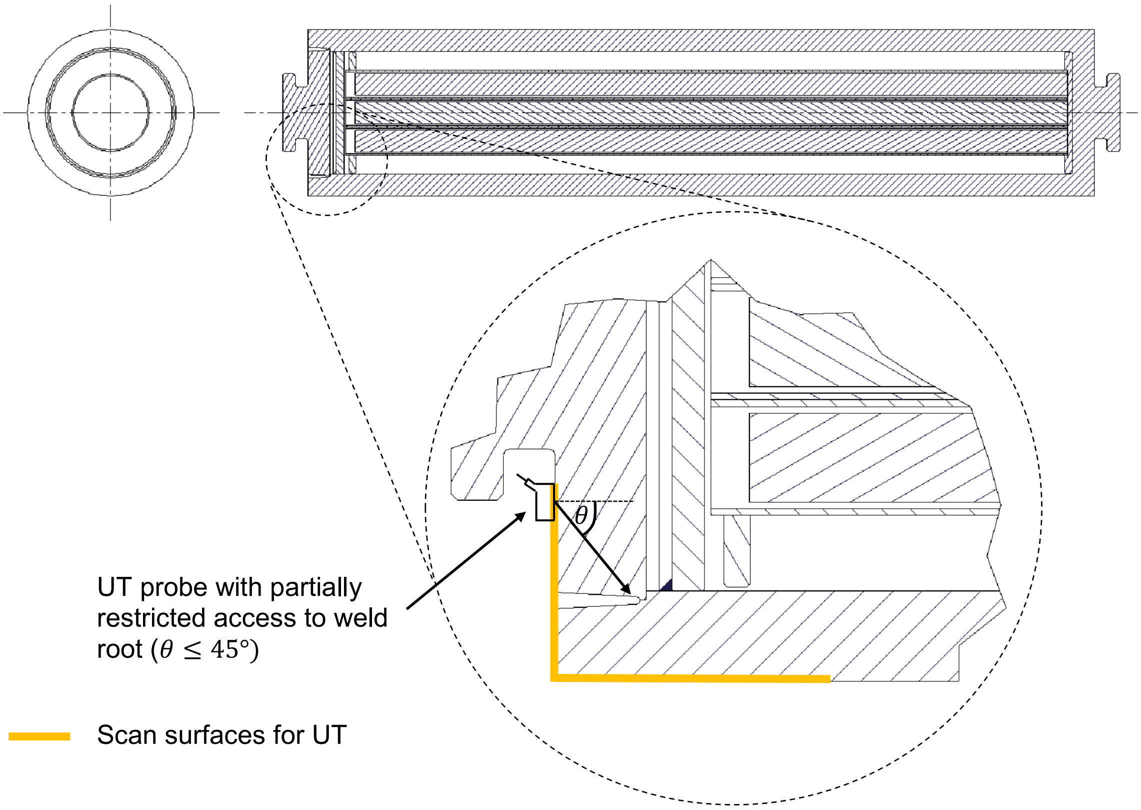



Fig. 11.10: Scanning surfaces for UT of set 'in' design (partially restricted access to weld root due to proximity of lifting feature).

# 12 Manufacturing

## 12.1 Introduction

This section contains recommendations on the most suitable option(s) for the manufacture of steel canisters that are capable of meeting the design requirements, based on current industrial best practices of making similar structures. The feasibility of the proposed method(s) for achieving required integrity based on the current design analysis is also reviewed. Other aspects of canister manufacturing considered include:

- Canister internal structure (for spent fuel canisters only).
- Marking and identification.
- Manufacturing QA plan.

Additional recommendations are made for further development work and plan for prototype manufacturing.

The requirements relating to manufacture are given in Box 12.1.

**Box 12.1 Requirements relating to manufacture**

RQ8 Structural integrity – long term.

RQ13 Residual stress reduction.

RQ18 Lifting and handling feature.

RQ20 Production rate.

RQ21 Marking/identification.

RQ22 Internal structure.

RQ28 Manufacturing best practice.

RQ30 Dimensions.

EN 13445-5 (BSI 2009c) is recommended for the control and access of records (see also Section 11.1). However, it is recommended that the retention of records is for a minimum period of the retrieval phase (currently assumed to be the first ~ 50 years after emplacement).

## 12.2 Canister body and lid manufacturing methods

### 12.2.1 Design requirements

Manufacturing of the outer canister involves producing the main body of the canister consisting of a cylindrical shell, a base (either integrated or welded), and a lid. The lid will be welded to the main canister body in a hot cell (also known as closure weld), after the waste content has been placed inside the canister.

The canisters are required to have the adequate dimension to accommodate SF and HLW (RQ30). They should also have the adequate dimensional accuracy to achieve the required fit-up for the closure weld. They need to have the quality level that meets the long term structural integrity (RQ8). In order to minimise the residual stresses as a result of welding (RQ13), the number of welds in the canister body should be minimised. All welds in the canister body (not including the closure welds) are required to have the adequate post-weld heat treatment (PWHT) cycle for residual stress reduction. PWHT of closure welds are reviewed in Section 9. Current manufacturing best practices need to be adopted for the selection of adequate canister manufacturing route (RQ28) and will be required to meet the canister production rate of 1 – 2 units per day (RQ20). The selected manufacturing route should be capable of incorporating a lifting feature to the canister lid and base (RQ18). Finally, canisters manufactured should meet the surface finish requirement that will permit NDT of the closure weld (RQ19).

### 12.2.2 Manufacturing best practices and their feasibilities

Current industrial techniques for manufacturing of nuclear waste containment and similar sized steel structures for safety critical applications include:

- Casting (steel).
- Forging.
- Pierce and draw.
- Plates formed to the required radius and joined together by welding.

Blank backward extrusion was also considered initially as a potential candidate. However, further investigation revealed that it is not feasible due to its size restrictions and limited supplier.

**Feasibility considerations**

The four manufacturing methods listed above are all capable of making components that meet the quality and dimensional requirements of the canister (RQ30 and RQ8). Based on the ECA reported in Section 10 (Table 10.5) and a safety factor of 10, a critical flaw size of 5.5 mm can be tolerated in the final closure weld with a yield magnitude residual stress and a fracture toughness of 150 MPa√m. In the canister body, the critical flaw size (calculated by ECA) is expected to be greater than 5.5 mm because there is no residual stress in the canister wall. All four manufacturing methods listed above are capable of meeting this criterion (5.5 mm) based on current industrial practices. Where welding is necessary, materials produced using the above manufacturing routes are readily weldable and the quality of welds are able to meet the requirements of the critical flaw sizes as discussed in Section 10.4.

Adequate dimensional accuracy and surface roughness can be achieved through machining for casting, forging and pierce and draw. This is to ensure that the internal structures for holding the HLW and SF can be properly inserted and an adequate fit between the two can be achieved during the canister manufacturing. For pressed plates, adequate dimensional accuracy can also be achieved through a controlled forming process, and certain areas of the canister lid and body can be treated to provide the surface condition required for NDT (RQ19). For the closure welds, adequate fit-up (variation of less than 0.4 mm in flatness) can be achieved by using a machined edge preparation.

All four manufacturing methods are capable of producing the required lifting feature on the canister lid and base (RQ18). However, for the forging, pierce and draw, and plate options, a large amount of machining may be required. For cast steel, the lifting feature can be cast to its required shape, so little machining will be required. Although casting the lid could be an attractive option due to reduced machining costs, it is more prone to manufacturing defects when compared to forging. It may be possible to use a cast lid on a forged body. However, this is not recommended because of differences in composition between the different product forms that may cause weldability issues leading to unacceptable flaws in the final closure weld.

The production rate of the canisters is largely determined by the speed of making the closure welds. With adequate planning, a sufficient quantity of canister bodies and lids can be produced in advance and made available for the closure weld operations. As such, there is no issue for any of the four manufacturing routes to meet the required production rate (RQ20).

Each of the four proposed manufacturing routes and their individual feasibilities are discussed below.

**Casting (steel)**

Casting is a very well proven method for making cylindrical structures. It has advantages in that it is relatively easy to incorporate an integrated lifting/handling feature on the canister lid and base. A small number of suppliers may be able to cast the steel canister in one piece, which brings added benefits of having only one fabrication weld. This depends on the limit in weight of the object that can be cast.

Casting defects such as porosity can be a potential disadvantage although they can be alleviated through the use of centrifugal casting albeit at a limited number of suppliers. The use of casting may also have an impact on the surface finish, and thus on the inspection and corrosion performance (see Sections 6.2.7 and 6.4). However, low-alloy cast steels are, in general, much easier to inspect by UT than cast iron (Krautkrämer & Krautkrämer 1990, Section 31.2), and they exhibit much less severe ultrasonic attenuation than that discussed in Appendix B1.2.2 for cast iron. An additional concern is the degree of segregation of alloy and impurity elements which is likely to occur in a large steel casting. This in turn would potentially cause variations in composition throughout the structure leading to inhomogeneity in mechanical and corrosion performance at different locations.

**Forging**

The following three options are considered for producing a steel canister based on forged components:

- Using two or three pieces of short forgings welded together.
- Using one piece of long forging with a welded base.
- Using one piece of long forging with an integrated base.

It is found that, despite being a very attractive option, making a long forging with an integrated base is not feasible, in that machining internal bore of the canister will be very difficult, and very few suppliers are capable of achieving this and meeting the required level of quality. The short forging (two or three pieces) option is feasible. However, a significant amount of welding (circumferential welds) is required, making this option less desirable than the long forging option due to the increased risk of potential defects in relatively large volume of weld metal being deposited. In addition, the entire canister will be subject to heat-treatment for releasing residual stress in the welds, increasing the risk of distortion as a result of heat-treatment. Using long forging with a welded base is more desirable than short forging because only one fabrication weld is required to attach the base to the canister wall, and local heat-treatment can be carried out for stress relief after welding.

**Pierce and draw (with or without integrated base)**

The principle for pierce and draw processing is described by Andersson (1998), and is illustrated in Figure 12.1. Vallourec & Mannesmann (V&M) in Germany is the only company in Europe that uses this method so there is potential issue with limited supplier. It is a proven manufacturing method for copper canisters currently manufactured for Svensk Kärnbränslehantering AB (SKB). It has the potential for making canisters with an integrated base and hence eliminates the need for any fabrication weld. However, a large amount of machining will be required after the piece and draw process to provide the required surface finish, which could be expected to give rise to high manufacturing costs.

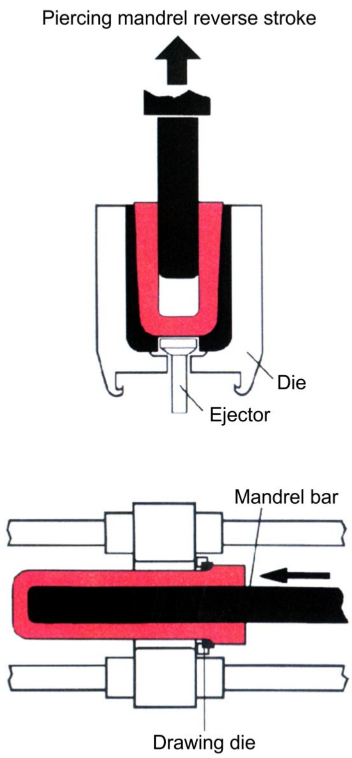



Fig. 12.1: Principle of pierce and draw (Andersson 2002).

**Pressed plates**

It is envisaged that four plates are required with length same as that of the canister body. Each plate forms a quarter of the canister wall. The plates are pressed to form the required radius. Due to their large thicknesses, bending is very unlikely to achieve the required radius so a pressing operation would be required. Handling plates of long length (around 5m) without any damage such as distortion can be difficult. A large amount of welding will also be required. Common issues associated with welding of thick cylindrical structures include weld edge preparation accuracy, fit-up difficulties and potential weld imperfections. However, with adequate control over the welding activities such as quality control to ISO 3834 requirements, this method can be seen as a feasible option for making both canister bodies and lids.

**Budgetary costs**

The budgetary costs (Table 12.1) for the long forging and the pierce and draw options are similar, at around 150 kCHF in terms of total fabricated costs. The pressed plate option is more expensive, with budgetary costs of around 230 kCHF (Table 12.1). A budgetary quote is not yet available for the cast steel option.

Table 12.1 summarises the main advantages and drawbacks of each of the manufacturing methods discussed.

Tab. 12.1: Comparison between shortlisted canister manufacturing options.

| Method | Advantages | Disadvantages | Budgetary Costs * [kCHF] |
|---|---|---|---|
| Cast steel | Ease of manufacture, low cost, minimal welding, can readily incorporate design features ie lifting rings | Porosity/density and limits of height that can be cast in one piece | Not available |
| Long forging with welded base | One fabrication weld, machined finish | Limited supplier | 160 (HZ) |
| Pierce and draw (with or without integrated base) | Proven design (SKB), minimal welding, machined finish | Limited supplier (V&M) | 150 (V&M) |
| Pressed and welded plates | Plates readily available | Lots of welding required | 236 (HZ) |

* Budgetary costs are total fabricated costs for SF canister with a wall thickness of 180 mm.

### 12.2.3 Conclusions on manufacturing methods

The following four methods of manufacturing the canister body are considered feasible and meet the design requirements as described in Section 12.2.1:

- Casting.
- Long forging with welded base.
- Pierce and draw (with or without integrated base).
- Pressed, rolled and welded plates.

Based on current available information, the long forging with welded base option is the most desirable manufacturing route. The main driver for this decision is primarily associated with the inherent high integrity of hollow forgings. The pierce and draw process is also attractive, but with single supplier (V&M only) it is only recommended to be the second best option.

Canisters produced using a casting process are more likely to contain shrinkage defects and probably would need to be cast as solid parts and subsequently bored. The hot pressing and fabrication method introduces the risk of weld flaws. The pierce and draw method also leads to some issues concerning variability in microstructure and levels of segregation in the centre of the integral base.

### 12.2.4 Potential Manufacturers

Potential manufacturers and their capabilities are summarised in Table 12.2 below.

Tab. 12.2: Potential manufacturers and their capabilities.

| Company | Geographical location | Type of supplier | Capabilities |
|---|---|---|---|
| Aubert and Duval | France | Material supplier | Capable of supply forged cylinders, but 5 m long in one-piece is too heavy to make. So it is only possible to supply short forgings (2 pieces) welded to make a 5 m long cylinder. |
| Sheffield Forgemasters | UK | Material supplier | Capable of supply hollow forgings (without integrated base) in one-piece. |
| Hitachi Zosen | Japan | Fabricator | Capable of press plates to the required radius.<br>Capable of welding and fabrication of forged, cast and wrought materials with large thickness.<br>Strong track record of fabricating road transport canisters for nuclear waste. |
| Casting Technology International | UK | Material supplier | Capable of supply cast steel cylinders but not sure whether they can cast canister wall in one-piece. |
| V&M | Germany | Material supplier | Capable of supply canister body in one piece, possibly with an integrated base. |
| Davy Markham | UK | Fabricator | Capable of welding and fabrication of forged, cast and wrought materials with large thickness. |
| Hadee Engineering | UK | Fabricator | Capable of welding and fabrication of forged, cast and wrought materials with large thickness. |

## 12.3 Workmanship and quality

It is in TWI's view that same level of workmanship and quality control for pressure vessel manufacturing should be achieved in SF and HLW canisters. In pressure vessel design codes such as EN 13445-5 (BSI 2009c) and ASME III (ASME 2010a), the results of inspection are normally assessed against 'good workmanship' or quality control acceptance criteria which are usually quite stringent. For example, the design codes do not accept planar flaws in full penetration butt welds including lack of fusion, lack of penetration and cracks. However, the inspection acceptance level will depend on the inspection capability and flaw reporting levels associated with the selected NDT techniques, which are discussed in detail in Section 11.2.

To ensure such stringent criteria are met by the two recommended welding processes for closure welds (NG-GTAW and EB), manufacturers need to demonstrate that a robust welding procedure has been developed using production welding equipment and tooling, and all welding operators are suitably qualified and are listed on a controlled 'approved welder register'. Canister manufacturers should also demonstrate adequate organisation and control of all manufacturing operations, particularly those classed as special processes such as welding, forming and heat treatment, in accordance with the requirements of EN 13445-3 (BSI 2009d) or ASME III (ASME 2010a). The quality requirements for welding defined in EN ISO 3834-3 (BSI 2005b) are required as a minimum.

## 12.4 Canister internal structure design

### 12.4.1 Design requirements

The internal structure is only required for the SF canisters. For the HLW canisters, there is no such requirement for having an internal structure. However, a spacer may be required inside the HLW canisters. Detail of this spacer is not included in the current HLW canister design but will be considered for detailed design in the future. The proposed internal structure design would be required to meet the canister design requirement, RQ22. The main purposes of the internal structures are to provide adequate clearance between the fuel rods and the canister wall, and to prevent damage to the fuels during handling and emplacement. The internal structure should remain sound during normal handling, including possible retrieval during the operational phase of the repository and should not affect the structural performance of the canister (e.g. machining grooves in the canister body in order to fit the internal structure).

### 12.4.2 Design approach

A detailed design approach is reported in Appendix E.

### 12.4.3 Recommended design concept

An internal structure consisting of 4 or 9 box sections made from carbon steels is proposed for the spent fuel canisters (Figure 12.2). The box sections are welded to each other and welded to the top and bottom plates as shown in Figure 12.2. Since there is a large span between the bottom and top plates, more disks will be used to support the box sections laterally. The number of supports required will be determined in further work. The fuel assemblies can be supported all the way along the length of the canister so that loading of the fuel assemblies is straight-forward. Depending on the detailed design, the internal structure can be made from off-the-shelf box sections in standard dimensions. Alternatively, box sections can be fabricated from two U channels joined by full penetration butt welds. A preliminary manufacturing sequence diagram of the internal structure is shown in Figure 12.3.

The current cassette dimensions were selected based on the current fuel dimensions available. Based on these dimensions, clearance was provided to take account of potential uneven geometry of the fuel such as bowing. The actual dimensions of the cassette will be reviewed and updated accordingly in future detailed design when the fuel bowing information is more readily available. The dimensions of the slots/cells can be easily modified by increasing or decreasing the thickness of the plates used for making the internal basket structure.

The use of cast iron for the fabrication of the insert was discarded due to concerns with overall weight, cost and manufacturing quality concerns.

To ensure that RQ22 is met, base materials will be required to meet the quality requirements of BS EN 10025 (BSI 2004 – 2009) or equivalent national/international standard. Welds in the structures will be designed to over-match the strength of the box section material and will be produced using a welding procedure qualified to BS EN ISO 15614-1 (BSI 2004c) standard. Welds will be subject to 100 % visual examination, and 100 % magnetic partial/liquid penetrant examination.

Based on the recommended box section design, a budgetary cost of between 4.5 and 34 kCHF is estimated for producing the internal structure depending on detailed design and manufacturer. The recommended design (using box sections) has the lowest budgetary costs compared to the other proposed concepts (Appendix E).


Fig. 12.2: Drawing of the recommended internal structure design for BWR canisters.

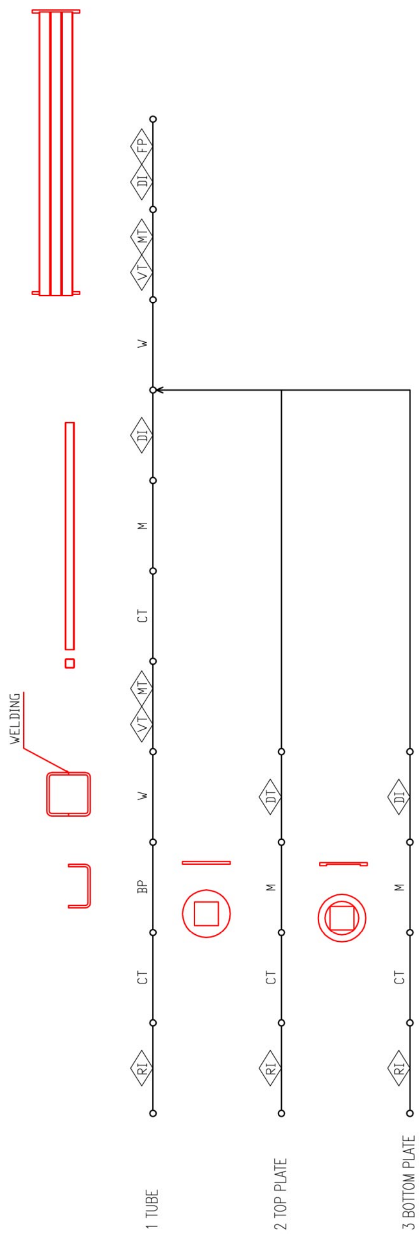



Fig. 12.3: Preliminary manufacturing sequence diagram for the recommended internal structure design.

## 12.5 Marking and identification

### 12.5.1 Requirements

It is required that a unique identification is given for each canister so that it is possible to identify the SF and HLW within the canister (refer to Task 1 report RQ21) and this identification can be incorporated on the lid or canister body. The marking is required to withstand several mm of corrosion during the operational phase (50 years) of the repository. It must be unique and unambiguous, and have a minimum effect on the material properties and long term corrosion performance of the canister.

### 12.5.2 Location of marking

Since the marking needs to be deep enough (at least several millimetres in depth) to withstand 50 years of corrosion and scaling from heat-treatment, it is required to be located in a region where the integrity of the canister is least affected. Therefore, the lifting feature integrated to the lid of the canister is an ideal location to place the marking, because this region is subjected to low stress. In addition, marking can be made relatively easily on the top of the lifting feature after the closure weld is made in the hot cell. In the event of retrieval, the lifting feature will be the first part of the canister that can be exposed for visual identification prior to retrieval.

### 12.5.3 Potential marking schemes and their feasibilities

A list of marking and identification methods has been generated after a brainstorm exercise, as shown in Table 12.3, together with feasibility and issues associated with each option.

Tab. 12.3: Possible marking and identification methods under initial consideration.

| **Marking and identification methods** | **Feasibility** | **Comments** |
|---|---|---|
| Hard stamping (low stress or ball face stamping) | Not feasible | Marking not deep enough to withstand 50 years of corrosion |
| Drilling round-bottomed holes | Feasible | Needs to be located at low stress region such as on the lifting feature |
| Grooves milled with ball-ended cutter | Feasible | Needs to be located at low stress region such as on the lifting feature |
| Bar code stripes | Not feasible | Corruption concerns |
| Ink/paint marking | Not feasible | Marking not durable enough to withstand the environment |
| Magnetic stripes | Not feasible | Danger of corruption |
| Milled alpha numeric | Not feasible | Danger of corruption, not as safe as binary coding |
| Separate tags (made of corrosion resistant metal) | Not feasible | Can fall off or galvanic corrosion issues |
| Embedded nails | Not feasible | Galvanic corrosion issues |

The following two schemes are regarded as feasible:

- Drilling round-bottomed holes.
- Grooves milled with ball-ended cutter.

### 12.5.4 Identification system

The preferred option is the binary dot matrix system, which can be marked by drilling holes on the top surface of the lifting feature (Figure 12.4) or cutting grooves along the edge of the lifting feature (Figure 12.5). Drilling holes is preferred than cutting grooves, for the following reasons:

- Orientation of the dots can be made to indicate the scanning sequence of the matrix.
- Holes can be made deep enough (e.g. 5 mm deep) to provide sufficient corrosion allowance for 50 years.
- Less risk of corruption than the alpha-numeric system.
- Can be filled with bentonite paste for added visibility.
- Straightforward to implement after completion of closure weld in the hot cell.
- Very little and simple robot (linear) movement is required compared to making grooves at the edge of the lifting feature.
- Marking can be easily read by most scanners currently available such as a laser scanner.

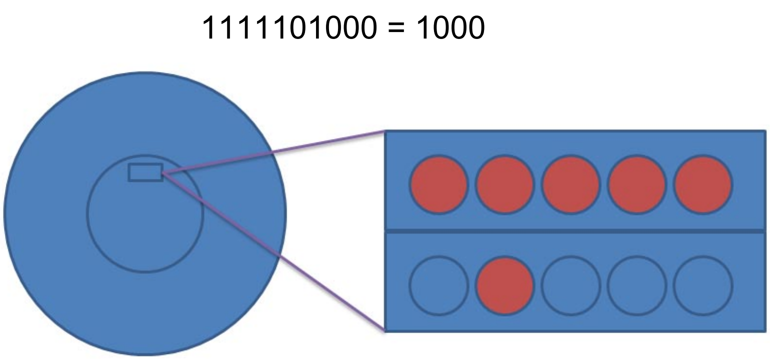



Fig. 12.4: Linear binary dot matrix system made by drilling round-bottomed holes in the lifting feature.

The marking indicates this is canister number 1000. Red indicates drilled holes and blue undrilled positions.

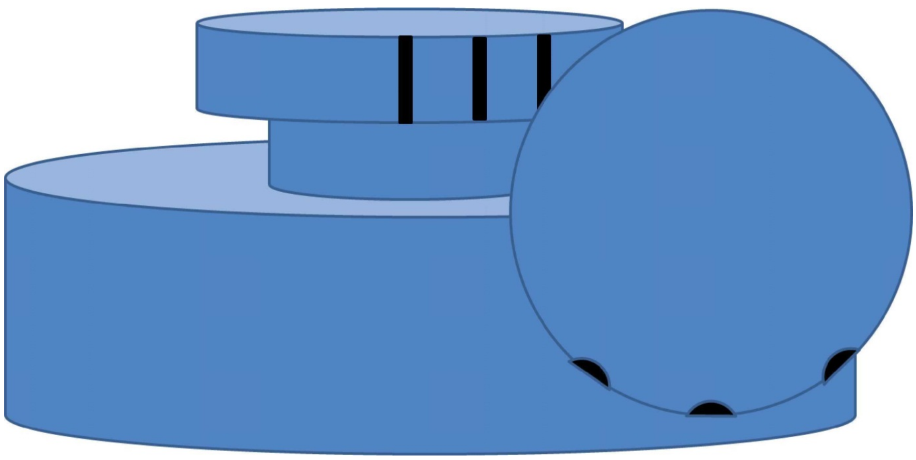


Fig. 12.5: Option for using binary system based on cutting grooves at the edge of the lifting feature.

### 12.5.5 Dimension of the marking

For the linear binary dot matrix system, the drilled holes should be at least 5 mm deep and the distance between each hole should be kept to at least 3 mm.

### 12.5.6 Conclusions on marking and identification scheme

A linear binary dot matrix system based on Figure 12.4 is recommended. The matrix will be located on the top surface of the lifting features by drilling holes that are at least 5 mm deep and 3 mm apart. Marking will be produced by a robot after the completion of closure weld in the hot cell. The dot matrix can be read using a laser scanner for the identification of canister prior to retrieval.

## 12.6 Manufacturing QA plan

The preliminary manufacturing sequence diagrams containing inspection and testing plans for each manufacturing methods (Section 12.2.3) are available in Appendix D. The will form an essential part of the manufacturing QA plan during detailed design.

## 12.7 Recommendation for further work to be incorporated in future canister development plan

- Produce a full-size forged canister body and carry out destructive testing and non-destructive testing to confirm mechanical properties and extent of flaws in the material.
- For the canister base-to-body weld, develop appropriate welding procedure to be qualified in accordance with BS EN ISO 15614-1 (BS 2004c) requirements. Qualification should include full PWHT cycle.

## 12.8 Summary

A number of requirements are addressed within the canister manufacture – including consideration of having a nominally stress free canister prior to manufacture of the closure weld (RQ13). Various canister manufacturing methods representing current industrial best practice (RQ28) were reviewed and the preferred method of using a long forged cylinder with a welded base is capable of achieving the required long-term integrity (RQ8) and the required production rate (RQ20). Canister dimensions and the required dimensional tolerance can be achieved by machining the internal bore of the forged cylinder (RQ30). An indelible unequivocal marking system has been devised which does not impact on the performance of the canister but is estimated to be legible after many hundreds of years after emplacement (RQ30). An internal structure with a box section arrangement has been proposed and is a cost-effective way of providing support to the fuel assemblies with the required sizes (RQ22).

# 13 Summary of Canister Design Concept Development

## 13.1 Introduction

The analyses described in the preceding chapters have found that a canister design that fulfils all of the pre-defined canister requirements is expected to be achievable for both spent fuel and high level waste. The critical requirement is that the canisters survive a minimum of 1'000 years in the anticipated repository environment without being breached. In turn this requirement raises the question of the mechanisms that potentially could cause breaching of the canister either singly or in combination during the lifetime of the repository.

Within this document, the approach adopted was, first, to propose concept designs for a SF canister and a HLW canister, based on sound engineering principles and considering knowledge developed in the preparation of the design requirements. The canister concept was then evaluated to assess whether the design requirements were met and, if not, modified accordingly. The process was repeated iteratively until all of the requirements were shown to be satisfied by an adequate margin.

It is important to note that the basic design focuses principally on meeting the requirements that are associated with structural performance without breach of containment over the canister life. This has been achieved through the selection of a parent material and welding consumable with low corrosion and no known cracking mechanisms in the environment, specification of adequate thickness to ensure sufficient load carrying capacity in the corroded condition, and the avoidance of fracture through limiting the size of welding defects allowable through inspection and repair and controlling residual stress. Therefore, the requirements related to structural performance set the basic assumptions for the design.

It will have been noted, as stated in Section 2, that many of the requirements use the phrase "adequate margin" in relation to the avoidance of "failure" of the canister. Both "adequate margin" and "failure" have been explained, earlier, but are reiterated here. The term "failure of the canister" should be interpreted as any loss of containment through the existence of a leak path between the inside and the outside. An "adequate margin" should be determined by a process designed to address levels of uncertainty and potential errors so that the risk of failure is reduced to be as low as reasonably practicable.

The process for determining an adequate margin should be based on current good practice for the construction of nuclear containment. Practices defined by relevant standards for unfired pressure vessels can be applied where these are appropriate since the purpose of these standards is to construct a vessel that maintains its containment when subject to a variety of possible loadings. Current good practice has been established and updated by industry standards committees.

It is recognised that a disposal canister is different to a pressure vessel in terms of constraints after filling with waste, the principal modes of loading and service conditions, and inaccessibility for in-service inspection. The requirements of pressure vessel standards may need to be modified to take these aspects into account. Where it is not possible or reasonable to apply normal practice (such as in the requirement for post weld heat treatment), then alternative measures, tests or analyses may be needed to provide sufficient specific evidence that the proposed construction is fit-for-purpose.

The design and construction should make assumptions that are suitably conservative. The level of conservatism on any particular aspect should reflect its uncertainty or variation. Partial safety factors are a way of dealing with aspects that may have differing levels of uncertainty or variation. A single factor (such as the use of a factor of three on tensile strength in the ASME III code; ASME 2010a) may not be a sufficient basis for design when multiple failure modes have to be considered.

Ultimately the project will define and propose a suitable design basis and acceptance criteria. As to what is "adequate" will finally be decided in a dialogue between the project and regulators following the principles above. In some jurisdictions (e.g. US) adequacy is defined solely by compliance with a code (e.g. ASME). This prescriptive approach may not be appropriate for nuclear waste canisters managed under a different regulatory regime.

## 13.2 Basic form

Initially, certain proposals were made about the geometry and basic form of the canister. These proposals were not arrived at arbitrarily but rather, were based on the structural performance and operation requirements defined in the canister requirements specification. This led to the basic design concept which dictated that:-

- The canisters would be produced from plain carbon steel.
- The canisters will be cylindrical in form with a lid and base that will be nominally flat. One or both ends of the canisters will have a handling feature.
- The design would enable SF or HLW to be loaded vertically from the canister top.
- An inner lid would be required to eliminate the risk of radioactive contamination in the closure welding cell. The design details have not yet been developed.
- Final closure before emplacement would be achieved by welding.
- The minimum thickness and diameter would be based on the quantities/dimensions of the fuel/waste, shielding, and strength considerations.
- The canister would be delivered for emplacement in an un-coated condition.

The proposed nominal dimensions and approximate weight of the HLW and SF canister designs (loaded and unloaded) are presented in Table 13.1, below. It should be noted that Nagra proposed the thickness of the lid of the SF canister of 180 mm after the design study had commenced. The SF canister design study was based on a nominal lid thickness of 140 mm although, in order to incorporate a self-locating weld joint detail of 10 mm, the uniform section thickness of the lid was actually 150 mm and this value was used for the stress analyses. The thickness value for the uniform section of the base used in the stress analysis was 140 mm.

Tab. 13.1: Nominal design dimensions and expected weights of HLW and SF canisters.

| | HLW Canister | SF Canister |
|---|---|---|
| Total length [mm] (including end features) | 3'233 | 5'350 [3] |
| Inside length [mm] | 2'613 | 4'660 [2] |
| Internal diameter [mm] | 440 | 770 |
| Outer diameter [mm] | 720 | 1'050 |
| Wall thickness of canister body [mm] | 140 | 140 |
| Nominal thickness of base [mm] [1] | 150 | 180 |
| Nominal thickness of lid [mm] [1] | 170 | 180 |
| Approx. unloaded weight of canister [kg] | 6'400 | 17'100 |
| Total weight of canister contents [kg] | 960<br>(2 flasks filled with HLW) | 4'960<br>(9 KKL BWR fuel assemblies + basket) |
| Loaded weight of canister [kg] | 7'360 | 22'060 |

[1] Not including the substantial handling feature.

[2] Inside length of SF canister which accommodates the longest fuel (KKL BWR fuel).

[3] This total length assumes a lid thickness and base thickness of 180 mm.

## 13.3 Material

It was concluded that the selection of material was a dominant factor which influenced most of the design requirements either directly or indirectly. Nagra stated that the material should be an iron based alloy which led to a choice between steel and cast iron. Cast iron, although considered to have appropriate physical properties and possibly could be manufactured in the product form required, was rejected on the grounds of suitability for closure welding. Deliberation on the selection of a suitable steel specification followed.

The basic requirements are that the steel is sufficiently strong with adequate ductility at the range of service temperatures proposed. The material also had to be readily weldable. It has to have low susceptibility to general or localised corrosion enhanced degradation mechanisms with adequate tolerance to hydrogen embrittlement.

For these reasons, and, in particular, because of a need to demonstrate a low probability of failure by stress corrosion or hydrogen induced cracking mechanisms after closure welding, a steel with lean composition and with specified tensile strength as low as reasonably practicable was proposed for the first design iteration.

The benefit of specifying a low strength steel is that with low hardenability and minimal alloy content the risk of generating levels of hardness and weld microstructures with susceptibility to SCC and HIC is reduced. General corrosion behaviour of this type of steel has been demonstrated already and toughness and ductility properties were specified taking account of the fact that the temperature of the material in the canister is not anticipated to drop below 35°C during the intended lifespan.

## 13.4 Corrosion

Following general consideration of anticipated environmental conditions and material selection a number of implications regarding the corrosion behaviour were identified and considered alongside the proposed canister design.

For the purposes of the long term stress analyses a wall loss of approximately 20 mm as a result of uniform corrosion was assumed by the end of the target design lifetime of 10'000 years.

The risk of SCC is highest during the early aerobic phase because of the need for a suitable environment and relatively oxidising conditions. As a consequence, techniques for relief of the near-surface residual stress and removal of surface-breaking (or near-surface) defects could significantly reduce the possibility of SCC.

In contrast, HIC/SOHIC are possible only during the long-term anaerobic period.

Therefore, both surface-breaking and sub-surface weld defects can potentially act as stress concentrators for HIC/SOHIC. Accumulation of gaseous $H_2$ (after many centuries) inside the canister could result in HIC/SOHIC from the inner surface, particularly at un-repairable defects or regions of high residual stress in the closure weld.

## 13.5 Closure welding

It was accepted in the basic design review that it was necessary to close the canister by welding. In view of the requirements for remote operation, material thickness and weld quality two processes were short listed: NG-GTAW and EB welding. Consideration of these processes and NDT requirements led to the decision that the lid configuration should be set-on rather than set-in and welding carried out in the ASME 2G (horizontal-vertical) position. The review showed that both processes were capable of achieving the required joint albeit with differences in weld properties and resultant residual stress distribution. Both processes require similar accuracy in terms of fit up and neither needs pre-heat in steel of the type selected. Also, the importance of avoiding surface flaws and the effect of surface condition on inspection sensitivity dictates that removal of excessive weld metal (weld cap) by machining or grinding would be necessary for both processes. Although the major differences between the processes are in productivity and implementation, both processes are able to meet the productivity requirements of completing 1 – 2 closure welds per day in the encapsulation facility (RQ20).The final choice of process may depend on the consequences of the benefit in a tenfold difference in productivity between EB and NG-GTAW measured against the complication of providing a reduced pressure environment for welding in a hot cell.

## 13.6 Residual stress

The basic FE analysis showed that the closure welding using either NG-GTAW or EB process generated regions of yield magnitude tensile residual stresses. Although the distribution of stresses differed for the two processes, calculations showed the combination of anticipated lower bound fracture toughness, worst case applied stresses and inspection capability, that this level of residual stress probably could be tolerated. It remains however, that the requirement to minimise the risk of SCC initiation and, in particular, HIC crack growth from the un-fused land at the weld root may indicate that reduction of tensile residual stresses is necessary at the internal surface and through the wall section. It needs to be established if it is necessary to reduce the tensile residual stresses arising from welding and manufacture and, if so, to what level. In view of the low strength steel selected (and the reduction in yield strength with temperature), and based on initial scoping calculations described in this report, it is proposed that a reduction of residual stress to 80 % of the specified minimum yield strength of the steel would be sufficient. This requires confirmation by experiment. Consideration of local post weld heat treatment by finite element analysis, as described in Section 9.7, has illustrated that a local thermal stress relief heat treatment could be applied with some restrictions to avoid the risk of overheating the waste package contents. This would provide the most comprehensive stress relieving solution although it is recognised that it may be possible to achieve an adequate degree of stress relief by other local methods. This aspect will form one of the main focus elements of the canister development programme.

## 13.7 Structural analysis

It was recognised that the proposed canister design should be assessed for resistance to the geological and hydrostatic loads, dynamic loads occurring as a result of a handling incident and for resistance to brittle fracture due to the combination of the presence of flaws and applied and residual stresses.

The most immediate requirement identified was that the sealed canister must accommodate the lithostatic load from the geological over burden. To this end it was necessary to assume that no buffering of stress is offered by the bentonite fill and thus the maximum possible lithostatic stresses can develop. It was assumed also that these loads are anisotropic and therefore 22/29 MPa was adopted as the proposed maximum load on the disposal canister.

Structural FE analysis carried out using the selected material properties showed that it was necessary to remove the local stress concentration caused by the detail provided for attachment of the inner lid when the long term stresses were applied. Similarly, introduction of a lifting/retrieval feature at either end of the canister significantly reduced the size of the regions of localised plasticity predicted on the inner surfaces of the base and lid regions under the most demanding long term conditions; i.e. where the canister wall was assumed to be reduced in thickness by 20 mm and the maximum anisotropic (22/29 MPa) stress levels had developed. Generally, due to the low levels of applied stress, the short term behaviour was considered safe. The security of the long term behaviour, however, was shown to rely on the ability of the canister to accommodate some plastic deformation and thus an acceptance criterion based on gross plastic deformation (5 % max.) was proposed in accordance with EN13445-3 (BSI 2009d).

This work predicted safe behaviour under the most severe loading conditions but also led to the conclusion that there was some uncertainty in loading conditions particularly with regard to internal pressurisation with time or the effect of evacuation if EB welding were to be employed. It also highlighted the necessity for a structured method for application of safety factors.

## 13.8 Engineering critical assessment

An engineering critical assessment was performed to assess the influence of residual stress and fracture toughness on critical flaw sizes. This indicated that the maximum applied stress combined with a yield magnitude residual stress for the base material and lowest envisaged level of fracture toughness (85 MPa√m) at ambient temperature resulted in the worst case situation with a critical flaw height of 22 mm. This also assumed a worst case situation where the flaw was surface breaking at the outer surface.

In consequence, it was concluded that on the basis of the calculations and assuming an arbitrary safety factor of 10 the canister would be safe if the detection and sizing limitation of the applied NDT processes could reliably detect and size flaws of 2.2 mm. By assuming a more appropriate safety factor of 2 the NDT detection and sizing requirement is increased to 11 mm which is considered readily achievable. Clearly there are many conservative assumptions here which are additive. Acceptance criteria, specification of minimum toughness requirements and target residual stress levels are to be defined.

The probability of flaws of this size (critical flaw height of 22 mm) existing in the canister are to be minimized by selecting manufacturing processes whose inherent integrity has been proven and by performing appropriate inspection throughout the fabrication process to detect defects of concern. The canister can be discarded at any point before the spent fuel or HLW is loaded. The greatest risk of introducing and failing to detect defects is from the closure welding process and subsequent inspection which have to be done remotely and as such are inherently less reliable than when there is direct manual oversight.

Comprehensive weld and inspection procedure development and qualification in the canister development programme can optimise and demonstrate the reliability of these processes. It will reduce the probability of detects of this size or greater existing in the canister. Current experience from comparable applications and engineering judgment suggest that the probability of such defects would be extremely low.

## 13.9 Dynamic behaviour

The requirements definition specification stated that the most severe handling incident might involve dropping the canister from 5 m onto the tunnel floor. FE modelling of the incident showed that in the absence of flaws and residual stresses the canister would remain intact during and following a 5 m drop event onto a solid concrete floor. The analysis constitutes a general test of robustness only, as the handling details are not yet defined.

## 13.10 Retrieval

Bosses were built into the design for the canister base and lid to provide local strengthening of the end of the canister as well as features to facilitate lifting and retrieval of the full canister. In addition it was postulated that the boss on the lid could be used for manipulation of the lid in the remote handling equipment in the closure welding cell and also provide a benign location for the canister identification marks. The retrieval loads were estimated and the bosses were concluded to have sufficient strength to accommodate the retrieval loads.

## 13.11 Implications of stress relieving of closure welds

The prime driver for the concept design for the canister is the demonstration of avoidance of breaching under the most severe conditions anticipated over the intended lifetime of the canister. To this end, all of the possible failure modes have been considered, many of which are dependent on interacting factors. In particular, the magnitude and distribution of residual stresses resulting from manufacture and closure of the canister have a direct influence on most of the possible failure mechanisms.

Minimising the level of tensile residual stresses reduces the risk of failure by brittle fracture by increasing the critical flaw size and thus reducing the demands on inspection efficacy. This argument requires that residual stresses are lowered throughout the canister wall thickness. Similarly, reduction of tensile residual stresses to below a certain level eliminates the risk of SCC initiation and HIC cracking. The former is an issue at the outer surface only, whereas HIC can occur from the inner surface of the canister. The use of a thermal stress relieving heat treatment can achieve sufficient reduction in tensile residual stresses to eliminate the risk of these failure mechanisms but has the disadvantage that the temperature and time may need to be restricted to protect the integrity of the contents of the canister. In addition the local application of traditional thermal post weld stress relief requires care to prevent the introduction of further stresses by excessively steep thermal gradients. It can also be a lengthy process impacting on throughput in the encapsulation process. Other localised methods for stress reduction have been identified which could be used to provide stress relief of the outer surfaces of the canister but need to be proven and the effective depth of treatment measured in the proposed canister development programme.

It is concluded therefore that the implications and constraints required for thermal stress relief be examined by modelling and experiment. The effectiveness of treatment at lower temperatures and soak times than employed traditionally should be examined in the canister development programme and compared with the results achievable with local surface applied methods.

## 13.12 Inspection

Having established a critical flaw size and considering the requirements for avoidance of brittle fracture and initiation of SCC it was concluded that some form of ultrasonic inspection is needed to satisfy requirement RQ14 for sub-surface flaws. It is concluded that conventional UT procedures can be designed to reliably detect the majority of foreseeable planar flaws of size 4 mm (TWE) × 15 mm (length) whereas it has been established in similar components that advanced UT procedures can be designed to reliably detect the majority of foreseeable planar flaws of TWE 2mm. It was noted that the use of RT in addition to UT would require a more complex canister design without any obvious benefit. This would have a negative impact on costs (RQ27) and structural performance.

Considering suitability for operation in a radiation field with a dose rate of the level stated, both UT and digital radiography systems have been successfully deployed remotely for other canister projects in a radiation flux orders of magnitude higher than anticipated here.

For surface inspection ET is well-suited to the canister environment (i.e. remote deployment and temperatures above ~ 50°C) relative to the alternative surface methods of MPI or PT.

It is recommended that both ET and remote visual testing should be used to supplement UT to enhance the reliability of detection of flaws at the outer surface of the welds and it is likely that ET procedures can be designed to reliably detect flaws of size 1mm (TWE) × 5 mm (length) at the outer surface as long as the surface is machined or ground smooth.

It is strongly recommended therefore, both for ET and other surface NDT methods that dressing of the weld cap is carried out for reasons of improving inspection reliability and avoidance of SCC initiation sites. This creates issues of its own (swarf, etc., potentially creating hazardous waste in the hot cell, the need for removal of excess material, and possible accidental damage to the surface due to grinding). These issues will need to be considered in due course in consultation with the manufacturer of the hot cells. Some nuclear waste canister projects have ground the weld cap. It is suggested that this practice is reviewed and the best practice adopted from these other projects.

The NDT procedures should be qualified to confirm that they are fit for purpose.

## 13.13 Manufacture

The manufacturing study showed that the canister design proposed can be manufactured in serial quantities by a variety of methods with open die forging and welding to produce a close end being preferred. The pierce and draw method is also an option but introduces some difficulties with machining the bore of the canister which appears necessary to achieve the surface condition for inspection and to allow fitment of the internal support structure. An indelible unequivocal marking system has been devised which does not impact on the performance of the canister but is estimated to be legible after many hundreds of years after emplacement. To ensure adequate workmanship and quality control, manufacturers are required to demonstrate compliance as a minimum to the requirements of the pressure vessel design codes EN 13445-3 (BSI 2009d) and ASME III (ASME 2010a), in terms of organisation and control of all their manufacturing operations for the SF and HLW canisters. Manufacturers performing any welding activities should be certified to ISO 3834-3 (BSI 2005b) requirements as a minimum.

## 13.14 Summary

In summary the analyses described in the preceding chapters have illustrated that a canister design that fulfils all of the pre-defined canister requirements has been achieved for both SF and HLW. The most critical requirement is that the canisters survive a minimum of 1'000 years in the anticipated repository environment without being breached. In turn this requirement raises the question of what mechanisms potentially could cause breaching of the canister either singly or in combination.

The most immediate requirement is that the sealed canister can survive the static stress from the geological over burden. It is assumed also that these stresses are anisotropic and therefore a vertical stress of 22 MPa and a horizontal stress of 29 MPa have been adopted as the extreme bounding case.

# 14 Conclusions and recommendations

Within this document, conceptual designs for the HLW and SF (PWR and BWR) disposal canisters have been developed. The canister designs have been supported by detailed discussion of material, corrosion, structural performance, weld design, inspection and manufacturing issues. Evidence has been sought to demonstrate that the proposed designs would be capable of reaching a minimum 1'000 year lifetime without breach of containment.

The disposal canister designs have been developed principally to meet the requirements that are associated with structural performance. In addition, the evidence presented gives confidence that the design concepts proposed should be capable of meeting or exceeding all of the canister requirements (RQ1 to RQ30), given further development work. The main concluding remarks and follow-on recommendations are presented here.

**Canister requirements**

- The canister requirements established at the outset of the study provided an essential basis for design development. The requirements need to be made progressively more quantitative which will allow assessing whether parameters are within defined acceptance criteria. The method of formally evaluating and accepting the requirements should be developed.

**Material and corrosion**

- Plain-carbon steel is the preferred material type for the SF and HLW disposal canisters, if steel is to be selected. A bespoke carbon steel composition with a low hardenability is suggested because it lends itself weldable by the selected processes and has a low susceptibility to general corrosion and stress corrosion cracking in the conditions predicted in the repository.
- The susceptibility of steels to stress corrosion and hydrogen induced cracking increases with yield strength. Therefore, it is proposed that the strength of the steel is specified to be as low as reasonably practicable within a specific range such that the yield strength is sufficient to meet the structural requirements of the canister. The steel selected should be subjected to a suitable testing regime to ensure that it achieves the mechanical property requirements.
- The exact level and distribution of hydrogen in the canister body at any given time is difficult to predict. Therefore the fracture toughness is assumed to be at a minimum value (of the order of 85 $MPa\sqrt{m}$ based on current data and understanding) for the life of the canister.
- Failure of the canister by SCC is considered unlikely because of the material selected, general absence of specific SCC agents in the repository environment and because of the absence of cyclic loading. Whilst SCC is unlikely to occur, the highest susceptibility would be during the early aerobic phase when a suitable environment and relatively oxidising conditions may exist. Relief of near-surface residual stress could significantly reduce the possibility of SCC. Further studies of the potential for SCC for conditions associated with the early stages after canister emplacement may be necessary. The tests should examine the effect on stress corrosion cracking susceptibility of a range of residual stress levels to provide an indication of the required level of residual stress reduction, should this prove necessary.

- Conditions for hydrogen-induced cracking (HIC) and stress-oriented hydrogen-induced cracking (SOHIC) could exist only during the long-term anaerobic period. Both surface-breaking and sub-surface weld defects could potentially act as stress concentrators for HIC/SOHIC. Accumulation of gaseous $H_2$ entering the canister by diffusion through the wall could result in HIC/SOHIC from the inner surface, particularly at defects or regions of high residual stress in the closure weld. Further studies in this area are needed and the specific conditions for such investigations depend on the outcome of welding and residual stress studies. A better understanding of long-term HIC and its relationship to residual stress is necessary and this should be obtained through mechanistic modelling and obtaining of better data for the threshold stress for crack growth.
- The likelihood of significant microbially-induced corrosion is low because the bentonite around the canister would limit microbial viability. Nonetheless, studies of corrosion of carbon steel in situ in bentonite / Opalinus Clay should be performed to assess the extent of microbial impacts on anaerobic corrosion rate.

**Closure welding and residual stresses**

- Welding is proposed for the final closure of the canister. Both electron beam (EB) and narrow gap gas tungsten arc welding (NG-GTAW) processes are possible options for the closure weld. Both are suitable for remote operation and welding parameters can be selected to achieve the required weld properties and quality. Appropriate welding procedures should be developed and qualified in accordance with BS EN ISO 15613 (BSI 2004b) requirements. In order for a decision to be made between NG-GTAW and EB welding, it is recommended that weld procedure qualification is achieved by welding a representative test piece under conditions as close as possible to production welding conditions using production tooling.
- A set-on lid design is recommended for both a NG-GTAW and EB closure weld. Also, the set-on lid design is preferable to the set-in design for inspection purposes.
- For NG-GTAW the 1 layer, 1 pass method with multiple welding heads, is recommended resulting in the time for completion of one closure weld to be estimated to be between 8-10 hours. For EB welding it is estimated to be approximately 70 minutes.
- Modelling of the EB and NG-GTAW welding processes show that residual stresses could be of yield level magnitude albeit with different range and distribution.
- An initial assessment of the magnitude, distribution and effects of residual stress from welding indicates is that there could be a possibility of hydrogen induced cracking (HIC) and stress corrosion cracking (SCC) after the canister is emplaced in the repository, unless the residual stresses are reduced sufficiently. As well as substantiating the risk more clearly, methods to reduce residual stress from welding should be evaluated in further work. The levels of residual stress and post weld stress reduction required need to be investigated.
- Mitigating residual stress while preventing overheating of the HLW is one of the most significant issues with the proposed design and more detailed analysis and experimental verification is needed. Thermal stress relief by post weld heat treatment (PWHT) is the standard method for achieving effective reduction of residual stress through thickness. A preliminary simplified steady state thermal FE analysis of local PWHT has shown that maintaining the canister closure weld at a relevant temperature for stress relief for a sustained period could also raise the temperature of the top of the HLW above its upper limit of 450°C. It is recognised that a transient heat transfer analysis of the entire PWHT cycle is necessary to optimise the local PWHT temperature and soak time and explore the effect of slight modifications to the canister's design to prevent overheating the HLW during PWHT. In addition, similar analyses of the SF canister should be performed.

- The best strategy for welding residual stress reduction lies between full post weld heat treatment (PWHT) and surface treatments. It will depend on the balance between the risks of overheating the HLW or SF contents with PWHT, and of the probability of brittle fracture, HIC and SCC occurring after the canister has been emplaced, given that residual stress reduction is more restricted if partial PWHT or surface treatments are used.
- Surface treatment methods, such as laser peening or burnishing have the potential to reduce tensile residual stress local to the outside surface, but would leave residual stresses elsewhere in the weld relatively unchanged. Surface treatment may be a viable option if risks of HIC from the weld root and brittle fracture of fabrication defects in reduced toughness material after hydrogen uptake can be shown to be acceptably small. Such treatments would need to be proven and justified for the proposed canister design.
- Current assessment is that even with good welding quality, inspection and repair strategy, stress relief would be necessary to achieve an adequate margin against fracture if the potentially low fracture toughness as a result of hydrogen uptake based on limited current data were confirmed. Improved knowledge of the effect of hydrogen on fracture toughness of relevant material is necessary as well as appropriate fracture toughness testing of suitably hydrogen charged specimens. A better understanding of the minimum stress required to guarantee the avoidance of HIC and SCC in the long term condition has to be obtained through mechanistic modelling backed up by long term corrosion testing.
- The final selection of welding process for closure welding will need to take account of ease of application, productivity requirements, achievable weld properties and the magnitude, range and distribution of residual stresses resulting from closure welding. The practical difficulties of applying and controlling local PWHT remotely using robotic devices in a closed cell need to be considered.
- An inner lid is required to ensure elimination of possible contamination in the welding cell. The details of the lid design remain to be developed.

**Structural performance**

- Initial structural analyses indicate that the proposed SF and HLW canister designs are not at risk from failure by plastic collapse under the worst case loading conditions in the repository:
  - In the short term condition the SF canister has a safety margin of ~ 10.
  - In the long term condition the SF canister (Design 2) has a safety margin of ~ 1.8, if 20 mm of corrosion is assumed.
  - In the long term condition the HLW canister has a safety margin of ~ 2.5.

  Further analysis to demonstrate compliance with EN 13445 (BSI 2002 – 2011) will be necessary.
- For the SF canister under long-term, in-situ conditions, (i.e. with anisotropic applied stress of 29/22 MPa), assuming a yield level residual stress (220 MPa) and fracture toughness value ranging from 100 to 300 MPa√m, a 30 mm semi-elliptical external reference flaw (postulated in the weld region) is calculated to be non-critical. Reducing the fracture toughness to a value of 85 MPa√m, results in a critical flaw height of 22 mm. Reduction of the assumed residual stress to 70 and 30 % of yield results in critical flaw heights to 35 and 70 mm, respectively. Based on these initial fracture mechanics results it is recommended that a more comprehensive set of postulated defects and loading conditions be analysed to

fully understand the defect tolerance of both the SF and HLW canister. The risk of fracture is to be managed by the detection and removal of defects of a size that could be of concern.

- The term "adequate margin" in relation to structural performance requires an evaluation of variations, errors, uncertainties and gaps in knowledge of aspects that could undermine integrity (e.g. loading, defects in the welds, fracture toughness, corrosion rate, SCC susceptibility). Sensitivity (or what if) analyses need to be undertaken to investigate the effect of different assumptions on the aspects that can affect integrity (e.g. loading, material properties, fabrication quality, corrosion rate, in-service degradation). The sensitivity to variations from best estimate assumptions should inform the design basis.
- It is normal practice to calculate a critical in-service flaw size from a fracture assessment making appropriately conservative assumptions regarding fracture toughness, tensile properties and residual and in-service loading stresses. An initial size of flaw that would with crack growth lead to the critical flaw size by end of life is then determined. Finally a reduced size of flaw that should be detected with high reliability as demonstrated by the process of inspection qualification is defined as a proportion of the initial flaw size. A factor of two is suggested consistent with practice used for the manufacturing of primary circuit components for the Sizewell B nuclear power plant.
- Whether or not a more conservative safety factor is needed depends on arguments related to crack growth probability and the mode of failure. This would involve further study of the magnitude and distribution of residual stress and obtaining a better understanding of the threshold stress intensity for HIC crack growth. The selection of the safety factor defining the size of the maximum allowable defect in relation to the initial flaw size also requires further study, although it may be noted that ASME use a factor of 10. In addition, flaws for reporting should be defined based on good workmanship standards and the characteristics of the NDT method used. Whether a reported flaw is allowed to remain in the canister will depend on an assessment of the severity of the flaw and the feasibility of repair on a case by case basis.
- Dynamic stress analyses simulating a handling incident of a drop from 5 m on to a concrete surface showed that a defect-free SF canister is not breached during and after the impact. The fuel assembly deceleration is predicted to exceed the specified maxima from the acceptance standard for both BWR and PWR fuel types. Therefore consideration would need to be given to safe retrieval of the canister contents following such an incident.
- Dynamic FE fracture analyses should be performed to model a representative handling incident, including assuming defects of various sizes in the closure weld, to assess defect tolerance. Including geometrical defects in the models analysed would lead to a more reliable assessment, allowing a reduction of the safety margins, especially if plastic yielding is extensive in the region of the defects. However, it is necessary to understand exactly how the canister will be handled before doing further work on modelling possible canister handling incidents.
- An analytical calculation shows that a SF canister can be retrieved from the repository without affecting its integrity.
- The details of design of an inner lid should be developed, including the method of sealing and the interaction of the lid with the canister wall in relation to structural analysis.

**Inspection**

- A form of automated ultrasonic testing is recommended to satisfy requirement RQ14 for the detection of sub-surface flaws. UT systems have been successfully deployed remotely for other canister projects.
- The NDT procedures should be qualified to confirm that they are fit for purpose.
- Full-scale closure weld test pieces should be produced and destructive and non-destructive testing performed to confirm mechanical properties and extent of flaws in the weld and parent material.
- Conventional automated UT procedures can be designed to reliably detect a high proportion of foreseeable planar flaws of size 4 mm (TWE) × 15 mm (length). Advanced automated UT procedures can be designed to reliably detect a high proportion of foreseeable planar flaws of TWE 2 mm.
- Eddy current testing and remote visual testing should be used to supplement UT to enhance the reliability of detection of flaws at the outer surface of the welds.
- The surface finish of the canister should ideally be better than 3.2 μm Ra to facilitate non-destructive inspection during manufacture and after the closure weld.

**Manufacture**

- Long forging of the cylindrical body with a welded base is considered to be the most desirable manufacturing route. Pierce and draw with an integral base is an equally suitable option, but with limited suppliers, it is thought to be the next best option.
- An indelible, unequivocal dot matrix marking system is proposed which does not impact on the performance of the canister but is estimated to be legible after many hundreds of years after emplacement.
- An internal structure with a box section arrangement is proposed as a cost-effective way of providing support to the spent fuel assemblies.
- The capabilities of a number of potential manufacturers have been summarised within this report.

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**Links (Appendix F)**

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# Appendix A Reference data for the SF and HLW canister design study

# A1 Reference data for the SF and HLW canister design study

This document presents the approved data for the TWI canister design study. It provides quantitative data that relate to the requirements for the design study. The assumptions for canister types for the study are:

- The HLW canister is to be designed to contain two HLW flasks.
- Two types of SF canisters are to be designed, one for BWR fuel assemblies and one for PWR fuel assemblies. KKL and KKM BWR fuel may be loaded into the same canister, thus the longest FA (KKL) dictates the canister inside length. Although there are four different fuel types, it is judged sufficient for the present design study to perform full structural design for only one type of SF canister (KKL) as this will be the longest and heaviest canister. The internal arrangements of all SF canisters (cassettes to hold FA) are to be drawn as part of the design study, to illustrate the physical arrangement and dimension of steel cassette elements needed to obtain a standard canister diameter for all FA types. As with the BWR FA, the cassettes for PWR fuel assemblies are intended to be able to hold both KKG and KKB assemblies, thus the internal cassette dimensions are the same.

## A1.1 Waste data

### A1.1.1 Spent fuel data for existing NPP

The dimensional data and total mass per fuel assembly for existing reactors are given in Table A1. The fuel quantities arising over 60 years reactor operation time are given in Table A2.

Tab. A1: Fuel assembly data.

| | KKL BWR fuel | KKM BWR fuel | KKG PWR fuel | KKB PWR fuel |
|---|---|---|---|---|
| **FA length [mm]** | 4481 | 4474 | 4293 | 3518 |
| **FA width [mm]** | 139 × 139 | 139 × 139 | 215 × 215 | 198 × 198 |
| **FA mass [kg]** | 294 | 270 | 666 | 480 |

Reference: McGinnes 2002

The quantities of BWR and PWR fuel are given in Table A2, which results in the data in Table A3.

Tab. A2: Spent fuel quantities for final disposal, 60 years operation time.

| | KKL BWR fuel | KKM BWR fuel | KKG PWR fuel | KKB PWR fuel |
|---|---|---|---|---|
| **Fuel (MTIHM)** | 1331 | 294 | 772 | 617 |
| **No. FA** | 7422 | 1616 | 1781 | 1913 |

Reference: Nagra unpublished data

Tab. A3: Spent fuel quantities for final disposal, 60 years operation time.

| | BWR | PWR |
|---|---|---|
| **Fuel (MTIHM)** | 1625 | 1389 |
| **No. FA** | 9038 | 3694 |

Reference: Nagra unpublished data

Table A4 gives the numbers of PWR and BWR fuel disposal canisters. The numbers of canisters have been calculated based on the maximum thermal loading at the time of disposal of 1500W, thus the numbers of canisters reflect the need to reduce the number of FA in some canisters to meet this requirement.

Tab. A4 Numbers of SF canisters (60 a operation time; no reprocessing, all reactors).

| Type | Diameter [m] (assumed) | Length [m] | No. of canisters |
|---|---|---|---|
| **BE- PWR** | 1.05 | To be determined | 1071 |
| **BE- BWR** | 1.05 | To be determined | 1090 |

Reference: Nagra unpublished data

Assumed emplacement schedule for SF (basis for acceptable thermal loading at emplacement):

BE-PWR & BWR: 2050 – 2064

The details of the HLW flasks are given in Table A5.

Tab. A5: HLW flask data.

| Flask type | AREVA | Sellafield Ltd. |
|---|---|---|
| **Flask length [mm]** | 1335 ± 2 | 1335 ± 2 |
| **Flask diameter [mm]** | 430 ± 2 | 430 ± 2 |
| **Overlap when stacked [mm]** | 67 | 67 |
| **Flask mass [kg]** | 480 | 480 |
| **No. of flasks** | 438 | 208 |

Note: Flasks are free of surface contamination

## A1.2 Disposal canister data

The data for the spent fuel canister are given in Table A6. Preliminary fabrication assessment information and canister surface dose rate calculations resulted in an initial assumption of wall thickness of 120 cm.

Tab. A6: SF canister data.

| **FA type** | **KKL BWR (Ref. case)** | **KKM BWR** | **KKG PWR** | **KKB PWR** |
|---|---|---|---|---|
| **Number of FA per canister** | 9 | 9 | 4 | 4 |
| **FA mass per canister [kg]** | 2646 | 2430 | 2664 | 1920 |
| **Length clearance inside canister [mm]** | 50 | | 50 | |
| **Canister minimum inside length [mm]** | 4531 | 4524 | 4343 | 3568 |
| **Cassette inside dimensions [mm]** | 159 × 159 | 159 × 159 | 235 × 235 | 235 × 235 |
| **Canister minimum wall thickness [mm]** | 120 | 120 | 120 | 120 |
| **Canister lid minimum thickness [mm]** | 120 | least 120 | least 120 | least 120 |
| **Sidewall surface neutron dose rate for 120 mm wall thickness**[1] | < KKG | < KKG | 34.5 | < KKG |
| **Sidewall surface gamma dose rate for 120 mm wall thickness**[1] | < KKG | < KKG | 100.3 | < KKG |
| **Lid surface neutron dose rate for 120 mm lid thickness**[1] | < KKG | < KKG | 3.3 | < KKG |
| **Lid surface gamma dose rate for 120 mm lid thickness**[1] | < KKG | < KKG | 19.4 | < KKG |

[1] Only the case of 3 $UO_2$ (BU = 55 GWd/tIHM) plus 1 MOX FA (60 GWd/tIHM) was calculated in detail as this gives the highest dose rate relative to other fuel types

Reference: Nagra unpublished data

The data for the HLW canister are given in Table A7. Preliminary fabrication assessment information and canister surface dose rate calculations resulted in an assumption of 140 cm wall thickness. Based on loading 2 flasks per canister, the number of HLW canisters is given in Table A8.

Tab. A7: HLW canister data.

| | |
|---|---|
| Number of HLW flasks per canister | 2 |
| Inside diameter [mm] | 440 |
| Length clearance inside canister [mm] | 10 |
| Inside length [mm] | 2613 |
| Wall thickness [mm] | 140 |
| Sidewall clearance [mm] | 10 |
| Sidewall surface radiation neutron dose rate [mSv/h][1] | 6.2 |
| Sidewall surface radiation gamma dose rate [mSv/h][1] | 125 |
| Lid surface neutron dose rate for 140 mm lid thickness[1] [mSv/h] | < ~ 10 |
| Lid surface gamma dose rate for 140 mm lid thickness[1] [mSv/h] | ~ 190 |
| Lid surface total dose rate for 180 mm lid thickness[1] [mSv/h] | < 30 |

[1] Dose rates in 2050; for the maximum waste loading case, the total sidewall surface dose rate would be ~ 160 mSv/h.

Reference: Nagra unpublished data

The lid surface dose rate is based on an AREVA flask adjacent to the lid. The design study should also evaluate the possibility of using a design with an 18cm lid thickness. If such a thickness were to be used, it should be determined if this would make a significant difference for developing the design or for the performance.

Tab. A8: Number of HLW canisters.

| | **AREVA and Sellafield Ltd.** |
|---|---|
| **No. of canisters** | 323 |

## A1.3 Repository in situ stress conditions

The in situ stress conditions in the repository are given below. The worst case conditions are represented by a horizontal to vertical stress ratio of 29/22.

Maximum principal stress (horizontal) at 900 m depth in Opalinus Clay – 29 MPa

Minimum principal stress (vertical) at 900 m depth in Opalinus Clay – 22 MPa

Reference: Nagra unpublished data

## A1.4 Canister production rate

It is assumed that canisters are completed at the encapsulation facility at a rate of 1 to 2 canisters per day. Completion means loading of waste and welding and final finishing, which defines the rate at which empty canisters must be manufactured for delivery to the encapsulation facility.

# Appendix B Material data

# B1 Supplementary information for Section 6

## B1.1 Degradation by hydrogen embrittlement

A number of studies carried out at TWI have identified the effect of hydrogen on toughness. For relatively low concentrations of hydrogen introduced to parent material as well as welds, the measured toughness is substantially reduced. In all cases, the effect of hydrogen results in a maximum load type load displacement trace, but the fracture face, and the results obtained clearly show the effect of hydrogen (Pargeter & Cheaitani 2011). This is clearly shown in Figures B1 and B2.

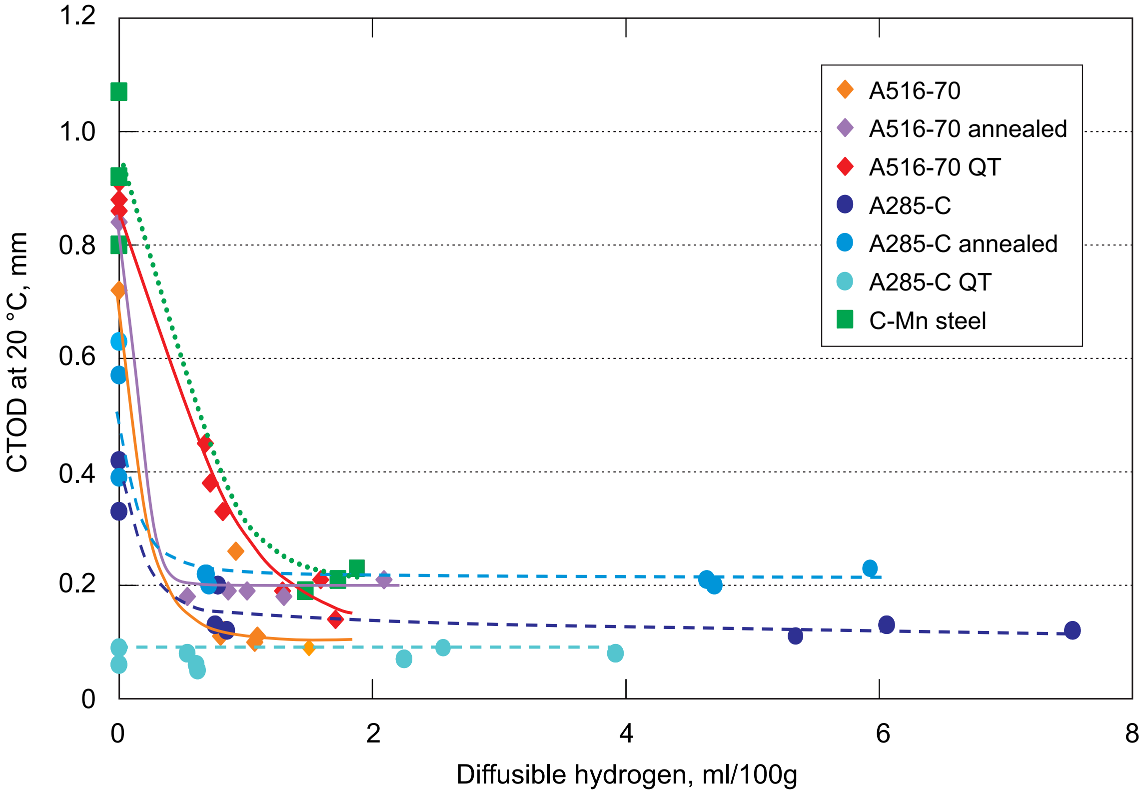



Fig. B1: The effect of diffusible hydrogen on the values of crack tip opening displacement (CTOD) obtained at 20°C.

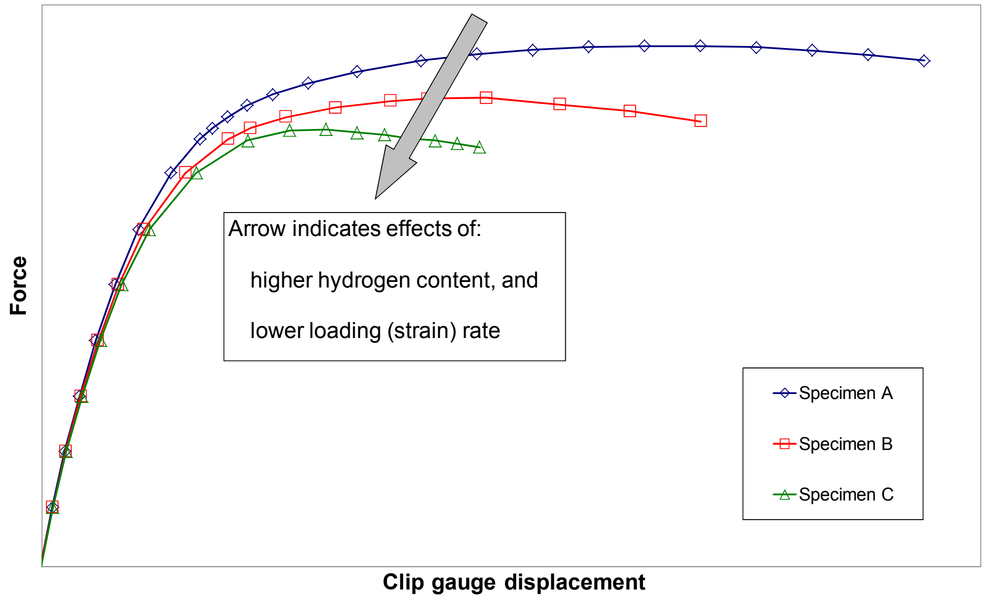



Fig. B2: Effect of hydrogen and strain rate on load-displacement traces.

## B1.2 Cast iron

### B1.2.1 Postweld heat treatment

To obtain moderately softened HAZ microstructures, preheating to 480°C is required, followed by slow cooling. However, to obtain maximum softening (ductility) in the HAZ, the weld region should be heated to 900°C, and held for 40 minutes per centimetre of thickness (for a canister lid thickness of 180 mm, this is 12 hours at temperature). Exposure to temperatures in excess of 450°C for the HLW and 400°C for the SF is outside of the stated requirements, so the limitations on weldability render cast iron unsuitable for the canister if welding is to be used for the final closure.

### B1.2.2 Ultrasonic testing

For ultrasonic flaw detection/sizing nodular cast irons having tensile-strength values above 200 MPa are, in principle, sufficiently transmissive for flaw detection. Emerson et al. (1971) indicate that the attenuation of 2 MHz compression waves in 100 mm thick GGG 42 cast iron, for instance, is ~ 0.02 dB/mm, i.e. ~ 6 dB loss, assuming a maximum testing range of ~ 300 mm; 140 mm thick cast iron would exhibit even higher levels of attenuation, UT techniques could almost certainly be adapted to accommodate the levels of attenuation at frequencies of ~ 2 MHz. However, the resolution of the UT would be necessarily limited by the ultrasonic wavelength (~ 3 mm for 2 MHz compression waves), which would, in turn, have a detrimental effect on flaw detection, characterisation and sizing accuracy. The attenuation is highly sensitive to frequency, increasing by a factor of ~ 6 for each doubling in frequency (Emerson et al. 1971), so there would be little scope for improving the resolution by using higher frequencies; Figure 27.3 of Krautkrämer & Krautkrämer (1990) suggests that the optimum testing frequency is ~2 MHz. In TWI's opinion, it would therefore be imprudent to set a target through-wall flaw size of less than 5 mm for inspection qualification in cast iron.

# Appendix C Structural performance analysis for 5 m drop simulation

**Drop test analysis of Nagra canister with BWR box type internal and BWR fuels by FEA, LS DYNA**

Hitachi Zosen

## C1 Conditions and criteria for the analysis

- Elastic-plastic analysis of canister drop onto concrete target is performed using FEM dynamic analysis code, LS-Dyna
- Horizontal drop from the height of 5 m is assumed
- Plane symmetric model is assumed
- Fuels are not modelled, but their weight is accounted for in the model
- No flaw is assumed in both mother materials and weld
- Dynamic effect of carbon steel is considered
- Low path filter of 340 Hz is used for evaluating deceleration
- Evaluate canister breaching by criteria below:
    - Combination of tensile strength and fracture strain
    - No plastic deformation on the inner surface of canister through circumferential direction

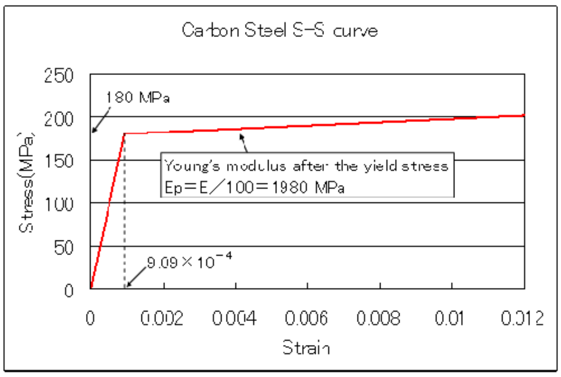
## C2 Material properties

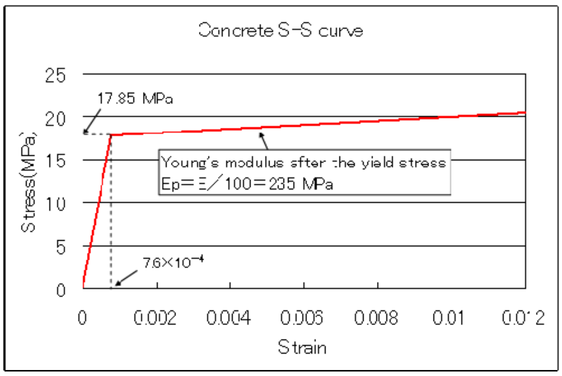
**Carbon Steel**

| | |
|---|---|
| Young's modulus | E = 198'000 MPa (100°C) |
| Poisson's ratio | v = 0.2 |
| Density | ρ = 7.85E-6 kg/mm³ |
| Yield stress | σy = 180 MPa |
| Dynamic effect | $1 + (\dot{\varepsilon}/C)^{1/p}$ C = 0.2/ms, p = 5 (Cowper-Symonds) parameter) |

**Concrete**

| | |
|---|---|
| Young's modulus | E = 23'500 MPa |
| Poisson's ratio | v = 0.2 |
| Density | ρ = 2.345E-6 kg/mm³ |
| Standard strength | σck = 21 MPa |
| Yield stress | σy = σck × 0.85 = 17.85 MPa |

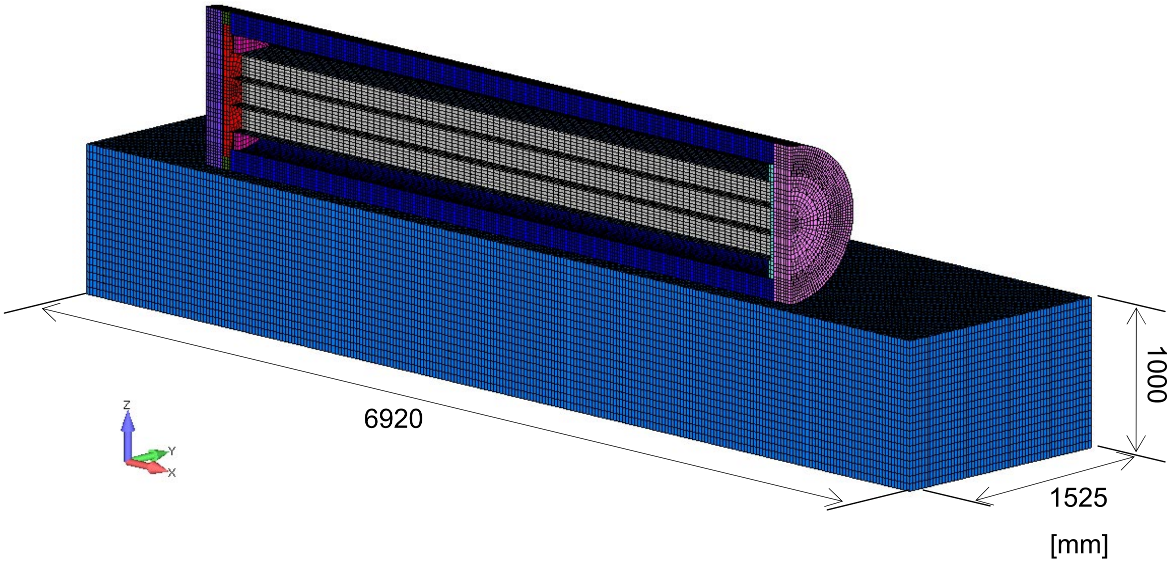


# C3 Analytical model and boundary conditions

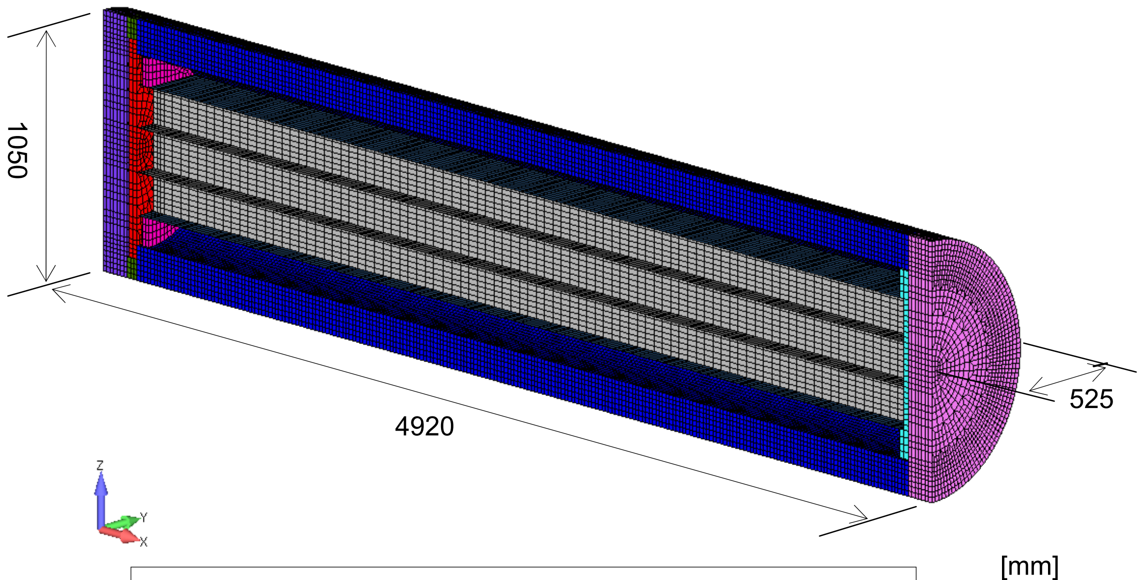
## C3.1 Analytical model and boundary condition 1

**Concrete**




## C3.2 Analytical model and boundary condition 2

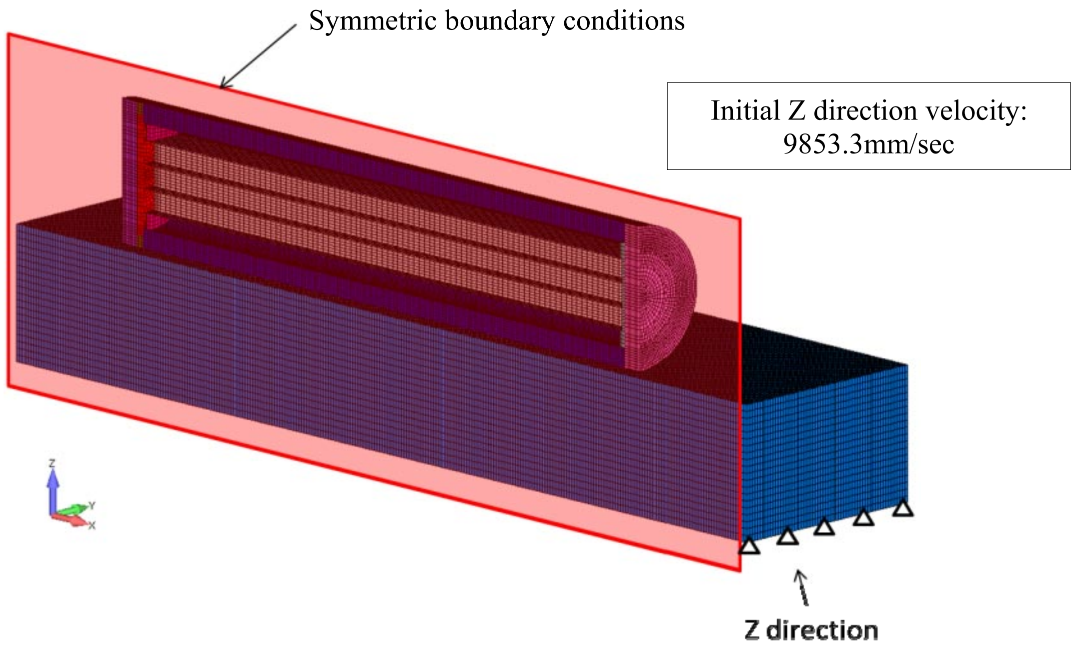
**Canister**




- Fuel weight (2646 kg) is accounted for in the model to increase the weight of lower part of square tubes.
- No defect or unwelded part is accounted for in the model.

## C3.3 Analytical model and boundary condition 3

**Boundary condition**



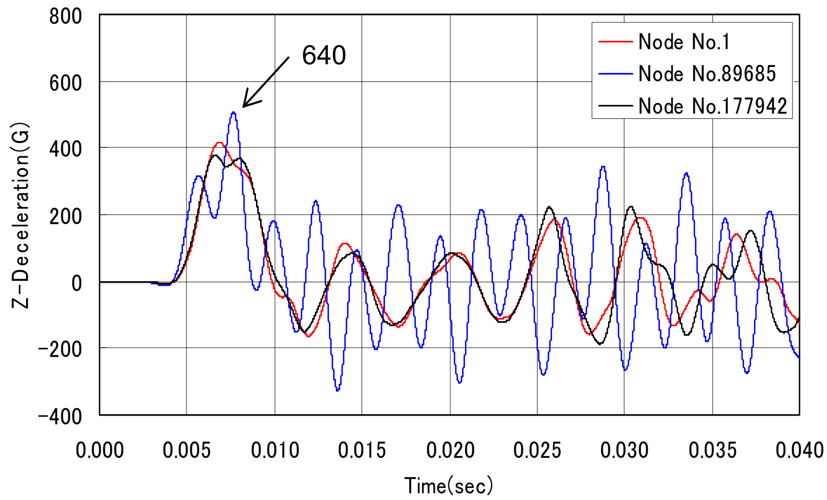

## C4 Summary of results

| Drop height | Item | Canister Body | Target | Reference |
|---|---|---|---|---|
| 5 m | Max. Deceleration [G] | 500 | — | |
| | Max. Displacement [mm] | 1.6 | 17 | |
| | Max. Von Mises Stress [MPa] | 396 | 54 | |
| | Effective Plastic Strain [%] | 0.09 | 20.43 | |
| | Max. Principal Stress [MPa] | 130 | — | below Yield Strength |
| | Min. Principal Stress [MPa] | -437 | — | |

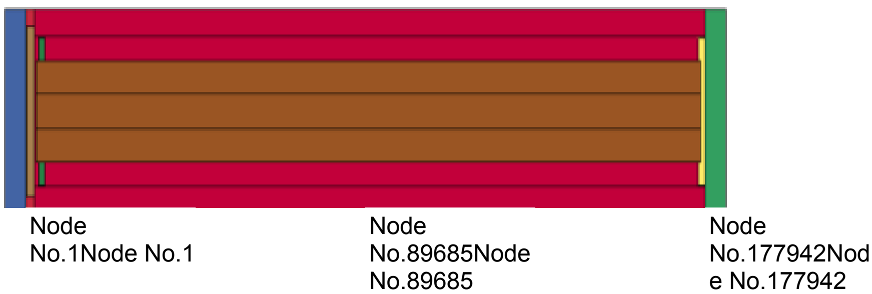
## C5 Evaluation and conclusion

- Deceleration was 500 G at 5 m drop, which may exceed the ordinary design condition for fuels.
- Higher stress was induced in the canister at the corner of both lid and bottom plate. However, the stress was compressive and strain is still lower than fracture strain.
- From these results, it is concluded that:
  - Canister is not breached (confinement is maintained) during and after the drop.
  - Fuel cladding may be breached, so that it needs careful attention in lid re-opening process.

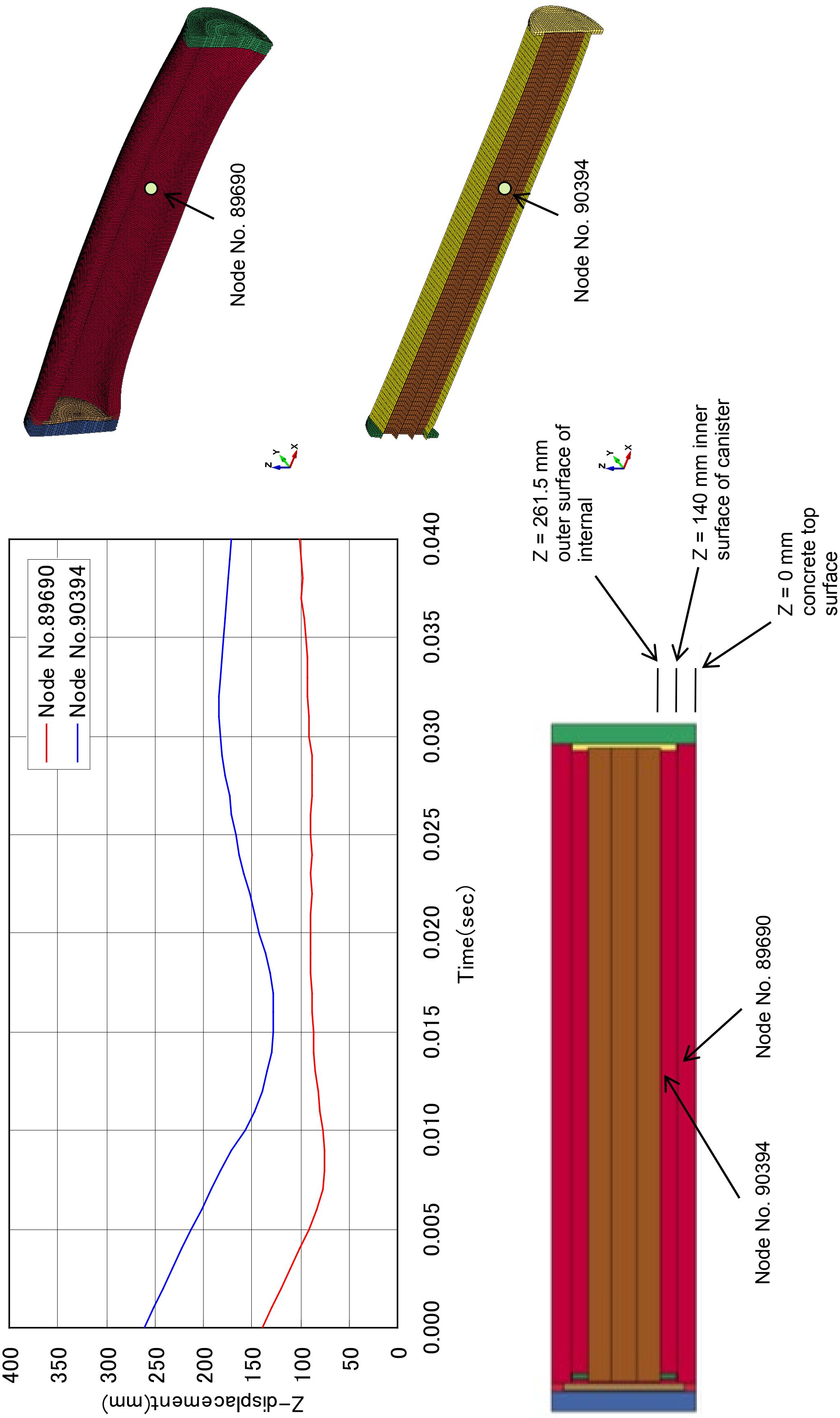
### C5.1 5 m drop – time history of deceleration




Cut off frequency: 340Hz
※Canister and Internal



## C5.2 5 m Drop – Time History of Displacement



## C5.3 5 m drop deformation, stress and strain at maximum stress

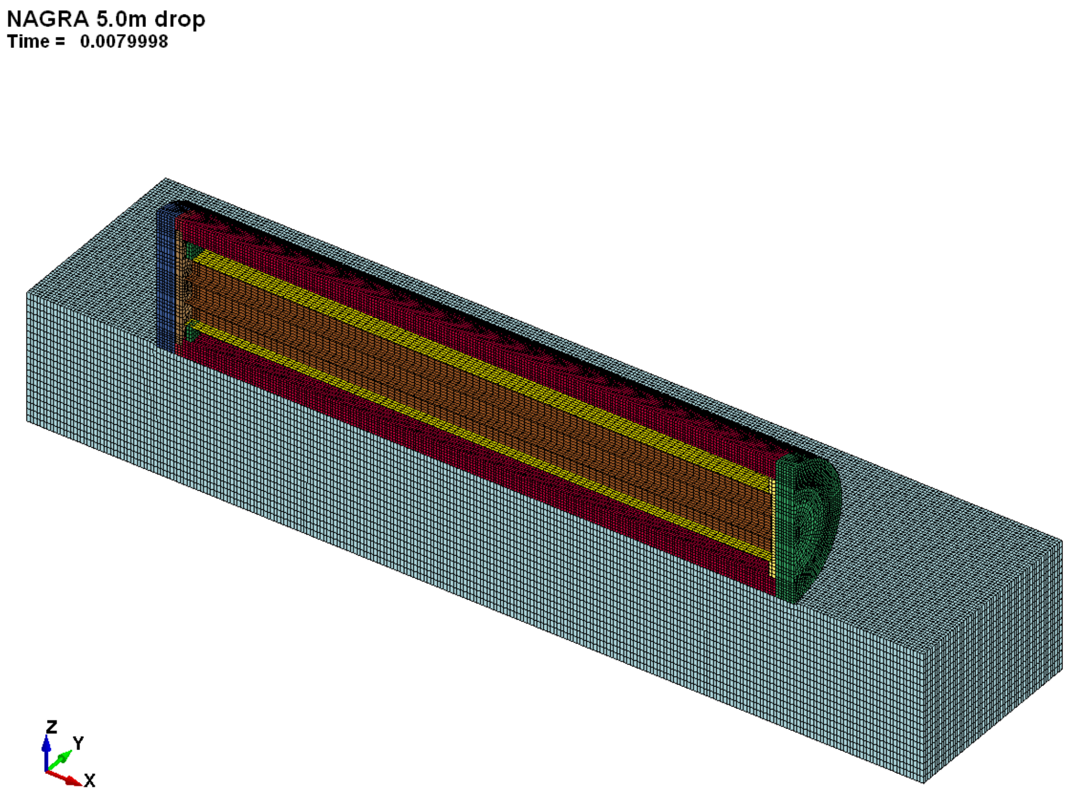
### 1. Whole model

- Deformation

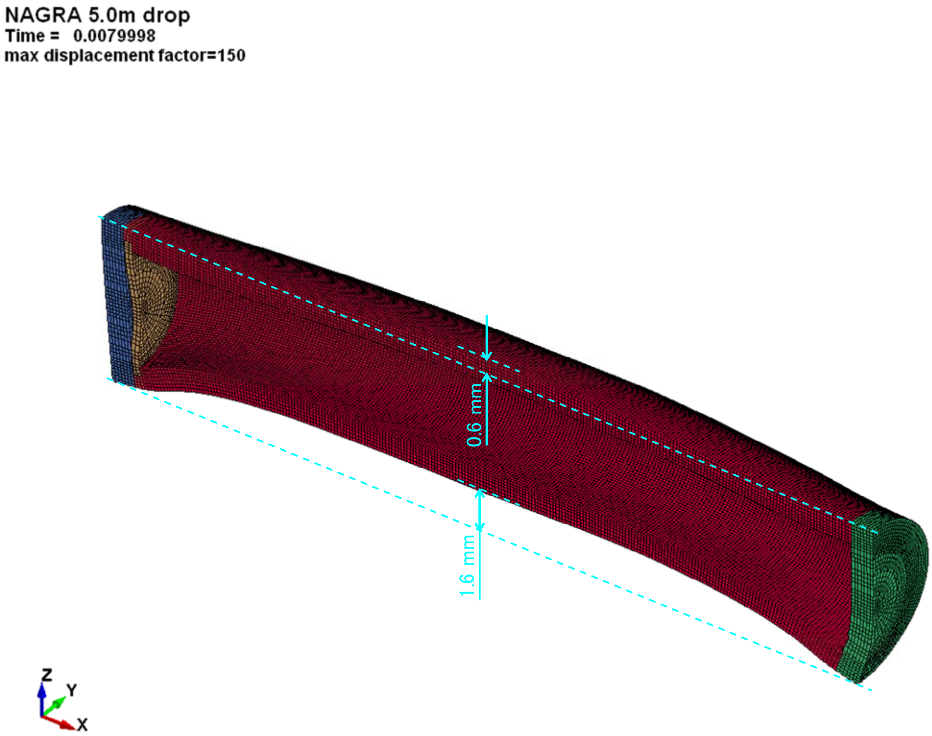
### 2. Canister body

- Deformation
- Stress and strain

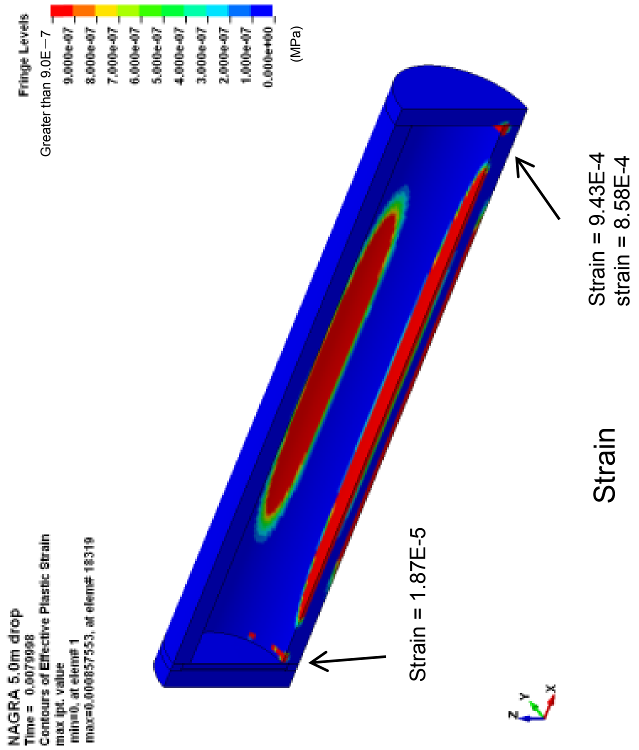
### Whole model – deformation

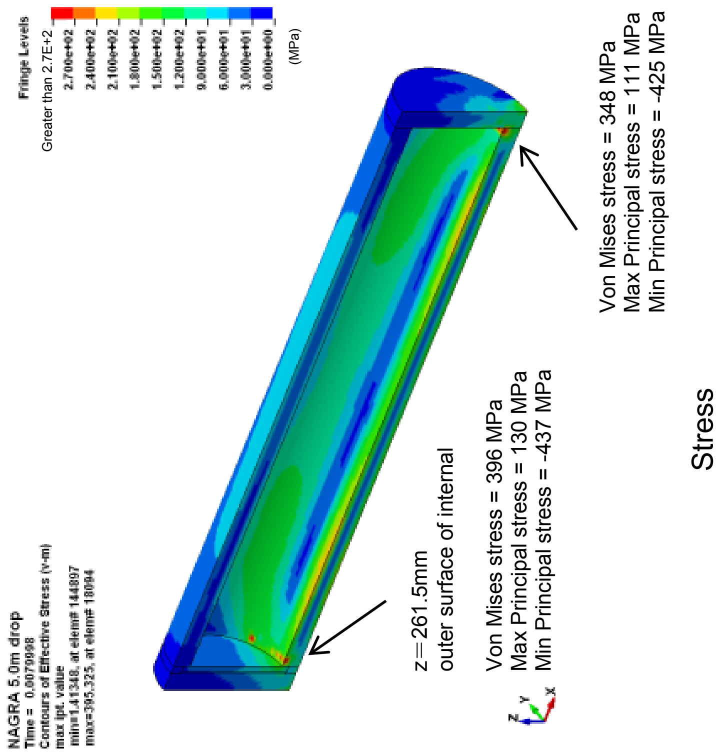


**Canister body – deformation**



**Canister body – stress and strain**



### C5.4 5 m drop deformation, stress and strain at rebound

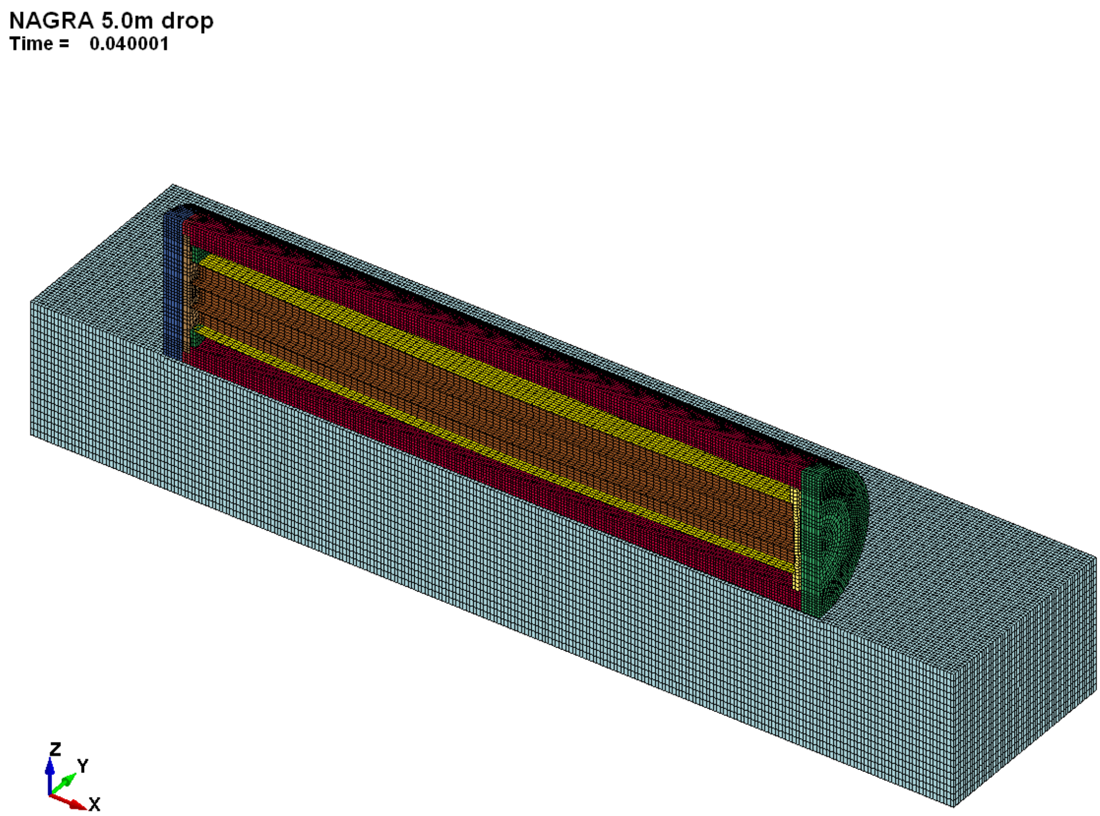
**1. Whole model**

- Deformation

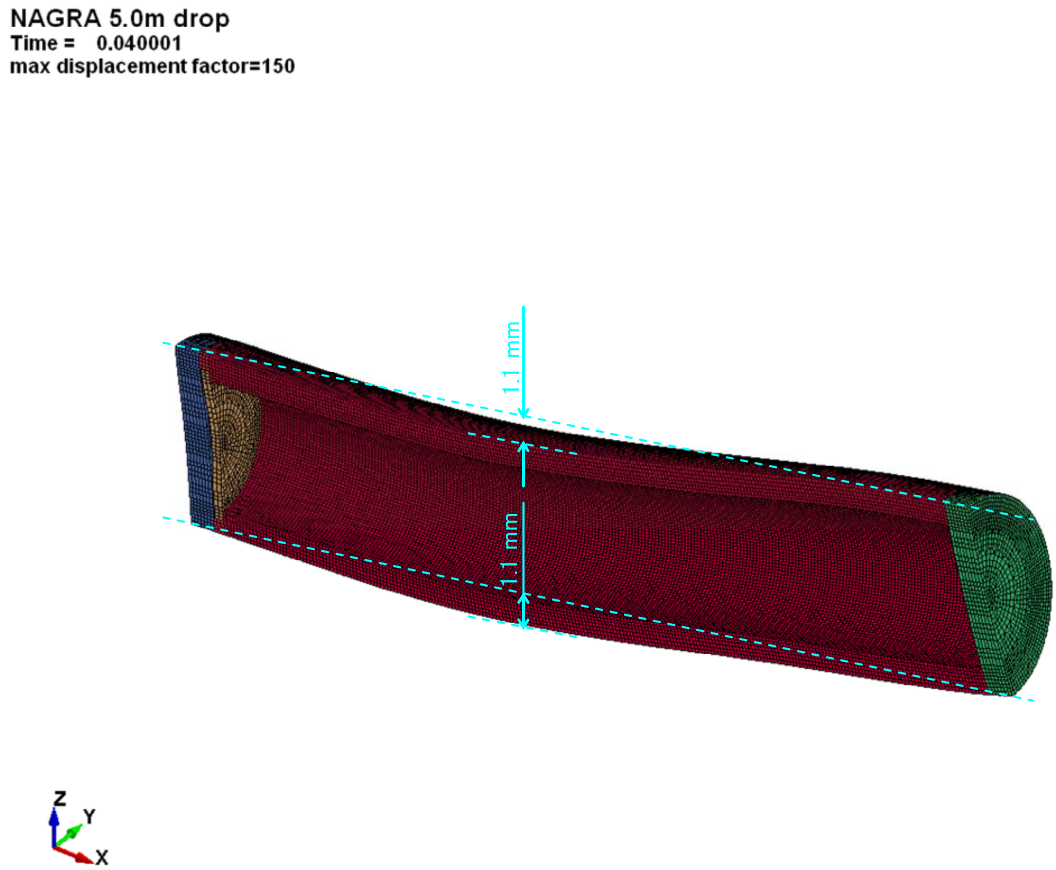
**2. Canister body**

- Deformation
- Stress and strain

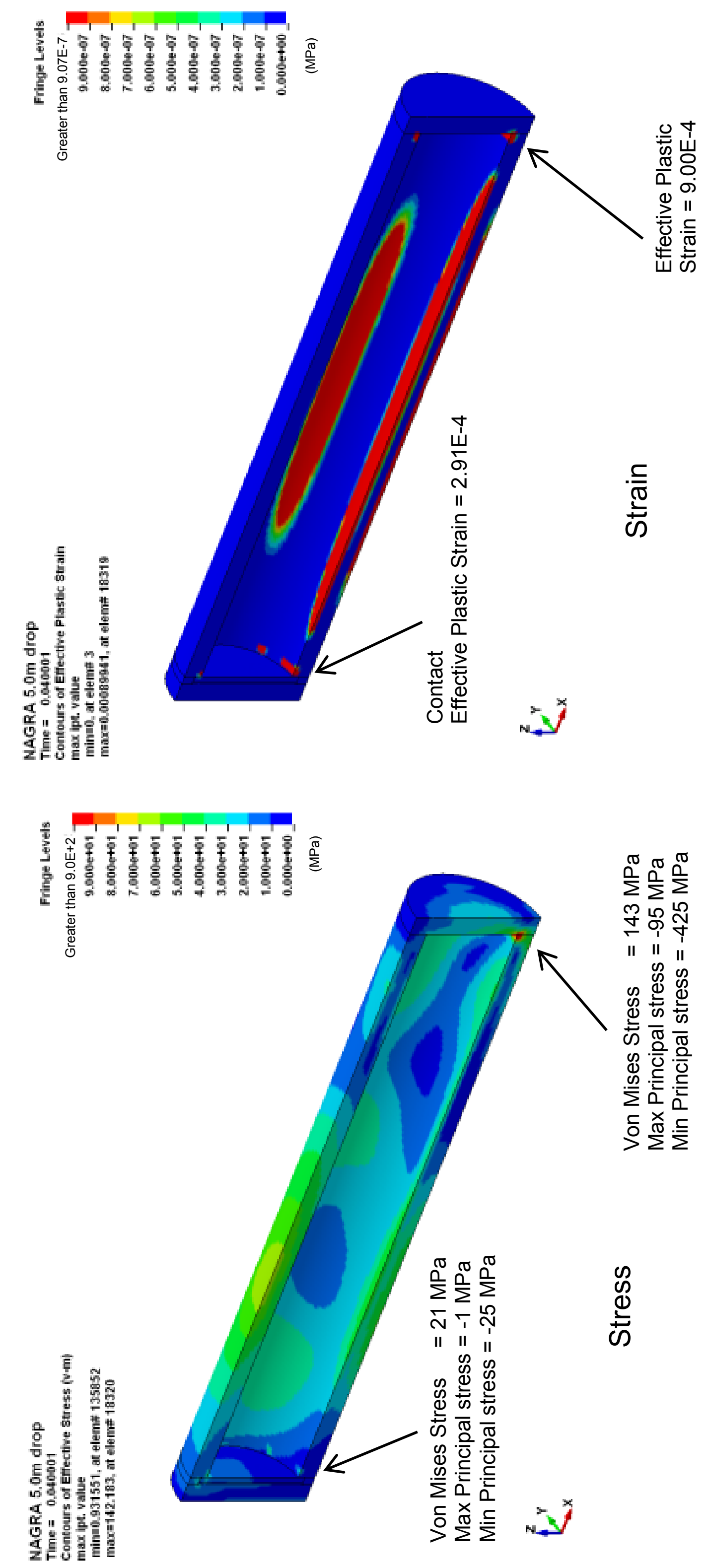
**Whole model – deformation**



**Canister body – deformation**



**Canister body – stress and strain**



# Appendix D Manufacturing plan

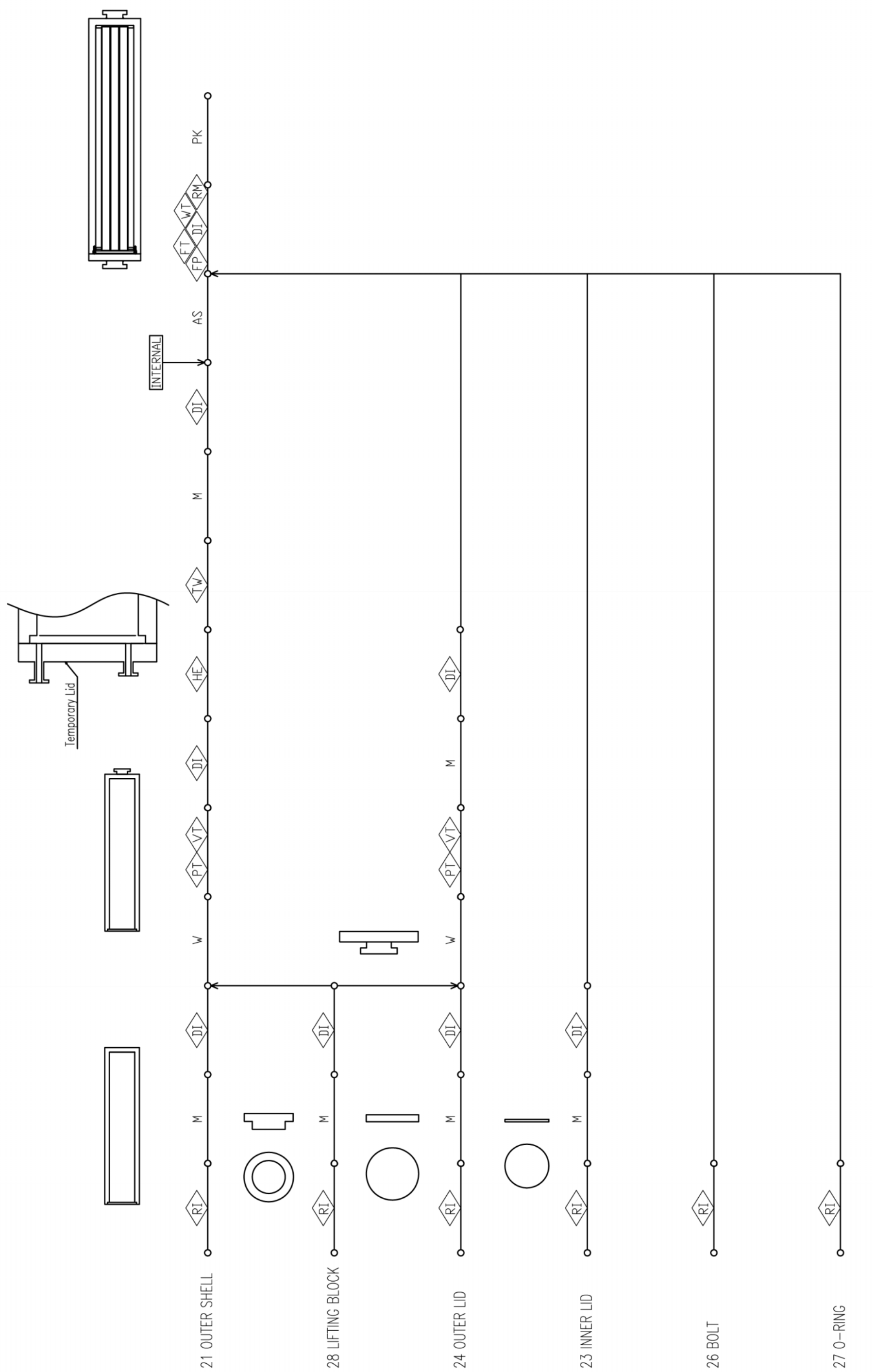



Fig. D1: Preliminary manufacturing sequence diagram for canister with an integrated base.

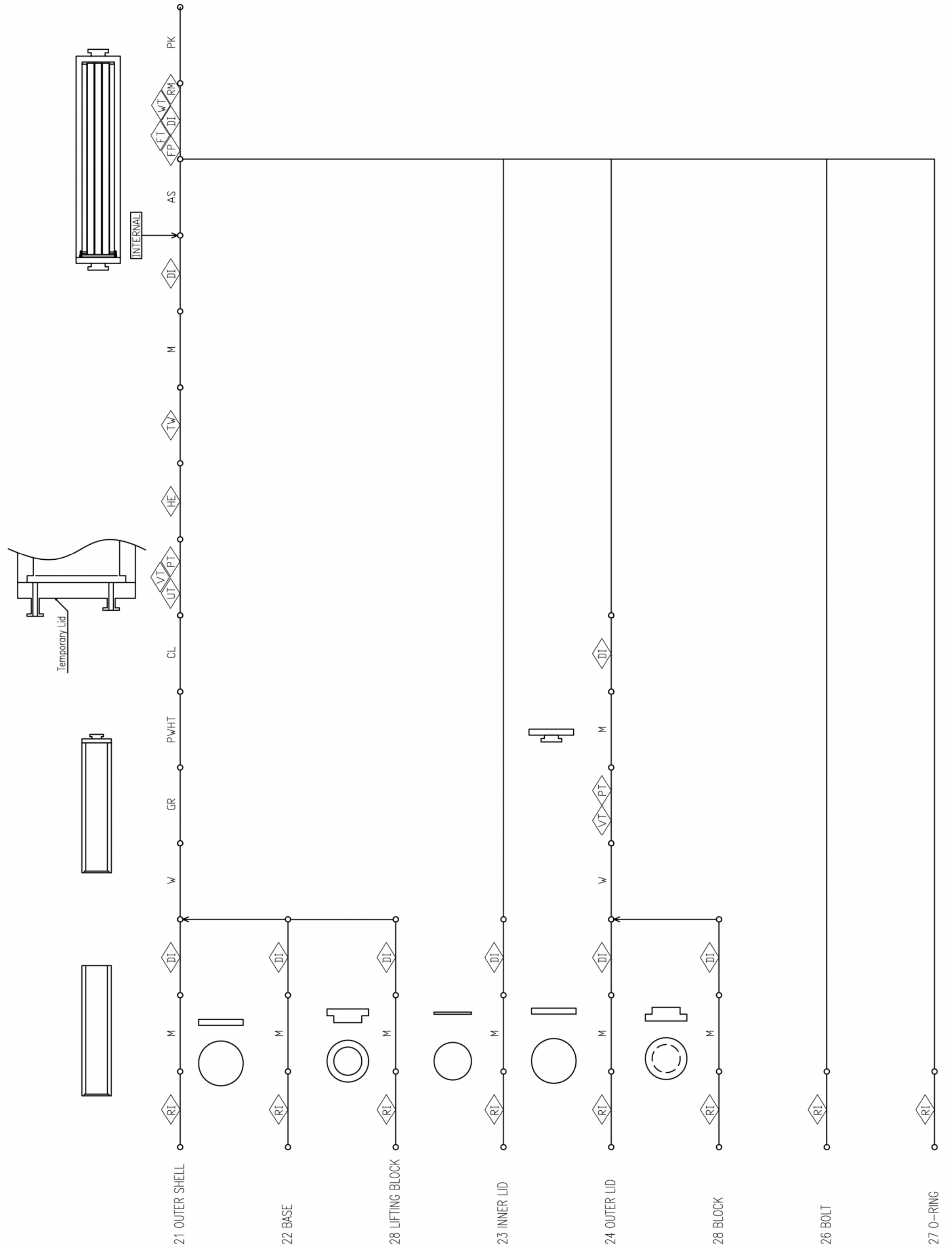



Fig. D2: Preliminary manufacturing sequence diagram for canister with a welded base.

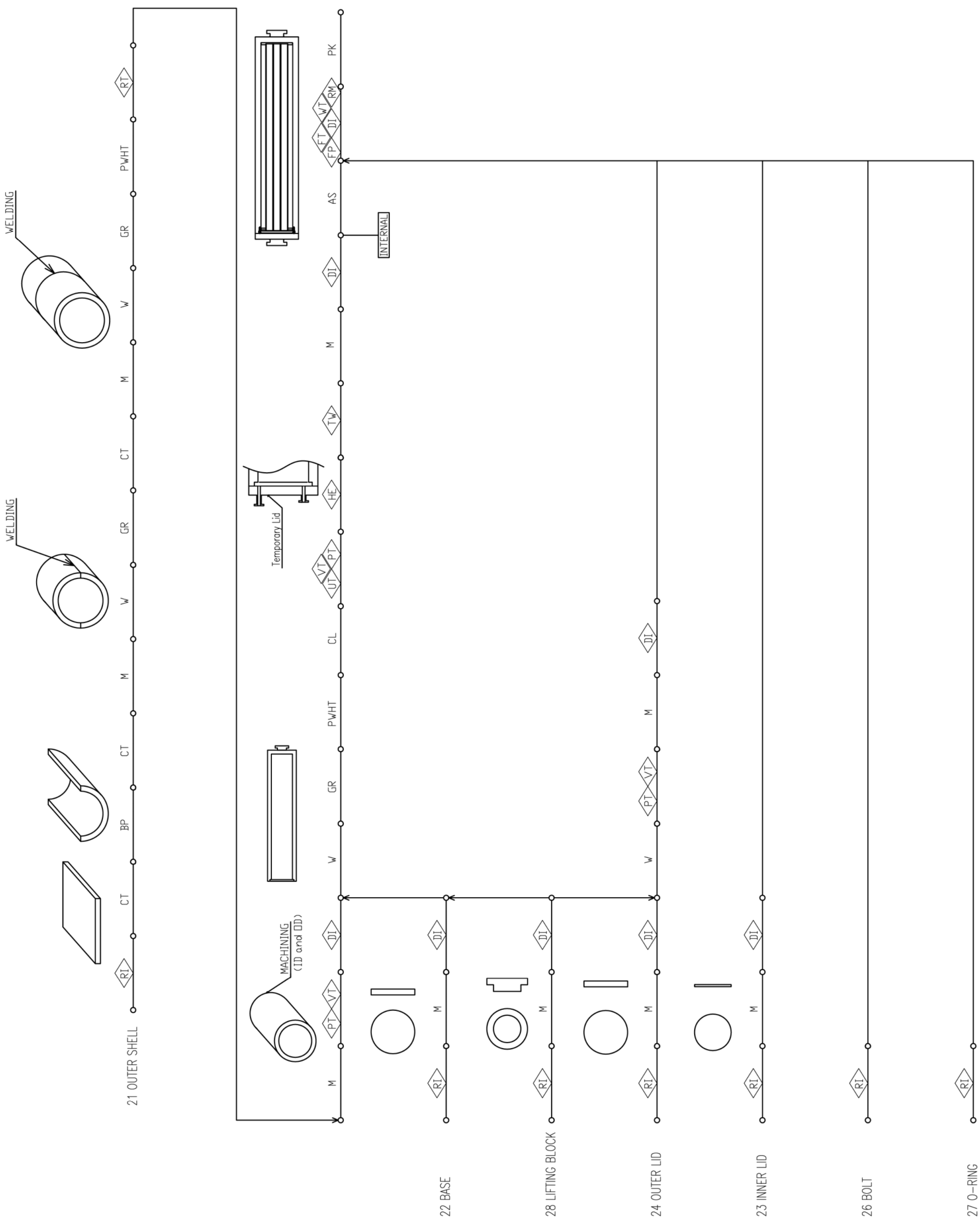


Fig. D3: Preliminary manufacturing sequence diagram for canister using pressed plates.

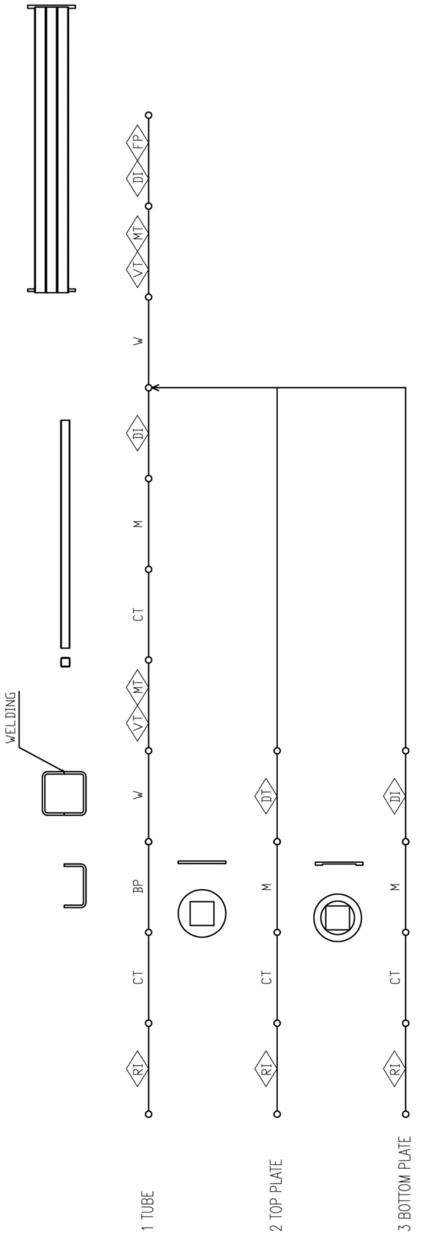



Fig. D4: Preliminary manufacturing sequence diagram for canister internal structures.

# Appendix E Canister internal structure design

## E1 Design approach

The design of the internal structures takes consideration of the arrangement and dimension of the compartments required for the spent fuels, materials, and manufacturing methods.

## E2 The arrangement and dimension of the SF compartments

Reference data for designing the internal structure is given by Nagra and is detailed in the Appendix of the Task 1 report (Patel et al. 2011). According to the reference data, two types of SF canister are to be designed, one for BWR fuel assemblies and one for PWR fuel assemblies. The BWR canister will be required to contain 9 fuel assemblies and the PWR canister will be required to contain 4 fuel assemblies. There are four different types of fuel assemblies to be stored in the repository, KKL BWR, KKM BWR, KKG PWR and KKB PWR. It is judged sufficient for the present design study to perform full structural design for only one type of SF canister. The KKL BWR fuel assembly was chosen since it is the longest and heaviest. The type and number of fuel assemblies, dimension, and required clearance are summarised in Table E1 below.

Tab. E1: Summary of fuel assembly type, number, dimension and clearance.

| **FA type** | **KKL BWR (Ref. case)** | **KKM BWR** | **KKG PWR** | **KKB PWR** |
|---|---|---|---|---|
| **Number of FA per canister** | 9 | 9 | 4 | 4 |
| **Length clearance inside canister [mm]** | 50 | | 50 | |
| **Canister inside length [mm]** | 4531 | 4524 | 4343 | 3568 |
| **Internal structure inside dimensions [mm]** | 159 × 159 | 159 × 159 | 235 × 235 | 235 × 235 |

Two types of cell arrangement were considered, namely the arrayed arrangement (Figure E1) and the square arrangement (Figure E2). It was envisaged that the square arrangement would provide the smaller canister internal diameter and therefore this arrangement was chosen for the internal structure design.

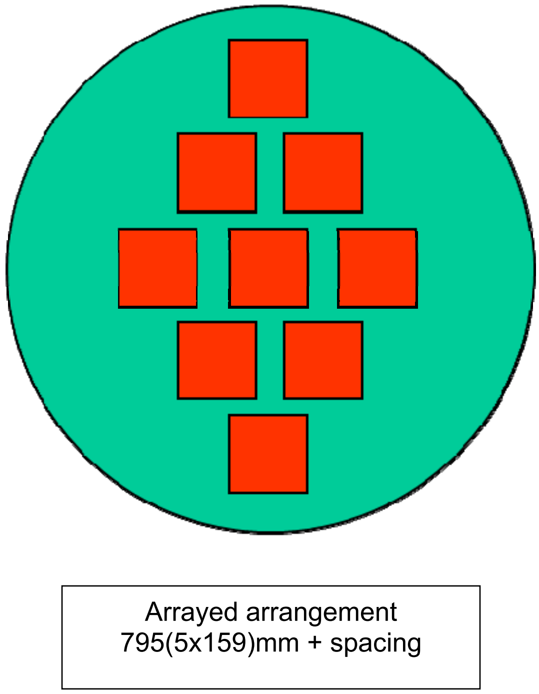



Fig. E1: BWR SF canister cell arrangement – arrayed arrangement.

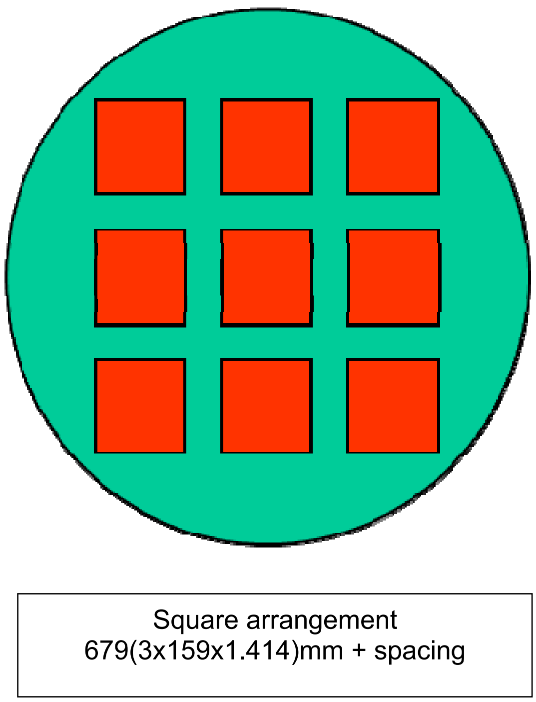



Fig. E2: BWR SF canister cell arrangement – square arrangement.

## E3 Materials for internal structure

The materials for the internal structure are chosen to be plain carbon steel because this will be sufficient to provide a close match to the canister material to avoid excessive differences in thermal expansion and contraction (refer to RQ22). The canister internal will be filled with inert gas before the being sealed, and hence it is expected that electro-chemical corrosion will be at a negligible level during normal operation (refer to RQ22).

## E4 Manufacturing concepts

Three manufacturing concepts are proposed for the internal structures:

- Interlocking plate concept
- Tube and plate concept
- Box section concept

Drawings for each of the concept are available in Figures E3 to E8. All three concepts give a canister internal diameter of 770 mm including a maximum clearance of 10 mm between the canister wall and the internal structure. The advantages and disadvantages for each of the three concepts are discussed in detail below:

### E4.1 Interlocking plate concept

Plates are fixed to each other by mechanical interlocking. There is no welding required in the assembly. Good dimensional tolerance can be achieved for loading the fuel assemblies. Fabricating the grooves required for the assembly can be costly depending on the method of cutting used.

### E4.2 Tube and plate concept

In this case squares are burned in a number of circular plates forming the compartments for the fuel assemblies and hence reasonably good dimensional tolerance can be achieved for loading of the fuel assemblies. Small amount of welding is required to join the plates to the outer tube. Costs for making the outer tube can be high. The major disadvantage is that the fuel assemblies is fully supported all the way along the internal structures, which may result in mis-feeding of the fuel assemblies during loading (i.e. risk of fuel assemblies being trapped), unless a separate guide tube is used to ensure fuel assemblies are loaded vertically into the canisters.

### E4.3 Box section concept

The box section is relatively simple to fabricate. In this concept the box sections are welded to each other and welded to the top and bottom plates. There is no requirement for an outer tube so significant cost savings can be made. In this case, the fuel assemblies are supported all the way along the length of the canister so loading of the fuel assemblies is straightforward. However, there may not be standard box sections available that meet the required dimension and high level of dimensional tolerance. Therefore the box sections may need to be made to order which will increase costs.

### E4.4 Budgetary costs

Budgetary quote for each concept from a number of potential manufacturers are available in Table E2.

## E5 Conclusion

It can be concluded that the box section concept has the most advantages in terms of its functionality as well as costs of manufacture.

Tab. E2: Budgetary quote for each internal structure concept.

| **Internal structure concepts** | **BWR internal structure [kCHF]** | **PWR internal structure [kCHF]** |
|---|---|---|
| **Interlocking plate** | | |
| Metalcraft | 54 | 34 |
| DavyMarkham | 14.6 | 13.3 |
| Graham Engineering | 31.5 | 28.6 |
| Hitachi Zosen | 28.2 | 25.9 |
| **Tube and plate** | | |
| Metalcraft | 66 | 63 |
| DavyMarkham | 16.7 | 12.9 |
| Graham Engineering | 23.8 | 20.3 |
| Hitachi Zosen | Indicated that this method has the highest costs among the three proposed options and therefore did not provide a quote. | |
| **Box section** | | |
| Metalcraft | 34 | 33 |
| DavyMarkham | 6.7 | 4.5 |
| Graham Engineering | 10.4 | 10.9 |
| Hitachi Zosen | 25.6 | 24.6 |

### E5.1 Currency conversion used

- 1 £ = 1.45 CHF
- 1 CHF = 96.27 JPY

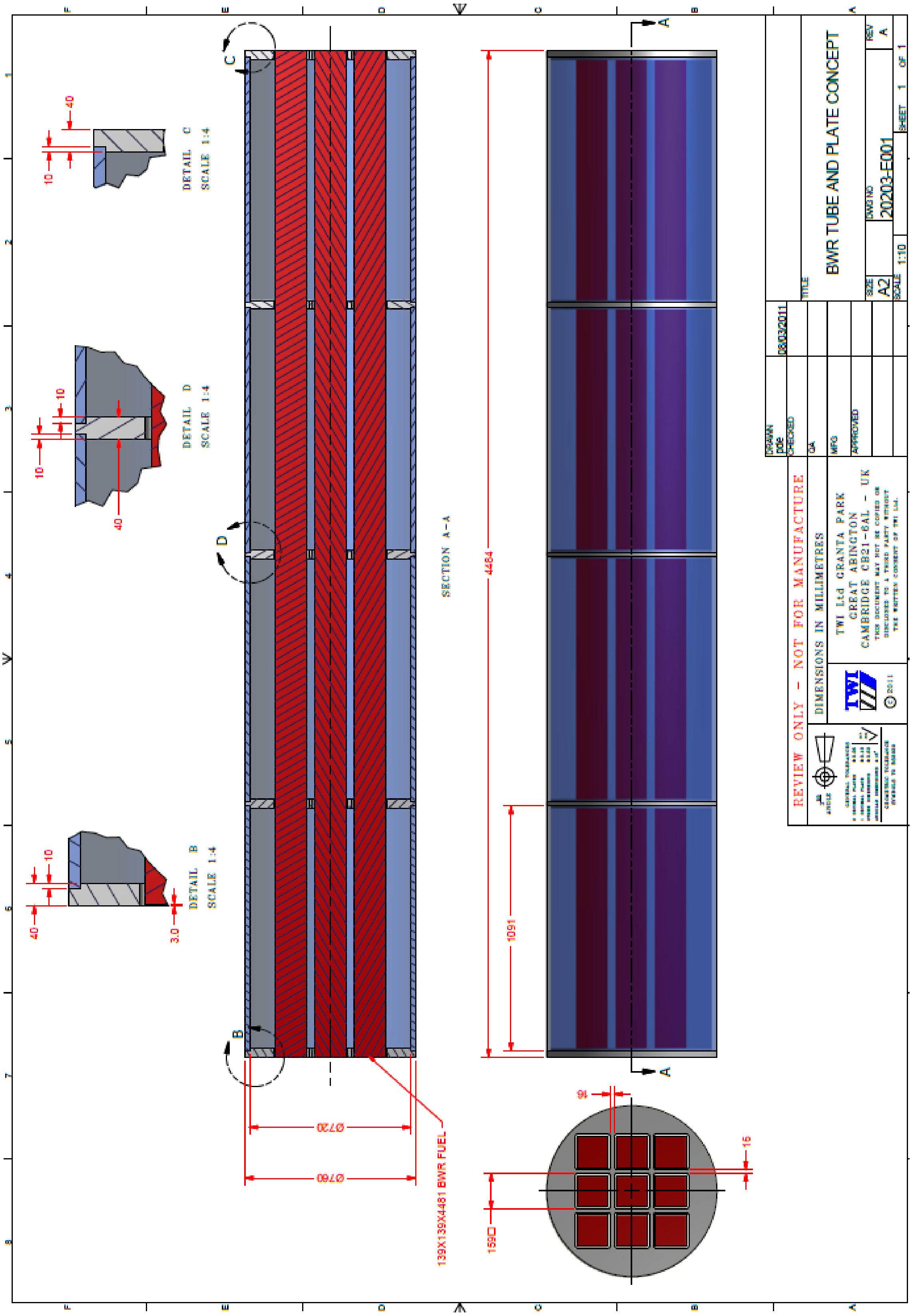



Fig. E3: Tube and plate concept for BWR spent fuels.

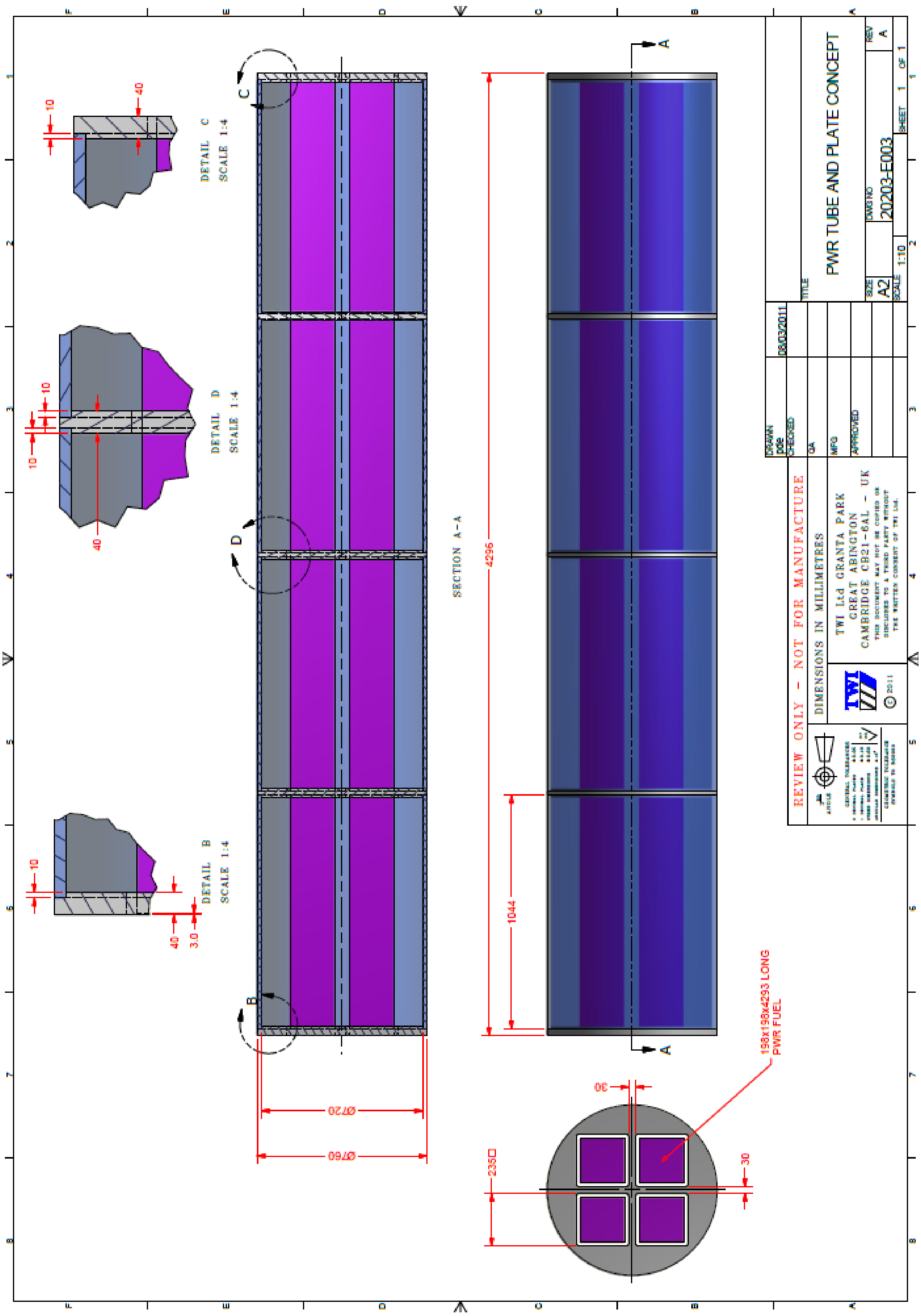


Fig. E4: Tube and plate concept for PWR spent fuels.

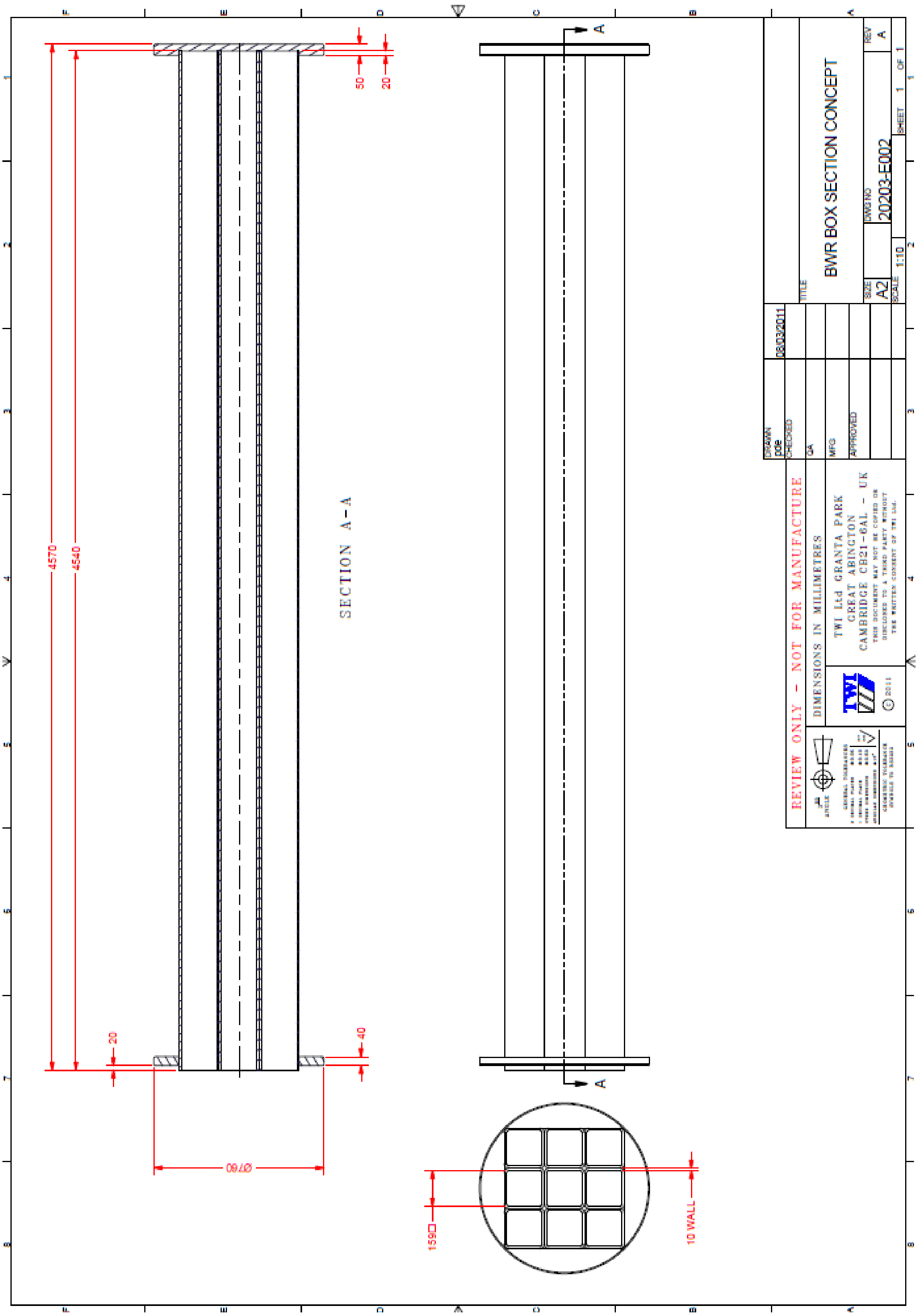



Fig. E5: Box section concept for BWR spent fuels.

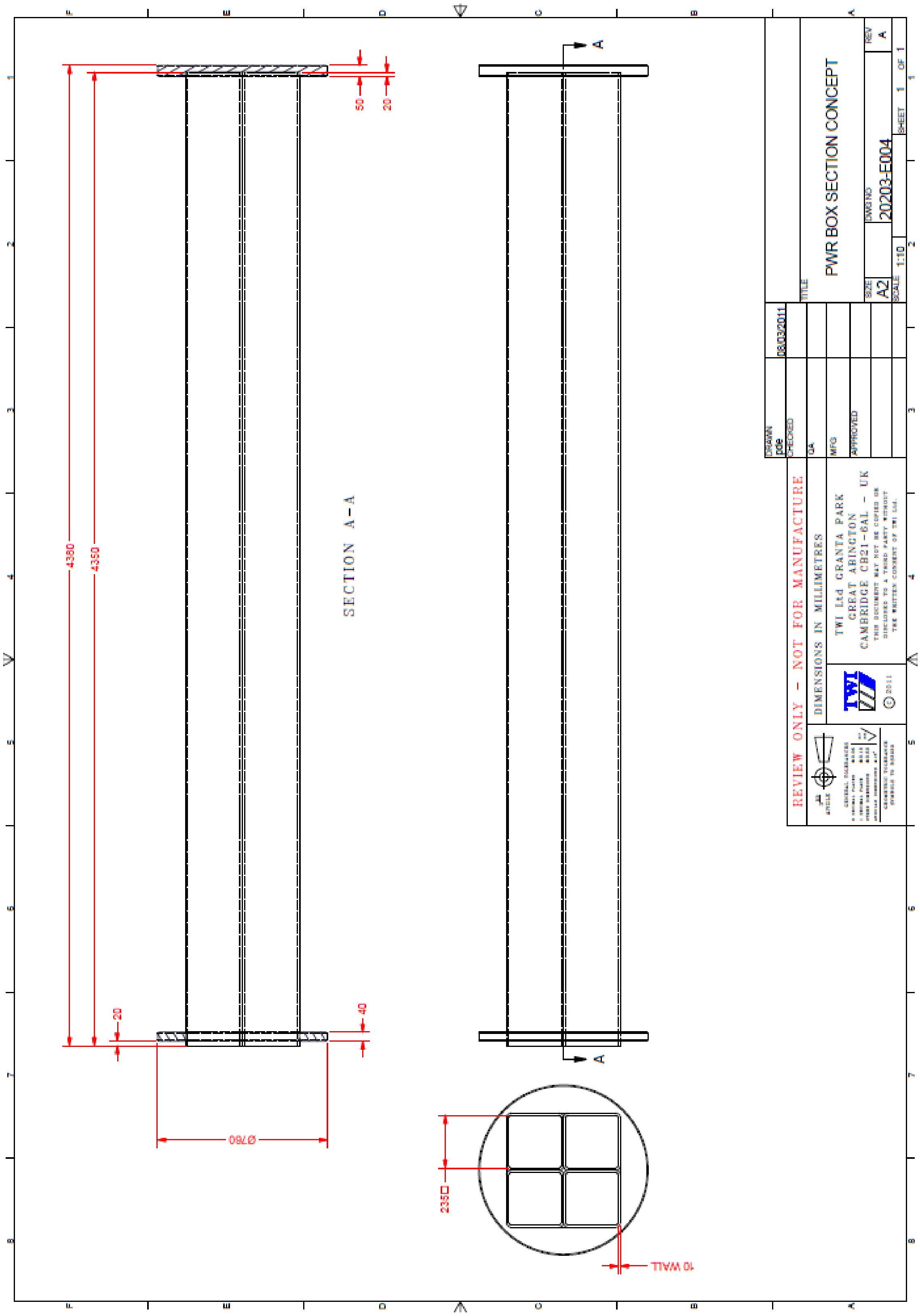



Fig. E6: Box section concept for PWR spent fuels.

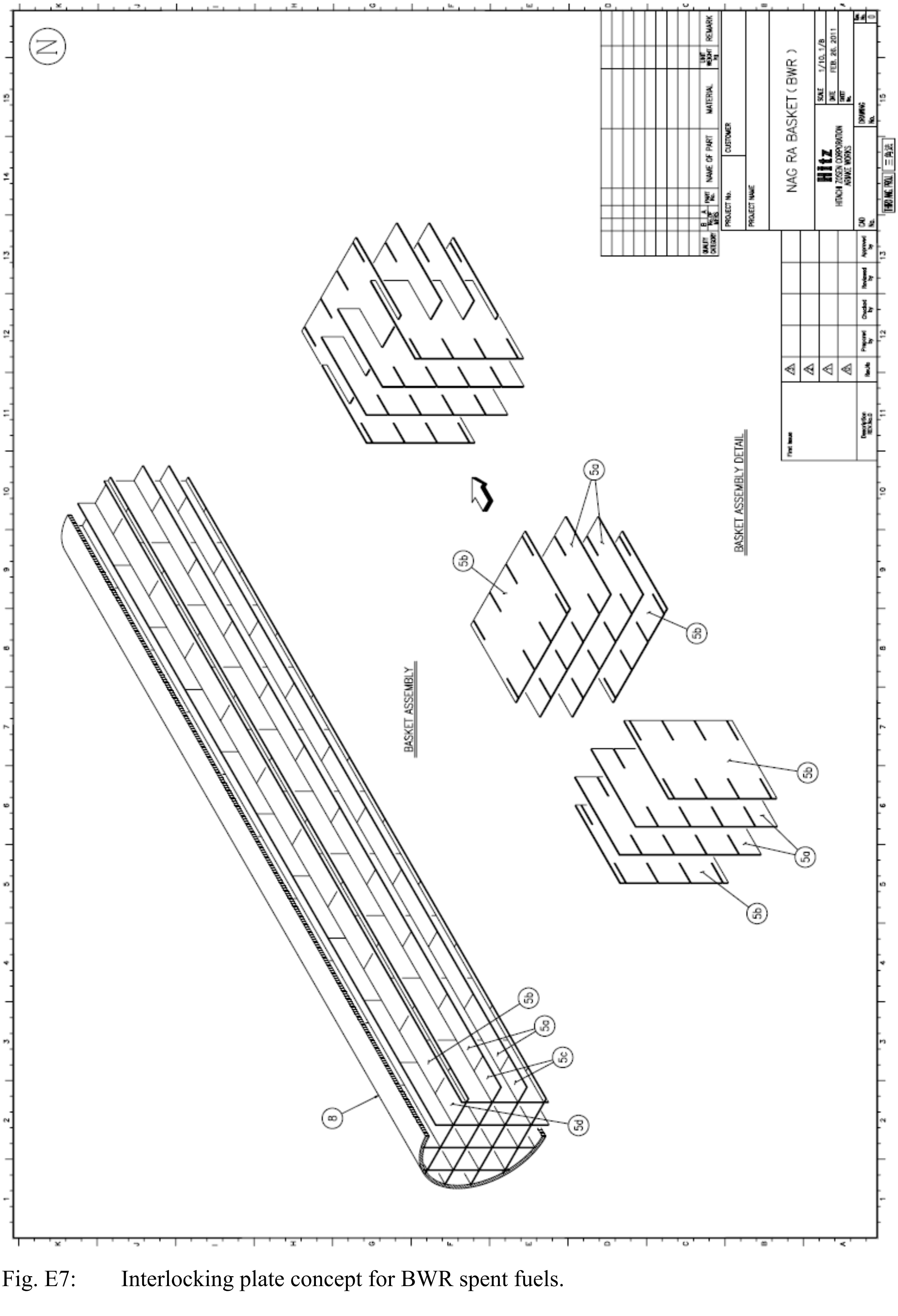



Fig. E7: Interlocking plate concept for BWR spent fuels.

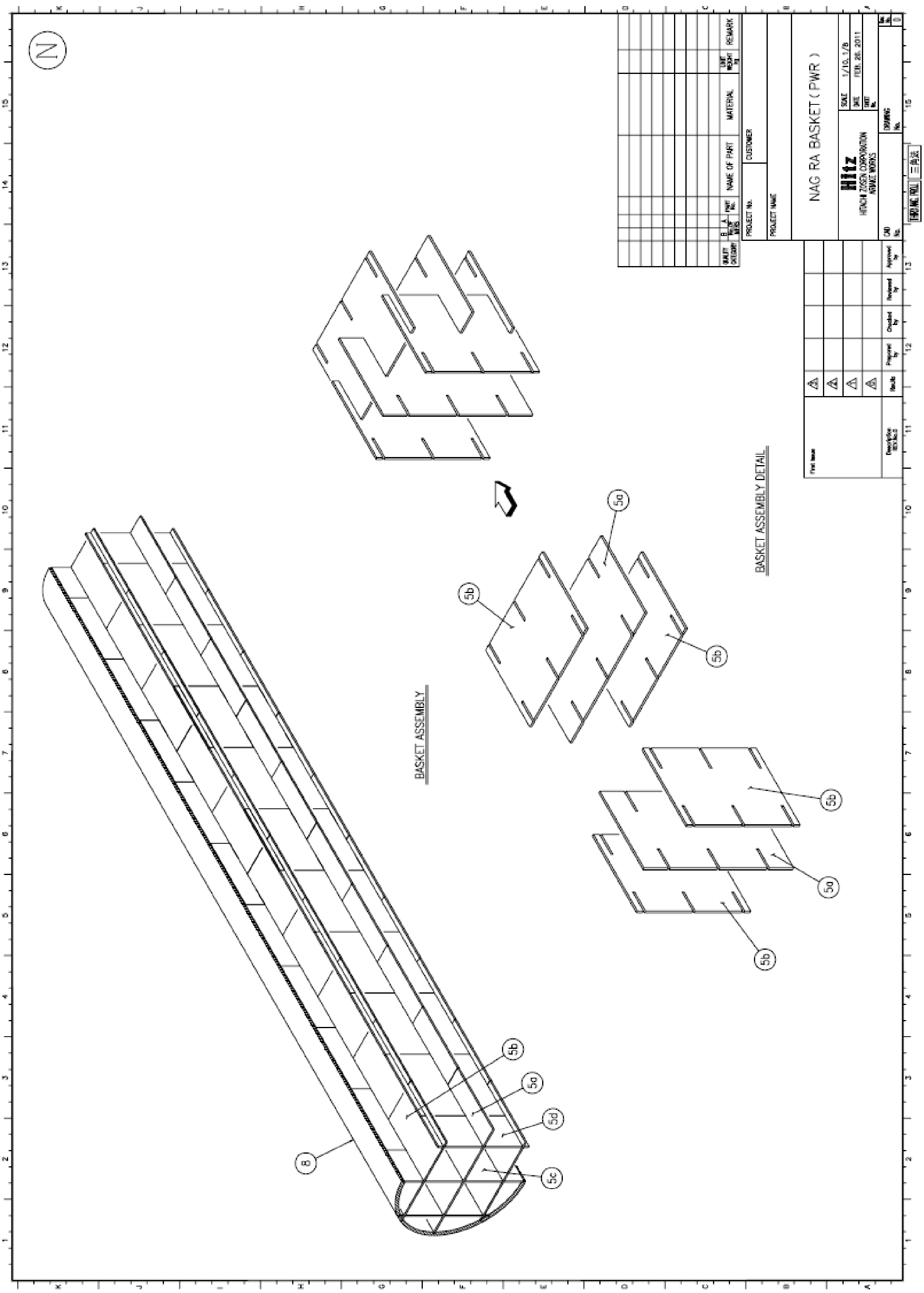


Fig. E8: Interlocking plate concept for PWR spent fuels.

# Appendix F FEA of PWHT for HLW canister

# F1 Introduction

A nuclear waste canister containing flasks of high level waste (HLW) is to be welded to secure the lid to the canister. Stress relief is required in order to bring the resulting tensile residual stresses to an acceptable level. One stress relief method to be considered is local post-weld heat treatment (PWHT). A nuclear waste canister containing spent fuel is also to be considered in the project, but the geometry is much more complex. Therefore, to investigate the expected effects of a local PWHT the canister containing HLW will be considered first and detailed in this report.

Local PWHT is defined by three distinct bands: the soak band (SB), heat band (HB) and gradient control band (GCB). Each of these is measured in millimetres (mm) from the weld. One standard governing local post weld heat stress relieving heat treatment (American Welding Society 1999) dictates that the temperature in the SB must be between 550 and 600°C for the duration of the PWHT. The HB is the area over which the heat is applied to the structure. The GCB is insulated during the PWHT.

There are concerns that during PWHT the HLW in the flasks will go above its maximum allowable temperature of 450°C. A thermal FE analysis was undertaken to investigate whether PWHT would cause this problem.

## F1.1 Objectives

- Carry out thermal FE analysis of PWHT on the canister. Output the HLW temperature when PWHT is applied.
- If temperatures are too high conduct a study investigating how changes to the PWHT method affect the HLW temperature.

# F2 Approach

## F2.1 Overview

The model was generated in Abaqus CAE version 6.11-2 using geometry from a CAD file of TWI's proposed design concept. The analyses were carried out using Abaqus/Standard. The PWHT involved a steady-state heat transfer analysis, as it is assumed that steady-state would be reached during the PWHT. An axisymmetric model was used because of the axisymmetry in the canister geometry.

A 5 mm radial gap between the canister and the flask was assumed. Initially, the simplest case of heat transfer was considered using only infra-red radiation across the gap between the canister and the flasks with no heat generation from the HLW. If this resulted in a HLW temperature above the allowable 450°C there would be no need to consider a more complex model with additional heat transfer mechanisms, because these would cause the temperature of the HLW to increase further. A further case incorporated nuclear heat generated within the HLW flasks. In order to reach steady-state conditions, heat loss by convection was included on the external surfaces of the canister that were not being heated or insulated.

### F2.2 Case list

The heated band length was altered once it was found that the temperature in the HLW was too high. Thus, four different cases were analysed, decreasing the length of HB each time. So, HB2 is longer than HB1, HB1 is longer than HB3 and HB3 is longer than HB4. These were calculated as detailed in Section 6. A fifth case including heat generation from the HLW was also considered for a more realistic result. An emissivity study was also carried out.

Case 1 – HB2 (longest heated band), no heat generation

Case 2 – HB1, no heat generation

Case 3 – HB3, no heat generation

Case 4 – HB4 (shortest heated band), no heat generation

Case 5 – HB4, heat generation

## F3 Geometry

The geometry for the model was taken from a CAD file of the axisymmetric structure. This consisted of a carbon steel canister surrounding 2 stainless steel flasks which contain vitrified high level waste (HLW) from AREVA and Sellafield Ltd. The contact between the two flasks in the canister was simplified by merging the boundaries and creating them as one part, thus assuming a perfect contact. This will not affect the output because it is far away from the heated region. Regions for the SB, HB and GCB were also created. This geometry can be seen in Figure F1. For heat generation, the best case was assumed where the AREVA flask with the lowest heat generation was placed at the top and the Sellafield Ltd. flask with the highest heat generation was placed at the bottom.

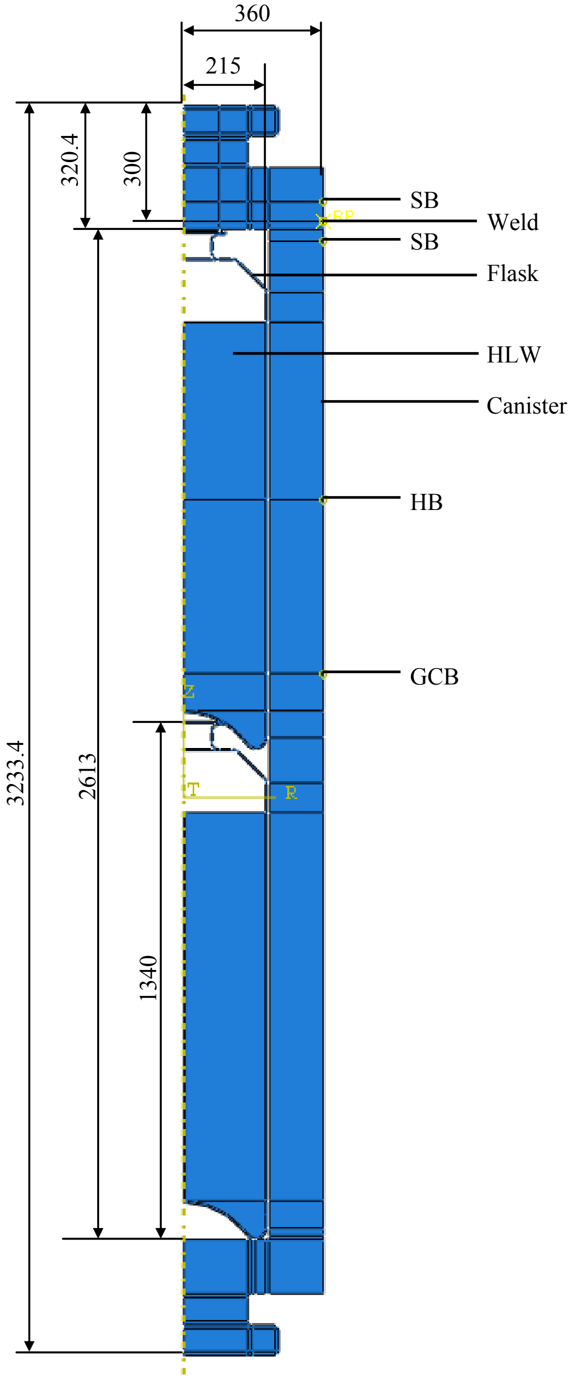



Fig. F1: Geometry and partitions used for the axisymmetric model.
Dimensions in mm.

## F4 Material properties

The material for the canister was assumed to be carbon steel. General material properties were used because the final material selection for the canister has not yet taken place. These properties can be found in Table F1 and Table F2 including references. Only the most reliable values were used. Where text book values were available these were used rather than web-based sources, as highlighted.

Tab. F1: General material properties for carbon steel.

| | |
|---|---|
| **Emissivity** | 0.8 [1] |
| **Convective heat transfer coefficient for heat loss from external surface to air [W/m² K]** | 25 [2] |
| **Density [kg/m³]** | 7870 [3] |

[1] 'Emissivity coefficients of some common materials', Engineering Toolbox (13/1/12)

[2] 'Convective heat transfer', Engineering Toolbox (13/1/12)

[3] 'AISI 1005 Steel', Matweb (13/1/12)

Tab. F2: Temperature-dependent material properties for carbon steel.

| Temperature [°C] | Thermal conductivity [W/m-°C] | Specific heat capacity [J/kg-°C] | Used |
|---|---|---|---|
| 25 | 54 [3] | | |
| 26.85 | | 447.67 [2] | Yes |
| 50 | | 481 [1] | |
| 100 | | 481 [1] | |
| 125 | 51 [3] | | |
| 150 | | 519 [1] | |
| 200 | | 536 [1] | |
| 225 | 47 [3] | | |
| 250 | | 553 [1] | |
| 300 | | 553 [1] | |
| 326.85 | | 573.015 [2] | Yes |
| 350 | | 595 [1] | |
| 400 | | 595 [1] | |
| 450 | | 662 [1] | |
| 500 | | 662 [1] | |
| 550 | | 754 [1] | Yes |
| 600 | | 754 [1] | |
| 850 | | 846 [1] | |

[1] 'AISI 1005 Steel', Matweb (13/1/12)

[2] Lide 1998

[3] Engineering Toolbox – Thermal conductivity

General stainless steel material properties were used for the flasks. These properties and their sources can be seen in Table F3 and Table F4.

Tab. F3: General material properties for stainless steel.

| | |
|---|---|
| **Emissivity** | 0.7 [1] |
| **Specific heat heat capacity [J/g-°C]** | 0.578 [1] |
| **Density [kg/m³]** | 7400 – 8000 [2] |

[1] 'Overview of materials for stainless steel', Matweb (13/1/12)

[2] 'Metals and alloys – densities', Engineering Toolbox (13/1/12)

Tab. F4: Temperature-dependent material properties for stainless steel.

| Temperature [°C] | Thermal conductivity [W/m-°C] |
|---|---|
| 25 | 16 [1] |
| 125 | 17 [1] |
| 225 | 19 [1] |

[1] 'Thermal conductivity of some common materials and gases', Engineering toolbox (13/1/12)

The material properties for the HLW were provided by Nagra and are detailed in Table F5 and Table F6.

Tab. F5: General material properties for the HLW.

| | |
|---|---|
| **Mass [kg]** | 400 [1] |
| **Volume [litres]** | 150 [2] |
| **AREVA flask heat generation [W]** | 606 [1] |
| **Sellafield Ltd. heat generation [W]** | 660 [1] |

[1] Nagra unpublished data

[2] STEAG & Motor Columbus 1985

Tab. F6: Temperature-dependent material properties for the HLW.

| Temperature [°C] | Thermal conductivity [W/m-°C] | Specific heat capacity [MJ/m³-°C] |
|---|---|---|
| 100 | 1.22 [1] | 2.6 [1] |
| 200 | 1.3 [1] | 2.8 [1] |
| 300 | 1.37 [1] | 3.2 [1] |
| 400 | 1.49 [1] | 3.4 [1] |

[1] Nagra unpublished data

## F5 Loading

A heat flux was applied to the outer wall of the canister in the heated band (HB) area. The length and magnitude of the applied heat flux was different for each case. Each of the heated band lengths were calculated as shown below, where $H_i$ is an empirically derived ratio of heat source area to heat loss area (taken to be 5, as suggested by American Welding Society 1999), OD is Outer Diameter, ID is inner diameter, R is outer radius and t is wall thickness. The SB was calculated as the maximum of 2 t or 51 mm, in this case 51 mm. The GCB was calculated from the HB according to ASW D10.10, as given below. The calculated lengths are each side of the weld, measured from the weld.

$$HB2 = \frac{H_i\left[\frac{OD^2 - ID^2}{4} + (ID \times SB)\right]}{OD}$$

$$HB1 = SB + 2\sqrt{Rt}$$

$$HB3 = SB + 1.5\sqrt{Rt}$$

$$HB4 = SB + \sqrt{Rt}$$

$$GCB = HB + 2\sqrt{Rt}$$

The heat flux was found by trial and error in order for the *SB* to be between 550 and 600°C. The final values for each case and the PWHT dimensions are summarised in Table F7.

Tab. F7: Values for SB, HB, GCB and final heat flux for each case.

| | | **SB [mm from weld]** | **HB [mm from weld]** | **GCB [mm from weld]** | **Heat flux [W/mm$^2$]** |
|---|---|---|---|---|---|
| Case 1 | HB2 | 51 | 719.72 | 1168.72 | 0.0019 |
| Case 2 | HB1 | 51 | 500.00 | 949.00 | 0.00335 |
| Case 3 | HB3 | 51 | 387.75 | 836.75 | 0.00435 |
| Case 4 | HB4 | 51 | 275.50 | 724.50 | 0.00570 |
| Case 5 | HB4 | 51 | 275.50 | 724.50 | 0.00550 |

Each of the applied heat flux regions are shown in Figure F2 for the different cases. The length of the heated band below the weld was reduced each time in order to reduce the maximum temperature in the HLW. The length of heated band was reduced above the weld as well in order to obtain a more desirable temperature distribution on the top of the canister because in HB2 this was well above the desired temperature of 600°C.

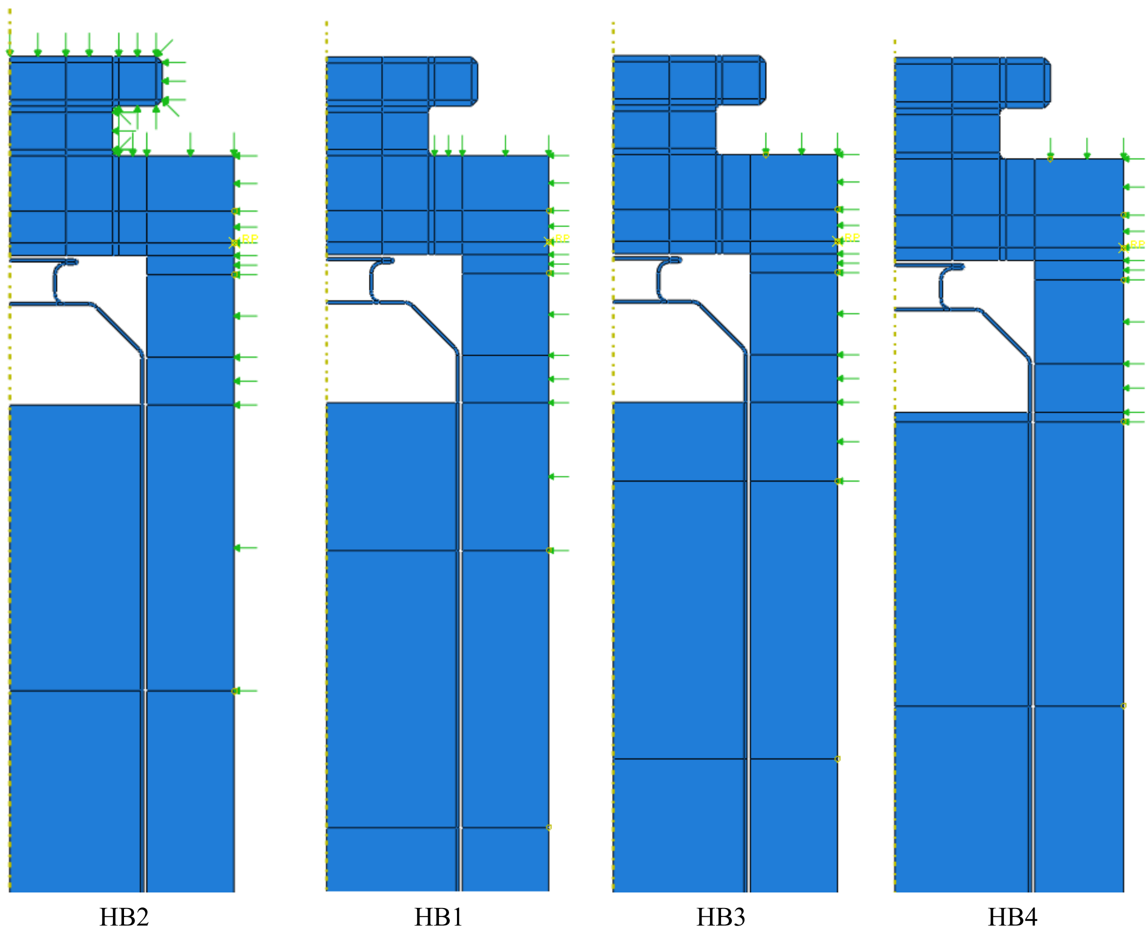
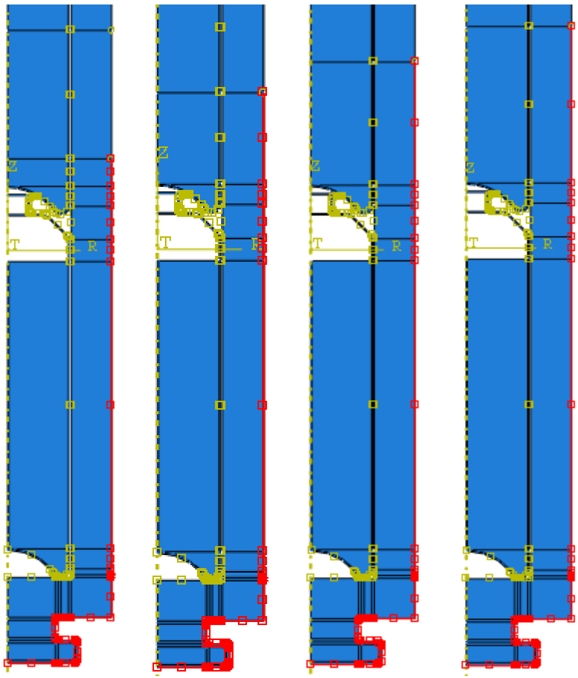



Fig. F2: Heated band load applied for different cases.

## F6 Boundary conditions

An initial temperature of 20°C was assumed for the entire assembly and the environment. No boundary conditions were specified on the GCB surface in order to model insulation. A surface radiation condition (emissivity 0.8) and convective heat transfer condition (convective heat transfer coefficient 0.000025 W/mm$^2$-°C) were applied to the outer surfaces of the canister which were not being heated or insulated. These can be seen in Figure F3.

Heat transfer was modeled only by infra-red radiation within the canister between the inner wall of the canister and the outer wall of the flaks only, as illustrated in Figure F4. Heat generated by nuclear radiation within the flask was ignored and it was assumed that there no convection.



HB2 HB1 HB3 HB4

Fig. F3: Surface radiation and convective heat transfer boundary conditions.

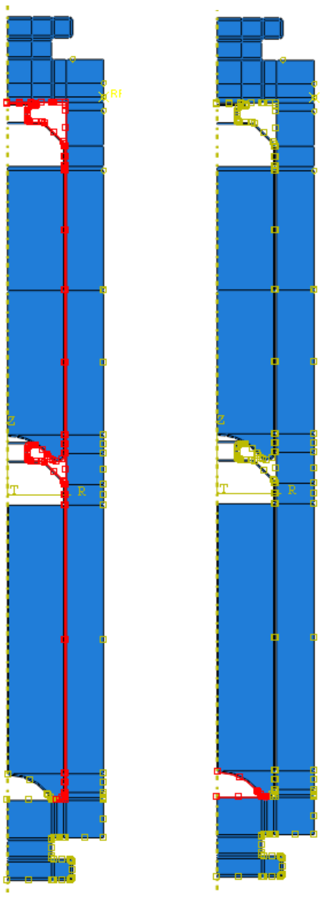


Fig. F4: Radiation boundary conditions.

## F7 Mesh

The model was meshed with predominantly 8-node heat transfer quadrilateral elements (type DCAX8 in ABAQUS) and some 6-node heat transfer triangular elements (type DCAX6 in ABAQUS). A finer mesh was used around the heated area at the top of the model because this is where the highest temperature gradients were expected. The mesh becomes gradually coarser away from the heated region to speed up computation time. The more complex regions of the mesh in the flask are highlighted in Figure F5. Four elements were used across the flask thickness to allow for adequate temperature gradients.

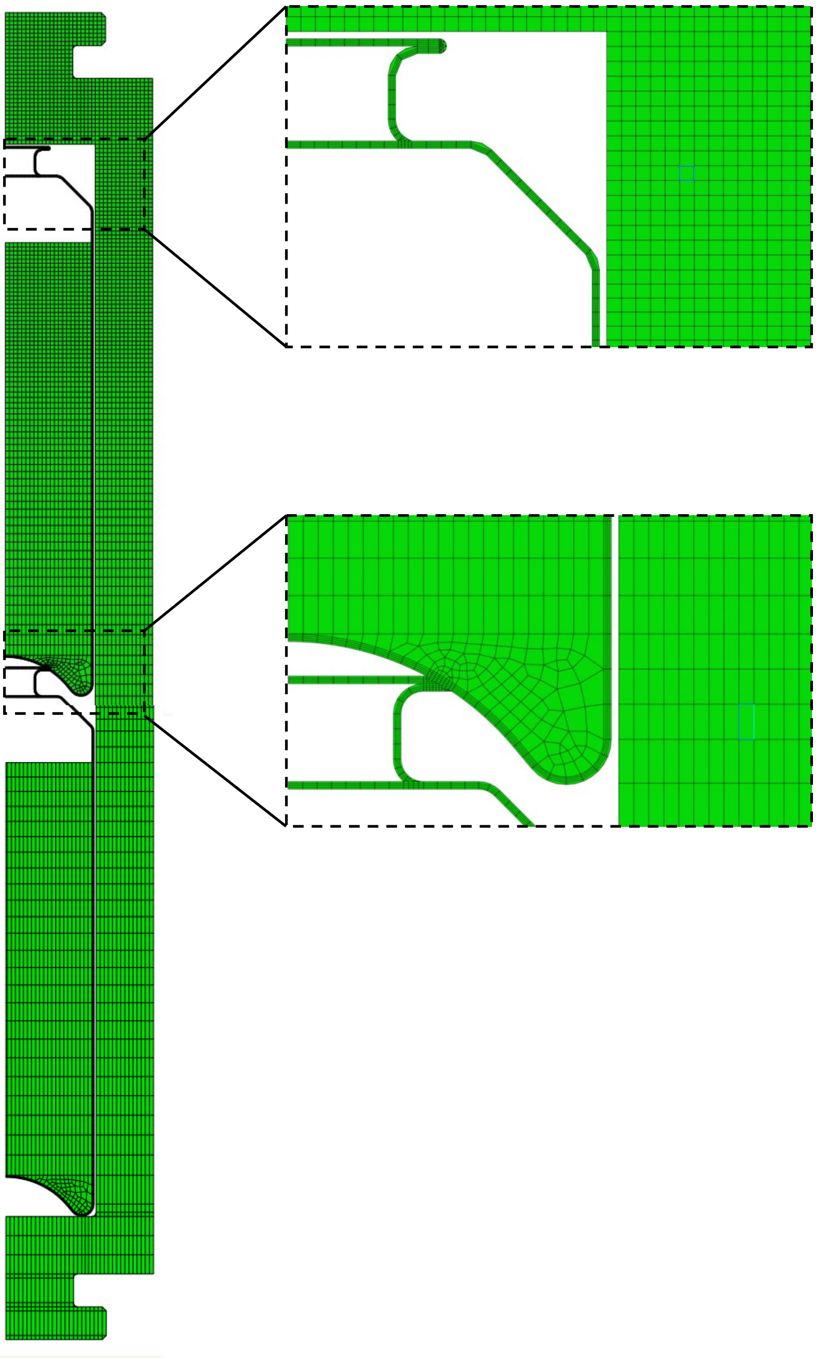


Fig. F5: Meshed geometry, with complex regions highlighted.

# F8 Results

## F8.1 Changes in heated band

The maximum and minimum temperatures in the SB were output for each analysis to ensure that the temperature was between 550 and 600°C, as specified in the standard (American Welding Society 1999). The analysis was repeated for each case, changing the heat flux applied until this condition was met. An example of this for HB1 is shown in Figure F6. The maximum temperature in the HLW was also output in order to see if the maximum temperature criterion of 450°C was being met. The final results for each case are summarised in Table F8 and illustrated in Figure F7. These show that decreasing the heat band size, and increasing the heat flux to meet the temperature requirements in the SB, reduces the maximum temperature in the HLW, bringing the temperature closer to its limit. The lowest temperature reached was 464°C with HB4, which is still over the limit of 450°C.

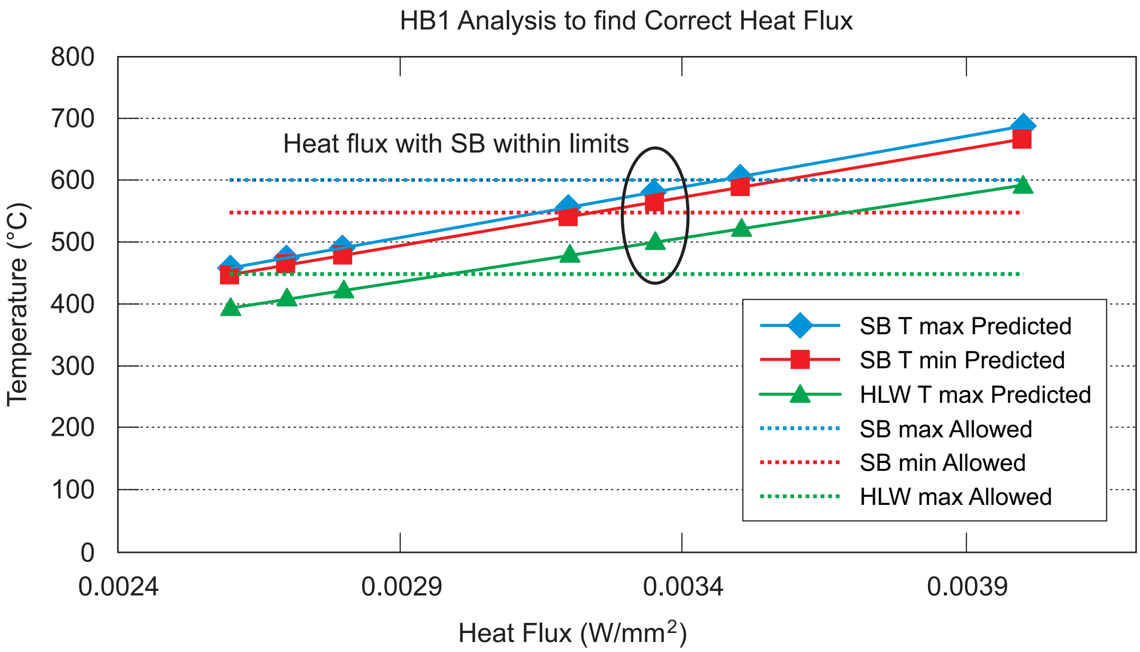



Fig. F6: Trial and error procedure used to find suitable heat flux for HB1.

Tab. F8: Final results for temperature of SB and HLW for each case.

| | Width of heated band | Heat flux [W/mm$^2$] | SB Tmax [°C] | SB Tmin [°C] | HLW Tmax [°C] |
|---|---|---|---|---|---|
| HB2 | Largest | 0.0019 | 591 | 566 | 518 |
| HB1 | | 0.00335 | 584 | 563 | 505 |
| HB3 | | 0.00435 | 576 | 552 | 482 |
| HB4 | Smallest | 0.0057 | 586 | 554 | 464 |

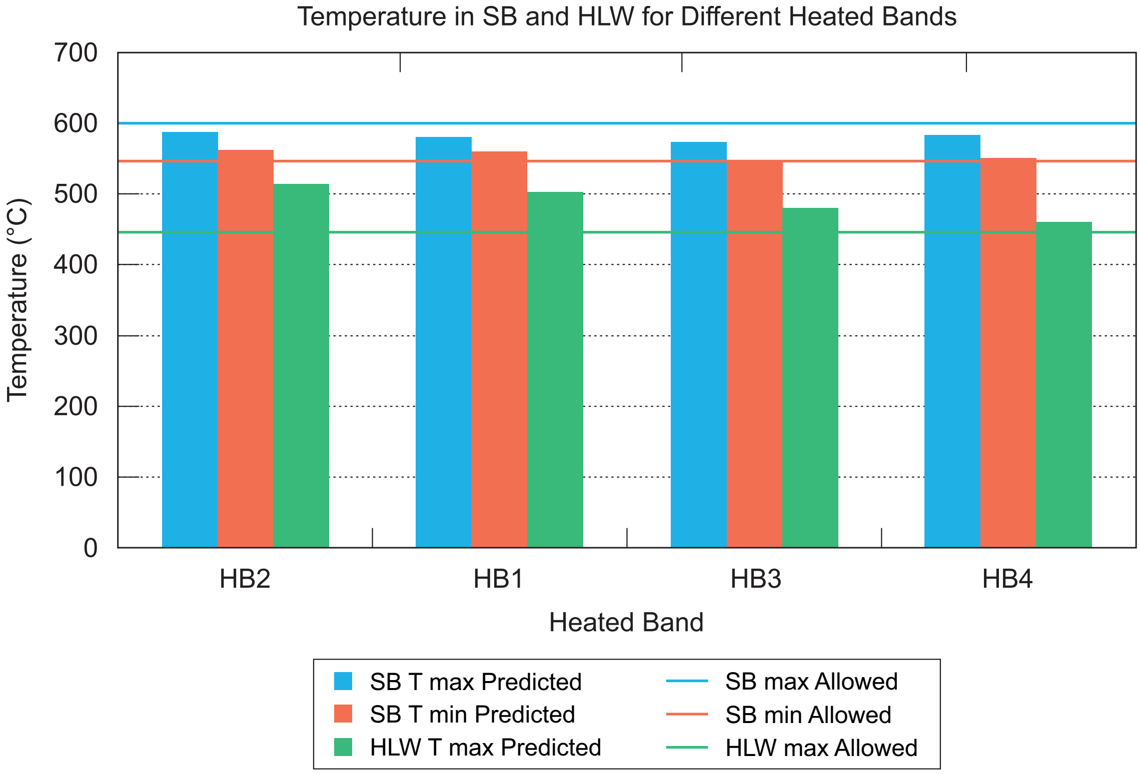



Fig. F7: Final results of temperature for SB and HLW for each case.

As the size of heated band was reduced, the temperature distribution over the upper part of the canister was also improved, as demonstrated in Figure F8. Using HB2, the temperature of the upper part of the canister was well above 600°C – much higher than required for the PWHT. HB4, however, shows a much more even distribution across the top of the canister, closer to the maximum of 600°C required, but also with a larger temperature gradient just below the weld because the heat flux is applied over a more concentrated area. This results in the reduced temperature in the HLW.

Reducing the heated band size greatly reduced the area of HLW above the limit of 450°C, as shown in Figure F9, where only the HLW from the upper flask is shown. The maximum temperature is always found in the top right corner of the HLW, as expected because it is closest to the heat source. The small region above 450°C for HB4 shows some promise for meeting the target maximum temperature of 450°C by changing other parts of the design.

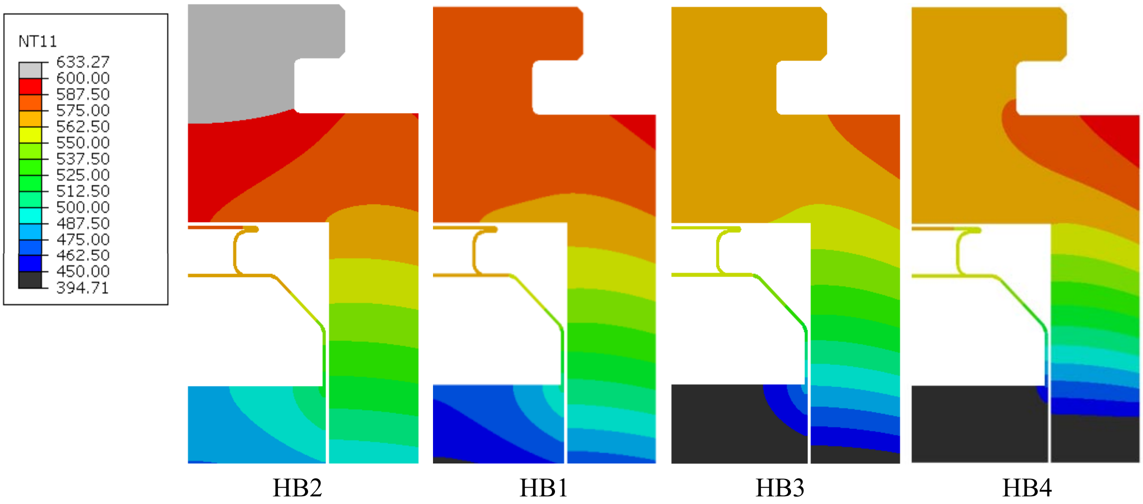



Fig. F8: Temperature distribution in top of model for each case.

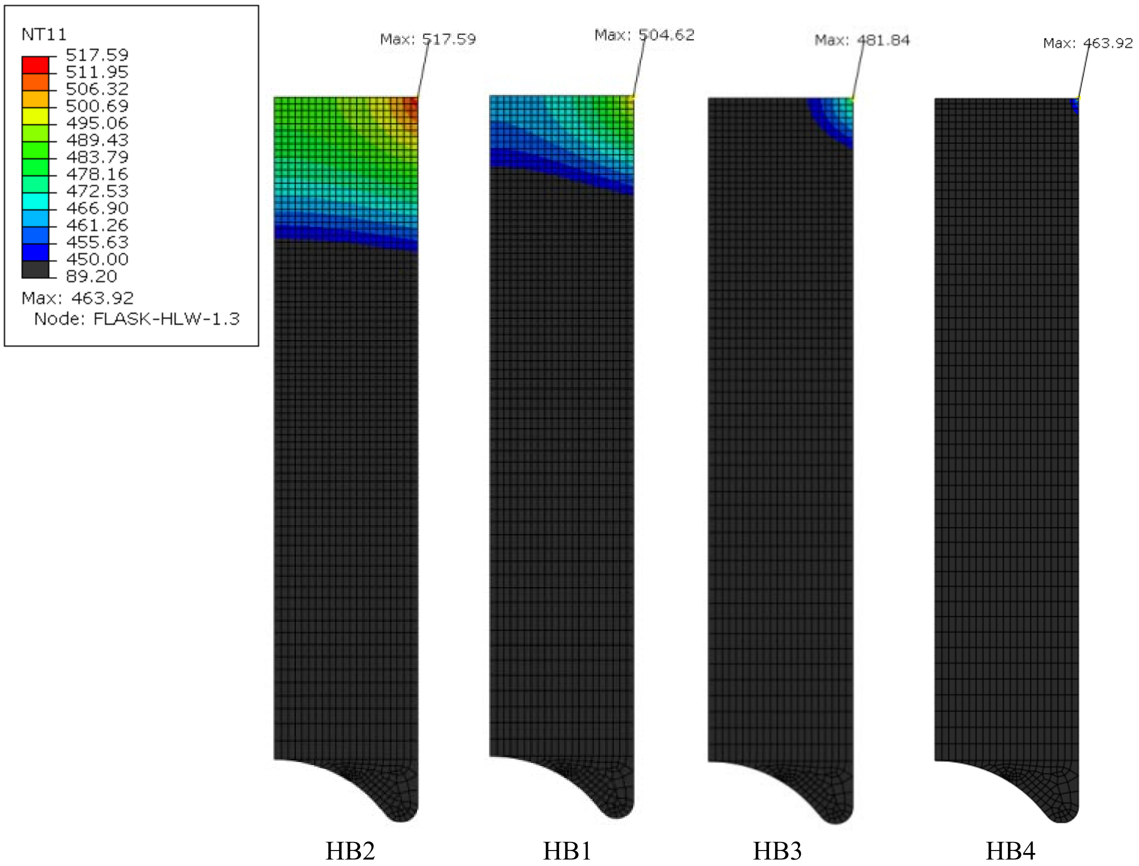



Fig. F9: Temperature distribution in HLW at top of canister for each case.

### F8.2 Emissivity study

A study was carried out on the effect of changing the emissivity of the flask and the canister, using HB1. The emissivity of the flask was changed from 0.7 to 0.5 to simulate polishing the flask, keeping the emissivity of the canister constant at 0.8. Similarly, the emissivity of the canister was changed from 0.8 to 0.6 while keeping the emissivity of the flask constant at 0.7. The results are shown in Table F9. Both cases reduced the maximum temperature of the HLW by 1 – 2°C, showing no significant improvement. It is expected that changing the emissivity by an order of magnitude would show more significant results, but this would perhaps be less realistic in terms of achievability.

Tab. F9: Emissivity study results for temperature of SB and HLW.

| | Emissivity of flask | SB Tmax [°C] | SB Tmin [°C] | HLW Tmax [°C] |
|---|---|---|---|---|
| **Flask** | 0.7 | 584 | 563 | 505 |
| | 0.6 | 584 | 563 | 504 |
| | 0.5 | 584 | 564 | 503 |
| **Canister** | 0.8 | 584 | 563 | 505 |
| | 0.7 | 584 | 564 | 504 |
| | 0.6 | 584 | 564 | 504 |

### F8.3 Heat generation

In order to make the model more realistic, heat generation in the flask was included. A best-case scenario was used such that the flask producing less heat (AREVA at 606 W) was placed at the top and the flask producing more heat (Sellafield Ltd. at 660 W) was placed at the bottom, away from the heat source. HB4 was used for this analysis. Because of the heat generated internally, a smaller heat flux was required of 0.0055 W/mm². However, the maximum temperature in the HLW still increased from 464 to 473°C. This is a relatively small increase but results in a much larger area of HLW above 450°C. This is because the heat generated by the HLW is greatest in the centre, whereas the heat input from the PWHT is greatest at the edge, resulting in a more even temperature distribution through the thickness of the HLW and the canister, as shown in Figure F10.

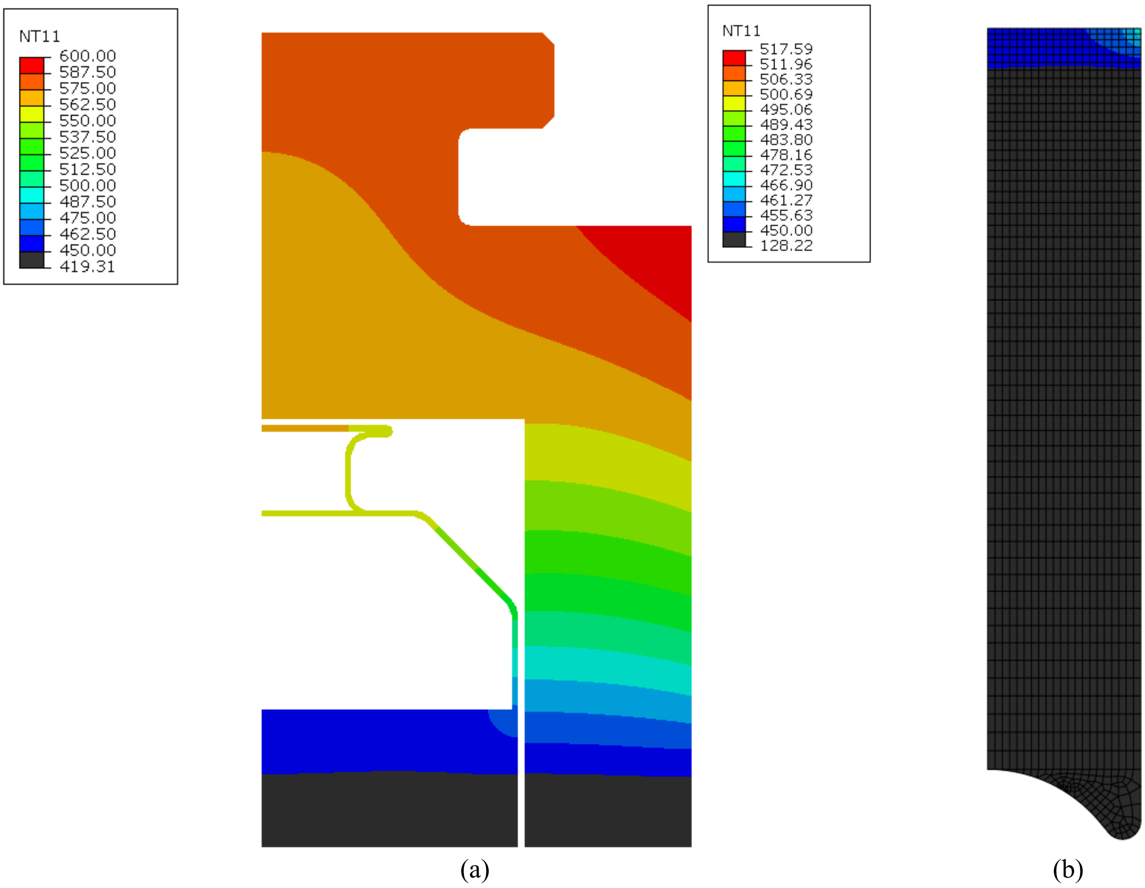



Fig. F10: (a) Temperature distribution in top of model including heat generation, (b) Temperature distribution in HLW including heat generation.

## F9 Discussion

The results presented are not fully representative of the real system because they only consider radiative heat transfer in the gap between the canister and the flask. In reality this would most likely contain air, and convection and conduction would also contribute to heat transfer. Using the model temperatures calculated in Section 9.3, it can be shown using Stefan's Law that the heat flux expected from conduction through air is an order of magnitude less than that of radiation. This means that conduction is also worth considering and would result in a further increase in temperature in the HLW. Convection would also be expected to increase the temperature of the HLW, but this would need to be confirmed with a full 3D FE analysis. A further analysis should also be carried out including the nuclear radiation from the HLW. It is also worth noting that the film condition parameter used for modeling the heat loss by convection at the external surface (25 W/m) was slightly higher than commonly used in the case of static air (12 W/m). It is not known how this difference can affect the temperature in the waste, and a sensitivity study to this parameter, similar to that carried out for the emissivity, should be conducted in the future.

It is clear from this analysis that changes in the PWHT process or canister design are required to keep the HLW temperature below 450°C. The PWHT could be altered by minimising the heated band to reduce the heat transfer to the HLW and reducing the soak time so that the steady state conditions are not reached. However, further FE analysis would be required in this non-standard case to ensure that the resulting residual stresses would be acceptable. The canister design could be altered by lengthening the canister so that the HLW is further away from the local PWHT thus reducing the heat transfer. Alternatively, a spacer could be introduced near the bottom of the flask, in order to promote heat transfer to the lower part of the HLW. This would increase the HLW temperature at the bottom of the flask, but decrease the temperature at the top, where the current maximum temperature is found. Further work is also recommended to validate the FE results by experimentation. The effect of local PWHT on the spent fuel assembly should also be considered using FEA.

The practicalities of implementing this local PWHT should also be considered. The heated blankets and insulation would need to be applied remotely using robotics in the encapsulation facility.

## F10 Conclusions

A thermal, steady-state finite element analysis was carried out on the PWHT of a nuclear waste canister containing flasks of high level waste considering only radiative heat transfer. It was found that decreasing the area over which the heat source is applied will reduce the high level waste from a maximum temperature of 517.6°C using the standards to 464°C. Unfortunately, this is still above the maximum allowable temperature of 450°C, although there was only a small area of the HLW above this temperature. Reducing the emissivity of the flask or canister by 0.2 made negligible difference to the temperature of the HLW. Including the heat generation from the HLW to make the model more realistic increased the maximum temperature of HLW from 464°C to 473°C, showing a relatively small increase. The temperature distribution in this case was much more even across the canister and the HLW.

The maximum temperature of the HLW was brought down to such a level that reaching the required temperature should be achievable. Changes in the PWHT process or the design of the canister are recommended to meet the requirements.

# Appendix G Canister design drawings

## G1 Introduction

This appendix presents drawings of the SF canisters (Design 1 and Design 2) that were used to generate the FE models to perform the structural analyses. Design 3 of the SF canister is essentially the same as Design 1 but without a notch.

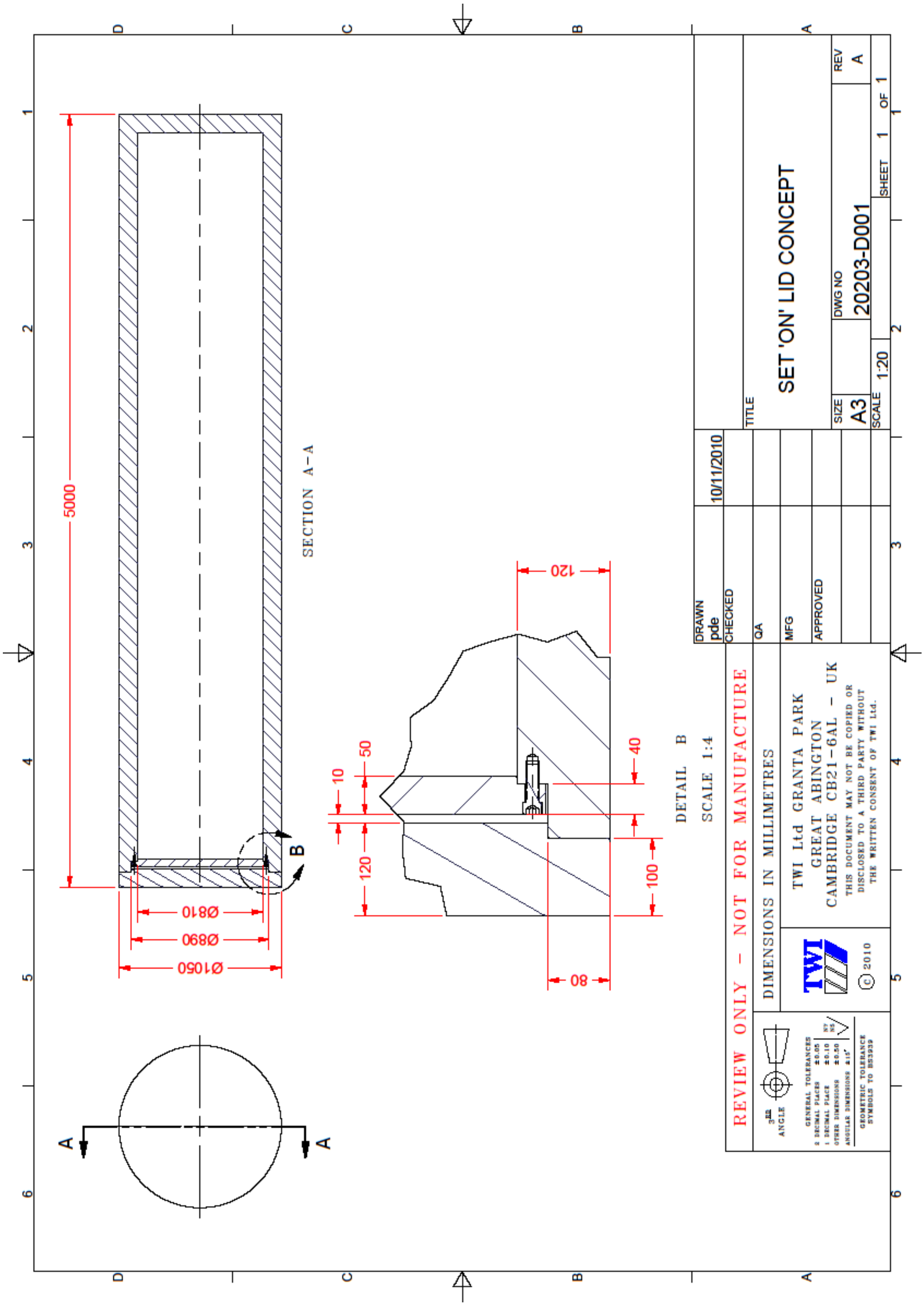



Fig. G1: Design 1 of the SF canister geometry.

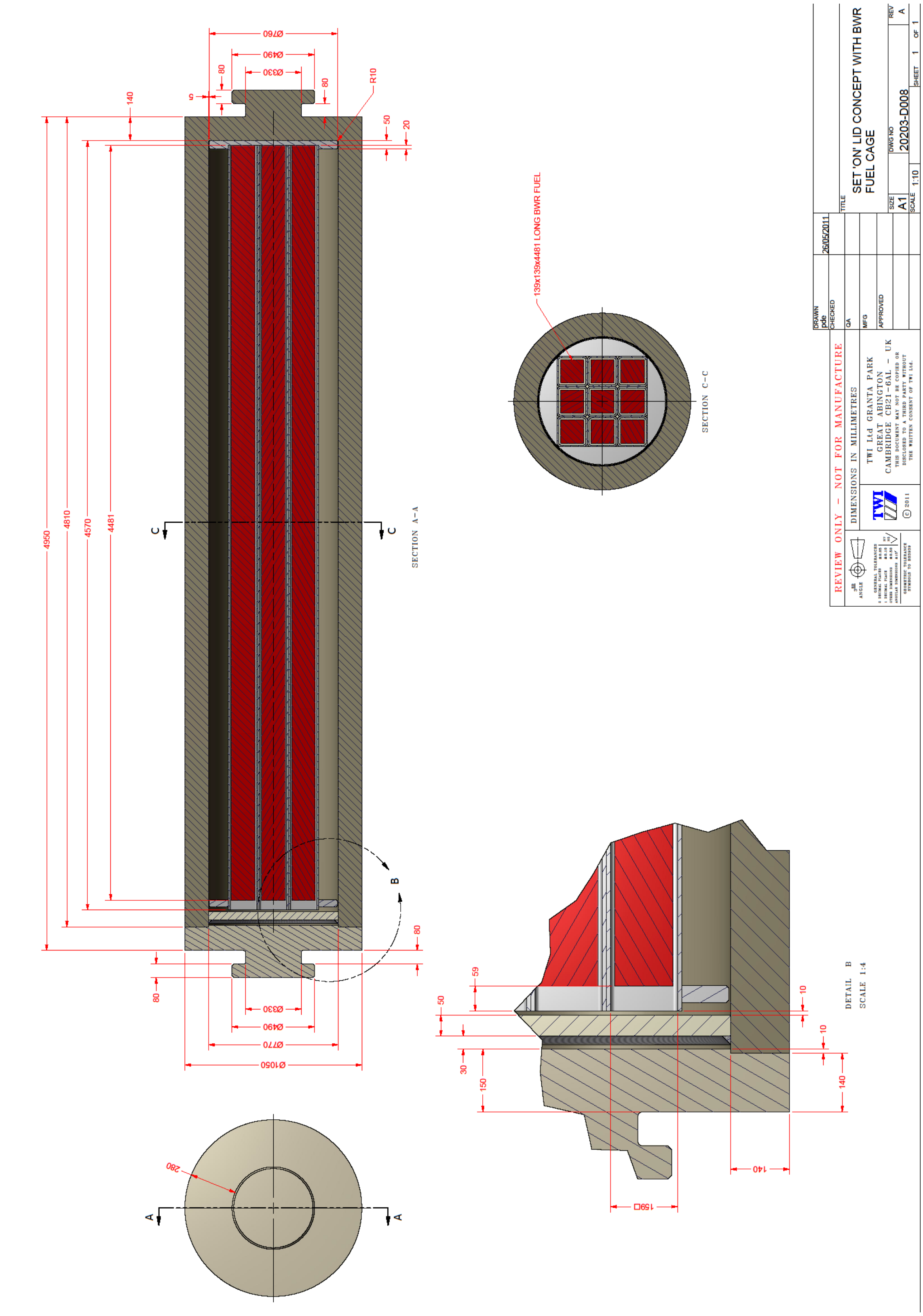



Fig. G2: Design 2 of the SF canister geometry.