Assessment of the Safety Case for the Reactor Pressure Vessel of the Beznau Unit 1 Nuclear Power Plant

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EXECUTIVE SUMMARY

In 2015 NDE investigations of the Beznau Unit 1 and Unit 2 RPVs were carried out to determine whether they contained hydrogen flakes like those found in the Belgian Reactors, Doel 3 and Tihange 2. UT indications were found in the RPV of Unit 1, with the highest numbers and densities in Shell C. They were however dissimilar to those found in the Belgian reactors.

As a result of the discovery of the flaws, at that point of an unknown nature and unknown influence on the integrity of the RPV, ENSI (the Swiss Nuclear Regulator) asked Axpo Power AG, the licensee, to produce a structural integrity review of the Beznau 1 RPV before recommissioning. This led to an extensive investigation by Axpo to establish the nature of the flaws and justify that they did not impair the structural integrity of the RPV.

ENSI appointed an International Review Panel (IRP) of experts to advise it. The role of the IRP was to advise ENSI on the completeness and adequacy of the Axpo's workplan, to advise on the adequacy of the results as they became available and, finally, to provide an independent assessment (within a defined scope) of the Safety Case produced by Axpo. The responsibility for the safety of the Beznau Unit 1 is Axpo's, and the decision on the acceptability of continued operation of the reactor is the responsibility of ENSI. This report provides the IRP assessment and advice related to those decisions.

Axpo also involved independent experts and several expert sub-contractors to advise and to do the considerable amount of work necessary. The IRP maintained a close contact with developments through workshops and meetings with Axpo and their experts, and ENSI during the period December 2015 to January 2018. It also had access to many interim reports as well as the final SC reports and support documents.

The IRP considers that the Axpo Safety Case is acceptable. This is based on the following:

- It has been established beyond all reasonable doubt that the flaws are laminar 'agglomerates' of alumina inclusions, formed during manufacture of the affected RPV shells, and which neither formed nor grew during service.
- It has been adequately demonstrated that such agglomerates do not significantly affect the materials properties relevant for structural integrity assessment or sensitivity to irradiation damage.
- The ultrasonic testing carried out on the RPV was sufficient to ensure that all flaws that might significantly affect structural integrity were detected and conservatively assessed.
- A fracture mechanics assessment of the flaws, using highly conservative assumptions, demonstrated that the case is robust.

The IRP was also asked to advise on whether there were any implications of the results of Axpo's work program on the formal methods and requirements used to set operational limits. This resulted in an IRP recommendation on the choice of method used to determine the fracture toughness lower bound for the Beznau Unit 1 irradiated material.

Contents

1 Introduction

1.1 Background to this report

This report is an assessment by the International Review Panel (IRP)[1] of the reports supporting the Safety Case (SC) of the Reactor Pressure Vessel (RPV) of the Beznau Unit 1 Nuclear Power Plant (NPP). The final SC was submitted by the licensee. Axpo Power AG (Axpo), to Eidgenössisches Nuklearsicherheitsinspektorat (ENSI) in December 2017. The submission was based on the SC report [1], four sub-project synthesis reports [2, 3, 4, 5] and many supporting documents.

The IRP is a panel of international experts[2], appointed by ENSI in September 2015 to provide independent advice on the SC for the Beznau Unit 1 (Beznau 1) RPV (‘the RPV’). The IRP had two main duties.

The first was to assess the roadmap (RM), or project plan, developed by Axpo to describe how it intended to develop the SC [6].

The second, the subject of this report, was to assess the SC, as given in [1, 2, 3, 4, 5] and in the supporting documents available to the IRP at the time of the final IRP workshop. The process was facilitated by presentations and discussions at several meetings between Axpo and their independent experts, and the IRP and ENSI[3].

1.2 IRP responsibilities and scope of the assessment

The IRP was appointed as an independent body responsible for its own activities. Its duty was to critically and independently assess the SC reports, within ENSI requirements and scope, to advise ENSI on safety-related aspects that are insufficiently justified, and to document its joint conclusions. The responsibility for the safety of the NPP rests with the licensee. The formal assessment of the SC, and the decision on the acceptability of continued operation of Beznau 1, are the responsibility of ENSI. The conclusions of the IRP, and the advice and opinion given in this report would not necessarily be endorsed by the organizations to which members are affiliated and are given in the context of the Beznau 1 RPV Safety Case.

The scope of the IRP assessment is based on the scope of the SC as defined by [1]. Within the overall scope, the IRP is excluded from some specific aspects. The validation[4] and verification of Non-Destructive Examination (NDE) and Destructive Testing (DT) were the responsibility of Schweizerischer Verein für technische Inspektionen (SVTI) in association with Vinçotte. This team included one member of the IRP, through whom the results of this process, and the interpretation of the NDE results, were made available within, and assessed by, the IRP. Independent assessment of the loadings and assessment of the numerical fracture mechanics (FM) were subcontracted by ENSI to independent organizations. The scope of the IRP assessment was limited to technical issues

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[1] Abbreviations and symbols are listed in Annex 1
[2] IRP members are listed in Annex 2.
[3] Workshops and meetings are listed in Annex 3
[4] Terminology is given in Annex 4

and was essentially qualitative. It did not have the resource to verify the quantitative information provided in the Axpo[5] reports.

The IRP assessment relates only to the specific case of the Beznau 1 RPV; it should not be assumed that the information and advice given in this report apply more generally. Further, this report is not a stand-alone document. It should be considered in the context of the Axpo and ENSI reports that document the background and requirements for a SC. The terminology used in this report is given in Annex 4. Where possible this follows the terminology used by Axpo in [1, 2, 3, 4, 5].

1.3 Safety case background

1.3.1 Context

As a part of the WENRA recommendation on flaw indications in forged reactor pressure vessels, ENSI requested an ultrasonic inspection of the Beznau 1 and 2 and other Swiss RPVs to verify whether they were affected by hydrogen-induced cracks (also referred to as hydrogen flakes) as in the core shells of the Doel 3 and Tihange 2 RPVs in Belgium. UT inspection using the Phased Array technique took place in 2015 during a periodic overhaul of those units. The upper core shell and areas of the lower core shell and nozzle shell of both RPVs were inspected. Numerous indications were detected in the Beznau 1 RPV. Additional UT inspections of that RPV were then performed, including the inspection of the core shells with the same tools as the ones used for the Doel 3 and Tihange 2 RPVs. The latter confirmed the presence of numerous indications smaller than hydrogen flakes within the thickness of the Shells B, C and E of the RPV. ENSI asked for an integrity review of the RPV by the licensee before recommissioning Beznau 1.

1.3.2 Safety concern

The integrity of an RPV[6] is ensured by a set of measures including the use of material of high quality. The quality of a steel is classically defined by a set of attributes including, by order of decreasing harmfulness, the soundness (i.e., the absence of cracks and porosities), the cleanliness (i.e., a low level of inclusions), and the chemical homogeneity (i.e., the absence of excessive segregation of carbon and impurities).

Any steel is expected to contain imperfections. For this reason, NDE, e.g., UT examination, is performed after manufacturing in accordance with the material specification to detect types of imperfection of potential concern. Only the indications above some threshold, i.e., the reporting level, need to be assessed. For the manufacturing inspection the UT threshold is set to a level such that the presence of imperfections under the threshold is not inconsistent with the acceptable workmanship and quality level for the fabrication of the component. Any steel fulfilling the material specification, as demonstrated by the NDE and acceptance testing to confirm chemical composition and key materials properties, may be used without any additional measures.

In-service inspection (ISI) is carried out at periodic intervals during the lifetime of the RPV to ensure that forewarning is given of any unexpected threat to structural integrity. The detection during

[5] Unless otherwise indicated 'Axpo' will be used to refer to the company together with its sub-contractors, including its expert advisors.

[6] Although this chapter refers to RPVs similar requirements apply to all pressure vessels and indeed all engineering structures that might present a hazard should there be a failure. The requirements are considerably more stringent for RPVs than for structures for which failure would have lower consequences.

operation of UT indications that were not previously reported or appear to have become larger raises questions concerning the safe performance of the RPV. Indications are evidence of a flaw in the material that might have developed or grown in service. There are many different types of flaw, ranging in size from microns to centimetres (in extreme cases metres). Whether they are harmful depends on their characteristics, dimensions, location within a structure and the service loading to which they will be subjected.

When ISI reveals something unexpected it is assessed to determine whether it is potentially significant to the structural integrity of the RPV. The Regulator for the country in which the RPV operates may require that the safety of the RPV for continued operation be demonstrated using methods that are defined in the Regulatory Codes authorized by that Regulator. When the safe performance of an RPV is potentially affected by material imperfections, it is necessary to establish that it still conforms to its design basis (that is that the safety factors required by the design codes are maintained). That is usually done by performing a 'fitness-for-(continued) service justification'. This situation applies to the Beznau 1 RPV and the Safety Case, required by ENSI and provided by Axpo, is therefore considered in this report as fitness-for-service justification.

1.3.3 Structure of the report

The report documents the assessment by the IRP of the Axpo Safety Case. The report structure reflects the key steps involved in a fitness-for-service justification. It should be noted that Axpo did much of the work in parallel and there are some significant interactions between some of the elements of the SC. The following provides a guide to the report; in the individual chapters cross-references are made where applicable to related information.

Chapter 2 - Origin, nature and root cause of the indications

A first requirement of the SC was to establish the origin of the UT signal (i.e. what is reflecting or impeding the sound wave), the nature of that object (i.e. the type of flaw and its characteristics), and, if possible, its root cause (why it came to be present). This information was needed to decide what was the safety concern. For Beznau 1 the origin of the indications (large agglomerates of alumina inclusions[7]) and the root cause were confirmed by producing a replica of RPV Shell C ('Replica C'). This replica was also used to validate NDE (Chapter 4), and to provide material to demonstrate that alumina had no adverse effect on material properties (Chapters 5 and 6).

Chapter 3 - Representativeness of Replica C

The Replica C forging was extensively used as a surrogate of RPV Shell C material to assess the potential effects of the alumina agglomerates on the mechanical properties of the RPV Shell C material. This required that the sufficient representativeness of Replica C for that specific purpose be demonstrated.

[7] Very small (micron-sized) isolated alumina (Al_2O_3) inclusions are a normal constituent of aluminium-killed RPV steels. In Beznau 1, very large numbers of these inclusions were found packed together in "agglomerates" surrounded by the steel matrix. These agglomerates were large in two dimensions (mm-sized) but relatively much thinner in a laminar orientation, surrounded by the steel matrix. These will be referred to as 'alumina agglomerates'. Usually, several agglomerates were grouped together, separated by matrix, these will be referred to as 'alumina conglomerates' or conglomerates'. Further details are given in Chapter 2. The term 'inclusion' may refer to individual alumina inclusions, agglomerates or conglomerates, or to other types of non-metallic inclusions found in steels. This will be clear from context.

Chapter 4 - Adequacy of NDE examination procedure to characterize alumina agglomerates

Usually, a UT examination is performed to detect a specific type of imperfection of potential concern. For each specific type of imperfection, the structural integrity engineer defines the size below which the imperfection would have no effect on structural integrity (by an adequate margin). For the selected NDE method, the NDE engineer sets a threshold, i.e., the reporting level, based on this. In the Beznau 1 case the UT procedure was originally set to detect and characterize hydrogen flakes. Work was therefore done to determine the adequacy of the reporting level to detect and size alumina agglomerates.

Chapter 5 - Effect of alumina agglomerates on mechanical properties relevant for the RPV safety case

Although very small alumina inclusions are a normal constituent of RPV steels, large agglomerates of such inclusions are not. Since there was no empirical data to determine whether such agglomerates adversely affected materials properties, material from Replica C was tested. Following the guideline ENSI B01, the ASME K_{IC} curve was used in the Beznau 1 SC. This curve is valid for RPV steels compliant with the ASME code, and it was verified that it is also valid relevant for the Beznau 1 steel containing alumina agglomerates

Chapter 6 - Effects of alumina agglomerates on irradiation embrittlement

For the assessment of the fitness-for-service of the Beznau 1 RPV it was demonstrated that the alumina agglomerates do not affect the irradiation sensitivity of the material.

Chapter 7 - Implications of the Replica C results to the Beznau 1 RPV

The effects of the alumina agglomerates on the steel mechanical properties were assessed on Replica C material. In this chapter the transferability of these results to the Beznau 1 RPV steel are discussed.

Chapter 8 - Structural integrity assessment (SIA)

The continued operating integrity of the Beznau 1 RPV, considering the effects of the alumina agglomerates, conservatively modeled as cracks, was demonstrated using the procedures set forth in Section III and Section XI of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code.

Chapter 9 - DETEC requirements

Swiss reactors must not be operated unless certain legally-required (DETEC) criteria are met. It was shown in the 2012 safety justification of the Beznau 1 RPV that the criteria were fulfilled until at least 54 FPY. This chapter discusses whether the alumina agglomerates affect this situation.

Chapter 10 - Discussion and conclusions

2 Origin, nature and root cause of the indications

UT indications are evidence of discontinuities or imperfections within a material that impede the sound wave. In general, they can originate from internal boundaries such as, cracks, crack-like flaws, and other imperfections. No structural steel is free from such features, however, whether they are significant imperfections, and thus potentially detrimental to RPV safety, depends strongly on their nature, that is: their origin (e.g. from cracks), and their location, size, orientation and other characteristics. NDE cannot, by itself, provide complete information about the origin and nature of indications; it can eliminate, or narrow down, the possibilities, but its resolution is much lower than that of a microstructural examination. UT data is therefore used in combination with other information, not only to confirm origin and nature of indications, but also to refine the NDE procedures to do so accurately, and to validate them.

2.1 Manufacturing review

To help establish the origin and nature of the UT indications, Axpo assessed all plausible root causes of imperfections that might arise in the Beznau RPV shells during fabrication or in-service. Axpo claim that this eliminated the great majority of these, including hydrogen flaking, with a reasonable degree of certainty.

The Root Cause Analysis (RCA) performed by Axpo included detailed assessment of manufacturing records, discussions with the RPV shell manufacturer, Société des Forges et Ateliers du Creusot (SFAC) on historic practices, and consultation with heavy section steel fabrication experts, Sheffield Forgemasters Engineering Limited (SFEL). The Root Cause Analysis showed that the most likely origin of the UT indications is large alumina (Al_2O_3) agglomerates. This was initially suggested because of the location of the indications mainly in the negative segregation zone. The root cause of the high densities of these agglomerates in Beznau 1 RPV Shell C, relative to the other RPV shells examined, could be explained by a combination of factors that plausibly occurred during manufacture. These include: late addition of aluminum (possibly in response to partial loss of vacuum); low steel pouring temperatures (which may plausibly have been a result of delays due to problems with the vacuum system) and high ingot mold height relative to diameter.

2.2 Confirmation of the root cause by the Replica C

Axpo produced Replica C to confirm the postulated root cause of the agglomerates. Replica C was made, as far as was possible, in the same way as Shell C, using the same specifications and, as far as achievable, processes. The only major deliberate deviations were in the cropping and piercing. The amount of the discard was reduced to ensure that as much material with high densities of alumina agglomerates would be available for testing. Even so, the forging ratios for Replica C and Shell C were similar so that the alumina agglomerates in the finished forgings would have similar characteristics. In addition, contrary to modern practice, no argon shielding was used in the transfers of molten steel between ladles. This was to increase the oxygen level in the steel.

The UT characteristics of the indications in Replica C were shown to be consistent with those in Shell C in terms of location of the indications in the wall and the size and amplitude distributions of the indications, the 'UT fingerprints'.

2.3 Examination of archive/surveillance material of Beznau 1 RPV.

Metallographic examination showed that the non-metallic inclusions in the acceptance ring of Shell C material, and in archive materials from Shell B, were also alumina. However, they were significantly smaller and in lower densities than those in Replica C. This was expected since the acceptance ring is removed from the bottom of shell and acceptance rings of RPVs shells are usually segregation-free.

2.4 Discussion

Alumina particles of a size of a few microns are normal constituents of aluminium-killed steels. In the case of Beznau 1, much larger numbers were formed in the ingot due to the presence of significant levels of oxygen and the added aluminium. The individual inclusions then coalesced into large clusters of alumina inclusions, subsequently termed ‘agglomerates’. This coalescence is a phenomenon that occurs because the particles are not wetted by the liquid steel so that the total surface energy of the latter is reduced by the formation and growth of the groups. The formation and growth rates depend on the likelihood of individual inclusions coming into contact, which depends on factors such as the particle concentration (number per cc) and the liquid metal flow rates and distributions within the ingot during pouring and cooling. During the forging process, which results in considerable deformation of the original ingot, the original clusters of inclusions are compressed radially and ‘smeared out’ circumferentially (mainly) and axially to produce thin laminar agglomerates, usually found in groups, termed ‘conglomerates’.

The IRP considers that Axpo have identified the origin of the UT indications, i.e., the features that reflect the UT beam, beyond reasonable doubt. The reason they were formed, the root cause, was the presence of significant concentrations of aluminium and oxygen in the melt in combination with the conditions under which the steel in the ingot froze. The sequence of events that led to the formation of high quantities of alumina agglomerates is not completely identified. The reason they were maintained in the finished product was because they were spread more widely in the sedimentation cone than the piercing diameter. However, it may be noted that, the piercing diameter for Shell B (with fewer indications) and Shell D with zero indications was not much different from that for Shell C. Thus, there is no reason to believe that it was not adequate for removing the imperfections that normally occur down the center of an ingot. The adequacy of piercing to remove casting imperfections above the sedimentation cone was confirmed by NDE. Had the piercing diameter been larger, the alumina agglomerates might have been removed. It is worth noting that the top and bottom discards for Shell C were also similar to other shells and NDE did not detect any imperfections resulting from inadequate top and bottom discards.

To summarize, late addition of aluminum in response to partial loss of vacuum appears to be a very credible reason of the presence of alumina agglomerates. Although the precise conditions of their formation are not known, given the evidence presented in Chapters 5 and 6 that they do not have a detrimental effect on structural integrity, this is not considered to be a concern.

The IRP considers that the origin and nature of the UT indications are sufficiently well known.

3 Representativeness of Replica C

Replica C has been used by Axpo to confirm the postulated origin and root cause of the indications, to provide surrogate material for assessing their effect on materials properties, and to provide material for validating the NDE. These aspects are interrelated, and the representativeness of the Replica C was evaluated with regard to: manufacture; chemical composition; microstructure; mechanical properties and the fingerprints of the UT indications.

3.1 Replica C manufacture, composition and materials properties

Replica C was made to be representative of Shell C in every way that could be controlled. Axpo has demonstrated that there is a close match between the chemical composition, microstructure and mechanical properties of Replica C with those of Shell C. This shows that the aim to produce a replica was achieved very successfully. The IRP does not doubt that it is sufficiently representative for assessing the potential effects of alumina agglomerates on the mechanical properties relevant to the structural integrity of the Beznau 1 RPV.

3.2 UT indications in Replica C and comparison with UT indications in the Beznau 1 RPV

Axpo demonstrated the similarity between the flaws in the RPV and in particular those in Replica C by comparing the ultrasonic fingerprints of the Replica C with those of the RPV shells that had indications. Both the replica and most of the affected RPV shells had very similar size, amplitude, location and density distributions. In addition, the indications were distributed very similarly spatially, and consistently with the root cause. Axpo had made the replica to represent Shell C because this was expected (and confirmed – see Chapter 8.3) to be the most limiting in the SC. Shell C contains the highest number and densities of reportable UT indications and has the highest combination of irradiation embrittlement and Pressurized Thermal Shock (PTS) loading.

Both Replica C and Shell C contain 'high amplitude indications' (HAI)[8]. Investigation, based on ultrasonic comparison of cumulated C-scan images with the 0°LW technique, simulation results with 45°SW angle beam techniques and metallographic examination, showed that it is plausible that HAI originate from alumina agglomerates with a larger total reflective area. However, a different type of flaw could not be completely ruled out, for example a dense concentration of agglomerates with cracking between the ligaments.

None of the other RPV shells, except Shell E, contained HAI, and none had the high densities and numbers of UT indications (no flaws were detected in Shell D). The HAI in Shell E had a higher amplitude than those in Shell C, but their distribution was more isolated. The UT amplitude distribution of the other indications in Shell E was similar to that in Shells B and C, but the location and sizing distributions were different, with a slight shift towards larger sizes. The latter might be explained by the different sizing method in the DEKRA technique, which was different from the Intercontrôle one (see Chapter 4). In addition, there was a difference in the distribution of

[8] These are indications that have a high amplitude with the 0°LW technique (above REF-6dB) and sometimes also having high amplitudes with the 45°SW techniques (up to around REF).

indications within the forging. Axpo argued that this was caused by a simple misidentification of the three sections of the ingot cut to provide sub-Shells E1, E2 and E3, which were then welded together for form Shell E. This uncertainty was addressed by Axpo in the structural integrity assessment of Shell E by treating the flaws as cracks (see Chapter 8.3).

For Shell F and areas of other shells that could not be inspected, Axpo have claimed that that flaws that would not have been detected during manufacturing inspection would be justifiable.

The above evidence, when taken in consideration with the alumina inclusions found in Shell C acceptance ring material, and the demonstration of root cause by manufacture of the replica, confirms that the indications in the replica are of the same physical nature as those in the RPV.

Axpo also evaluated the representativeness of Replica C at the location of the CT specimens used in the material testing program (see Chapter 5). For those specimens that had relevant flaws on the fracture surface, cumulative C-scan views were obtained at the exact location of the specimen. These were compared to similar images from two limiting extended areas EA-600 and EA-740[9] (see Chapter 8.3). The images were categorized according to five categories, A to E,[10] of increasing severity. Axpo demonstrated that all categories were represented in the regions of fracture toughness test specimens from which cleavage fractures initiate. HAIs were present in a small number of specimens, but not in locations where they might influence fracture.

As discussed in Chapter 5, the mechanical testing results revealed no degrading effects of agglomerates of inclusions on the properties of the steel matrix. There is no reason to believe that this result does not apply to higher densities of agglomerates.

3.3 Discussion

The reproduction of a 1960's forging, with the achievement of a close match between the chemical composition, mechanical properties, microstructure, UT signal, and inclusion characteristics of Replica C and Shell C, is evidence of the today's high level of technical understanding and practice of steelmaking and forging. Most importantly, it shows that the aim of producing a surrogate material was achieved very successfully.

The IRP considers that Replica C is representative of Shell C in respect of the purposes for which it has been used in the Safety Case, in particular:

- ***It confirms the root cause of the indications.***
- ***It provides suitable material to investigate the effect of alumina agglomerates on materials properties in the most critical areas of the RPV.***
- ***It provides suitable material for validating the UT procedure.***

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[9] The extended areas are regions of Shell C with high densities of inclusions that were scanned in more detail than other regions of the shell.

[10] The severity categories A to E were defined by Axpo to provide a tool to qualitatively perform the comparison exercise between the RPV and the test specimen, by categorizing the observed combinations of amplitude and density in Shell C, as observed on cumulated C-scan views.

4 Adequacy of the NDE examination procedures to characterize alumina agglomerates

This chapter describes the NDE examination of the RPV and the validation of the UT procedures. The use of the procedures to examine the replica and test specimens is described in Chapter 3.

4.1 RPV inspections

The NDE investigations of the RPV shells were more extensive and detailed than is usually the case for the in-service inspection of RPVs. The 2015 UT inspections of the Beznau 1 RPV shells were extensive both in terms of the volume of material inspected, the number of inspections and the sensitivity/resolution of these inspections. These were carried out by different contractors using different equipment and techniques. Besides the examinations for (quasi)-laminar[11] flaws by DEKRA and Intercontrôle, there were complementary examinations to look for under-clad cracking (UCC) and planar flaws. These additional examinations allowed Axpo to conclude that, apart from the eight planar flaws detected by the UCC technique, there were no concerns to be considered other than the flaws detected with the Intercontrôle examination technique. Axpo therefore considered it appropriate to use the results of the Intercontrôle examination as the main input for the further evaluation of the case. The examinations focused on Shells B and C. The eight planar flaws detected using the UCC technique were not a major concern, but were assessed in the SIA (Chapter 8.4).

The Intercontrôle examination procedure applies both Longitudinal Wave (LW) straight beam techniques and Shear Wave (SW) angle beam techniques. The inspection results with the Intercontrôle procedure resulted in high resolution due to small beam size (approximately 3 to 5 mm) for the first 50 mm depth, where most of the indications were detected, and fine indexing steps. They were also more sensitive than is usually the case for RPV inspections due to the very low detection threshold with the straight beam techniques. The SW angle beam techniques did not reveal additional flaws. Almost all indications are characterized as (quasi-)laminar. Eddy Current and Remote Visual Inspections (RVI) provide a level of confidence that there are no surface breaking flaws in the areas of Shell C with UT indications.

The Intercontrôle examination could not be applied to parts of Shell A, nor to Shells E and F, because the AREVA GmbH manipulator used only allowed scanning on cylindrical surfaces. In the case of Shell A, some parts of flange are conical, in the case of shells E the geometry is hemispherical and partly inaccessible and in the case of shell F the geometry is inaccessible. The accessible parts of shell E were assessed with the DEKRA examination results. Although parts of Rings A and E, and the end-cap, F, were not inspected in 2015, Axpo claim that the SIA has shown that any structurally significant cracks in these would have been detected by the manufacturing NDE.

4.2 UT procedure validation

As discussed above, structural steels inevitably contain imperfections. Normally, a UT examination is performed to detect, locate and size the specific types of imperfection that are both potentially present in a component due to manufacture or service-induced, and may also have a significant effect on structural integrity. The decision on which imperfections may be significant is defined by code or the structural integrity engineer responsible for the SIA. The NDE engineer is responsible

[11] '(Quasi)-laminar' indicates both laminar and quasi-laminar flaws, see Annex 4

for developing a procedure to meet these requirements, and to validate that they have been met. So, typically, the only imperfections reported to the structural integrity engineer are those that may have a significant effect on the component's structural integrity. The reporting level is set by defining an amplitude threshold of the UT signal (in dB relative to the reference level). Indications below the threshold may be recorded but are not normally reported to the structural integrity engineer.

4.2.1 UT procedure validation for Beznau

The situation with the Beznau 1 RPV was different. As discussed above, the Intercontrôle UT procedure was initially developed for the detection and characterization of hydrogen flakes. It therefore had to be retrospectively demonstrated that the procedure would, with a high level of confidence, provide the information required to assess the structural integrity of the RPV. By extension, such confidence would also apply to UT inspections of Replica C and other materials.

In the case of Beznau 1 no detection target was pre-defined, so Axpo decided to evaluate which size of flaw could be reliably detected at a pre-defined threshold. Thus, to address the detection capacity of the UT procedure, first the 'size' of the agglomerates had to be defined. This task is complicated because both metallographic and UT images reveal that the start and end of an agglomerate of inclusions cannot be defined with precision because they are (ultrasonically) both scattered and aligned and are (physically) discontinuous. In the final validation exercise, Axpo developed an area-based method to classify agglomerates of inclusions as 'red,' 'yellow,' and 'green;' where the 'red' classification corresponded to continuous surfaces of more than 0.02 mm^2 in area on the metallographic image, while the 'yellow' and 'green' classifications represent smaller agglomerates. This reflects a judgement by Axpo that the 'red' agglomerates are the only ones that are potentially significant to structural integrity, and therefore should be sized so that they could be evaluated by SIA.

Thereafter, validation of the UT procedure focused on the ability to detect 'red' agglomerates. This was mainly performed by comparing metallographic and UT images from a cube of material taken from an area with a high density (4 – 4.5cm^{-3}) of agglomerates from Replica C. A face of the 30x30x30 mm cube was progressively ground in 0.5 mm steps. Each of the sixty-one surfaces (includes original top and bottom surfaces) were metallographically examined as they were exposed. The ground surfaces were oriented such that the largest size (agglomerates are stretched out in the circumferential direction) was visible in the 30x30 mm metallographic images. The metallographic images were compared with the UT images corresponding to the same section through the cube. Amongst the thousands of agglomerates of inclusions found metallographically in the 61 slices, a total of 133 red agglomerates were detected with a length between 0.2 and 3 mm. In about 30 % of the cases the 'red' size was augmented with adjacent 'yellow' agglomerates (with a surface between 0.002 and 0.02mm^2 on the metallographic image) that were visually almost not separated. The 'red' designation was retained for these augmented agglomerates.

From this Axpo claim that, with the UT procedure used:

- 'Red', agglomerates with a length greater than 2 mm could be reliably detected.
- 'Red' agglomerates with a length smaller than 2 mm could be detected with a reliability of 60%.
- The smallest 'red' agglomerate that could be ultrasonically detected was 0.34 mm long.

Axpo also claim that the UT validation also demonstrates that the sizing of indications was conservative and the positioning accurate.

4.2.2 Discussion

In the UT validation, Axpo focused on detection of the agglomerates with a greater surface area of more than 0.02mm² (i.e. the 'red' agglomerates). The yellow and green agglomerates were excluded, but the yellow agglomerates were all shorter than about 1 mm (determined metallographically), a tiny size relative to structural integrity. The green ones were shorter still. Red, yellow and green agglomerates tend to be co-located as conglomerates (groups of agglomerates). The Beznau 1 flaws are very clearly not cracks and the morphology of the agglomerates is fully consistent with the 'smearing out' of the original alumina agglomerates, which would have originally been more globular when formed during ingot pouring, by the extensive deformation of the solid steel during the forging process. Furthermore, the materials testing and evaluation (Chapter 5) has shown that the material between agglomerates is sound and that the agglomerates do not initiate cleavage failure. The IRP therefore accepts that the Axpo approach is justified.

In the Intercontrôle UT procedure for Beznau 1, the flaw size is determined with the 6dB drop method. This sizing method sizes indications smaller than the beam size as equal to the beam size. The metallographic examinations show that this is conservative for most flaws. In the case of flaws greater than the beam size, it is possible that flaw sizes could be under-estimated at each extremity due to the scanning increments. However, this underestimation is likely to be infrequent, and the IRP do not consider it a significant concern due to the many conservatisms in other parts of the SC.

From an NDE-perspective the sizing accuracy with the 6dB drop method was demonstrated on isolated flaws. However, in areas with high densities of HAI, there persists a risk of relevant undersizing of flaws with this method, because the individual UT maxima in high densities of HAI might not be clearly separated in the UT data. A larger drop (such as a noise-drop or a drop to e.g. REF - 12dB) would combine these in a more realistic way, thereby restoring the reliability of the sizing method for the flaws in areas with high densities of HAI. The SIA of the HAI is discussed in Chapter 8.4.

The IRP considers that the UT validation was adequate for its use in the Safety Case.

5 Effect of alumina agglomerates on mechanical properties relevant for the RPV safety case

Very small alumina inclusions are a normal constituent of aluminium-killed steels. However, as far as is known, no other RPV contains the very large numbers of large alumina agglomerates as found in the Beznau 1 RPV. This was an unprecedented finding, and a deviation from the normally expected quality of RPV material in terms of cleanliness. As a result, it was considered necessary that work be done to determine whether the agglomerates had a detrimental effect on the material properties relevant to the structural integrity of the RPV. Axpo addressed this through a test program on the unirradiated Replica C.

To determine the magnitude of the effect of the agglomerates (if any), Axpo took samples from regions of Replica with three different densities of UT indications. Density E0 corresponded to zero UT indications down to noise level (-36 dB); E3 had a medium density of UT indications (1.0 cm^{-3}) corresponding to the density in the Extended Area 740 (EA-740) in RPV Shell C; and E1 had a high density of indications (2.3 cm^{-3}) corresponding to EA-600 in RPV Shell C. These EAs were chosen because they were the most limiting areas in the SIA (see Chapter 8.3).

Although HAI were present in Replica C, no materials test data were obtained from regions containing them. Because this, and the uncertainty about their nature, they were designated as HAI and Axpo assessed their effect on structural integrity by conservatively assuming that they were cracks (Chapter 8.4).

In respect of structural integrity, the most important materials properties are the tensile properties, and fracture toughness in the ductile-to-brittle transition and on the upper shelf. These are discussed in Chapters 5.1, 5.2, and 5.3 respectively.

Of these properties, avoidance of brittle cleavage fracture initiation is the most important concern in an RPV safety case as brittle fracture may result in RPV failure by through-wall cracking if the conditions for cleavage propagation are met. So, in the current context, a key requirement is to demonstrate that the fracture toughness lower bound used in the SIA remains valid for material containing alumina agglomerates. The lower bound is determined by the ASME K_{IC} curve indexed on the reference temperature, RT_{ref} (see Annex 1), which accounts for the effect of irradiation on this curve. Chapter 5.4 discusses whether there is an effect of alumina inclusions on the fracture toughness lower bound and Chapter 6 discusses whether there is an effect of alumina on irradiation shift. An associated issue is the method by which the toughness lower bound for irradiated material is determined. An IRP recommendation for this is discussed in Chapter 7.

5.1 Tensile properties

5.1.1 Testing and results

Tensile testing was performed by Axpo on specimens of circular cross-section machined from regions of Replica C having the different densities of UT indications, E0, E3, and E1. The first set of tests was performed on 5 mm diameter T-oriented (i.e. parallel to the axial direction of the forging) specimens at five temperatures over a wide range (-196 °C to 300 °C). At each test temperature, testing was carried out on three specimens, one each from E0, E3 and E1. No significant effect of the agglomerates density on yield stress ($R_{p0.2}$) and tensile strength (R_m) was evident, but the ductility as measured by the percentage plastic extension at maximum force (A_g) and reduction of area (Z) was reduced by a factor that increased with the density of the agglomerates. It was considered that the reduced ductility was probably an artefact of the small specimen diameter compared with the size of agglomerates of inclusions.

A second set of tensile tests was performed on the 12.5 mm diameter L-oriented (i.e. parallel to the circumference of the forging) specimens, as used for the acceptance tests of Beznau 1 Shell C. The test specimens were taken from regions of the replica having medium (E3) and higher (E1) density of agglomerates. Tests were performed only at 23°C and 300°C. The strength ($R_{p0.2}$ and R_m) and ductility (A_g and Z) of those specimens fulfilled the acceptance criteria of the material specification.

5.1.2 Discussion

The IRP considers that those results are consistent with expectations. There is no reason to suppose that the alumina inclusions would affect the properties of the steel matrix and this is confirmed by the lack of effect on yield stress. At higher stresses than yield, however, the effect of alumina agglomerates as discontinuities within the matrix become potentially important. Aluminum oxides are not bonded to the steel matrix and may be considered as voids. As a result, the elastic-plastic behavior of steel with alumina agglomerates may be described by the porous metal plasticity theory. The ductility of steel with alumina agglomerates as measured by tensile testing is, therefore, heavily dependent on the size and distribution of the alumina agglomerates while the elastic-plastic behavior of the metal between the agglomerates is not affected by the alumina. For that reason, the significant loss of ductility observed from the 5 mm dia. test specimens taken from the E1 region is consistent with their fracture surfaces which show regions with dense alumina conglomerates. On the contrary, the 12.5 mm dia. test specimens taken from the E1 region do not show significant loss of ductility, consistent with the scattered distribution of alumina agglomerates on their fracture surfaces. That conclusion was supported by numerical modelling of ductile damage in the tensile test specimens as performed by Axpo using the Gurson-Tvergaard model implemented in the ABAQUS/Explicit finite element code.

Structural integrity assessments of large structures typically depend on the use of failure criteria that are based on experimental testing of laboratory-sized specimens. The results of the tensile testing should therefore be assessed with respect to the demonstration of the load-carrying capacity of the RPV. In the context of the SC, it has been shown (Chapter 8.1) that the RPV wall is not stressed as high as the material yield stress. The effects of alumina inclusions and specimen size on apparent ductility is therefore not a concern. The IRP is confident that if numerical modelling, similar to that carried out by Axpo on the tensile specimens, of ductile damage in the RPV shells under design pressure loading were to be performed, it would show a negligible effect of the alumina agglomerates on the load-carrying capacity of the RPV.

> ***The IRP considers that the alumina agglomerates do not degrade the tensile properties of the RPV materials, and have no significant impact on the load carrying capacity of the RPV.***

5.2 Fracture toughness in the ductile-to-brittle transition region

5.2.1 Testing and results

To study the influence of alumina agglomerates on fracture toughness in the ductile-to-brittle transition range (DBT), Axpo carried out 100 tests on the Replica C forging with 0.5T-CT specimens (i.e. thickness B = 12.5 mm) of different orientations (TL, LT, SL) in accordance with the ASTM standard test method E1921. The TL orientation is the primary orientation specified in the ASME code because it is the most relevant orientation with respect to the loading in the pressure vessel wall.

Specimens were removed from the three zones E0, E1, and E3. The 0.5T-CT specimens were tested at a range of temperatures. As a final check of the representativeness of the test specimens, Axpo examined the UT scans for the limiting EAs (EA-600 and EA-740) in the RPV and visually identified five categories, A to E, with increasing severities of amplitude distribution and amplitude, category E being the most severe. These scans were accumulated over the same thickness of material as a test specimen and were compared with the equivalent scans for Replica C material from each location from which a test specimen had been taken. It was shown that Categories A to E were adequately represented. There were three specimens in Category E that also contained HAI, but these were too far from the process zone to play any part in specimen fracture. This was one of the reasons why the effect of HAI on integrity was address by SIA (Chapter 8.3.5).

The following values of the reference temperature T_0 were obtained: -80°C for E0, -85°C for E1 and -84°C for E3. In a subsequent testing phase, upon a request of ENSI (which was based on a recommendation of the IRP), 30 1T-CT-specimens (i.e. thickness = 25.4 mm) were tested to:

- Provide fracture toughness data in the upper part of the transition range;
- Verify the statistical distribution of K_{Jc}-data at the temperature of interest;
- Clarify questions concerning the size effect that was observed between 10 mm and 25 mm thick specimens results in the unirradiated Shell C acceptance block as part of the irradiation surveillance program of the Beznau 1 RPV (see Chapter 7).

As recommended by the IRP, these specimens were tested at the relatively high temperature of T_0 + 50°C (T_0 being the reference temperature as obtained from the 0.5T-CT specimens, and T_0 + 50°C is the upper limit for determination of T_0 in ASTM E1921).

Axpo also examined the fracture surfaces of each test specimen. This was done to check that the test met the ASTM E-1921 validity criteria for the fatigue pre-crack and to provide information to interpret the results, particularly on two key aspects. First, to determine the number and size of alumina agglomerates visible on the fracture surface, most importantly in the ‘process zone’ which is the (three dimensional) region near the crack tip from which cleavage fracture initiates. Second, to identify (where possible) the point from which cleavage failure initiated and whether any alumina agglomerates were associated with initiation.

Axpo’s initial analysis was based on assessment of sets of specimens with E0, E3 and E1 UT indication densities. No effects of alumina agglomerates were observed, and there was no indication from the fractography that alumina agglomerates played any part in cleavage initiation for specimens in all three orientations. Subsequently, more refined analyses were done in which Axpo compared results based on the size and density of alumina agglomerates in the process zone. These analyses confirmed the first conclusion.

As is normally the case for forgings, the results showed that specimens in the TL orientation have a lower fracture toughness than the LT orientation. The reference temperature T_0 for SL orientated specimens was higher than that in TL by about 30°C, but there was no difference in T_0 with small and large agglomerates, and no evidence that alumina aggregates played any part in brittle fracture initiation. A lower fracture toughness is expected in the SL-orientation but is not normally a concern since the stresses in the operating RPV for that orientation are much smaller than the two other principal stresses. However, in Shell E the situation is different, since the agglomerates are no longer quasi-laminar, but inclined with respect to the inner surface, so the in-plane stresses lead to mixed-mode loading that includes load-components in the S-direction of the forging. Therefore, fracture toughness in the SL orientation becomes more relevant. For this reason, Axpo used RT_{NDT} to index the ASME K_{Ic}-curve, which is known to cover uncertainties about material inhomogeneity such as segregation zones. This is discussed in Chapter 8.5.

For the 75 tested specimens in the TL orientation, substantially more than 5% of the K_{Jc}-values (11 of the 75) were lower than the 5% percentile of the Master Curve (MC) tolerance bound. None of these had high densities of agglomerates; to the contrary, the specimens with the higher density of agglomerates tended to have higher fracture toughness. The T_0 value for the smaller specimens was lower than those for the larger specimens (see Chapters 5.4and 7). Axpo performed a number of analyses to investigate this and concluded that these effects could have been produced because of the relatively small numbers of specimens tested (statistical sampling effect) or because of local inhomogeneities in the material. Furthermore, fractographic analyses revealed that cleavage fracture was always initiated remote from alumina agglomerates.

5.2.2 Discussion

From the T_0 values obtained in the three zones and the fractographic analysis of the broken specimens the IRP was reasonably confident in January 2017 that Axpo's claim that alumina agglomerates do not affect cleavage fracture toughness was most likely correct. The additional large specimens were expected to provide confidence that this claim would also be demonstrated at the upper part of the transition range where fracture toughness levels correspond more directly to the crack driving forces used in the flaw evaluation. The additional fracture toughness testing and fractography, in conjunction with the additional analysis approaches used by Axpo have strengthened the January 2017 conclusion. The additional fracture toughness tests do, however, show substantial evidence of a large effect of specimen size, the significance of this is discussed in Chapters 5.4 and 7.

Finally, the IRP notes that the T_0 determined for the zone with no inclusion agglomerates is equal or higher than those determined for the zones with inclusion agglomerates.

> **The IRP considers that the alumina agglomerates do not degrade the cleavage fracture toughness properties of the RPV materials.**

5.3 Fracture toughness on the upper shelf

5.3.1 Testing and results

Fifteen fracture toughness tests on the Replica C have been performed at upper shelf temperatures according to ASTM E1820 to examine the upper shelf behavior of the Replica C in the unirradiated state. The 12.5 mm thick CT specimens with a TL orientation were removed from the three zones E0, E3 and E1.

The fracture surfaces of each broken specimen were examined by means of scanning electron fractography to confirm the presence of alumina agglomerates in the ductile fracture process zone. Although they differ in density and size, all specimens present alumina agglomerates.

Axpo concluded that there is no detrimental effect of the alumina agglomerates on fracture toughness in the ductile region.

5.3.2 Discussion

The IRP notes that no specimens were tested without inclusion agglomerates in the ductile fracture process zone. However, there were tested specimens with low and high density of agglomerates that exhibit no effects of agglomerate density on the ductile fracture toughness, $K_{Jc0.2}$ (the stress intensity calculated from the J-integral at 0.2 mm of ductile crack growth) The IRP also notes that the ductile toughness of the material containing alumina agglomerates remains reasonably high in comparison with typical RPV forgings.

Ductile fracture is less of a concern for Beznau 1 because the ductile fracture toughness is relatively high and, moreover, ductile crack propagation beyond initiation can only happen with continuing loading, and it is not likely that the limiting crack driving force for ductile initiation would be reached before that for cleavage initiation.

The IRP considers that this issue has a relatively lower technical importance due to the unlikelihood of ductile failure relative to cleavage fracture.

> ***The IRP considers that there is no indication that alumina agglomerates degrade the ductile fracture toughness initiation properties of the RPV materials.***

5.4 Relevance of the ASME fracture toughness curve for ferritic steel containing a high density of alumina agglomerates

Avoidance of cleavage fracture initiation is the most important concern in all RPV SIAs because the corresponding unstable crack extension may result in catastrophic failure of the RPV. According to the ASME code, safety against brittle fracture must be demonstrated by showing that a postulated crack remains stable under operational and emergency conditions. This demonstration must rely on conservative input data. The fracture toughness considered in the SIA is obtained indirectly by means of the fracture toughness (KIc) curve indexed on the reference transition temperature, RTref, defined according to Guideline ENSI B01. This fracture toughness curve is the same curve as the ASME Code, in Appendix G of Section XI, though indexed on RT_{ref} instead of RT_{NDT}. This curve is accepted as a suitable lower bound for fracture toughness in the ductile-to-brittle range. In Guideline ENSI B01, Method II, RT_{ref}, is derived from the reference temperature, T_0, from ASTM E1921. The question is whether or not this lower bound still holds in the presence of a high density of alumina agglomerates.

The fracture toughness tests performed by Axpo on Replica C showed that T_0 in the zone of Replica C without alumina agglomerates is greater or equal than that of the zones affected by the agglomerates according to the interpretation of Axpo and IRP expert independent interpretation. This leads to the conclusion that the fracture toughness results measured on the acceptance test block of Shell C are relevant to estimate fracture toughness in the zones affected by agglomerates.

Furthermore, these tests showed that the ASME curve indexed using the RT_{ref} of the zone of Replica C without alumina agglomerates provides an adequate lower bound to the fracture toughness data measured from specimens sampled in the Replica C zones with or without alumina agglomerates, provided that the RT_{ref} is defined from tests on 1T-CT specimens. Similarly, the initial fracture toughness data measured on the acceptance test ring of the Beznau 1 RPV Shell C are also bound by the ASME curve indexed by RT_{ref} defined from the 1T-CT specimen tests.

> ***The IRP considers that the ASME K_{IC} curve indexed using RT_{ref} remains valid for use in the SIA of the Beznau 1 RPV provided $RT_{ref}(0)$ is determined from 1T-CT-specimens.***

6 Effect of alumina agglomerates on irradiation embrittlement

6.1 Testing and assessment

Axpo assessed the possibility of an effect of alumina agglomerates on irradiation damage through a literature survey supported by some testing of archive surveillance samples. The literature survey showed that alumina would not itself be significantly affected by irradiation in the lifetime of the Beznau RPV; for example, there would be no swelling that could increase local stresses, and there was no evidence that it would have any effect on the composition of the surrounding matrix in a way that would increase irradiation sensitivity. There was only a limited amount of experimental evidence to support these theoretical findings, so an assessment was made of hardness and composition of the matrix around agglomerates in the Beznau surveillance specimens. These gave no indication of adverse effects.

A separate concern was that the agglomerates in the RPV might be in a region of the forging with material of higher irradiation sensitivity than the surveillance sample. It was confirmed that the acceptance ring, from which surveillance samples are taken, was towards the bottom of the ingot, a location, which by comparison with the positive segregation regions towards the top of the ingot, may have reduced concentrations of carbon, and of those elements that might increase irradiation sensitivity. However, the orientation of Shell C was not documented after the acceptance ring had been removed. It was thus possible that the forging had been installed upside down relative to the original ingot. If so, the high densities of agglomerates would be located in the top of the ingot, where there is potentially positive segregation and, thus potentially higher irradiation sensitivity. This was discounted by Axpo on the basis that the origin of the indications was established, as confirmed by the distribution of inclusion agglomerates (at the bottom of the ingot) in Replica C. The distribution of the indications in RPV Shell C was entirely consistent with that in Replica C.

6.2 Discussion

The IRP considers that Axpo have adequately justified that alumina inclusions are stable under irradiation conditions relevant to Beznau 1 and do not damage the surrounding matrix through swelling or other nucleonic reactions. The IRP also considers that Axpo have adequately justified that alumina agglomerates do not have a significant influence on the irradiation sensitivity of the surrounding matrix. The mechanisms of irradiation damage in RPV steels are sufficiently well understood, and the IRP considers that Axpo’s arguments have a sound technical basis.

> ***The IRP considers that the alumina inclusions and agglomerates in the Beznau 1 RPV do not affect irradiation sensitivity.***

7 Implications of the Replica C results to the Beznau 1 RPV

In Chapter 5 it is concluded that the IRP considers that the alumina agglomerates do not degrade the tensile properties, nor the cleavage fracture toughness properties, nor the ductile fracture toughness initiation properties of the RPV materials.

Furthermore, in the course of Axpo's surveillance test program, it was observed that the CT specimens with 10 mm thickness made from the broken halves of 25 mm thick CT-specimens of unirradiated archive material of Shell C delivered much lower T_0 than the original 25 mm CT specimens (-81°C±7 vs.-36°C±8.), a difference of 45°C. The T_0 obtained from two sets of fracture specimens with the same thickness (10x10mm PCCV and 10 mm thick CT) were found to be relatively close to each other, with the T_0 from the PCCV specimens being lower by 10°C. It is worth noting that the PCCV specimens were taken from an area in the Shell C archive material close to the 25mm thick CT specimens. Taking into account the PCCV bias of 10°C according to Equation (b) in Guideline ENSI B01, there is also a difference of about 45°C between the T_0 of the PCCV and the 1T-CT specimens. These differences are substantially larger than would be normally expected for RPV steels and, on the basis of MC statistics, very unlikely to have occurred by chance. This suggested that some factor associated with Shell C material or testing might be having an influence. This was one of the reasons that the IRP recommended additional tests on Replica C material using 25mm CT specimens.

Qualitatively, the Replica C material exhibited a similar (albeit lower) inconsistency between the T_0 obtained from small and large CT specimens: a difference in T_0 of 19°C (-85°C ±5 vs. -66°C ±5) was obtained between CT-specimens of 12.5 mm and 25 mm thickness, respectively. In isolation, this could be rationalized by MC statistics as a rare chance event, but a not an impossible one. However, the size effect is in the same direction (smaller specimens give lower T_0, in both the replica and in Shell C), and for both materials a significantly higher number of K_{Jc}-data than expected lie outside the scatter-band given by the 5% - 95% - percentiles of the MC. Furthermore, similar tests on Beznau 1 Shell D material found a size effect of 40° C, the smaller specimens again having the lower T_o. The results taken as a whole, suggest that the Beznau materials exhibit an unusual size effect.

The physical reasons for this unusual behaviour are not clear. Possible mechanisms were discussed within the IRP, including one involving the effect of alumina inclusions on fracture toughness, but no common position was reached. The IRP considers that the specimen size effects in Replica C and Beznau 1 Shells C and D strengthens the case that that Replica C is representative of the RPV shells. This confirms that the effects of alumina agglomerates on tensile properties and fracture toughness observed in the replica are transferable to the RPV with adequate confidence. Correspondingly, the IRP considers that specimens removed from the ¼ t and ¾ t locations of the Shell C acceptance ring are appropriate for determining material properties of Shell C even for regions with high densities of agglomerates. Furthermore, since it has been shown that alumina agglomerates do not increase irradiation sensitivity, this conclusion can be extended to the material used for surveillance testing.

The observed size effect does, however, have significant implications for the method of determining the fracture toughness lower bound for irradiated material used in the SIA. Guideline ENSI-B01 allows alternative methods. ENSI-B01 Method II Variant A uses the irradiated T_0 measured directly from the Capsule T results. However, the Capsule T results were from PCCV specimens, so, if the size effect discussed above is generally applicable to Beznau material, they might not be conservative. For this reason, the IRP considers it prudent to adopt ENSI-B01 Method II Variant B to determine RT_{ref}. This determines the unirradiated T_0 (thus, the $RT_{ref}(0)$) from 25-mm CT specimens (from the Shell C acceptance ring) and the irradiation shift ΔT_{41J} from the surveillance program Charpy impact test. CT specimens with thickness B=25 mm are the most widely used standard specimens, well accepted in the FM-community and big enough for the structural effects that might cause size effects not to be important. The Charpy impact shift is well-established and the results for Capsule T are in line with results from previous Beznau 1 capsules.

The IRP recommends ENSI-B01 Method II Variant B in place of Method II Variant A to determine $RT_{Ref,ART}$

8 Structural integrity assessment

This Chapter summarizes the IRP's assessment of the SIA performed as part of Axpo's safety case for the Beznau 1 RPV. The SIA follows the procedures set forth in Section III ('ASME III') and Section XI ('ASME XI') of the American Society of Mechanical Engineers Boiler and Pressure Vessel Code (hereafter, 'the Code' or 'Code') [7][12]. Axpo carried out the SIA for Shells A, B, C (the leading shell) and E, which they identified as the only ones requiring detailed Code evaluation. Shell D could be excluded because no indications were reported.

Chapter 8 includes the following sub-chapters:

- Chapter 8.1 - A check of primary stress limits in accordance with Section III Article NB-3000 of the Code;
- Chapter 8.2 - Evaluation of fracture toughness requirements in accordance with Appendix G of ASME XI;
- Chapter 8.3 - An evaluation of the indications in Beznau following the requirements of ASME XI;
- Chapter 8.4 - Evaluation of the HAI zones (Chapter 3.2) and the planar flaws found by AREVA, which are assumed to be cracks;
- Chapter 8.5 - An assessment of Shell E, which presented different analytical challenges arising from its different geometry (a spherical as opposed to a cylindrical section) and different flaw orientation (non-laminar);
- Chapter 8.6 - A brief overall discussion, including the justification of Shell F and other uninspected regions, and conclusions.

The first three of these chapters address the usual requirements of an SIA in relation to the agglomerates of alumina inclusions found in Shells A, B and C. Chapters 8.4 and 8.5 cover assessments that were made separately by Axpo. Chapter 8.6 discusses those regions of the RPV that could not be inspected, including parts of Shells A and E, and the whole of Shell F.

In Chapter 8.3, the IRP emphasizes that flaw assessment in conformity with the requirements of ASME XI described in this sub-Chapter does not reflect the actual physical behavior of the alumina agglomerates, but, rather, is a highly conservative representation thereof. As shown in the metallographic images, the alumina agglomerates are a continuum of agglomerates, a part of which are captured by the UT examination. Furthermore, any alumina agglomerate is a volumetric[13] flaw without sharp extremities and so cannot initiate brittle fracture, as confirmed by the materials testing program, and also cannot interact between themselves as cracks do. The analyses described in Chapter 8.3 should therefore be considered as a worst-case estimation of their contribution to the risk of brittle failure of the RPV. As will be reviewed in this sub-Chapter and as is detailed in the many Axpo reports, the analyses demonstrated that the provisions of the ASME Code with respect to flaw evaluation and brittle fracture evaluation are nevertheless satisfied.

[12] Code procedures are developed by a professional consensus body and are applied internationally to the design and assessment of nuclear pressure vessels. The administrative and scientific peer-review processes used by the Code to develop and test these procedures is known to ensure their conservatism.
[13] In a microstructural sense, not in the NDE context, where 'volumetric' means 'having a significant extent in three dimensions', ISO standard 16827:2014.

8.1 Primary Stress Limits (ASME III)

A flaw assessment according to ASME XI IWB 3600 is accompanied by a verification of the primary stresses according to ASME III NB-3000, taking into account the reduction of structural cross-section due to the flaws. NB-3228 allows this verification of the primary stress limits to be replaced by a plastic analysis, to demonstrate that the design pressure does not exceed two-thirds of the plastic collapse load. Axpo used this clause and performed the numerical calculation by using a finite element model in which the NDE 3D-boxes were assumed as voids. Axpo made the conservative assumption that the void density within the sector of 45° with the highest volume fraction of voids applies to the full circumference of the RPV.

The IRP regards Axpo's procedure as compliant with the ASME code. Assuming the NDE 3D-boxes as cubic voids with zero strength corresponds to the requirement of IWB 3610, which accounts for the local area reduction.

Axpo also checked the primary stress limits of ASME Section III assuming that the extended areas were empty regions having no load bearing capacity. In all cases the ASME requirements for primary stress limits were satisfied.

> ***The IRP considers that the primary stress analysis was adequately performed, using a conservative model.***

8.2 Fracture Toughness Requirements (ASME XI Appendix G)

The objective of Appendix G in ASME XI is:

a) To determine the allowable pressure and temperature loads under level A/B normal and upset service conditions service conditions, referred to as the 'P-T limit curves,' that account for the fracture toughness under irradiated conditions;
b) To determine whether the fracture toughness under irradiated conditions is sufficient to prevent brittle failure under level C/D emergency and faulted service conditions service conditions.

For normal and upset service conditions, item a), a surface flaw of depth equal to one-quarter of the vessel wall thickness and length 1.5 times the wall thickness is postulated and is assessed using the requirements of ASME XI Appendix G, which differ from those required for evaluating flaws found in service.

For emergency and faulted service conditions, Appendix G does not provide any requirements but allows the principles of the Appendix to be applied where considered applicable. Rules for flaws found in service appear in ASME XI Subsections IWA and IWB, which refer to non-mandatory Appendix A for analytical procedures. The evaluation of the flaws found in the Beznau 1 RPV are discussed in Chapter 8.3 of this report

The analysis required by ASME XI Appendix G was performed for Beznau 1 for all service conditions in 2012. As the alumina inclusions have no observed impact on the fracture toughness and irradiation sensitivity, there is no reasons to re-perform or otherwise question the 2012 analysis.

> ***The IRP considers that the alumina agglomerates do not affect the demonstration, made in 2012, that the fracture toughness requirements in ASME XI Appendix G are met.***

8.3 Flaw Evaluation (ASME XI)

Axpo performed an SIA of the indications found in the Beznau 1 RPV following the procedures set forth in ASME XI for flaw evaluation [7]. Flaw evaluation in accordance with ASME XI is known to be conservative. Some of the built-in conservatisms are as follows:

- The flaw characterization rules of ASME XI are based on the assumption that indications that are derived from crack-like defects, slag inclusions, porosity, laminations, etc. are resolved into simple geometrically defined planar defects.
- ASME XI includes rules for combining neighboring indications into a single more-conservative indication.
- It includes rules for resolving non-planar flaws into two planar flaws by projection of the flaw area into planes normal to the maximum principal stresses.
- It requires use of the ASME XI fracture toughness curve which is a lower bound.

In addition, the basic principles for safety demonstration based on deterministic analysis, and in particular the application of the IAEA defense-in-depth principle, require that the loads used in flaw evaluation be conservative, enveloping, estimates of the actual loads.

Axpo strictly followed the ASME XI procedure with the exception of the grouping rule. ASME XI includes rules for characterizing laminar flaws but, those are over-conservative and Axpo used alternate grouping rules defined by AREVA instead (see Chapter 8.3.2)

The following sub-chapters provide further detail of the flaw evaluation.

8.3.1 Volumetric Indications Modelled as Planar

In their flaw evaluation, Axpo modelled all indications revealed by NDE, regardless of their true physical nature (e.g., planar, volumetric) as planar cracks. However, as observed in the metallographic examinations performed on CT specimen fracture surfaces (see Chapter 5), alumina agglomerates are not bonded to the steel matrix and, microstructurally (see footnote 13 above), are volumetric (i.e. three dimensional without sharp crack tips). In structural terms they are, in effect, voids and the stress concentrations produced when they are loaded are substantially less than those produced by an equivalent crack. IRP therefore considers that Axpo's flaw model is undoubtedly conservative

8.3.2 Flaw Grouping

Many of the individual indications found in the Beznau 1 RPV shells were in close proximity and Axpo grouped them according to ASME XI rules. The reason for these rules is that the high stress concentrations, that are developed at sharp crack tips which are close together, interact. This increases the stress intensity of the flaws in combination with each other, relative to the values for the individual flaws considered in isolation. The rules also provide protection against the possibilities that the ligament between flaws may fracture to form a larger flaw, or that the UT has failed to find connectivity between flaws.

However, the metallographic and UT evidence shows that peripheries of the alumina aggregates are blunt, and the great majority (see Chapter 8.4 for discussion of the HAI) are separated by 'bridges' of sound metal. These factors reduce the interaction between them relative to the interaction between sharp cracks. The ASME XI flaw grouping rules are conservative, and more so for blunt agglomerates of inclusions relative to sharp cracks. It is also noted that combination of quasi-laminar cracks by cleavage fracture is not possible, since they mutually disturb the required local constraints. Thus, neighboring cracks shield rather than amplify each other.

In this safety case, Axpo used ASME XI, IWA-3300, to combine flaws lying in a common plane. For flaws in parallel planes, combination was performed to an AREVA procedure [8][14] This is less conservative than IWA-3300, but there are several precedents [9]. [10], [11] for alternative procedures developed for the relatively unusual situation of closely spaced flaws. The AREVA procedure applied to Beznau was validated using a finite element analysis performed by IWM, which demonstrated its conservatism. Validation of the AREVA procedure was not within IRP scope.

8.3.3 Flaw Orientation

The predominant orientation of the alumina agglomerates and conglomerates is laminar (i.e. nearly parallel to the inner diameter and outer diameter surfaces of the RPV). The stresses that act to open nearly laminar flaws in a cylindrical RPV are relatively low. However, Code practice requires the projection of these flaws onto the more highly stressed axial and circumferential planes. This practice, which was followed by Axpo, ensures that the applied stress intensity factor calculated for the flaws as modelled, exceeds that associated with the actual physical situation.

8.3.4 Conservatism of Inputs

It is a normal requirement that input to an SIA are conservatively estimated. The IRP is satisfied that the inputs for the assessment of agglomerates of inclusions, and within the IRP scope (Chapter 1.2) have been determined with adequate conservatism in accordance with code requirement. Significant additional conservatisms, relative to the code, may result from the following:

- The sizing of the large numbers of indications below the beam size at the beam size (Chapter 4), leading to larger combined groups of agglomerates than if more realistic sizes were used;
- The projection of laminar agglomerates onto the axial and circumferential planes;
- The use of ASME flaw combination rules for sharp cracks when the inclusion agglomerates do not have sharp crack tips (Chapter 8.3.2).

8.3.5 Modelling of Extended Areas as Single Large Flaws

To provide further confidence in the overall conservatism of the safety case, Axpo performed additional SIA analyses that are not part of a typical Code analysis. These additional analyses added further conservatisms to the flaw grouping rules by considering all the indications found in the sixteen ‘extended areas’ (see Chapter 4) to be part of very large flaws, in some cases approaching half a meter in length [5]. Despite these large flaw sizes, the margins calculated were considerable for all extended areas except for EA-740.

The thermo-hydraulic loadings are outside IRP scope, but it understands that the values assumed in the assessment have not been validated. It therefore regards these results as indicative rather than fully demonstrated.

[14] It may also be noted that the AREVA procedure documented has provided the technical basis for a recently accepted ASME Code Case N-877.

8.3.6 Summary

The information presented by Axpo and summarized in this section leads the IRP to conclude that, for the indications produced by alumina agglomerates:

- Axpo performed SIA using appropriate ASME Code procedures, which are known to be conservative, or verified alternatives, which have also been shown to be conservative.
- The inputs to the Code analysis that are within IRP scope were determined using conservative methods.
- The results of the analysis showed that all indications originating from alumina agglomerates satisfied the acceptance criteria of the code.
- The SIA incorporated additional conservatisms, relative to the code because the alumina agglomerates that did not meet acceptance standards and were analyzed as flaws do not behave as sharp cracks and are laminar.
- Assessments of EAs considered as single large flaws provide indicative evidence of additional conservatism.

For these reasons:

> ***The IRP considers that the SIA performed by Axpo using ASME flaw evaluation rules for Shells A, B and C demonstrates the acceptability of all indications originating from alumina agglomerates found in the Beznau 1 RPV***

8.4 Modelling of HAI and planar flaws found by the AREVA procedure

As described in Chapter 3.2, RPV Shell C contained 20 HAIs, which might possibly be associated with, cracks. In addition, the original AREVA inspection[15] found eight embedded planar flaws. Axpo [12] assessed all these separately as flaws using the procedures described in Chapter 8.3. Of the total of 28 flaws, four projected axial flaws, and one projected circumferential flaw, were grouped. The largest dimensions for any axial flaw (or grouped axial flaw) were 9.7 mm in Y and 3.6 mm in Z; for circumferential flaws 25 mm in X (planar flaw) and 4.5 mm in Z (planar flaw). The largest dimensions were not combined in a single flaw or group.

Axpo used the acceptance standards for sizes of allowable planar flaws specified in ASME XI, IWB-3500 to assess these flaws. The largest circumferential projection of a planar flaw had a length of 25mm, which was 2 mm smaller than the ASME allowed size of 27 mm, making it acceptable. Similarly, the largest circumferential projection of an HAI was 3 mm smaller than the ASME allowed size. As evidenced by the more detailed analyses done by Axpo for grouped agglomerates using ASME's procedures for analytical evaluation of planar flaws specified in ASME XI IWB-3600, the differences between IWB-3500 allowable flaw sizes and those estimated for Beznau significantly underestimate the true margin of the Beznau RPV against failure.

However, as discussed in Chapter 4.2.2 it is possible that the HAI contain cracks and are undersized because the 6dB drop method might be non-conservative in regions of high densities of indications. Axpo have addressed these concerns by grouping the HAI in EA-600 visually (a method equivalent to those suggested in Chapter 4.2.2). This resulted in seven HAIs being grouped to give overall dimensions 43 x 13.9 x 7.3 mm (X, Y, Z) compared with the largest dimensions of any HAI

[15] This inspection was designed to detect UCC, these planar flaws were not UCC (and no UCC were found).

of 25 x 9.7 x 3.6 mm, reported above. An eighth HAI was remote from the others and did not need to be considered.

The limiting projected flaw was 7.3 x 43 (Z, X, circumferential plane) at a distance from the wetted surface of 7.3 mm. This was enveloped by the postulated UCC and PTS flaws. These were assessed according to ASME XI, IWB-3600 to determine the allowable reference temperature, $RT_{ref,allow}$. Using verified conservative inputs, values of 84°C and 82.5°C, respectively, were obtained. These compared with conservative estimates of $RT_{ref,ART}$ after 60 years of operation of 76.7°C and 76.3°C (at the actual location of the flaws). These values were derived using ENSI B01 Method II Variant B. Axpo therefore concluded that the HAI were acceptable.

The IRP agrees with this conclusion. The method used to calculate $RT_{ref,ART}$ is that recommended by the IRP (Chapter 7), and the grouping of the seven HAI is certainly a conservative approach.

> ***The IRP considers that Axpo have adequately demonstrated the acceptability of the HAI and the embedded planar flaws found by the AREVA UCC procedure.***

8.5 Assessment of Shell E

The information presented in Chapter 8.3 pertains to the beltline shells (designated B and C) and the inspected regions of Shell A. Parts of Shells A and E, and the whole of Shell F, could not be inspected in-service and are discussed in Chapter 8.6. No indications were reported in Shell D.

Indications found in the inspected regions of Shell E (part of the hemispherical head at the bottom of the RPV) were assessed using the same procedures as described in Chapter 8.3.

The report detailing this part of the SIA claims that the ASME Code assessment demonstrated that all indications in Shell E, and all groups formed therefrom, to be acceptable. Shell E was addressed separately because the principal stress directions do not coincide with TL or LT. Due to the inclination of the idealized flaw, the TS direction is also affected by the mixed-mode crack-tip loading.

The IRP considers that, despite a slight under-estimation in the applied stress intensity factor due to mixed-mode loading, the SIA for Shell E is undoubtedly conservative for the following reason. Due to its position at the bottom of the vessel Shell E is not subject to damage by irradiation embrittlement. Furthermore, the RT_{ref} is based on RT_{NDT} (i.e., using Charpy impact and NDT dropweight tests) and equal to 4°C. This value, which is known to be conservative by analogy with the findings from Replica C, results in a large margin, of 62 °C, relative to the allowable value, $RT_{ref,allow}$.

> ***The IRP considers that the SIA performed by Axpo for Shell E has demonstrates that it is acceptable for continued service.***

8.6 Assessment of other areas and overall discussion

The SIA carried out by Axpo for Shells A, B, C and E has demonstrated that the RPV meets the primary stress limits of ASME III and the fracture toughness requirements of ASME XI Appendix G. Detailed evaluation of the flaws found in the RPV by UT inspection to the requirements of ASME XI with conservative inputs has shown that all flaws are acceptable, even if they were cracks rather than alumina agglomerates. A further level of confidence was obtained by modelling the most limiting Extended Areas as cracks.

The IRP considers that Axpo's claim is justified that the other shells and uninspected regions of Shells A and E are less limiting than Shells B and C. Shell D has no reportable indications. Shells A, E and F are not significantly embrittled by neutron irradiation, and the IRP accepts Axpo's claim that, if there were significant flaws in the uninspected regions of these shells (it was not possible to inspect any of Shell F in service) they would have been detected during the manufacturing inspections.

> ***The IRP considers that the flaw analysis shows that risk of failure of the Beznau 1 RPV as a consequence of the indications detected can be excluded.***

9 DETEC Requirements

Regardless of demonstration of safety based on fracture mechanics analyses, DETEC (Swiss Federal Department of the Environment, Transport, Energy and Communication) requires the following two criteria to be fulfilled [13]:

1. $RT_{ref,ART}$ < +93 °C. Here RT_{ref} is evaluated at the ¼-position.
2. Charpy fracture energy on the upper shelf ≥ 68 J.

Since it was demonstrated that the non-metallic inclusions have no detrimental effect on either fracture toughness or on the tensile properties, Axpo considers the irradiation embrittlement curve evaluated according to ENSI B01 Method II Variant A and approved by ENSI in 2012 as still valid. The 2012 analysis established a value of $RT_{ref,ART}$ = +80 °C at 54 FPY.

However, Method II Variant A is based on the T_0 value measured (in this case) on PCCV specimens from Capsule T. Although Variant A makes allowances for use of these 0.4T SENB specimens rather than 1T-CT specimens, the allowance is small compared with the observed differences in the fracture toughness reference transition temperature, T_0, between small and large specimens from both Replica C and Shell C material, (see Chapter 7). It is the IRP's opinion that $RT_{ref.ART}$ should instead be obtained using ENSI B01 Method II Variant B. This is based on the unirradiated T_0 (determined in this case from 1T-CT specimens), and irradiation shift, estimated from tests on Charpy specimens.

The use of Variant B is considered better founded in this case because it avoids dependence on small fracture toughness specimens, which may give non-conservative results compared with conventional 1T-CT specimens. Furthermore, it avoids dependence on a single set of results from Capsule T. Charpy tests have long been accepted as a reliable method of determining irradiation shift. The Charpy test results from Capsule T are consistent with the results from other Beznau 1 capsules

If Variant B is used, $RT_{ref,ART}$ at 54FPY is calculated to be 89 °C at the inner surface and 83 °C at the t/4 location so that the DETEC criterion 1 ($RT_{ref,ART}$ < 93 °C) is still fulfilled.

The upper shelf criterion (energy ≥ 68J) is not affected by the new findings. Therefore, the conclusions of the previous assessment concerning upper shelf remain valid.

> ***Based on Axpo data, the IRP agrees that the DETEC requirements for $RT_{ref,ART}$ < +93 °C would be met with the IRP's recommendation to use ENSI B01 Method II Variant B.***

10 Discussion and conclusion

The structural integrity of nuclear reactor pressure vessels at the time they first become operational is assured by long-established and well-founded codes and standards. These include standards to ensure that design and manufacture use well-established methods that are sufficiently conservative to take account of the non-detected flaws and materials inhomogeneities that are present in all structural engineering materials. A further layer of protection is provided by in-service inspection to confirm that flaws have not grown in service.

It is rare that ISI results in an unexpected finding. When this happens, it is often the result of applying more modern and more sensitive UT techniques than were available or necessary for the pre-service inspection. When there is an unexpected finding, the course of the subsequent investigation depends on the applicable regulator and the regulatory codes in force. In the case of the Beznau 1 RPV, ENSI asked for an integrity review of the RPV before recommissioning. In response, Axpo and their sub-contractors have carried out a very extensive programme of work over a three-year period. The size of this programme, resulted from the unexpected nature of the flaws found in the ISI and the need to assume, initially, that they might be cracks.

The IRP has confidence in the Axpo SC for the following reasons:

- It has been established beyond reasonable doubt that the great majority of UT indications are from agglomerates of alumina inclusions. This confidence is founded on the success of Replica C in confirming the original root cause hypothesis and reproducing, with considerable accuracy, the distribution and characteristics of the agglomerates in the RPV shell materials. It is very difficult to conceive that the manufacture of a replica using essentially the same methods, and values of key variables, as those known to have been used in the production the RPV could produce a different type of flaw from those in the RPV.
- It has been established beyond reasonable doubt that alumina agglomerates as found in Replica C and the RPV do not have an adverse effect on the materials properties that are important to structural integrity, or on irradiation sensitivity. This is consistent with theoretical expectation. Although the agglomerates do not affect the properties of the steel matrix, they can act as voids when under tensile stress. This can modify the behavior of the structure in which they are embedded. However, such effects are limited to the scale of the agglomerates and there are no concerns on the scale of the RPV.
- The above structural effect only applies beyond the yield stress of the material, a situation that cannot occur even with extremely conservative assumptions. The agglomerates cannot initiate failure below the yield stress because they have rounded tips and do not act as sharp cracks. Axpo have demonstrated this at toughness levels relevant to the flaw evaluation.
- Extensive SIA has confirmed that other potential issues are not of concern. These issues include fatigue crack growth, ductile tearing, plastic collapse and the possibility that the HAI might be from regions in which agglomerates are associated with cracks. The requirements of Section III and Section XI of the ASME Code, which are known to produce a conservative SIA, have been used and met by Beznau. In addition, the SIA for Beznau 1 contains additional conservatisms, including considering the alumina agglomerates as sharp cracks. Even with these additional conservatisms, the Code analyses have shown that there are adequate margins against structural failure.

- The NDE carried out on the RPV, the Replica, archive materials and test samples has been a vital component of the program. The techniques used were highly sensitive and have been well-validated. The information provided by NDE is considered by the IRP as adequately reliable and shows that there are no significant defects in the RPV other than those which have been considered in the analysis.
- The only issue of doubt to the IRP is the reliability of defining T_0 for RPV shell materials with small (~10mm) specimens. This is because of the observed unusually large size effect and scatter of the K_{Jc}-data exhibited by both the Replica C and the Shell C acceptance ring materials. To address this doubt, the IRP recommends that, for the present situation, $RT_{ref,ART}$ is based on ENSI B01 Method II Variant B, i.e. using start of life RT_{ref} (obtained from 25 mm CT specimens) and Charpy shift.

The IRP considers that the safety case is acceptable.

The IRP recommends that $RT_{ref,ART}$ be determined using ENSI B01 Method II Variant B.

ANNEX 1 ABBREVIATIONS AND SYMBOLS

ΔT_{41J}	Irradiation shift, as measured using Charpy tests, indexed at the 41J energy level
1T-CT	One inch thick compact tension (specimen)
A_g	Elongation (in tensile test)
Al_2O_3	Alumina (Aluminium oxide)
ART	Adjusted Reference Temperature
ASME BPV	American Society of Mechanical Engineers Boiler and Pressure Vessel Code
ASME III, ASME XI	Sections III and XI of the ASME Boiler and Pressure Vessel Code
ASTM	American Society for Testing and Materials (now ASTM International)
Axpo	Axpo Power AG
Beznau 1	Beznau Nuclear Power Plant Unit1
DEKRA	Multinational (German) Inspection Company
DT	Destructive Testing
E0	Reference material (from Replica C) with no UT indications, down to noise.
E1	Replica C material with a high density of UT indications covering the 'maximum average densities' in EA-600 in Shell C (2.3 cm^{-3}) [1, S3.5.2]
E3	Replica C material with average density of UT indications 'comparable to' EA-740 in Shell C (1.0 cm^{-3}) [1, S3.5.2]
EA	Extended Area (areas found in the first inspections to have high densities of inclusions, and which were subsequently scanned more precisely to better resolve individual inclusions and clusters)
ENSI	Eidgenössisches Nuklearsicherheitsinspektorat
FM	Fracture Mechanics
FPY	Full Power Years
IRP	Independent Review Panel
K_{Ic}	Plane Strain Fracture Toughness characterized by K-factor
LT	Longitudinal Transverse. – orientation of a toughness or fatigue crack growth specimen in which the fracture plane is perpendicular to the surface of the component and the crack propagation direction is perpendicular to the principle working direction of the plate or forging (see TL and SL)

LW	Longitudinal Wave
MC	Master Curve
NDE	Non-destructive examination
NDE box	The rectangular box that encloses an NDE indication, or unresolvable group of indications.
NPP	Nuclear Power Plant
ORNL	Oak Ridge National Laboratory
PCCV	Pre-cracked Charpy V-notched (specimen)
PTS	Pressurized Thermal Shock
RCA	Root Cause Analysis
RM	Roadmap
$R_{p0.2}$	0.2% offset proof stress – the engineering definition of yield strength
R_m	Ultimate tensile strength
RPV	Reactor Pressure Vessel
RT_{NDT}	Reference Temperature Nil-Ductility Temperature (from ASME)
RVI	Remote Visual Inspection
RT_{ref}	RT_{ref} Reference temperature, according to ENSI B01, that defines the position of the lower bound toughness curve to be used in SIA
$RT_{ref}(0)$	RT_{ref} for unirradiated material
$RT_{ref,ART}$	RT_{ref} for irradiated material
$RT_{ref,allow}$	Allowable value of RT_{ref} calculate in the SIA (for a specific flaw and loading condition); there must be a margin between this and the RT_{ref} of the material at the location of the flaw (including allowance for effect of irradiation if applicable
SC	Safety Case
SFAC	Société des Forges et Ateliers du Creusot
SFEL	Sheffield Forgemasters Engineering Limited
SIA	Structural Integrity Assessment
SL	Short-transverse Longitudinal – orientation of a toughness or fatigue crack growth specimen in which the fracture plane is parallel to the surface of the component and the crack propagation direction is in the principle working direction of the plate or forging (see LT and TL)

SVTI	Schweizerischer Verein für technische Inspektionen (Swiss Association for Technical Inspections)
SW	Shear Wave
T_0	The MC transition temperature – the temperature at which the median fracture toughness is 100 MPa√m
TL	Transverse Longitudinal – orientation of a toughness or fatigue crack growth specimen in which the fracture plane is perpendicular to the surface of the component and the crack propagation direction is in the principle working direction of the plate or forging (see LT and SL)
UCC	Under-clad Cracking
UT	Ultrasonic Testing
WENRA	Western European Nuclear Regulators Association
Z	Reduction in area (tensile test)

ANNEX 2 – IRP MEMBERS

Member	Organization
Isabelle Delvallée-Nunio	IRSN
Mark Kirk	USNRC
Randy Nanstad	R&S Consultants LLC (Formerly ORNL)
Guy Roussel	Bel-V
Hans-Jacob Schindler	Mat-Tec AG, ETHZ
Hans Vandriessche	Vinçotte
Tim Williams (IRP Chair)	39bhr Limited

ANNEX 3 – WORKSHOPS AND MEETINGS

Start date	Duration (days)	Title and main topic (location)	Attendance
14/12/15	3	First IRP Workshop: assess RM; (Brugg)	All IRP, ENSI, (Axpo and its experts for part of meeting)
11/05/16	3	Second IRP Workshop: initial assessment of results to date; NDE, fabrication; Root Cause Analysis (Baden)	All IRP, ENSI, (Axpo and its experts for part of meeting)
04/08/16	1	Meeting: Status of test material (Replica C) (Beznau NPP)	IRP members, ENSI, Axpo and its experts
25/08/16	1	Meeting: Formation mechanism of flaws (Beznau NPP)	IRP members, ENSI, Axpo and its experts
08/09/16	1	Meeting: Structure of SC + intermediate results on replica (Beznau NPP)	IRP members, ENSI, Axpo and its experts
21/09/16	1	Meeting: Flaw assessment concept (Beznau NPP)	IRP members, ENSI, Axpo and its experts
29/09/16	1	Meeting: NDE and UT validation (Beznau NPP)	IRP members, ENSI, Axpo and its experts
12/10/16	1	Meeting: Test results for Replica C with laboratory visits (AREVA Erlangen)	IRP members, ENSI, Axpo and its experts, particularly AREVA
29/11/16	1	Meeting: Status of safety case; size effect in Master Curve. (Beznau NPP)	IRP members, ENSI, Axpo and its experts
13/12/16	2.5	Third IRP Workshop: assessment of SC (Beznau NPP and Brugg)	All IRP, ENSI, (Axpo and its experts for a small part of the meeting)
25/01/17	2.5	Fourth IRP Workshop: Assessment and preparation of report. (Brugg)	All IRP, ENSI
1501/18	5	Fifth IRP Workshop. Assessment of further Axpo work and preparation of this report	All IRP, ENSI

ANNEX 4 – TERMINOLOGY

Words in **bold** are terms defined elsewhere in the table.

Term	Context	Explanation	Source
Adequate(ly) / Accept(able)		Satisfactory, sufficient for the needs of the case. Example 'The [**claim**] has been adequately **demonstrated**', means that (in the context of the importance of the **claim**) no further work need be done.	
Agglomerate	Inclusions	A group of aluminum oxides completely surrounded by the steel matrix.	Axpo
Claim	SC	An assertion or statement made explicitly or implicitly in an SC on which the safety of the subject of the SC may depend.	
Confidence		Belief in the certainty of something: The engineers determined with confidence that the ship could withstand heavy seas.	
Conglomeratio n	Inclusions	A group of **agglomerates** separated by the steel matrix	Axpo
Conservative	SIA	Used to describe methods, models, data and assumptions which will lead to SIA results that are **demonstrably** on the safe side, to an **acceptable** level of **confidence**. The degree of conservatism of the individual elements (e.g. loadings) of an SIA must be proportionate to the level of uncertainty and the overall significance of that element to the safety case as whole. In general, the conservatisms required are defined by regulatory codes and specifications. (Also see **margin**.)	
Defect	NDE	One or more **flaws** whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable (ASTM E 1316-91b)	ASTM
Demonstrate:		Clearly show the existence or truth of (something) by giving proof or evidence (For example 'the fracture toughness data used are demonstrably **conservative**')	
False indication	NDE	An **indication** that is interpreted to be caused by a condition other than a discontinuity or imperfection. These are normally removed from the **indication** list in the final version of an NDT report, so that **indications**, which are not false **indications**, are exclusively the NDE image of imperfections or discontinuities (ASTM-E 1316-02a),	ASTM
Flaw	NDE	An imperfection or discontinuity that may be detectable by non-destructive testing and is not necessarily rejectable (ASTM E 1316-91b)	ASTM

Imperfection	NDE	A departure of quality characteristic from its intended condition, (**flaws** do not necessarily correspond to a material discontinuity (ASTM-1316-02a))	ASTM
Importance		The significance of a **claim** in the overall SC; the more the SC depends on a **claim** the greater the confidence needed that the **claim** is justified.	
Inclusion		Particle of non-metallic material in the **matrix** of the alloy that is not an inherent constituent of the alloy. Inclusions may be a normal feature that results from alloy production or processing, but absence of inclusions would not be a cause for concern.	
Indication	NDE	Evidence of a discontinuity that requires interpretation to determine its significance (ASTM Standard Terminology for Non-Destructive Examinations ASTM E 1316-91b)	ASTM
Justify		Show or prove to be right or reasonable ample, 'since the cladding has been **demonstrated** to be intact, it is justifiable to use the 'dry' fatigue crack growth rate curve.'	
Laminar	Flaws	Inclined at less than 10° to the surface (see also quasi-laminar)	ASME
Matrix		(In this context) the steel surrounding the alumina **inclusions** and **agglomerates**	
Margin	SIA	The temperature difference between the most limiting combination of fracture toughness bound and crack driving force, both including regulatory conservatisms. See also Safety Factor.	
Origin	Indications	The source of the UT reflections; the discontinuity in the material that provides the UT signal received by the probes. (see also **Root Cause**)	
Quasi-laminar	Flaw	Inclined between 10° and 20° to the surface	ASME
Replica	Material	A close or exact copy	Axpo
Representative	Material	Able to reflect the properties of the material it represents	Axpo
Root cause	Alumina inclusions	The factor(s) that caused the agglomerates to be present in the steel (see also **Origin**).	
Safety Factor	SIA	The ratio of materials toughness to crack driving force K_{IC}/K_I, both conservatively derived. Must be greater than the factor (>1) specified by the codes (see also **Margin**). Also known as structural factors or safety coefficients.	

Significant		Sufficiently great or **important** to be worthy of attention. A **claim** would be significant if the effect of plausible errors in it could reduce the operating margin to zero or below.	
Validation:		The process of confirming, e.g. by use of objective evidence, that the outputs from an activity will meet the objectives and requirements set for that activity	ONR SAP
Verification		The process of confirming, e.g. by use of objective evidence, that an activity was carried out as intended, specified or stated	ONR SAP

KEY

ASTM (American Society for Testing and Materials) – the specific standard/guide is referenced in the description column

ONR SAP UK Office for Nuclear Regulation (ONR) Safety Assessment Principles for Nuclear Facilities (SAPs)

11 REFERENCES

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4. TM-530-MQ17022 Synthesis Report: Determination of material Properties of RPV Steel containing alumina inclusions, [redacted] [redacted] (Rev 3, 04/12/2017)

5. TM-530-MB16059, Synthesis Report of Structural Integrity Assessment (SIA), [redacted], Axpo, (Rev 2, 29/11/2017).

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11 ASME SC-XI, Division 1 Code Case N-877, "Alternative Characterization Rules for Multiple Planar Flaws"

12 KKB530D0341 Beznau 1 results of assessment of NDE recordable flaws found in Beznau 1 RPV with higher amplitude, Rev B, 2018-01-17, [redacted].

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