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Swiss Federal Nuclear Safety Inspectorate ENSI

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ENSI Review of the Axpo Power AG Safety Case for the Reactor Pressure Vessel of the Beznau NPP Unit 1

Revision 1, May 31, 2018

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1 Introduction

1.1 Background

After ultrasonic testing (UT) inspections in the Belgian nuclear power plants (NPP) Doel-3 and Tihange-2 in 2012 reported a series of indications in the base material of those reactor pressure vessels (RPV), the Swiss Federal Nuclear Safety Inspectorate (ENSI) requested investigations from the Swiss licensees. In particular, following the corresponding WENRA recommendations /1/ ENSI demanded a reassessment of the quality of the forged base material of the vessel /2/. As first part of the reassessment, a technical report was requested on the material quality, the fabrication process and past inspections of the RPV base material. Axpo Power AG (in the following Axpo) submitted said technical report /3/ in October 2013 to ENSI. As second part of the reassessment, ENSI requested a supplementary ultrasonic inspection of the base material validated for the detection of hydrogen-induced flaws, since hydrogen flakes had been unambiguously established as root cause of the indications found in the Belgian RPVs.

In the case of the Beznau NPP Unit 1 (in short: Beznau-1 or KKB-1), the ultrasonic inspections of the RPV were carried out during the planned 2015 outage, after the qualification process of the non-destructive testing procedure. These inspections resulted in a series of indications, which required justification and a detailed assessment of the Safety Case (SC) of the Beznau-1 RPV.

1.2 Assessment and review process

By letter /4/ dated August 2015, ENSI required from Axpo that the assessment process be based on an overall project plan called ‘Roadmap’. ENSI mandated the International Review Panel (IRP) to assess the safety case in an independent and critical manner. The IRP as a group of seven internationally recognized experts was available throughout the review process (of the initially eight-expert group one of the experts resigned due to personal reasons in April 2016[1]).

The experts were tasked with providing advice on whether the SC had been adequately demonstrated. The IRP had to assess the suitability of new or non-standard procedures for use in the safety case and to identify aspects of the case that were not sufficiently justified.

In November 2015, Axpo submitted a set of four documents describing the overall project plan and constituting the Roadmap /7/. This set of roadmap documents /8/, /9/, /10/, and /11/ was assessed by the IRP /6/ and independently by ENSI /14/.

Subsequently, ENSI as well as the IRP proceeded with the assessment of all tests, investigations, and reports submitted by Axpo for the SC. Several meetings accompanied this process between Axpo and their experts on one side and the IRP, ENSI and other ENSI appointed experts on the regulatory side.

The review process of the IRP and ENSI included five workshops during the period 2016-2018. ENSI continuously provided Axpo with various results of its interim assessments, preliminary conclusions, and general feedback /177/ to /187/. All review results were preliminary, since the adequacy and acceptability of the safety case can only be assessed with confidence after the structural integrity assessment (SIA) is complete.

Revision 1 of the SC submitted by Axpo in November 2016 was reviewed by ENSI and the IRP. The reviews concluded that the SC contained insufficient supporting data on the effect of the inclusions on material properties as well as incomplete validation of the UT testing method. This resulted in ENSI requesting Axpo to extend the materials characterization program and to submit an updated SC. Axpo submitted the final report on the SC (revision 2) in December 2017 /31/. Based on ENSI feedback /187/ additional explanations and revised reports were subsequently filed by Axpo until February 2018 /28/, /29/, /30/, /192/, /203/, /204/, /205/.

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[1] https://www.ensi.ch/de/2016/11/16/ensi-prueft-eingereichten-nachweis-zum-reaktordruckbehaelter-von-beznau-1/

At the end of February 2018, the IRP submitted its final assessment report /191/ to ENSI. The additional explanations and revised reports for the Beznau-1 SC were considered by ENSI in their entirety up to February 2018.

1.3 Scope of ENSI review

ENSI review covers the objectives described in the Roadmap /9/, the responses to the ENSI requests in /14/, and supplementary conclusions based on new knowledge resulting from the SC revision 2 report documents.

The various and extensive investigations by Axpo to establish the nature of the UT indications and to justify the structural integrity of the RPV were developed during a 2.5-year period and resulted in more than 100 reports. Some of the studies and investigations were performed in parallel, which required the definition of a set of working assumptions by Axpo. As these assumptions were confirmed or invalidated by evidence and/or further analytical considerations, the technical reports of the SC needed to be revised accordingly. This revision process of the SC documentation has not been completed in a coherent way by Axpo (see Chapter 8).

ENSI therefore limited the scope of its review to the relevant technical justifications for the demonstration of structural integrity and regulatory compliance of the Beznau-1 RPV. Other statements and conclusions by Axpo that are not considered relevant for this objective, have not been assessed.

Although the advice of the IRP has been considered and incorporated in the present report, the decision on the acceptability of the Axpo SC /31/, and any requests or obligations formulated in the present report are the sole responsibility of ENSI.

1.4 Content of the present report

Chapters 2 to 7 of the present report cover the review performed by ENSI of the documents submitted by Axpo concerning the SC. Each chapter starts with a description of the part of Axpo’s assessment considered relevant by ENSI for the acceptance of the SC.

Chapter 2 deals with non-destructive examinations (NDE) of the Beznau-1 RPV. Chapter 3 covers the root cause analysis performed to identify the physical causes of the indications in the Beznau-1 RPV.

As a replica shell (Replica C) of a Beznau-1 RPV ring was forged to be used as a fundamental part of the SC demonstration, Chapter 4 discusses the representativeness of this Replica C. Material properties of the Beznau-1 RPV as characterized by means of the Replica C are the subject of Chapter 5, while Chapter 7 covers the SIA of the whole vessel. In Chapter 9, the results of the IRP assessments are briefly summarised.

Chapter 10 concludes the report by summarizing the results of ENSI’s review and defines the requirements for continued operation of Beznau-1 to be fulfilled by Axpo after recommissioning.

1.5 Legal basis

According to article 22 paragraph 2 letter a of the Nuclear Energy Act, a licensee has to comply with all specified operational limits and conditions, part of which are contained in the Technical Specifications.

The Technical Specifications require that the integrity of pressurized components is assured and verified by means of periodic inspections. The licensee has to prove this integrity with periodic non-destructive examinations (NDE) of such components as well as with additional inspections based on events and findings.

At the end of each refuelling outage, before fuel loading is allowed, ENSI issues a formal permit. Such a permit is granted only in the event that all conditions for safe normal operation for the following subsequent cycle are guaranteed, including the fulfilment of all requirements of the Technical Specifications.

Currently, the reactor of Beznau-1 is in cold shutdown; resuming normal operation will only be permitted by ENSI after the integrity of the RPV has been demonstrated by the licensee and accepted by ENSI.

Regulatory basis for ENSI review

Nuclear Energy Ordinance (NEO) of 10 December 2004 (Version 1 June 2017) /161/

DETEC Ordinance on the safety classified vessels and piping of Nuclear Power Plants (VBRK) of 9 June 2006 (Version 1 January 2009) /170/

DETEC Ordinance on the methodology and boundary conditions for checking the criteria for the provisional shutdown of nuclear power plants of 16 April 2008 (Version 01 May 2008) /169/

ASME Boiler & Pressure Vessel Code, Section III and XI, Edition 2015 /162/, /163/

KTA standards, valid issue 2015 respectively /164/

ENSI Guideline ENSI-B01, Aging Management, August 2011/165/

US-NRC Regulatory Guideline 1.99, Rev.2, May 1988 /168/

2 Non-destructive examination of the reactor pressure vessel

2.1 Introduction

In 2015, NDE investigations were carried out on the base material of the RPV of Beznau Units 1 and 2, to determine whether they contained hydrogen flakes similar to those found in the Belgian NPP of Doel 3 and Tihange 2.

Whereas only few and isolated indications (77 in total) were detected in the RPV of unit 2, many indications were found in RPV Unit 1 with the highest number in the lower part of Shell C /32/, /47/.

2.2 Detection and characterisation of UT indications

Safety case description

Inspection of Shells A, B, C and D

The initial NDE investigations in 2015 were carried out by DEKRA, who applied an ultrasonic phased array technique with straight beam and 10°L insonification in 4 orientations, with dynamic depth focusing, time corrected gain and electronic linear scanning, using a 2D matrix immersion phased array probe.

The highest number of indications was found in Shell C of unit 1. Most indications were situated in the first 50 mm of depth (measured from the wet cladded surface) and in a narrow band of 25 cm height in the lower part of the ring (close to weld RN5). It could be concluded from preliminary NDE results that the orientation of the flaws was most likely quasi-laminar, as in Doel 3 and Tihange 2. However the size of the individual indications appeared smaller and their density higher.

The amplitude of the Beznau 1 indications could not directly be compared with those of Doel-3/Tihange-2 because the type of transducers and the sensitivity settings of the DEKRA procedure were different than those of the Intercontrôle procedure applied in Doel-3/Tihange-2.

Because the DEKRA method was not qualified for measurements in the depth range between the wet cladded surface and 10 mm depth and because of the difficulties encountered in comparing the amplitudes between Beznau-1 and Doel-3/Tihange-2, Axpo decided to perform a complementary UT examination in Beznau-1 with the Intercontrôle procedure.

The Intercontrôle procedure /89/ was originally developed and qualified for the detection and characterization of laminar flakes of 6 mm with a tilt up to 16°. It uses different focused immersion probes with 0° longitudinal wave (LW) orientation for three depth ranges and 45° shear wave (SW) probes in two depth ranges and in four orientations. The width of the ultrasonic beam of the 0°LW technique in the depth range 0 to 50 mm varies from 3 to 5 mm (the lowest value for the shallowest position). The width of the ultrasonic beam of the 45°SW techniques in the depth range of 0 to 50mm is larger (i.e. about 10 mm).

The standard resolution of the raster scanning (during detection phase) is 2 mm, both in the X-direction (axial) and Y-direction (circumferential). The standard data acquisition format is CIVACUVE, which stores a discrete number of amplitudes and times of flight.

Axpo summarized the inspection results for the number of quasi-laminar indications in the RPV as follows /31/:

- Shell A: 2
- Shell B: 119
- Shell C: total 3511, of which 2689 indications were located in 16 so-called high density “extended areas” (EA), inspected with the data format CIVAMIS (see below).
- Shell D: 0

The average size of the indications in axial and circumferential direction is about 3 to 5 mm which is comparable with or smaller than the beam size, depending on the depth position. The extension in radial (depth) direction is significantly smaller(less than 1 mm). An important result of the Intercontrôle UT examination was that the amplitude of the great majority of the indications was significantly lower (about 10dB lower) than in Doel-3/Tihange-2. Together with other elements from the root cause analysis (RCA, see Chapter 3.2), they provided a strong evidence that the observed indications in the Beznau-1 RPV shell forgings were not hydrogen flakes /46/.

The indications in Shells B and C showed comparable amplitude distributions. Most of the indications are located near the bottom of the rings in a depth range measured from the inner side (cladding interface) up to about one fourth of the thickness. The maximum reported depth was 50 mm. Axpo claims that these findings support the conclusion that all indications are caused by the same type of reflectors /85/.

In addition to the large number of reported indications, Shell C showed also densely populated clusters. In the EA, the density of the indications was so high that the individual indications could no longer be resolved with the standard technique. Therefore, these EA were rescanned with an improved technique, using a finer scanning step size (about 1.2 mm) and full A-scan data registration (CIVAMIS data format), such that finally all individual indications above the reporting threshold, even those in the EA, could be properly assessed.

Extended area 600 was identified as the leading area in terms of UT results (high density of inclusions, high amplitude indications).

The reportable indications are not evenly distributed over the entire volume of the most affected Shell C, but concentrate on spatially limited bands and zones. Outside these areas, the material is almost free of indications. It was demonstrated that about 4 times more indications appear when lowering the reporting threshold down to the noise level (approx. REF-36 dB), but that globally the additional indications appear in the neighbourhood of the already affected material volume only, so that generally the non-affected volume remains non-affected /43/.

Axpo performed a range of complementary inspections on the RPV, in addition to the inspections focused on the detection and characterisation of laminar indications. An inspection technique qualified for RPV welds was applied to the RPV base material in order to detect any possible non-laminar planar defects. The inspected zone covers the extended areas in Shell C. The inspection revealed no planar defects /42/.

The integrity of the base material near the cladding and the cladding interface of the RPV Shells C and D were inspected with a technique qualified for detection of underclad cracks (UCC). Eight reportable but acceptable indications were found /159/. These indications do not exhibit the characteristics of UCC /171/. Furthermore, these indications were not located in areas with laminar indications.

Axpo carried out a 100 % visual inspection of the entire inside surface of the RPV /54/, /123/. The RPV Shells C and D and the RPV nozzle bores were inspected with a VT-1 inspection; furthermore an eddy current inspection was performed on the inside surface /52/. No surface-breaking cracks were detected.

Evaluation of High-Amplitude Indications

Axpo reported that 20 of the indications in Shell C have UT amplitudes of more than REF-6 dB and were thus labelled high-amplitude indications (HAI) /149/.

The depth distribution of the HAI lies within the depth distribution of the other reported indications in the RPV. The size distribution is shifted slightly towards larger UT sizes. Comparison of this data with the UT results obtained from inspection of the Replica C showed a comparable echo dynamic for both the HAI in the RPV and the HAI identified in the Replica C (for a detailed explanation of Replica C see Chapter 4). In some of the EA that contained high amplitude indications, 45°SW reflexions were also observed.

Axpo explained the presence of HAI with the complex morphology of the Al_2O_3 inclusions. In the case of HAI, more Al_2O_3 inclusions with a beneficial orientation to the ultrasonic beam are present and therefore increase the total reflective area. To exclude the presence of another type of flaw as origin of the HAI (e.g. volumetric indications or planar cracks), Axpo demonstrated with detailed ultrasonic modelling that the observed 45°SW signals can be reproduced by closely spaced reflectors, with a bigger cumulative reflective surface /149/.

Inspection of Shell E

Early in the development of the SC, it was decided that the Intercontrôle data would be used as the main input. However, the Intercontrôle procedure could only be applied to the cylindrical parts of the RPV.

Shell E is non-cylindrical and was inspected between weld RN 7 and weld RN 9 using the DEKRA method. However, the inspection procedure was not qualified for inspecting the conical shape of the RPV calotte and the non-grinded cladding condition. Therefore, a best-effort evaluation was performed.

The performances of Intercontrôle and DEKRA procedures were tested on the uncladded reference blocks also containing many artificial reflectors. It was concluded that comparable results were obtained with the DEKRA best-effort procedure. Furthermore, simulation results indicated that the hemispherical curvature of Shell E would not significantly influence amplitude and sizing of the indications /51/.

The DEKRA measurements for Shell E revealed isolated indications, which do not form dense clusters and are predominantly located in the first 20 mm from the cladding interface. The measurements may also contain some artefacts (false calls) due to the down-to-noise sensitivity used for data assessment of non-grinded cladding surfaces /48/, /49/.

The distributions of the UT indications in Shell E were slightly different from those in Shell C, particularly a small shift towards larger sizes was observed. This shift might be explained by the different sizing method in the DEKRA technique.

Summary

Based on the NDE carried out, Axpo concluded that the NDE were sufficiently detailed to deliver the necessary input to confirm the RCA and in particular that:

- The laminar indications had been detected and sized appropriately.
- Planar indications (perpendicular to the inner surface) had not been detected.
- Radial connections between the numerous small laminar indications had not been detected.
- The overall cladding integrity in Shell C and D had been sufficiently demonstrated /83/.

ENSI review

Inspection of Shells A, B, C and D

Based on the data provided by Axpo as well as the reviews and assessments of the Swiss Association for Technical Inspections (SVTI) /171/ and Vinçotte /172/ on the in-service inspections, ENSI concludes that all relevant flaws in the RPV have been properly detected and characterized. The inspections are well documented and their consistency with formal requirements is confirmed by the Technical Support Organizations (TSO).

ENSI agrees with the conclusion by Axpo that it is plausible that the UT indications are caused by quasi-laminar Al_2O_3 inclusion agglomerates (see also Chapter 3).

There is no evidence neither for any relevant radial connection between the laminar indications or for any planar flaws perpendicular to the inner surface taking into account the detection limit for those defects.

The overall cladding integrity in Shells C and D has sufficiently been demonstrated by the applied NDE /83/.

Evaluation of High Amplitude Indications

ENSI agrees with Axpo`s conclusion, that it is plausible that HAI are caused by Al_2O_3 inclusion agglomerates as well, with the higher amplitude being related to a locally larger total reflective area. However, a different type of flaw cannot be completely ruled out. For example, the HAI could also be caused by dense concentrations of agglomerates with cracking of the ligaments between them. Since the HAI were conservatively considered as planar flaws in the SIA (see 6.2.2), this uncertainty has no impact on the conclusions of the SC.

Inspection of Shell E

Although the DEKRA procedure applied to Shell E does not completely meet the performance of the Intercontrôle procedure, the DEKRA NDE results can be accepted as input for the SIA. Shell E contains only isolated HAI (>REF-6 dB), which are considered as cracks in the SIA (see Chapter 7.2.3). ENSI agrees that this is a conservative approach.

Since the indications that were detected with the UCC inspection technique are acceptable /159/ and do not exhibit the characteristics of underclad cracks /171/, they are considered not relevant for the structural integrity of the RPV.

2.3 Limitations of the non-destructive examination

In the SC Axpo discusses the following influential parameters for the applied Intercontrôle UT inspections of the RPV /31/.

2.3.1 Non-inspected areas

Safety case description

The areas of the RPV that could not be inspected in 2015 because of accessibility reasons are the conical region of Shell A (due to the geometry of the ring), the lower part of Shell E (below RN 9) and the bottom calotte F (due to the bottom-mounted instrumentation).

After fabrication, Beznau-1 RPV passed the final quality controls based on requirements from the construction code and internal specifications (multi-stage UT inspections, testing of mechanical properties, pressure test).

For the areas of the RPV not inspected in 2015 Axpo claims that flaws critical to safety would have been detected during or after fabrication /31/.

ENSI review

ENSI confirms that no reportable flaws were identified by the quality controls during the manufacturing of Shell E and Calotte F.

2.3.2 Reflectivity of UT indications

Safety case description

The majority of indications were sized at 3 to 5 mm in both the X and Y direction. This size range corresponds to the beam size range of the applied 0°L probe. Axpo compared the amplitudes of the UT measurements with the reflectivity of a modelled smooth, continuous, flaw of laminar orientation with a size of 3.6 mm and concluded that such 3 to 5 mm flaws would cause significantly higher UT amplitudes. The lower amplitude of the actual RPV indications is consistent with the RCA result that they are caused by agglomerates and conglomerates of Al_2O_3 inclusions, which are not ideal reflectors.

Within this context, Axpo further discussed scenarios where the inclusion morphology might preclude detection by UT. Of primary interest in this context are large planar flaws, tilted with a significant angle. However, none of the destructive tests on the Replica C have revealed such flaws (see Chapter 2.4). Axpo stated that in agreement with the RCA, the forging process should exclude the formation of such difficult-to-detect, strongly tilted, continuous large flaws. With respect to conglomerates, a tilt does not affect their detectability because the single agglomerates themselves are detectable /50/.

ENSI Review

ENSI confirms that the influence of the reflectivity of UT indications on the detection and sizing of the flaws is adequately addressed in the SC. It is plausible that any large planar flaws significantly tilted with respect to laminar Al_2O_3 agglomerates and conglomerates would have been reported.

2.3.3 Shadowing effect of neighbouring indications

Safety case description

The potential shadowing effect of super-imposed reflectors was studied by Axpo experimentally as well as by means of simulations /57/.

No measurable drops were observed in the signal from the reflection at the back wall of the RPV or of the Replica C. In total 33 measured configurations were numerically analysed, in which shadowing could be suspected, i.e. configurations of indications with identical X and Y coordinates, but with different depth Z. It was observed that the number of cases for which the amplitude of the smaller-depth indications was lower than the amplitude of the larger-depth indications, was about the same as the number of cases for which the opposite was true. If shadowing were relevant, it would most likely result in the larger-depth indications being statistically lower in amplitude than the smaller-depth indications. This was however not observed.

Axpo concluded that shadowing is not a significant effect because of the discontinuous morphology of the oxide conglomerates. . This morphology allows much of the ultrasound to go right through the conglomerates. Therefore shadowing does not need to be further considered.

ENSI review

ENSI confirms that no significant shadowing effect was observed experimentally and that the detailed ultrasonic modelling supports this observation. Only very small indications close to the reporting threshold and only within areas of very high densities may have been missed. An UT shadowing effect is therefore negligible /50/, /57/.

2.3.4 Cladding effects

Safety case description

Axpo discussed the influence of the cladding on the detection and sizing capability. The Intercontrôle UT procedure /89/ defines for the 0° MER longitudinal wave probe a gain of 6 dB to compensate the attenuation of the cladding. Axpo stated that a value of 6 dB is in line with practices found in the literature for this type of cladding and measurement configuration.

Because the RPV is cladded and most parts of the Replica C were not, the effects of the cladding on the measured UT signals must be assessed. Also, Intercontrôle’s reference block (with 2 mm side-drilled-hole as reference flaw) is not cladded. The determination of the cladding effects was conducted by cladding a small part of the Replica C and by comparing the amplitude and sizing results before and after cladding and by comparing the differences for a statistically number of indications /55/.

For estimating the influence on the amplitude, a total of 369 indications were considered for the MER probe and 45 indications for the 45°SW techniques. In order to estimate the influence on the sizing performance with the MER probe 53 indications were considered.

On the basis of the comparison of the results of UT measurements with and without cladding, Axpo concluded that the average influence of the cladding on the amplitude for the LW MER probe is properly taken into account by an additional gain of +6 dB.

ENSI review

ENSI confirms that the influence of the cladding on the detection and sizing of the flaws is adequately addressed in the SC.

2.4 UT procedure validation

Axpo inspected the Beznau-1 RPV shells with an ultrasonic procedure formally qualified for hydrogen flakes /89/. The RCA (see Chapter 3) showed that the UT indications are caused by agglomerates of Al_2O_3 inclusions and not by hydrogen flakes. No qualified UT method existed for this kind of flaws. Therefore, a validation was required to confirm that the applied UT inspection procedure was able to adequately detect and size the agglomerates of Al_2O_3 inclusions /32/, /82/.

2.4.1 Detection capacity

Safety case description

No structural flaw was predefined for the UT validation. The size of aluminium oxide agglomerates ranges from a few micrometres up to several millimetres. The objective of the validation of the detection capability of the UT procedure was to determine the minimal flaw size that could be detected with a high reliability applying a reporting threshold of REF-24 dB /50/.

The validation process relied on examinations of selected blocks of the Replica C (see Chapter 3.2). The replica blocks were inspected with the same UT system (Intercontrôle - CIVAMIS) as the one applied for the inspection of the extended areas of the RPV shells /89/.

Axpo performed comprehensive studies to correlate the indications detected by UT with metallographic findings in the specimens. At first, Axpo correlated the Al_2O_3 agglomerates visible on fracture surfaces of broken C(T) specimens with UT indications above the reporting threshold /50/. Only a limited correlation was found for significant number of samples /69/. Several factors were discussed that prevented the results of this direct correlation from being quantitatively considered for the validation process /59/, /60/They included the accuracy of superimposing the test specimen with the position of the UT indication, the influence of the deformation of the fracture surface during the test and the coalescing of neighbouring agglomerates on the surface.

The validation results were therefore subsequently based on the destructive metallographic evaluation on a cube of size 30 x 30 x 30 mm^3 containing an zone with high density of UT indications /50/, /113/. A series of incremental metallographic cross sections with 0.5 mm spacing were prepared from this cube. This procedure ensured a precise correlation of UT findings and metallographic results.

Axpo developed a qualitative red-orange-green coding system to characterize and size the metallographic findings /50/. Findings with high inclusion density are labelled red indications and called agglomerates. Findings with medium inclusion density separated by the steel matrix are labelled orange indications and called conglomerates. Finally lines of small inclusions separated by the steel matrix are isolated conglomerates and labelled green.

Based on this approach, a systematic assessment of the large amount of metallographic results was performed using an automated area-based image processing tool. Some results were manually adjusted if required.

133 red-coded features were observed in the 61 metallographic cross sections and 99 UT indications were reported in the 30x30x30 mm^3 volume. A correlation between the UT indications and the superimposed metallography images was then established in a very detailed study.

It was shown that red conglomerates with a length > 2 mm could be reliably detected. Considering a forging ratio in X (axial) and Y (circumferential), the detection capability corresponds to an area of around 1 mm^2

Axpo compared and validated the stated detection capability with comprehensive UT modelling results as well as with actual measurements on defined reflectors (side-drilled-holes SDH and flat-bottom holes FBH).

Axpo demonstrated that the applied UT threshold of REF-24 dB is close to practical technical limits and leads already to a diminishing sizing capability for the detected flaws. With a reporting level of REF-24 dB the inspection data still has enough “headroom” with respect to the noise level off approx. REF-36 dB.

Reducing the UT reporting threshold will increase the number of reported very small flaws of the same nature and the number of possible false UT calls due to acoustic interactions. Axpo stated therefore, that the applied UT threshold had been well chosen. Taking into account the results of the material testing programme, the chosen threshold is suitable and does not limit the results of the structural integrity assessment.

ENSI review

ENSI had requested a sound correlation between UT indications and metallographic findings. Based on the metallographic findings in a 30x30x30 mm^3 cube made out of replica material ENSI agrees with the main conclusion, that the Intercontrôle UT examination guarantees detection of red-coded conglomerates of Al_2O_3 inclusions with a length of at least 2 mm. For indications with a red-coded length below 2 mm, the rate of detection was about 60 %. Since the detectability of all red-coded indications was not influenced by their tilt, ENSI also agrees with the statement by Axpo that tilt is not an issue in the present case.

ENSI recognises some inconsistencies in the documentation, which mainly relate to the utilisation of the semi-automated image processing used for characterising the multiple metallographic features in the cube. However, ENSI confirms that the key results of the validation are not affected or jeopardized.

The validation of the detection capacity was closely supervised and reviewed by SVTI and Vinçotte /171/, /172/.

ENSI confirms that the applied reporting threshold of REF-24dB is adequate for the depth range from 0 to 35mm.

2.4.2 Sizing accuracy

Safety case description

The UT sizing technique for the CIVACUVE and CIVAMIS inspection data is based on an echo-dynamic 6 dB approach. The sizing is starting from the maximum amplitude of an UT indication, the 6 dB drop is performed in all three directions (X, X, Z) defining the dimension of the 3D-UT box. The scanning step (measurement increment) is the limiting parameter: for the CIVAMIS inspection data it amounts to 1.1 mm in circumferential (X) direction and 1.2 mm in axial (Y) direction.

The sizing capability was validated by comparison of UT sizing measurements, with measurements on metallographic cross sections of test blocks taken from the Replica C. The validation was further supported by extensive UT modelling studies /50/, /122/.

Based on the validation results, Axpo stated that a conservative and reliable sizing of the oxide agglomerates can be demonstrated. The sizes of agglomerates larger than the beam size can be reliability determined by the 6 dB drop method; smaller agglomerates will be sized to the dimension of the beam size of approximately 4 mm.

Axpo stated that the theoretical maximum under-sizing error could be 2 scanning increments considering a continuous reflector. But the individual reflectors that cause the reflections are significantly smaller than the UT size determined by the 6 dB drop method. Therefore, the 6 dB drop leads to a consistent oversizing of the mostly discontinuous agglomerates.

ENSI review

ENSI confirms that the sizing of the aluminium oxide agglomerates with the 6 dB drop approach is generally conservative. This was demonstrated by a detailed comparison of the UT size with the metallographically determined size in cross section of selected specimens of the Replica C. The results indicate a systematic oversizing for most indications when applying the 6 dB drop method.

ENSI agrees with Axpo that for the large majority of indications the possible effect of an under-sizing error of two increments can be neglected. This general statement was also confirmed by the IRP and TSOs.

The sizing of the indications was validated for isolated flaws and the procedures are accepted to cover all isolated flaws detected in Shell C /171/, /172/. However, the validation does not cover dense groups of HAI, as present in three areas in Shell C. According to /172/ dense groups of HAI might potentially be undersized. For such groups a more conservative sizing method based on a local noise drop down to -12dB is considered to be more adequate.

The sizing issue was addressed by Axpo with an additional data review /205/. A dense group of HAIs in EA600 in Shell C was conservatively modelled as a crack enveloping all the indications of the group and assessed by a SIA.

2.5 Stability of flaws

Safety case description

The RCA demonstrated that the UT indications detected in 2015 were caused by manufacturing-induced alumina agglomerates. Axpo carried out a literature review of potential damage mechanisms that may lead to changes of the alumina inclusions and their agglomerates during operation. Axpo claims that fatigue damage due to thermo-mechanical loading is the only potential mechanism that may influence the inclusions. Referring to the root cause analysis, Axpo claims, that the stability of the flaws is independent from the accumulated neutron fluence and that there is no need for further UT testing of the base material of Shell C /27/.

ENSI review

ENSI confirms that low-cycle fatigue due to thermo-mechanical loading is the only potential mechanism that could lead to changes in the alumina inclusion agglomerates present in the Beznau-1 RPV and their surrounding matrix. Moreover, it is rather unlikely that the detected Al_2O_3 inclusion agglomerates in RPV Shell C will undergo modifications during operation.

As explained in Chapter 2.2 it cannot be completely ruled out that the observed HAI are caused by a dense concentration of agglomerates with cracked ligaments between them. ENSI therefore considers a follow-up UT inspection of the regions with UT indications to confirm stability of the HAI to be essential.

ENSI request

In 2022, Axpo has to repeat the UT inspections of the base material of RPV Shell C in the area of indications with amplitudes higher than REF-6 dB.

2.6 ENSI conclusions on the NDE of the RPV

Based on the data provided by Axpo, as well as the reviews and assessments of SVTI and Vinçotte, ENSI confirms that all relevant flaws in the RPV of Beznau-1 have been properly detected. The majority of them are of quasi-laminar character parallel to the inner surface of the RPW wall, with an average size comparable to the beam size. All relevant limiting factors of the UT inspections have been identified by Axpo and assessed accordingly. ENSI agrees with Axpo that on the basis of the results of the UT validation, the identified limiting factors can be neglected.

By correlating UT indications and metallographic findings in the replica material, Axpo demonstrated, that the detection limit of the UT examination is 2 mm for sufficiently dense inclusions and that the appropriate sizing procedures were used for the alumina agglomerates and the HAI.

To confirm stability of the detected HAI during operation, ENSI requests a follow-up UT inspection of the regions with HAI in 2022.

3 Origin, nature and root cause of the indications

3.1 Manufacturing review

Safety case description

The Beznau-1 RPV was manufactured by the Société des Forges et Ateliers du Creusot (SFAC), France, between 1965 and 1967.

A review of the manufacturing documents of the Beznau-1 RPV was carried out to verify code compliance and to identify indications for possible causes of the UT indications. Both Westinghouse and SFAC were involved in this process. The results of the manufacturing review are summarised in /81/, which contains a compilation of the process parameters with reference to material and process specification, as well as statements of compliance for each forging of the Beznau-1 RPV. Axpo concluded that the procedures and practices used during casting of the Beznau-1 RPV ingots were, at that time, state-of-the-art.

However, the peculiarities of the process parameters and their comparison to known measures to avoid certain types of imperfections suggested a higher probability for formation of non-metallic inclusions. This is particularly the case when reviewing the process parameters of Shell C (high ingot mould-height-to-diameter ratio, smaller piercing diameter /64/)., Curiously, the comment ‘air pouring’ was added in the record of Shell C /81/, while vacuum pouring is also mentioned on the same file page. Axpo claims that the comment of air pouring should be understood as an indication of a non-optimal vacuum quality. This possible deviation is important in the context of the RCAin Chapter 3.2.

Quality control was performed by ultrasonic inspections during and after manufacturing. The acceptance criteria for the back-wall response of ASME BPVC III.1 NB-2015 were met with a large margin. The review of manufacturing records of Beznau-1 RPV showed that for Shell C only one single volumetric defect was reported for stage III /81/, described as a “pin-point”. A comparison of the UT technique applied at that time with the technique used in 2015shows that the latter was more sensitive.

The fact that one Shell D of Beznau-2 RPV was rejected due to hydrogen flaking shows that SFAC was aware of the hydrogen flaking risk and that the UT inspection during manufacturing was capable of detecting hydrogen flakes. Axpo concludes that the manufacturing review confirmed the adequacy of the UT investigations performed during fabrication and that hydrogen flakes in the Beznau-1 RPV would have been detected by the applied UT technique.

ENSI review

Vacuum pouring and a sufficient ingot discard are required by ASTM Specification SA-508 in order to avoid the occurrence in the final forging of flaws, such as clusters of non-metallic inclusions. Several RPVs in France, Belgium, and Switzerland were recently tested with the same UT inspection technique as Beznau-1 RPV, showing no comparable UT indications. This observation confirms that the manufacturing practices based on steelmakers’ internal expertise around the time of the fabrication of the Beznau -1 RPV were able to prevent the formation of such clusters. Note, however, that the Beznau-1 RPV was one of the first vessels fabricated.

The manufacturing documentation confirms that the manufacturer of Beznau-1 RPV himself was aware of the need to discard a sufficient part of the segregated regions of the cast ingot. However, the UT indications from 2015 show that the zone with negative segregations at the bottom of the ingot was probably insufficiently cut out.

ENSI considers it reasonable to interpret some indications in the manufacturing documentation of the Beznau-1 RPV as deviations from the then best practices, which may have increased the probability for the presence of non-metallic inclusions in the final forging. This comment is particularly relevant for the fabrication parameters of Shell C

3.2 Root cause analysis

Safety case description

The objective of the RCA was to identify the origin of UT indications in the Beznau-1 RPV. The RCA focused on Shell C of the Beznau-1 RPV because it contains the highest number of UT indications, but its validity was also double-checked for the UT indications detected in the other shells.

At first, possible formation mechanisms, both during fabrication and service, of certain flaws causing the detected UT indications were screened /81/. The list of possible flaw formation mechanisms was reduced by excluding non-plausible formation mechanisms. Axpo summarises all possible formation mechanisms and provides specific reasons for excluding most of them /31/.

Formation of hydrogen flakes in positive macro-segregation zones, was excluded from the screening process. It was, however, assessed independently in more detail, because Doel-3 and Tihange-2 RPVs and the rejected Beznau-2 Shell D have shown that it was a probable defect formation mechanism at the time of manufacturing of these forgings. Furthermore, hydrogen flakes were the initial inspection target for the UT inspection performed on the Beznau-1 RPV in 2015.

The following supporting arguments were gathered from manufacturing documentation /81/, state-of-the-art knowledge about the metallurgy of large steel forgings /33/, /64/ and safety case investigations (Chapters 2, 4 and 5):

- The occurrence and characteristic spatial distribution of hydrogen flakes in the positive macro-segregation zones (A-segregations) of large cast ingots is different from the distribution of the detected UT indications in Beznau-1 RPV Shell C.
- The quality control process during manufacturing should have found hydrogen flakes. The same process was applied for Beznau-2 Shell D and led to its rejection because of the presence of this type of flaw.
- The hydrogen content measured at the beginning and end of the casting campaign of the Beznau-1 RPV shells was relatively low.
- A measured sulphur content of 0.011 wt-% together with a relatively low hydrogen content do not represent critical conditions for hydrogen flaking.
- Manufacturing documentation confirms a heat treatment tailored to prevent hydrogen flaking.
- The temperature of the forging during the manufacturing process was kept above the critical temperature for hydrogen flaking (>200 °C).
- Spatial and amplitude distribution of the UT indications differ from Doel-3, Tihange-2, and the rejected Beznau-2 RPV Shell D.
- Hydrogen flakes were found neither in the acceptance test Shell C material of the Beznau-1 RPV nor in the Replica C material.

Agglomerates of non-metallic inclusions were identified as the only likely cause for the UT indications. A detailed study was carried out to gather as much information as possible regarding the metallurgical knowledge about the formation of this type of flaws. Reports /29/, /59/ and /76/ provide background information regarding the formation mechanism of non-metallic inclusions and the theoretical metallurgical model to explain their occurrence in the sedimentation cone with negative segregations at the centre bottom of the ingot.

The following main arguments supporting the view that alumina inclusion agglomerates are at the origin of the detected UT indications were gathered from manufacturing documentation /81/, state-of-the-art knowledge about the metallurgy of large steel forgings /33/, /64/ and safety case investigations (Chapters 2, 4 and 5):

- Beznau-1 RPV material is an aluminium-killed steel (to deoxidise the steel) without any additional calcium treatment.

- High ingot mould-height-to-diameter ratio for Shells C, B and the different Shell E forgings (all with UT indications) compared to Shell D (without UT indications).
- Smaller piercing diameter for Shells C, B and different Shell E forgings (all with UT indications) compared to flange A and Shell D (without UT indications).
- Possible degradation of vacuum during ingot pouring of Shell C and, because of this, late addition of aluminium and low steel pouring temperature.
- Confirmation of alumina inclusion agglomerates as origin of UT indications in the Replica C (comparable to Shell C Beznau-1 RPV).
- Occurrence of alumina inclusion agglomerates in a zone with partially negative segregations (measurement of lower carbon content).

Axpo stated that there is no record that the bottom of Shell C with higher number of UT indications is also the bottom of the original ingot. Invoking the results of the Replica C investigations, Axpo concluded that alumina inclusion agglomerates in a density present in Shell C can only be located at the bottom of the ingot.

The RCA of Shell C applies for all shells. Especially the spatial distribution of the UT indications in Shell B is very similar to the distribution Shell C, but the number of indications is much lower /31/. The size distributions of UT indications in Shells B, C and E are very similar, which strongly suggests that the origin of UT indications for these three shells is the same.

Nevertheless, Shell E is discussed in detail in the RCA because of its different manufacturing process. The manufacturing documentation states that Shell E1 containing the highest amount of UT indications (among the three E shells) was taken from the middle of the ingot. This location does not coincide with the negative sedimentation cone. Axpo explained this discrepancy with the fact that the blanks of Shells E1 and E3, which have the same size, were switched during hot cutting /31/. Therefore, Axpo assumed that the original blank positions from the metallurgical top of the ingot were E2, E3, E1.

ENSI review

Axpo assessed all plausible root causes of imperfections that might arise in RPVs during fabrication (casting, forging, heat treatment, cladding) or during service, in analogy to the safety case for Doel-3 and Tihange-2 /84/. Axpo narrowed down the possible origin of the UT indications by eliminating the vast majority of potential imperfections with a reasonable degree of certainty. This screening process took into account the specific characteristics of UT indications of the Beznau-1 RPV, the manufacturing review, and state-of-the-art knowledge about the metallurgy of large steel forgings.

In view of the arguments provided, ENSI considers it plausible that the UT indications are caused by alumina inclusion agglomerates originating from the sedimentation cone at the centre bottom of the ingot.

ENSI also considers it plausible that the bottom of Shell C with higher amount of UT indications was also the bottom of the original ingot /64/, /82/. Report /64/ indicates that the centre bottom of large ingot is a preferential location for non-metallic inclusions, which is not the case for the centre top of the ingot.

The results from other shells with UT indications (Shells B, C and E) show a similar pattern of UT indications, which is evidence for the same root cause. However, ENSI acknowledges the need to analyse the UT indications of Shell E in the structural integrity assessment, because of the uncertainties in the process of fabrication and testing for this shell (see Chapter 6.2.3).

3.3 Confirmation of the root cause by the Replica C

Safety case description

Axpo concluded in the RCA that the UT indications in the Beznau-1 RPV are caused by agglomerates of alumina inclusions originating in the sedimentation cone with negative segregations at the bottom of the ingot. To confirm this conclusion Axpo decided to fabricate a replica of Shell C.

A detailed UT characterisation of selected Replica C segments containing UT indications was performed with the same UT equipment and technique used for Beznau-1 RPV Shell C. Axpo concluded that the UT indications found in the Replica C are comparable with the UT indications found in the Beznau-1 RPV with respect to spatial distribution, amplitude response spectrum, density and size.

In the UT validation process, the UT indications of Replica C were correlated with the corresponding findings in the metallographic investigations. It was found that the UT indications are caused by agglomerates of inclusions of millimetre size scale. Micro-chemical energy dispersive X-ray (EDX) analyses demonstrated that the agglomerates consist of alumina inclusions, some of which were partly removed during the preparation of the test specimens.

Invoking the findings of the Replica C investigation /82/ as evidence and confirmation, Axpo concluded that agglomerates of alumina inclusions are the origin of the detected UT indications in the Shells B, C and E of the Beznau-1 RPV.

ENSI review

Although the RCA assumptions of Axpo were reasonable for ENSI, an experimental confirmation of the RCA was required. With the fabrication of a replica for Shell C, Axpo succeeded in the reproduction of the expected type of flaws in the relevant lower part of the shell. The characteristics of the UT indications obtained with the same UT equipment and technique in Shell C and Replica C turned out to be very similar.

Taking into account the tailored modifications in the replica fabrication process (ingot piercing, bottom cropping and final machining process) ENSI considers it plausible, that Replica C contains more residual material with the expected type of inclusions.

On the strength of the following findings in the Replica C investigation, ENSI agrees that the RCA is confirmed:

- The UT indications in the Replica C and the affected RPV shells are comparable in size, amplitude, location and density distributions and consistent with the RCA result.
- Al_2O_3 inclusion agglomerates and conglomerates were identified as the source of the measured UT responses in the Replica C. The UT characteristics match the morphology of the alumina inclusion agglomerates.
- When the unremoved 30 mm thick layer of the Replica C (no machining of the inner layer) is taken into account, the radial (Z) location of the UT indications is comparable to the location in Shell C.
- No hydrogen flakes or other type of flaws were found in the Replica C.
- Multiple manganese sulphide inclusions were identified on the micrographs, which, however, did not produce any UT response. No other type of flaws was found in the metallographic and fractographic investigations, which could impact the RCA.
- The measured carbon content of the zone with UT indications is slightly lower than that of zone without indications. This observation confirms the assumption that the alumina inclusion agglomerates causing the UT indications are embedded in a zone of partially negative segregation.
- The microstructure, the local chemical composition and the measured mechanical properties for the matrix around the alumina agglomerates do not show any particularities (see Chapter 5).

3.4 ENSI conclusions on the root cause analysis

ENSI agrees with the procedure Axpo adopted for the RCA. Axpo performed a screening and assessment of all plausible root causes for the UT indications. Based on this assessment, Axpo was able to identify non-metallic inclusions as the most likely origin of the UT indications The Axpo assessment and results are conclusive for ENSI.

Referring to the arguments provided by the investigations of Replica C, ENSI confirms that the UT indications detected in 2015 are caused by agglomerates of alumina inclusions originating from the sedimentation cone at the centre bottom of the ingot.

4 Representativeness of Replica C

4.1 Replica C manufacture, composition and material properties

Safety case description

Replica C was produced by Sheffield Forgemasters (SFEL) in summer 2016 on the basis of the manufacturing documentation for Beznau-1 RPV Shell C and of recommendations of participating experts. The Replica C fabrication aimed at reproducing in sufficient quantity the same type of UT indications in the same ingot zone as observed in Shell C.

The replica fabrication procedure at SFEL followed as closely as possible the practice used by Le Creusot in 1965-1967 for the manufacturing of the Beznau-1 RPV Shell C. It goes without saying that this older fabrication practice does not reflect today's SFEL standard fabrication processes /33/.

Specific casting process parameters (low casting temperature, lower vacuum quality, late addition of aluminium) obtained from the manufacturing documentation were taken into account. In addition, contrary to modern practice, no argon shielding was used during the transfers of molten steel between ladles, which resulted in an increased oxygen level in the steel.

The only major deliberate deviations from the Le Creusot practice of the 60s concerned the piercing (solid instead of hollow punch) and cropping of the ingot, as well as the final machining of the inner surface of the ring. The reason for these deviations was to increase the probability for the occurrence of zones with the predicted type of flaws in the ingot /66/.

Comparison of process parameters from the Replica C and from RPV Shell C provides evidence that a close match was achieved regarding chemical composition, ingot dimension, casting process, top discard, ingot weight, amounts of work put into the material during hot forming and the primary and quality heat treatments /33/.

Metallographic images of the Replica C exhibit a homogenous ferritic-bainitic microstructure comparable to the microstructure found in the acceptance test ring of the Beznau-1 RPV Shell C. This is the case for the base material and the matrix material around the alumina agglomerates. According to the RCA, alumina inclusion agglomerates originate in the sedimentation cone with negative segregations at the bottom of the ingot. This conclusion is confirmed by the measurement in Replica C of a slightly lower carbon content for the matrix around the alumina inclusion agglomerates (see also 3.3).

The base material properties of the Replica C were tested at three different positions from the top of the ring. The test specimens were taken from the T/4 thickness position. The mechanical properties were compared to the properties obtained for the acceptance test ring of the Beznau-1 RPV Shell C /33/:

- The yield and tensile strengths of Replica C material at room temperature are slightly higher but comparable to those of the RPV Shell C material:
- The toughness is characterised by the Fracture Appearance Transition Temperature curve (FATT) derived from Charpy tests. Both the Replica C and the RPV Shell C show similar material toughness.

Axpo concluded that the Replica C is representative of the RPV Shell C with regard to the chemical composition, microstructure und material properties.

ENSI review

The fabrication process of Replica C was tailored to reproduce the properties of Shell C as closely as possible. Modified ingot piercing (solid instead of hollow), less cropping and no final machining of the inner surface aimed to leave a sufficient quantity of the predicted type of flaws in the replica.

ENSI considers the fabrication of the representative Replica C as a key element of the Safety Case. The conclusions given in the RCA were confirmed by metallographic investigations on the Replica C material and by mechanical testing.

ENSI accepts the claims related to the representativeness of Replica C for RPV Shell C in terms of chemical composition, microstructure and material properties.

4.2 UT indications in Replica C

Safety Case description

The size and spatial distributions of the UT indications in Shell C and Replica C are very similar. The amplitude distribution for most indications within Shell C is in the range of REF-18 to REF-24 dB. Most indications in the Replica C inspection data show a comparable amplitude distribution if a cladding attenuation of 6 dB is applied to data from the un-cladded blocks of Replica C /59/.

However, the depth distribution of the UT indications is different. Most of the indications in the Replica C are located within the first 50 mm from the inner surface (maximum depth approximately 100 mm), whereas in Shell C, the majority of indications are within 30 mm of inner surface (with a maximum depth of approximately 50 mm). Axpo explains this difference with the different piercing method used in the production of the Replica C and differences in the machining procedure.

ENSI review

Considering the comparable amplitudes, sizes, and spatial distribution of the UT indications in Replica C and RPV Shell C material, ENSI accepts the main conclusion drawn by Axpo regarding the UT representativeness of the Replica C.

4.3 Representativeness of test specimens

Safety Case description

The Replica C material was divided into 10 test blocks. Two blocks were partly cladded for further evaluation of the cladding influence and three blocks were selected for machining of specimens for mechanical and fracture tests. Within these three blocks, several zones were identified as being comparable to the leading zones in the RPV Shell C. The positioning and machining of samples was supervised by a TSO on behalf of SVTI/ENSI.

Axpo documented a comprehensive comparison to demonstrate that the location of the machined test specimens within the Replica C are sufficiently representative to cover the most significant indications in the RPV Shell C /151/. For this comparison, the cumulated C-Scan images of the test specimens were compared with the C-Scan image of the RPV with identical cumulated thickness. The absence of cladding on the replica was accounted for and a Distance Amplitude Correction (DAC) was applied as well.

For qualitative comparison, five severity categories A to E were defined by Axpo. The categories correspond to increasing inclusion density and simultaneously increasing UT amplitude. Axpo concluded that the selected specimen set is representative for a broad range of combinations of densities and amplitudes so that the specimens are suitable for investigating the mechanical properties of the steel matrix.

Furthermore, the appearance of sub-threshold indications in both RPV Shell C and Replica C was compared using suitable C-Scans. For all severity categories, a sufficient number of counterparts were identified in the Replica C /150/ /203/. Axpo states that category E indications (corresponding to HAI with amplitudes ≥ REF-6 dB) are not covered conservatively by the samples tested and need to be assessed separately. Therefore, their acceptability was assessed by means of a SIA (see Chapter 6.2.2).

ENSI review

Axpo started to assess the representativeness of Replica C on the basis of various definitions of the global and local densities of UT indications. ENSI didn’t accept this inclusion density based approach and therefore requested a comprehensive documentation in order to demonstrate that the relevant UT indications in RPV Shell C were covered by the selected test specimens. This documentation was finalised in December 2017 /150/ and demonstrated the overall representativeness of the test specimens taken from Replica C material.

The assessment of the representativeness of Replica C based on the five categories A to E of indications is a robust engineering tool, which allows to select test specimens from Replica C to characterize indirectly different areas of the RPV Shell C. The comprehensive documentation for each test specimen visualizes the position of the UT indications and compares them to a corresponding category in the RPV Shell C.

In addition, ENSI requested a verification of the actual position of the test specimens with a measurement of the location, number and size of inclusions on the fracture surface of each test specimen (Chapter 5).

Taking into account the additional tests conducted by Axpo in 2017, ENSI confirms that all categories A to D are well represented in the test specimens. The notable exception is category E, which essentially corresponds to HAI. Axpo demonstrated that HAI were present in a small number of specimens, but not in locations where they might influence fracture. ENSI agrees with Axpo that areas of HAI are not fully covered by the mechanical testing programme and need to be addressed by the SIA (see Chapter 7.2.2).

4.4 ENSI conclusions on the representativeness of Replica C

The fabrication of Replica C aimed at reproducing the same type of UT indications as found in Shell C. It was based on the process used by Le Creusot in 1965-1967 for the manufacturing of the Beznau-1 RPV.

All relevant NDE and mechanical testing steps related to Replica C were supervised by TSO on behalf of ENSI. The supervision covered the NDE data acquisition on Replica C, sampling and machining of tests specimens, and performance of the mechanical tests.

ENSI confirms that Replica C is representative of RPV Shell C with respect to chemical composition, microstructure and material properties.

The amplitude, size, and density distributions of the UT indications in Replica C and RPV Shell C are very similar. Replica C material is therefore suitable for validating the UT procedure used to characterize RPV Shell C.

Moreover, ENSI confirms, that the locations of test specimens machined from Replica C are sufficiently representative to cover all indications, except the HAI in the RPV Shell C, which were hence addressed separately with a fracture mechanics approach in the structural integrity assessment.

5 Material properties

Manufacturing process, material properties, chemical composition, material tests (drop weight, Charpy, tensile) and the surveillance program of the Beznau-1 RPV materials are documented in /92/. The main results of the surveillance program are summarised in Chapter 3.8.7 of the Safety Case (full version) /31/ and in Chapter 7.1 of the Summary Report SIA /34/.

The forgings of the Beznau-1 RPV are made from MnMoNi-Steel 1.2 MD 07, which is essentially equivalent to SA-508 steel, grade 3, class 1 (earlier: SA-508 class 3). The weld deposit of the submerged-arc welded joint between forged Shells C and D are made with a SAF-UM-40 wire (4 mm) and Linde-709-5 powder.

5.1 Hardness and Chemical Composition

5.1.1 RPV Shell C

Safety case description

In addition to the existing surveillance program, Axpo performed metallographic examinations on unirradiated and irradiated specimens of the acceptance test Shell C material. Results are summarised in /94/. The examination was performed on 12 broken C(T)-25 mm specimens. Additionally, UT and hardness measurements were carried out. The same inclusion types, shapes, and orientations were found in all examined specimens. Mainly three different types of non-metallic inclusions were observed: elongated MnS inclusions, elongated Al_2O_3 inclusions, and a combination of MnS inclusions, Ca and fine globular Al_2O_3 inclusions. All specimens showed a homogeneous distribution of inclusions and the average inclusion content was in the range of 0.13 % to 0.45 % volume fraction. The sulphide inclusion lines have a maximum length of 0.93 mm and the alumina inclusion lines of 0.90 mm.

Furthermore, at the broken halves of the C(T) specimens no significant UT indications were found. However, no material pieces were available from the inner surface area of the acceptance test Shell C material, which would be representative of the area where most of the UT indications inside the Beznau-1 Shell C were found. The results of hardness measurements showed comparable values of 197 HV5 up to 243 HV5 in all positions. These values are typical for the low-alloy RPV steel 1.2MD07. Axpo noted that all of these observations are reflected in the material behaviour determined during previous mechanical testing.

ENSI review

Metallographic investigations and Vickers hardness measurements on the acceptance test Shell C material show that the presence of non-metallic inclusions and the distribution of hardness values are typical for low-alloy RPV steels. The maximum length of MnS and Al_2O_3 inclusion lines is 0.93 mm. No Al_2O_3 inclusion agglomerates were found. ENSI agrees that the results of the additional metallographic investigations on specimens of the acceptance test Shell C material are consistent with the results of the previous mechanical testing documented in /92/.

6 Replica C

Safety case description

A large number of micro-hardness measurements (exceeding 800 on Replica C material alone, and more than 150 on RPV Shell C material) and extensive chemical analyses (Scanning Electron Microscopy SEM, SEM/EDX mapping, and 41 Spark Discharge Optical Emission Spectroscopy SD-OES measurements) were carried out on Replica C material /61/. The measurements cover regions around small and large inclusions and between inclusions, as well as regions at the edges of and near the Al_2O_3 inclusion agglomerates.

HV10 hardness was measured at different axial positions over the full thickness of the Replica C material. HV0.5 micro-hardness data were obtained near Al_2O_3 inclusion agglomerates and in the base material. At all axial positions, comparable hardness values ranging from 192 to 210 HV10 were measured over the complete thickness /61/. HV0.5 micro-hardness measurements were carried out between two separate positions with Al_2O_3 inclusion agglomerates. Micro-hardness values of 195 up to 213 HV0.5 were obtained /61/, which are in the same range as the HV10 hardness values. The chemical mapping investigations focused specifically on elements known to promote neutron embrittlement: Nickel, Copper and Phosphorus. No areas of significantly increased concentration of these or any other elements were observed in or near Al_2O_3 inclusion agglomerates. No significant amounts of trace elements such as Titanium, Vanadium, Chromium and Cobalt were detected anywhere in the investigated Replica C and surveillance material.

Neither the micro-hardness nor the chemical mappings show any anomalies. The chemical elements found in the vicinity and between the Al_2O_3 inclusion agglomerates are in full conformance with elements in the base material far away from the inclusion agglomerates and correspond to the specification for this type of steel. Axpo concluded that hardness values and chemical composition of the steel matrix near Al_2O_3 inclusion agglomerates are not significantly affected by the presence of the Al_2O_3 inclusions found in Replica C and RPV Shell C materials /61/.

ENSI review

No original Beznau archive material representative for the areas of the Beznau-1 RPV with UT indications was available. Available unirradiated material from the acceptance test Shell C and irradiated material from the surveillance capsules show a microstructure and hardness typical for low-alloy RPV steels, including presence of elongated Al_2O_3 and MnS inclusions with a maximum length up to 0.93 mm. For an assessment of material properties with Al_2O_3 agglomerates like the ones found in the Beznau-1 RPV, Replica C material was used.

Chemical analyses and hardness measurements were performed at different axial positions over the complete thickness of the Replica C material in areas with both small and large agglomerates of inclusions. There was no significant difference in hardness beyond the expected scatter range, for the results both with and without inclusions. At all investigated positions, EDX mapping revealed a homogeneous distribution of all elements of the base material, both in the vicinity of inclusions and away from inclusions. No dependence of the chemical composition and the hardness of the Replica C matrix material on the Al_2O_3 inclusion density was observed.

ENSI agrees that the measured hardness values in the Replica C material and the micro-hardness values in the ligament between Al_2O_3 inclusion agglomerates are typical for low-alloy RPV steels and are not influenced by the presence of these Al_2O_3 inclusion agglomerates. Similarly, the amounts of trace elements such as Titanium, Vanadium, Chromium, Cobalt, Nickel and Copper in the vicinity of inclusions is comparable to the concentrations in the base material and is typical of concentrations for low-alloy RPV steels.

6.1 Fracture toughness of unirradiated material

Fracture toughness expressed in terms of reference temperature RT_{ref} is the relevant material property for fracture mechanics assessments according to the ASME Code Section XI. To determine the reference temperature RT_{ref}, the Master Curve (MC) transition temperature T_0 is calculated using the standard MC method as prescribed in ASTM E1921-15a. The reference temperature $RT_{ref}(0)$ for the unirradiated condition is the basis for assessing material embrittlement using Guideline ENSI-B01 /165/ and US-NRC Regulatory Guideline 1.99 Rev. 2 /168/.

6.1.1 RPV Shell C

Safety case description

In 2009, in the process of the SIA for operation beyond 40 years, reference temperature T_0 was determined by means of Master Curve tests according to ASTM E 1921-09a. C(T)-25 mm specimens, C(T)-10 mm specimens and SE(B)-10 mm specimens (pre-cracked Charpy V notch specimens) were tested from the acceptance test Shell C and D material under the supervision of the German Authorized Inspection Body TÜV-Süd.

In all cases, the orientation was T-L. A large difference was found in the Master Curve reference temperature T_0 measured with C(T)-25 mm specimens tested in 2009 on the one hand, (T_0 = -35.5 °C) /92/ and the specimens extracted from the broken halves of these 25 mm specimens: C(T)-10 mm specimens (T_0= -81°C) /148/ and SE(B)-10 mm specimens (T_0= -91 °C) tested in 2012 /147/ on the other. The difference is so large that it cannot be explained as an effect of specimen size or type alone.

It is known that for thick-walled forgings local differences in fracture toughness may occur due to different heating and cooling rates during manufacturing (casting, forging, heat treatments). Since the value of the MC transition temperature of the C(T)-25 mm specimens taken from the centre of the acceptance Shell C material is relatively high (T_0 = -35.5 °C), a zone of lower fracture toughness should be assumed for the wall centre region. More precisely, it should be lower than the fracture toughness at the ¼ and ¾ depth positions, where the surveillance samples were taken.

The Beznau-1 RPV results were compared with data of international projects dealing with size effects in fracture mechanics. This comparison showed, that T_0 does not increase significantly as specimen thickness increases above 25 mm. Therefore, Axpo concluded, that the T_0 value determined with C(T)-25 mm specimens is conservative.

ENSI review

Shell C material shows indications of inhomogeneity of the fracture toughness depending on the position within the wall. However, the observed unusually large difference of about 45 °C between T_0 from the small and large C(T) specimens cannot be explained by this inhomogeneity.

Because of the unresolved issue of size effect on T_0 of the acceptance test Shell C material and the inhomogeneity of the fracture toughness, which is less pronounced when using large specimens raise questions as to what method for determining T_0 should be selected. In particular, the application of Method II-A of guideline ENSI-B01, which permits determination of T_0 from small SE(B)-10 mm (pre-cracked Charpy V notch) specimens is potentially not conservative.

On the basis of these considerations, ENSI agrees that the MC transition temperature T_0= -35.5 °C obtained from standard C(T)-25 mm specimens is conservative for the unirradiated conditions.

6.1.2 Replica C

Safety case description

Tests were performed on Replica C material to evaluate the possible influence of Al_2O_3 inclusions on fracture toughness and on the MC transition temperature T_0 in the ductile-to-brittle transition range. The influence was evaluated by testing C(T)-12.5 mm specimens both with and without Al_2O_3 inclusions. Tests were performed primarily in the T-L orientation, because this is the orientation of importance to the SIA. Additional testing in the L-T and S-L directions is carried out to cover all orientations. C(T)-25 mm tests in the T-L orientation at T_0+50K (T_0 being the reference temperature as obtained from the C(T)-12.5 mm specimens, and T_0+50K the upper limit for determination of T_0 in ASTM E1921) were performed in order to demonstrate the applicability of the Master Curve approach.

In total 130 C(T) specimens were tested. The results of all C(T)-12.5 mm specimens for all orientations are shown in Table 1 /61/.

Type T-L	**Number**	**T_0 [ºC]**	**SINTAP**
No inclusions	17	-80±6	IH
Inclusions < 2mm	16	-84±6	H
Inclusions ≥ 2mm	12	-85±7	H
All	45	-83±5	H
Type L-T	**Number**	**T_0 [ºC]**	**SINTAP**
No inclusions	7	-87±8	IH
Inclusions < 2mm	9	-92±7	H
Inclusions ≥ 2mm	15	-98±6	H
All	31	-94±5	H
Type S-L	**Number**	**T_0 [ºC]**	**SINTAP**
No inc. & inc. < 2mm	8	-59±8	H
Inclusions < 2mm	6	-63±8	H
Inclusions ≥ 2mm	16	-55±6	H
All	24	-56±5	H

Tab. 1: Summary of T_0 results based on various grouped C(T)-12.5 mm specimens in T-L, L-T and S-L orientation. IH = inhomogeneous, H = homogeneous

For the determination of T_0 in T-L orientation, 45 C(T) specimens were extracted from Replica C material. The data was analysed using the standard MC method to determine the transition temperature T_0 for different sets, characterized by the size of inclusions in the process zone at the fracture surface. All sets show T_0 values within a ±2.5 ºC deviation. The statistical uncertainty (1σ) is on the order of 5 ºC. Thus, the average toughness is the same in all cases, with a 95 % confidence level. The data does not indicate any systematic effects of the Al_2O_3 inclusions on the fracture toughness.

The standard MC method ASTM E1921 was developed for macroscopically homogeneous data sets. The SINTAP method /188/ provides a screening criterion to determine when the data set may be representative of a macroscopically inhomogeneous material. Table 1 indicates that the SINTAP screening criterion does not detect an inhomogeneity in sets with inclusions, whereas an inhomogeneity can be detected in the data without inclusions.

Steel forgings are known to exhibit inhomogeneity in their material properties as a function of depth. As the aim of the testing program was to obtain results for materials with Al_2O_3 inclusions, specimens were taken from a range of depth of the Replica C, resulting in a large depth variation. In order to thoroughly examine the effect of the specimens' extraction position, the C(T)-12.5 mm data was sorted according to distance from the inner surface of the Replica C ring. The data do not indicate a lower toughness of the material with Al_2O_3 inclusions compared to the matrix. If this effect existed, the data for specimens with inclusions should be scattered around to lower mean values compared to specimens with no inclusions. This is not the case, however. With the exception of the layer closest to the inner surface, the other layers display homogeneous material behaviour and a slightly decreasing toughness with increasing depth.

For the L-T orientation 31 C(T) specimens were tested. The reference temperature T_0 decreases slightly for specimens with small and large inclusions, but is still similar for all data sets. Thus, the presence in the fracture surface of alumina inclusions in the process zone and their size have no negative effect on T_0 determined by standard MC analysis. Only the set without inclusions shows a strong inhomogeneity, which is probably a depth effect similar to the effect observed for the T-L specimens. The Al_2O_3 inclusions have no negative effect on T_0. As is normally the case for forgings, the results demonstrate that specimens in the T-L orientation have a lower fracture toughness than those in the L-T orientation.

For the S-L orientation 24 C(T) specimens were tested. Because only two specimens without inclusions were found, the T_0 for the set without inclusions could not be statistically evaluated. Instead, the sets without inclusions and with small inclusions were grouped together into one set. No inhomogeneity in the data sets is observed in Table 1. The reference temperature T_0 is similar for both data sets, thus the existence and size of inclusions in the process zone has no influence on T_0 determined by standard MC analysis.

100 C(T) fracture toughness tests were performed in the transition range on Replica C material with Al_2O_3 inclusions in the process zone; 55 with small inclusions and 45 with large inclusions. Al_2O_3 inclusions did not initiate cleavage fracture in any of these specimens, as shown by fractographic investigations /61/. Most of the specimens examined showed crack initiation sites macroscopically far away from Al_2O_3 inclusions. However, in some specimens, the crack initiation sites were located in the area of Al_2O_3 inclusions. At higher magnification the SEM revealed that ductile fracture features are present in the area of Al_2O_3 inclusions but that the microscopic crack initiation sites are located in the area of cleavage fracture at a certain distance from the inclusions /61/.

Cleavage fracture of low-alloy RPV steels is generally initiated at carbides. In RPV steels, titanium carbo-nitrides as well as small isolated MnS inclusions can also be found at the initiation sites. When the MnS inclusions are gathered into clusters, they can affect the cleavage fracture by acting as stress concentrations favouring cleavage initiation in their vicinity. In the specimens from Replica C, both small isolated MnS inclusions and large elongated MnS inclusions were found in the area of crack initiation sites on the fracture surface of specimens with both high and low fracture toughness values /61/. This confirms that these microstructural features did not influence the statistical distribution of the measured fracture toughness values. Titanium carbo-nitrides were not found in the Replica C specimens.

Axpo concluded from the fractographic investigations that Al_2O_3 inclusions do not promote crack initiation. Crack initiation sites do not coincide with alumina inclusions as demonstrated by SEM observations.

Additional fracture toughness tests were performed at higher temperatures in the ductile-to-brittle transition region. Three series (each consisting of 10 specimens) of C(T)-25 mm specimens in T-L orientation were tested at a temperature of -30 ºC (T_0+50 ºC). The objective of these tests was to validate both the C(T)-12.5 mm results and the applicability of the MC methodology.

The results of the standard MC analysis are shown in Table 2 /61/. Because only 4 specimens without inclusions were available, their results were combined with those for specimens with small inclusions.

Type T-L	**Number**	**T_0 [ºC]**	**SINTAP**
No inc. & inc < 2mm	18	-60±6	H
Inclusions < 2mm	14	-62±6	H
Inclusions ≥ 2mm	12	-72±7	IH
all	30	-66±5	IH

Tab. 2: Summary of T_0 results based on various grouped C(T)-25 mm specimens at -30 ºC in T-L orientation. IH = inhomogeneous, H = homogeneous

The MC transition temperature values T_0 has a scatter of ±6ºC. Based on the standard MC analysis, no negative effect of the Al_2O_3 inclusions and Al_2O_3 inclusion agglomerates on the MC transition temperature was identified. This observation verifies the C(T)-12.5 mm results.

The SINTAP criterion indicates that the data set with small inclusions is homogeneous, but the data set with large inclusions is inhomogeneous. The main difference is that the large inclusion data set shows a larger scatter /61/. Three fracture toughness values fall below the standard 2 % MC and this behaviour was assumed to indicate strong inhomogeneity.

Axpo performed a special analysis to investigate the material behaviour of these three specimens with low toughness values. The results are given in /155/. The detailed fractographic examination generally showed the same cleavage fracture characteristics in the area of crack initiation without any anomalies when compared to the other specimens with higher fracture toughness. Fracture initiation occurred predominantly at carbides, mainly grain boundary carbides. The hardness measurements, microstructural characterization, and chemical analysis showed that in the investigated positions a homogeneous macrostructure is present in the Replica C, without the presence of pronounced macro-segregations. Based on a literature survey, Axpo concluded that it is not unusual that fracture toughness data points fall below the 2 % failure probability curve of the MC and such a deviation does not rule out the application of test standard ASTM E1921.

Based on the results of all 130 fracture toughness tests Axpo finally claimed that there is no negative effect of Al_2O_3 inclusions and Al_2O_3 inclusion agglomerates on the brittle fracture toughness. Fractographic investigations showed that cleavage fracture characteristics are present in all specimens and that the presence of Al_2O_3 inclusion agglomerates on the fracture surface and in the fracture process zones has no influence on fracture toughness and crack initiation. Inhomogeneity was observed for some data sets, though this was shown to be unrelated to the Al_2O_3 inclusions but rather due to effects of the position of the specimens along the depth of the Replica C thickness and to statistical uncertainties.

ENSI review

In the first phase of fracture mechanics and microstructural investigations on the possible influence of agglomerates of Al_2O_3 inclusions on fracture toughness and MC transition temperature T_0, 10 specimens without UT indications, 10 specimens with high density of UT indications, and 10 specimens with a low density of UT indications were tested. Material testing was performed in T-L orientation. The measured T_0 values confirmed that agglomerates of Al_2O_3 inclusions do not have a significant effect on fracture toughness even at higher temperatures in the transition region. 10 additional C(T)-25 mm specimens with a low density of UT indications in T-L orientation were tested at -30 °C. The data points were in good agreement with the existing scatter band from the C(T)-12.5 mm specimens tested at temperatures up to -50 °C, but two data points fell below the 2 % failure probability curve. Microstructural investigation showed that fracture of these two specimens was not influenced by Al_2O_3 inclusions, even though Al_2O_3 inclusions were present on the fracture surface and at the initial fatigue crack front.

ENSI evaluated the safety case based on these investigations and concluded that the data base for the determination of the MC transition temperature T_0, including microstructural investigations, was too small to permit a reliable assessment of the impact on fracture toughness of agglomerates of Al_2O_3 inclusions in the fracture initiation region. By letter dated 21 December 2016 /178/, ENSI requested from Axpo that complementary material tests be carried out on Replica C material and that grouping criteria for samples be defined, based on features of the fracture surface in the process zone.

Subsequently, Axpo tested a large number of additional C(T) specimens and evaluated a total of 100 C(T)-12.5 mm specimens in T-L, L-T, and S-L orientation as well as 30 C(T)-25 mm specimens in T-L orientation. Axpo defined three groups of specimens, as follows:

- Group „large inclusions“: at least one Al_2O_3 inclusion agglomerate in the process zone with length equal to or exceeding 2 mm
- Group „small inclusions“: at least one Al_2O_3 inclusion agglomerate in the process zone with length between 0.1 mm and 2 mm

- Group „no inclusions“: no Al_2O_3 inclusion agglomerate in the process zone or none exceeding 0.1 mm in length

All tested specimens fell in either one of these groups.

Sample selection was performed in such a way as to ensure their representativeness in terms of density of UT indications and UT amplitude for the extended area EA600 of Beznau-1 RPV Shell C.. ENSI reviewed the representativeness of the samples and the validity of the criteria for grouping them for the fracture toughness assessment. It confirms the suitability of this approach for reliably investigating the impact of agglomerates of Al_2O_3 inclusions on fracture toughness and MC transition temperature T_0. HAI are not covered conservatively by the samples tested and are assessed separately, as already pointed out under 4.4.

In addition to the fracture mechanics tests, Axpo also significantly expanded microstructural investigations. The fracture surface investigations aimed at determining the type, number, and size of the non-metallic inclusions as well as the location of fracture initiation. Further comprehensive micro-hardness measurements and chemical investigations in regions around small and large inclusions and between inclusions, as well as in regions at the edges and in the vicinity of large agglomerates of Al_2O_3 inclusions were performed on Replica C material, to investigate potential changes of the microstructure effected by the agglomerates (see Section 5.1).

The results of these supplementary fracture mechanics and microstructural investigations performed in 2017 enabled Axpo to construct a simpler and more consistent safety case by proving that the essential material properties are not altered by the presence of the agglomerates of Al_2O_3 inclusions in comparison with the base material without agglomerates.

The evaluation of the tests with C(T)-12.5 mm specimens yielded the following values for the mean MC transition temperature T_0 for all samples with and without agglomerates of Al_2O_3 inclusion: -83 °C for the T-L orientation, -94 °C for the L-T orientation, and -56 °C for the S-L orientation, with a standard deviation of 5 °C for each mean value. There were no significant differences in T_0 for the data sets "no inclusions", "small inclusions" and "large inclusions"; the differences were equal to or less than the standard deviation. Orientations T-L and L-T showed a trend of slight decrease in T_0, i.e. an increase in fracture toughness, from samples without Al_2O_3 inclusions to ones with small inclusions and finally large inclusions. As expected, T_0 for the L-T orientation was smaller on average than T_0 for the T-L orientation, i.e., fracture toughness was higher and does not need any special consideration in the SIA.

In S-L orientation, the samples lie radially inside the vessel wall and the crack propagates in circumferential direction. As expected, the value for T_0 is higher than in T-L orientation. However, S-L toughness data are only needed for the assessment of findings in Shell E, because a mixed-mode load has to be taken into account there due to the conical shape of the forging rings.

The SINTAP procedure only indicated signs of inhomogeneity for the datasets without agglomerates of Al_2O_3 inclusions in the orientations T-L and L-T. It was assumed that this result was due to the different depths from which the samples were taken and not to the presence of agglomerates. Therefore, the agglomerates of Al_2O_3 inclusions do not preclude application of the standard MC method according to ASTM E1921.

The results presented by Axpo provided no indication that Al_2O_3 inclusion agglomerates affect the Master Curve transition temperature T_0. Results were strongly reinforced by examinations of the fracture surface of the tested Replica C(T) specimens. Cleavage initiation is primarily a critical stress controlled process, where stresses and strains acting on the material produce a local failure, which then develops into a dynamically propagating cleavage crack. Fractographic investigations on the Replica C specimens showed, that no case of crack initiation from an Al_2O_3 inclusion was observed.

Additional investigations of the C(T)-25 mm specimens in T-L orientation tested at the upper limit temperature for the MC method of -30 °C showed a mean value of T_0 = -66 °C ± 5 °C for all samples without and with Al_2O_3 inclusions. It lies 17 °C above the T_0 obtained for the smaller C(T)-12.5 mm specimens in T-L orientation. Thus, the Replica C material showed a size effect in the T_0 determination using MC similar to, although less pronounced that for Shell C material.

The inhomogeneity of the dataset for material with large inclusions was confirmed by the SINTAP criterion. It is probably due to the different positions along the wall thickness from which the samples were taken, since primarily areas with large UT amplitudes and UT indication densities were selected. However, the results for the C(T)-25 mm specimens also indicated that with large inclusions the T_0 values become smaller and the fracture toughness values larger. This trend confirms the result obtained from the smaller C(T)-12.5 mm specimens, i. e., the agglomerates of Al_2O_3 inclusion have no negative impact on fracture toughness, even at relatively high temperatures in the ductile-to-brittle transition region.

Three tests yielded low fracture toughness values lying below the 2 % MC failure probability curve. This result may be due to the higher variance of toughness values measured at higher test temperature in the transition range and to inhomogeneity of the material. Axpo carried out special fractographic investigations on these three material samples, which showed that crack initiation occurs on grain boundary carbides and that the mechanism thus does not differ from that in the other samples with higher fracture toughness. Agglomerates of Al_2O_3 inclusions present in the process zone have no effect on crack initiation in these samples.

In summary of its review of all Axpo fracture test results, ENSI confirms that the agglomerates of Al_2O_3 inclusions present in the Beznau-1 RPV do not significantly affect fracture toughness in the ductile-to-brittle transition regime.

6.2 Fracture toughness on the upper shelf

Safety case description

A total of 15 tests with C(T)-12.5 mm specimens in T-L orientation were performed according to ASTM E1820-15a at temperatures of 75 °C, 100 °C and 300 °C in order to determine the fracture toughness on the upper shelf. Results of these ductile fracture tests are documented in /109/.

Fractographic investigations showed that all specimens contain a significant number of inclusions in the process zone on the fracture surfaces. The fracture surface of 7 of these specimens contained large inclusion agglomerates of length up to 8.5 mm. However, the inclusions did not act as crack initiators. At 100 °C, the mean $K_{Jc0.2BL}$ value from specimens with large inclusions was 9 % lower than that for the specimens with the small inclusions. At 300 °C, the trend was reversed, with specimens with small inclusions showing a 10 % lower mean $K_{Jc0.2BL}$ value than the specimens with large inclusions. Axpo claims there is no significant effect of the inclusions on the fracture toughness on the upper shelf. Invoking the correlation between fracture toughness and Charpy Energy, one can then also conclude that the agglomerates of Al_2O_3 inclusions do not significantly affect the Charpy upper shelf energy.

ENSI review

Fracture toughness tests have been performed on Replica Shell C material from areas with different densities of inclusions at temperatures high enough to guarantee ductile fracture behaviour. Only small differences were found for the parameters characterizing ductile fracture initiation according to ASTM E1820-15a. The fracture process zones of the examined samples contained a significant number of inclusions, with sizes exceeding 2 mm in 7 samples and sizes between 0.1 mm and 2 mm in 8 samples. The fracture surfaces demonstrated ductile fracture behaviour between the agglomerates of Al_2O_3 inclusions. In all samples, the regions of crack initiation lied outside the agglomerates, which therefore do not significantly affect the fracture process.

ENSI accepts the conclusion of Axpo that the agglomerates of Al_20_3 inclusions found in the Beznau-1 RPV do not have a significant influence on fracture toughness in the ductile region. An equivalent conclusion can be derived for the Charpy upper shelf energy (USE).

6.3 Tensile properties

Safety case description

The first set of tensile tests was performed using small round tensile specimens with a 5 mm diameter over a wide range of temperatures (-196ºC to 300 ºC). Tensile specimens were manufactured from regions of Replica C material with different densities of inclusions. Results of these tests are given in /132/.

No significant effect of agglomerates of Al_2O_3 inclusions on yield strength ($R_{p0.2}$) and ultimate tensile strength (R_m) was observed, but ductility (elongation at maximum force A_g, and reduction of area Z) decreased with increasing inclusion density. Even with the lower inclusion density, A_g was reduced to below 10 % at both 23 °C and 300 °C. At these temperatures, Z for material with low inclusion content was 61 % and 32 % respectively, whereas for the material with a higher inclusion content, the Z values were 24 % and 6 %, respectively.

Because of these finding, additional tests were performed using standard tensile specimens with a diameter of 12.5 mm. Results are documented in /130/. The ductility values obtained with standard specimens satisfy the ASME materials specification (A_g >18 %, Z >38 %) even for a high density of inclusions and at 300 ºC.

Fractographic investigations of all tensile specimens showed that they contain a significant number of large inclusions at the fracture surface. The scatter of yield strength vs. number and maximum length of inclusions was analysed. The scatter was within the usual 5 % and no correlation was observed.

Axpo explains the low ductility measured with the small tensile specimens with the relatively high proportion of inclusions in the 5 mm specimens causing a strong stress triaxiality (notch effect). A FE simulation with a micromechanical model verified this behaviour. The area covered by inclusions in the fracture surface of 5 mm specimens was approximately 2 mm^2 (10 % of the specimen fracture area). The fracture surface contained up to 18 inclusions of a length of up to approximately 3 mm. Axpo claimed that the agglomerates of Al_2O_3 inclusions have no significant effect on the yield and ultimate strength. To achieve representative ductility values, larger specimens are required, which are not affected by local phenomena.

ENSI review

Tensile tests were performed at temperatures between -196 ºC and +30 using small 5 mm and standard 12.5 mm diameter specimens, both with and without UT indications. Axpo sho0ºC wed that the measured values of yield strength and ultimate tensile strength for both the 5 mm and 12.5 mm specimens are within the scatter band for all temperatures. The examination of fracture surface characteristics for the 5 mm and 12.5 mm tensile specimens tested at different temperatures and containing different inclusion sizes showed no significant influence of the Al_2O_3 inclusion agglomerates on the measured yield and tensile strengths.

The applicable ASME material specification requires ductility values of A_g (percentage elongation at maximum force) and Z (percentage reduction in cross section area) at room temperature to be larger than 18 % and 38 %, respectively. Axpo considered the low ductility values observed for the small tensile specimens at 23 °C and 300 °C as a structural effect. Specimens with a 5 mm diameter containing inclusions are not representative for the ductility because the ratio of area and size of inclusions to area and size of the specimen is so large that the stress field in the specimen is significantly affected by the inclusions. ENSI confirms that the influence of inclusions on the stress state is comparable to the notch effect and not due to a change in material properties. The fracture surface evaluation also confirms no change in the ductile fracture behaviour of the matrix between inclusions.

Additional tests were performed using standard tensile specimens with a diameter of 12.5 mm whose measured values of ductility satisfy the ASME requirements (A_g >18 %, Z >38 %) for all tested densities of inclusions and all temperatures.

In summary, ENSI confirms that agglomerates of Al_2O_3 inclusions present in the Beznau-1 RPV do not degrade the tensile properties of the RPV materials.

6.4 Fatigue crack growth rates

Safety case description

Because Al_2O_3 inclusions found in the Beznau-1 RPV are a result of the manufacturing process, Axpo carried out a literature review of potential damage mechanisms that may lead to changes to the shape and size of the alumina inclusions during operation. Axpo claimed that fatigue damage due to thermo-mechanical loading is the only potential mechanism that may influence the inclusions. Axpo estimated the effect of inclusions on fatigue crack growth from the fatigue pre-cracking data of the fracture toughness specimens taken from Replica C and acceptance test Shell C material /31/. The results for all samples were scattered around the fatigue crack growth curve given in ASME XI and there was no indication of an effect of the agglomerates of Al_2O_3 inclusions on the fatigue crack growth rates.

ENSI review

ENSI confirms that low-cycle fatigue due to thermo-mechanical loading is the only potential mechanism that could lead to changes in the agglomerates of Al_2O_3 inclusions present in the Beznau-1 RPV. As required in the design specification, Axpo considered a potential fatigue crack growth in the structural integrity assessment of the RPV.

The reference curve of ASME XI Appendix A for sub-surface flaws covers the fatigue crack growth rates evaluated from the fatigue pre-cracking procedure of the C(T) specimens. Comparison of specimens fabricated from Replica C material with and without inclusions and RPV acceptance test Shell C material reveals that there is no significant difference in the fatigue crack growth rates. Axpo explains the scatter of the measured data with underestimated ΔK values as result of the convex fatigue pre-cracking front, low resolution of the specimen crack length measurements, and the presence of large inclusions at the crack front.

ENSI confirms that the agglomerates of Al_2O_3 inclusions present in the Beznau-1 RPV do not significantly affect the fatigue crack growth rates.

6.5 Irradiation sensitivity

Mechanisms of irradiation embrittlement of low-alloy RPV steels are well understood. In the past, extensive research has been undertaken to investigate microstructural characteristics of embrittlement, to develop models and to provide databases. In comparison, there are only few investigations into the influence of non-metallic inclusions on irradiation embrittlement. This is because non-metallic inclusions are not bonded with the surrounding matrix and there is no doubt that non-metallic inclusions themselves are not subject to irradiation embrittlement.

Axpo carried out a literature review of irradiation damage in RPV steels with particular reference to alumina inclusions. This provided no reason to doubt the theoretical expectation that alumina inclusions would neither themselves be affected by irradiation, nor would influence the irradiation embrittlement of the surrounding steel matrix.

Neutron embrittlement of RPV steel becomes significant for neutron fluences exceeding 10^{17} cm^{-2} (E > 1 MeV). Increasing neutron fluence increases hardening and embrittlement of the steels, which results in a higher ductile-to-brittle transition temperature (T_o from MC tests, T_{41} from Charpy tests). Direct matrix damage and the influence of positive segregation (Phosphorus) and precipitation (Copper) lead to RPV irradiation embrittlement. According to Axpo, the available open literature suggests that for RPV fluences up to 10^{20} cm^{-2} (E > 1 MeV), no significant irradiation embrittlement of alumina inclusions and no significant swelling of the inclusions causing stresses in the surrounding matrix should be expected.

To support the results from the literature, investigations on material from Shell C and Replica C were performed.

6.5.1 RPV Shell C

Safety case description

In a first step, SEM/EDX, micro-hardness, and chemical element mapping measurements were conducted around the alumina inclusions in two selected specimens: one unirradiated, broken specimen SE(B) in T-L orientation from the material for the acceptance test Shell C and one irradiated specimen from the RPV irradiation surveillance set S of Shell C (1.07×10^{19} cm^{-2}). The extension of the Al_2O_3 inclusions in both specimens is in a range between 40 and 100 µm. Results of the examinations are summarised in /102/. The microstructure of the material in the vicinity of inclusions was checked by both optical microscopy and SEM: no indication of any radiation-induced modification of the microstructure was found. No accumulation of elements such as Copper, Nickel and Phosphorus was observed around the inclusions. The small reduction in hardness close to Al_2O_3 inclusions is comparable in both reference and irradiated samples. The slightly higher matrix hardness of the irradiated specimen compared to the unirradiated specimen can be explained by the influence of neutron irradiation. These results were confirmed by microstructural examination of 9 irradiated specimens from the surveillance program and 10 unirradiated broken specimens from the centre region of the material for acceptance test Shell C.

Additionally, 2 irradiated specimens from the RPV irradiation surveillance program (capsule S, 1.1×10^{19} cm^{-2}) and 2 specimens with a higher irradiation dose (capsule N, 2.3×10^{19} cm^{-2}) were investigated by micro-hardness testing, chemical element mapping, and EDX measurements. Areas in the vicinity of Al_2O_3 inclusions and areas between inclusions were analysed.

None of these tests on unirradiated and irradiated materials for acceptance test Shell C showed any unusual enrichment of Copper, Nickel and Phosphorus or zones of increased micro-hardness in the vicinity of Al_2O_3 inclusions, between the inclusions and in the surrounding matrix. No significant swelling of the inclusions that could cause stresses in the surrounding matrix was observed in the irradiated specimen.

Axpo concluded from these observations that the literature information indicating that the presence of Al_2O_3 inclusions does not affect the sensitivity to radiation embrittlement of the surrounding matrix is adequately confirmed.

ENSI review

Micro-hardness measurements, chemical element mapping, and energy dispersive X-ray (EDX) analysis performed in the vicinity of alumina inclusions, did not show any significant differences between the results for irradiated and unirradiated specimens. ENSI therefore supports Axpo's conclusion, that that the presence of Al_2O_3 inclusions does not affect the sensitivity to radiation embrittlement of the surrounding matrix. However, the alumina inclusions present in the specimens of Shell C are relatively small and not representative in size and density for the alumina agglomerates found in the most affected zones of Shell C. Furthermore, no comparative investigation on the surrounding matrix between single Al_2O_3 inclusions or large agglomerates was carried out.

To fill this information gap, ENSI requested /178/ extended micro-hardness, chemical mapping and EDX measurements in the vicinity and between large alumina agglomerates using representative Replica C material (see 5.6.2).

6.5.2 Replica C

Safety case description

At ENSI's request, Axpo extended the investigations to Replica C material with agglomerates of Al_2O_3 inclusions of different sizes in 2017. A large number of micro-hardness measurements, SEM/EDX point measurements, EDX chemical mappings and SD-OES measurements were carried out. The measurements cover regions around small and large agglomerates of Al_2O_3 inclusions over the full thickness of the Replica C as well as different planes and orientations. Results are given in /113/.

On the basis of these results, Axpo claimed that neither the micro-hardness nor the chemical mapping showed any abnormality. The chemical elements found in the vicinity and between the inclusion agglomerates fully meet the material specifications.

The chemical elements known to influence the irradiation behaviour (Copper, Nickel, Phosphorus, Manganese, Sulphur, Vanadium), are not significantly enriched in the ligaments between the Al_2O_3 agglomerates compared to the composition of the base material without agglomerates.

ENSI review

None of the additional tests on Replica C material showed any unusual enrichment of chemical elements known to influence the irradiation behaviour or increased micro-hardness zones in the vicinity of agglomerates of Al_2O_3 inclusions, between them and in the surrounding matrix.

ENSI confirms that agglomerates of Al_2O_3 inclusions present in the Beznau-1 RPV do not significantly affect the material behaviour under irradiation.

6.6 Fracture toughness of irradiated material

Historically, the adjusted reference temperature for indexing the ASME lower bound toughness curve (K_{IC}) has been determined on the basis of RT_{NDT}. This parameter is based on the combined results from Charpy V notch and drop-weight nil-ductility transition temperature tests on unirradiated material as defined in the ASME Code. The adjustment for neutron irradiation is based on Charpy tests of surveillance material with an added margin according to the Regulatory Guide 1.99 Rev. 2, Position 2. In the case of forgings and plates, this indexing parameter is overly conservative relative to the real toughness of low-alloy RPV steels.

The MC fracture toughness method with tests according to ASTM Standard Test Method E 1921 is an indicator of fracture toughness behaviour in terms of a directly measured toughness index, T_0, and statistically derived tolerance bounds. This method is technically sounder than the RT_{NDT} approach and uses the statistical nature of measured fracture toughness properties and direct fracture tests of surveillance materials.

The MC methodology is state-of-the-art and has worldwide acceptance. The application of the MC methodology in Switzerland is regulated in the Guideline ENSI-B01 and is considered equivalent to the RT_{NDT} approach. The conservativeness of the applied methods given in ENSI-B01 was demonstrated by several research programs. The advantage of T_0 over RT_{NDT} as an index temperature for the K_{IC} curve can be shown by indexing fracture toughness test data with both parameters and comparing the results. Using T_0 instead of RT_{NDT} leads to reduced scatter in fracture toughness data. This can also be observed for the forgings of Beznau-1 RPV /88/.

Guideline ENSI-B01 allows two alternative options for the MC method. ENSI-B01 Method II-A uses the irradiated T_0 measured directly from the surveillance material. According to Method II-B, the MC transition temperature T_0 for the unirradiated material is determined using standard C(T)-25 mm specimens while the temperature shift of each set of irradiation samples is derived from classical Charpy test results.

6.6.1 Determination of the adjusted reference temperature

Safety case description

The fluence of the Beznau-1 RPV has been monitored by qualified analysis since the early years of the plant. As a result, actions were taken in the 1990s to reduce the impact of fluence on the RPV by using low leakage core loading. With this modification the original design fluence will be reached after 60 instead of 40 operating years. Fluence analysis is updated on a yearly basis, based on core loading in the previous operating cycle.

Due to neutron irradiation the ASME lower bound fracture toughness curve K_{IC} is shifted to higher temperatures by means of the reference temperature RT_{ref}. Assessment of the RPV neutron embrittlement of Beznau-1 RPV for a planned operating lifetime of 60 years has already been performed, with a surveillance program accepted by ENSI.

Results of the last surveillance capsule T with a fluence equivalent to about 67 operating years are summarised in Table 3. They are based on surveillance specimens from the acceptance test Shells C and D as well as from the weld material representing the circumferential weld between Shell C and D.

The surveillance specimens of the base material were taken from a position of ¼T and ¾T from the outer surface. The fracture mechanics specimens used to determine the fracture toughness in the unirradiated condition for the Shell C and D were obtained close to the centre region (½T) of the acceptance test shells.

Reference temperatures are determined according to guideline ENSI-B01 /165/. Charpy shift methodology $RT_{ref}(0) + \Delta T_{41}$ (Method II-B) was applied for Shell C and D and MC methodology $RT_{ref}(0) + \Delta RT_{ref}$ (Method II-A) was applied for Shell C.

Beznau-1 RPV, surveillance capsule T, fluence: 6.04E19 [cm^{-2}]				
Material	**RT_{NDT} or RT_{ref} (0) [ºC]**	**ΔT_{41} [K]**	**RT_{ref} [ºC]**	**Method according to ENSI-B01**
Upper beltline Shell C	-1	105	104	Method I
	-16	105	89	Method II Option B
	-	-	70	Method II Option A
Lower beltline Shell D	-5	68	63	Method I
	-22	68	46	Method II Option B
Weld between C and D	-18	58	40	Method I

Tab. 3: Results for surveillance capsule T of Beznau-1 RPV at inner surface

As shown in Table 3, the irradiation effect is higher on Shell C material than on Shell D material. The main reason is the higher content of Copper in Shell C material.

Adjusted reference temperatures ART (RT_{ref}) are determined according to Regulatory Guide 1.99 Rev. 2, Position 2 based on RT_{ref} (0) + ΔT_{41} + margin for capsules V, R, S, N and P as well as RT_{ref} (0) + ΔRT_{ref} + margin for capsule T. Results are summarised in Table 4. Axpo used these reference temperatures as a function of fluence for deterministic Pressurized Thermal Shock (PTS) - analyses.

EFPY	**Azimuthal angle [º]**	**Position relative to RPV total wall thickness**	**Fluence [cm^{-2}] E>1MeV**	**$RT_{ref,54FPY}$ [ºC]**
54	0	inner-surface	5.59E+19	80
		¼ thickness	3.55E+19	74
	30	inner-surface	2.39E+19	68
		¼ thickness	1.51E+19	61

Tab. 4: Shell C reference temperature $RT_{ref,54FPY}$ at the location of maximum fluence (azimuthal angle 0º) and maximum PTS loading (azimuthal angle 30º) at inner-surface, in ¼ and ¾ of RPV wall thickness

ENSI review

Axpo carried out an assessment of irradiation embrittlement of the Beznau-1 RPV for a planned operating lifetime of 60 years, applying the requirements of Guideline ENSI-B01 /165/ and US-NRC Regulatory Guideline 1.99 Rev. 2 /168/. Implementation and documentation of the irradiation surveillance program, as well as test results were reviewed and accepted by both ENSI and Oak Ridge National Laboratory. The assessment showed that the procedure satisfies regulatory requirements and corresponds to the state-of-the-art.

Both Shell C and Replica C materials show inhomogeneity of the fracture toughness depending on position within the wall. Method II-A of guideline ENSI-B01 permits determination of T_0 from small SE(B)-10 mm (pre-cracked Charpy V notch) specimens instead of standard C(T)-25 mm specimens. The method is potentially non-conservative because of the unresolved size effect on fracture toughness of the material for acceptance test Shell C and because of the inhomogeneity of the fracture toughness, which is less pronounced when using large specimens.

ENSI, however, agrees that the MC transition temperature T_0= -35.5 °C obtained from standard C(T)-25 mm specimens for the unirradiated conditions is conservative. Since the transition temperature T_0 for the unirradiated material in Method II-B is determined using standard C(T)-25 mm specimens while the temperature shift of each set of irradiation samples is derived from classical Charpy test results, ENSI considers that this latter procedure is conservative and therefore requires application of Method II-B for the SIA of the Beznau-1 RPV Shell C.

6.6.2 DETEC criteria for the provisional shutdown of nuclear power plants

The DETEC Ordinance on the methodology and boundary conditions for checking the criteria for the provisional shutdown of Nuclear Power Plants /169/ defines criteria for material properties that have to be met by nuclear power plants. Among other requirements, the licensees have to provisionally shut down the plant if the following conditions are met:

- The reference temperature $RT_{ref,ART}$ exceeds 93°C at ¼ wall thickness;
- The Charpy upper shelf energy (USE) is less than 68 J (105 J for L-T).

Because there is no need for an additional temperature shift or margin considering the potential influence of alumina inclusion agglomerates on irradiation embrittlement, the assessment of the Beznau-1 RPV based on the results of the surveillance program remains the same as for the case without agglomerates of Al_2O_3 inclusions. After completion of the surveillance program in 2012, results for the reference temperature $RT_{ref,ART}$ at location of maximum fluence (azimuthal angle 0°) for 54 EFPY and the Charpy upper shelf energy can be summarised as follows:

- $RT_{ref,ART}$ using method II-B: inner-surface 89°C, ¼ wall thickness 83°C;
- Charpy upper shelf energy (USE): 150 J.

Accordingly, for long-term operation of the Beznau-1 RPV, the limits specified by the DETEC criteria for provisional shutdown of nuclear power plants are not reached and there are sufficient margins (10 °C for the reference temperature and 45 J for the Charpy upper shelf energy).

6.7 ENSI conclusions on material properties

Using Replica C material Axpo was able to show that the agglomerates of Al_2O_3 inclusions present in the Beznau-1 RPV do not significantly affect the fracture toughness in the ductile-to-brittle transition and upper shelf regions, the tensile strength, the fatigue crack growth rate and the microstructure near and between Al_2O_3 agglomerates /57/. Furthermore, Axpo has shown by micro-hardness measurements and SEM/EDX chemical mapping that the alumina agglomerates do not promote factors that would affect irradiation sensitivity.

Both Beznau-1 RPV and Replica C materials show inhomogeneity of the fracture toughness depending on position within the wall. Method II-A of guideline ENSI-B01 permits determination of T_0 from small SE(B)-10 mm (pre-cracked Charpy V notch) specimens. The method is potentially non-conservative because of the unresolved size effect on fracture toughness of the material for acceptance test Shell C and because of the inhomogeneity of the fracture toughness, which is less pronounced when using large specimens. ENSI therefore requires the application of Method II-B of guideline ENSI-B01, which uses larger C(T)-25 mm specimens to determine T_0 of the unirradiated material and classical Charpy tests to derive the temperature shift.

Considering the results of the application of Method II-B of guideline ENSI-B01, ENSI confirms that the limits specified by the DETEC criteria for the provisional shutdown of nuclear power plants are not reached for the long-term operation of Beznau-1 up to 54 effective full power years.

7 Structural integrity assessment

The purpose of the SIA is to verify, using a conservative flaw model, that the structural integrity of the RPV is maintained under all operating and accident conditions, even in the presence of inclusions.

The SIA was performed for all governing loading conditions according to the applicable rules of ASME Section XI. It consists of the following four separate assessment steps:

- Load cases and boundary conditions: determination of the stress states for all governing operating and accident conditions.
- Flaw assessment: evaluation of in-service degradation based on the ASME XI procedure.
- Fracture toughness requirements: verification of the fracture toughness requirements, in accordance with the rules of ASME XI Appendix G.
- Deterministic PTS analysis: assessment of the resistance against PTS events according to KTA standards.

Beyond that, the SIA is complemented by the demonstration of the conservatisms present in the integrity assessment.

7.1 Load cases and boundary conditions

Safety case description

The assessment for the RPV considers the stress state for all governing operating and accident conditions. The boundary conditions and load cases have been updated in the Axpo “Hauptstudie 2016”/173/.

The governing operating conditions (normal and upset) consider:

- A heat-up rate of max. 35 K/hour;
- A cool-down rate of max. 55 K/hour;
- Pressure control by the overpressure mitigating system.

The governing emergency and faulted conditions consider:

- Loss-of-coolant accident (LOCA) inducing a PTS;
- Leading leak sizes with 3 cm^2 (nozzle region) and 70 cm^2 (beltline region) in the hot leg;
- Plume effect.

Welding residual stresses are considered according to the provisions of the KTA standard /164/. The influence of thermal expansion of the cladding has been considered by a conservative stress-free state assumption in the finite element model. The conservatism of this approach has been confirmed by different studies and investigations /98/.

Cladding integrity has been sufficiently demonstrated by the performed NDE inspections, according to the KTA standard /83/ (see Chapter 2). Consequently, the effect of the undamaged cladding may be and is credited in the SIA.

The flaw evaluations are based on local loading and local fluence distribution.

ENSI review

The governing operating and accident conditions concerning thermal hydraulic transients were reviewed by ENSI as part of the Long Term Operation (LTO) verification /175/. The ENSI review was supported by an expert evaluation /174/. In this review, the determination of the leading accident transients was confirmed, using sensitivity studies and state-of-the-art methodologies.

The number of operating transients considered was based on the transient cycle report, which is updated annually according to the guideline ENSI-B01 /165/. Additional specified design transients were included in the Axpo assessment. ENSI confirms that the assessed load cases cover a period of 54 effective full power years (EFPY). The conservatism of this extrapolation must be demonstrated by Axpo every year, for the actual loading history of the plant.

As requested by ENSI in /14/, the open issues from the LTO assessment regarding the thermo-hydraulic load cases were addressed and verified in separate reports /173//174//175/.

ENSI confirms that all potentially relevant design transients are covered in the SC when local loading conditions are used in the flaw assessments for PTS-relevant locations. The thermo-hydraulic analysis and the stress state of the vessel have been checked and confirmed by Gesellschaft für Reaktorsicherheit (GRS) GmbH/174/, and the cladding integrity according to KTA standard has been confirmed by SVTI /176/.

For local loadings outside PTS-relevant locations, a discussion and validation by Axpo and references to third–party reviews are missing (see Chapter 5.1 of /14/). It should be noted, however, that the flaw assessments which involve not-yet-validated loadings, are used only to demonstrate margins. They are not relevant to demonstrate structural integrity (see Chapter 6.5.2).

7.2 Flaw assessment

Axpo decided to perform a flaw assessment according ASME XI procedures, considering the UT indications as cracks. It consists of the following steps:

- Primary stress limits assessment: satisfaction of the primary stress limits according to ASME III NB-3000, taking into account the presence of the flaws.
- Evaluation of the HAI: HAI are assumed to be cracks and are addressed separately from the alumina agglomerates (the latter are covered by the material investigation program, see Chapter 5).
- Assessment of Shell E: separate evaluation to cover uncertainties.

7.2.1 Primary stress limits assessment

Safety case description

The allowable local reduction of area of the RPV cross section caused by agglomerates of Al_2O_3 inclusions is calculated following the procedure of ASME III NB-3324.1. The minimum required wall thickness was determined for Shells A, B, C and E, on the basis of the allowable primary stress limit Sm derived from the material properties for material with indications /98/ /94/. The minimum required wall thickness allows the calculation of the acceptable reduction of area of the cross section on the basis of primary membrane stresses. The minimum required wall thickness can then be compared to the local axial and circumferential cross section reduced by the detected groups of flaws.

For the determination of the reduction of the cross section all indications identified in the NDE were taken into account. A possible growth of the flaws by fatigue was considered. The flaws were sized conservatively using enveloping boxes.

The code requirements /163/ for acceptable local reduction of area in the different shells to ensure acceptable primary stress levels are fulfilled and demonstrated for Shells A, B, C /99/ and E /145/. The relatively small margins are owed to conservative models for the reduced areas of the cross section.

A supplementary numerical elastic-plastic analysis was performed to demonstrate a more realistic but still conservative calculation of the margin.

The acceptance criterion of the chosen code option requires the verification of a safety factor of 1.5 on the design pressure compared to the collapse load. The numerical analysis demonstrated a safety factor of 1.7 /95/. This additional evaluation covers Shells A, B and C.

The yield stresses for all calculations are based on the unirradiated condition /98/, /117/.

ENSI review

The wall thicknesses and design pressures used for the analysis are given in /31/. All other input values can be found in /94/, /95/, /99/, /145/, /98/. The use of the yield stress based on the unirradiated condition is conservative with regard to stress evaluations of embrittled material.

IWB-3610 requires that the primary stress limits of NB-3000 be satisfied in combination with an analytical flaw evaluation assuming a reduction of area equal to the area of the detected flaws.

The great majority of indications could have been neglected in the primary stress assessment, because the material tests showed that they have no influence on strength, and the remaining indications are covered by general acceptance standards for fabrication flaws. Nevertheless, all indications were enveloped by UT boxes to evaluate the reductions of areas of the cross sections. The possible under sizing of some flaws mentioned in /172/ is well compensated in this process. ENSI confirms the conservatism of the process to calculate the reduction of area. This conservative approach demonstrated margins compared to the required safety factor defined by the code.

In addition to the conservative analytical demonstration that primary stress limits are met, numerical elastic-plastic analyses were performed that quantify possible additional margins using more realistic design procedures /99/, /95/, /106/, /156/. Both, elastic-ideal-plastic and hardening material behaviour were analysed. The latter results were submitted to ENSI but could not be reviewed thoroughly, since the implementation of the analysis and the interpretation of the results by Axpo was not documented in a verifiable manner /95/.

ENSI accepts the assessment of primary stress limits required by IWB-3610 for all Shells A, B, C and E, in which flaws were detected.

In summary, ENSI regards the procedure applied and results obtained by Axpo for assessing primary stress limits as conservative.

7.2.2 Assessment of the HAI in Shell C

Safety case description

The relevant information on the flaw assessment of HAI is described in Chapter “Methodological Approach and Key Findings” of /31/, in report /159/ and in /205/.

The experimental material investigations of Replica C did not completely cover flaws associated with indications with amplitude distributions above REF-6 dB such as the HAI found in the RPV Shell C. Therefore, a small number of HAI was evaluated by fracture mechanics according to the flaw assessment rules of ASME Section XI /163/. These indications are most probably also Al_2O_3 inclusions, but another origin cannot be excluded (see Chapter 2). To account for this uncertainty, 20 indications recorded with the Intercontrôle NDE system (all with amplitudes higher than REF-6 dB and located in Shell C) were assessed as cracks.

The assessment also included the 8 embedded planar flaws found by the AREVA UCC.

Cladding integrity for Shell C is confirmed by NDE. Therefore, in the fracture mechanics evaluation all flaws can be treated as embedded or as underclad cracks. Environmentally assisted fatigue due to exposure to primary water can be excluded.

The inclination of the flaws is based on the NDE results and all flaws were resolved into projected axial and circumferential planar flaws according to IWA-3340. In doing so, a minimum inclination of 10° is generally assumed.

When the proximity rules of IWA-3000 for cladding-base metal interface are considered, all 20 flaws can be categorised as subsurface flaws. The grouping of the projected planar flaws was done according to the ASME Section XI IWA-3300. It was also performed using a less conservative combination of ASME XI rules coupled with a specific AREVA procedure /98/. The more conservative IWA-3300 procedure resulted in three groups of axial and circumferential flaws respectively.

The acceptance procedure of IWB-3510 demonstrates that all the groups and the remaining individual flaws are acceptable without further evaluation /159/.

A group of closely spaced HAI within EA600 was conservatively combined in an enveloping box and evaluated as a single flaw /205/. The acceptability of the postulated flaw was demonstrated by analytical evaluations.

ENSI review

ENSI agrees that based on the results of the material properties investigations (see Chapter 5) in connection with the NDE results (see Chapter 2), the flaw evaluation to demonstrate code compliance can be limited to the assessment of 20 indications. The corresponding flaws are most likely also laminar agglomerates of alumina inclusions, but because of some differences in their UT response it cannot be completely excluded that they are possibly associated with cracks /172/, /191/.

The sizing of the indications was validated for isolated flaws and the procedures are accepted to cover all isolated flaws detected in Shell C /171/, /172/. In the case of clusters of closely spaced HAI (see Chapter 2.4.2) ENSI does not accept the combination process as described in /159/.

ENSI confirms the acceptability of all HAI according to the acceptance standard of IWB-3510, representing the allowable size for planar fabrication flaws, with the exception of closely spaced HAI located in EA600.

For the closely spaced HAI in EA600, Axpo provided /205/ a conservative procedure with respect to the recommended modified sizing in /172/ In the new approach the flaws are represented by an area of 7.3 mm x 43 mm, which is then substituted by an underclad crack of size 10 mm x 60 mm. ENSI agrees that this procedure is conservative. The analytical evaluation that confirmed flaw acceptability in /205/ is accepted by ENSI. The comparison of this evaluation with already approved allowable flaws for PTS transients /175/ corroborated the acceptability.

7.2.3 Assessment of indications in Shell E

Safety case description

The NDE results for Shell E are based on a different inspection method from that used for the other shells. For conservatism all indications were considered in the flaw assessment /145/ based on two methods /98/.

In the first method, an allowable flaw size calculated in a previous generic flaw assessment /98/ was used for comparison with a region enveloping all projected flaws. The indications in Shell E are covered by this flaw size except for four isolated flaws in a depth of more than 25 mm from the cladding interface.

The second method follows the code procedure described in /98/, which started with the screening criteria for planar flaws according to the acceptance standard of IWB-3500. In total, 42 axial and 65 circumferential groups of flaws failed the screening criteria and needed analytical evaluation.

The analytical evaluation according to IWB-3600 involves conservative boundary conditions. Enveloping loading conditions inside a plume and at the height of the upper weld seam were considered. Crack growth for another 20 years of operation was also taken into account.

The applicable material reference temperature was conservatively based on RT_{NDT} and resulted in a conservative value of $RT_{Ref,ART}$ = +4 °C. This value is much higher (i.e., demonstrates significant margins) than the T_0 value for the S-L fracture orientation, which is representative for Shell C material with inclusions and results in a $RT_{Ref,ART}$ = -40.5 °C.

The grouping rules have been modified for applicability in the present case considering an effect of flaw interaction on the stress intensity factor of less than 2.5 %.

With these boundary conditions, the governing flaw group showed a margin for the reference temperature of 62.4 °C.

ENSI review

The reviewing experts expressed no concerns regarding sizing or flaw type for Shell E /171/, /172/, /191/. Including all these flaws in the flaw assessment of Shell E, regardless of whether or not they were covered by the material investigations, is a conservative approach. As discussed in Chapter 3.2, the assessment was done to cover uncertainties with respect to the fabrication documentation.

ENSI can only endorse the second method based on the code procedure described in /98/ for the demonstration of acceptability of the four isolated flaws located deeper than 25 mm in /145/,

The loadings considered inside a cooling plume (based on a PTS-relevant 70 cm^2 leak size) evaluated at a specific height (weld 4 / RN 7) all around the circumference are conservative.

ENSI accepted the application of the specialized grouping rules for the assessment (see Chapter 6.5.2). Crack growth for specified transients during another 20 years of operation is marginal, but nevertheless considered before grouping.

The material reference temperature established for Shell E is conservative.

Because of the fabrication method applied for Shell E (conical part machined from a cylindrical part), the indications in Shell E are not quasi-laminar but inclined. The stress intensity factor applied in /145/ does not consider the resulting mixed-mode loading, which is not conservative for this situation. However, even an increase of 20 % in stress intensity will not exhaust the existing margins in reference temperature.

In summary of its review, ENSI confirms that the results of the structural integrity analysis of Shell E is conservative and can therefore be accepted.

7.3 Fracture Toughness Requirements (ASME XI App G)

Safety case description

ASME Section XI, Appendix G /163/ defines the fracture toughness requirements for low-alloy steels used for the primary components of NPP. The pressure-temperature domain, in which the reactor can be operated safely, is characterized by the pressure-temperature operating limits given in the form of pressure-temperature (p-T) curves.

The verification of fracture toughness is performed for operational and accident conditions under consideration of postulated flaws. The ART reference temperature at 54 effective full power years (EFPY) of operation $RT_{ref,54FPY}$ is relevant for this assessment. With the re-evaluation of $RT_{ref,54FPY}$, exclusion of brittle fracture must be verified using postulated flaws for operating conditions (levels A/B) as well as for accident conditions (levels C/D).

The pressure limitation curve is determined according to ASME Section XI, Appendix G, considering the ART reference temperature at the end of operation $RT_{ref,54FPY}$. The resulting p-T curve is compared with the existing curve given by the overpressure mitigation system (OMS). If the OMS curve represents an upper bound for the new p-T curve, brittle fracture safety is ascertained.

Axpo claims that the p-T curves integrated into the plant's Technical Specification remain valid also under consideration of the agglomerates of Al_2O_3 inclusions found in the Beznau-1 RPV and do not have to be updated /94/.

The verification of safety against brittle fracture for levels C/D is covered by the deterministic flaw assessment given in /34/.

ENSI review

Because there is no need for additional temperature shifts or margins to account for a potential influence of agglomerates of Al_2O_3 inclusions on irradiation embrittlement (see Chapter 6.5), the assessment of the Beznau-1 RPV based on the results of the surveillance program remains the same as without the UT indications detected in 2015 /92/.

ENSI agrees that the p-T curves integrated into the plant's Technical Specification can be used as defined after the assessment of the last surveillance specimens in 2012 and that the verification of safety against brittle fracture for accident conditions is covered by the deterministic flaw assessment. The 2012 assessment covers the evaluation of the material embrittlement according to guideline ENSI-B01 method II-B (Chapter 6.6).

7.4 Deterministic PTS analysis

Safety case description

In 2017, Axpo finished an update of the standard PTS assessment for LTO to take into account actual methodology, new software versions of RELAP and KWU-MIX and relevant boundary conditions /173/.

For stresses and temperatures under emergency and faulted conditions, the most severe governing loss-of-coolant accidents (i.e., PTS) are considered.

Axpo credited the integrity of the cladding demonstrated by complementary NDE inspections /83/. Accordingly Axpo based the PTS-analysis on a postulated Under Clad Crack (UCC).

As the flawed regions which require fracture mechanics assessment are distant from the centre of the plume near the cold leg and because the dimensions of these indications are well bound by the PTS flaw postulate, the demonstration of safety against PTS transients prepared for LTO assessment is still valid /205/, /159/.

ENSI review

The updated deterministic standard PTS analysis is based on the KTA standards /164/ and was independently reviewed and approved /174/ at the request of ENSI. This analysis does not consider possible effects of the indications found in 2015.

The suitability of the applied NDE to prove the integrity of the cladding was confirmed by SVTI /176/.

ENSI has accepted the updated standard PTS analysis /175/. All open issues related to the thermo-hydraulic load cases have been resolved.

Crediting the standard PTS analyses to assess the material behaviour with respect to the indications found in 2015 is accepted by ENSI for two reasons. First, as discussed in Chapter 5, for the great majority of indications it could be demonstrated that the material properties are not affected. Second, the remaining regions, for which indications are conservatively sized and assessed by fracture mechanics, are covered by the PTS flaw postulate (see Chapter 5.2.2).

Further, as a benefit from the 2015 UT inspection, the detection capability of the NDE is now considerably improved compared to standard inspections. The risk of undetected flaws is well covered by the justified flaw postulate of a 12 mm x 72 mm size.

7.5 Demonstration of conservatism and of the margins of the SIA

7.5.1 Conservatism of the integrity assessment

Safety case description

In the synthesis SIA report /34/, Axpo focuses on the following conservatism aspects of the integrity assessment:

Conservatism of the NDE input data

Based on the results of in-service inspections, Axpo concludes that all relevant flaws in the RPV have been properly detected. Axpo claims that the agglomerates of Al_2O_3 inclusions that are smaller than the beam size are assumed to be equal to the beam size. This applies to the majority of the indications. The size of the ligament between inclusions is therefore generally underestimated.

The HAI are not covered conservatively by the tested fracture specimens. Their acceptability is assessed separately by means of a SIA. In this analysis, the interconnected HAI areas of the EA600 were geometrically combined into one enveloping area and evaluated as a single flaw: this approach is conservative /205/. Its acceptability was demonstrated by analytical evaluations.

Conservatism of the flaw model

The applied model, which considers the flaws projected onto both axial and circumferential planes perpendicular to the maximum principal stresses (crack opening mode) as single cracks, is very conservative. The projected flaws are planar flaws although the inclusions can be considered as laminar flaws. In line with fracture mechanics, all flaws were considered as cracks despite blunted shape of the agglomerates of Al_2O_3 inclusions. To account for the interaction of closely spaced defects, adjacent flaws were combined. The conservatism of the applied grouping rules was demonstrated and confirmed.

Conservatism of the analysis of loads, stresses and crack driving forces

The transient description for normal operation Level A shutdown is conservative with regards to the actual operating practice, thermal gradient and pressure values. The pressure limitation curve given by the OMS is compared to a representative normal operation shutdown, which has a smaller thermal gradient of 30K/h than the design gradient of 55K/h.

ENSI review

Regulatory codes require data and calculations entering into a SC to be conservative, in order to provide protection against statistical variability and unknown factors. The total conservatism in a SC for the RPV must be sufficient to lead to an extremely low probability of failure. This conservatism is reached through the use of bounding toughness data and safety factors on allowable loadings.

The most important aspects to demonstrate adequate conservatism are those related to flaw modeling, the treatment of inclusions as cracks, their projection onto the axial and circumferential planes and their combination using the grouping rules for cracks.

ENSI agrees that the flaw model applied in the SIA is conservative because:

- alumina inclusions are replaced by cracks, although the detected inclusions have a blunt volumetric shape (voids) associated with a significantly reduced stress concentration;
- the cracks are projected into both axial and circumferential direction perpendicular to the operational and accidental stresses;
- the cracks have an extension in depth although most of the flaws are laminar.

For the closely spaced HAI in EA600, Axpo applied a conservative procedure /205/ with respect to the recommendation for modified sizing in /172/ . In the new approach, the closely spaced HAI in EA600 are combined in one single flaw of an area of 7.3 mm x 43 mm, which is then treated as an underclad crack of 10 mm x 60 mm. ENSI agrees that this procedure is conservative (see Chapter 6.2.2).

ENSI confirms that the adjusted reference temperature $RT_{ref,ART}$ determined using ENSI B01 Method II-B is conservative for the SIA of the Beznau-1 RPV Shell C.

7.5.2 Margin discussion

Safety case description

The material tests showed that the indications, with the exception of the HAI, which are treated separately, do not significantly influence the relevant material properties. In order to demonstrate margins, Axpo also evaluated the acceptability of all indications based on fracture mechanics.

First, all indications as detected by NDE were considered as cracks following the evaluation procedures developed by ASME XI /98/, /99/. The surface interaction rules of IWA-3300 for characterizing surface and embedded flaws were used without exception. For flaws requiring evaluation by analysis according to IWB-3600, the cladding was taken into account.

Because of the nature of the clusters of inclusions, new grouping rules were provided in /98/, which differ from the standard procedure described in the code. The verification of these rules is based on work by AREVA using results of Hasegawa /98/ as well as on a numerical simulation done by AREVA /100/. An increase in the stress intensity factor K_I by more than 2.5 % because of interacting flaws was selected as grouping criterion for the current case. This criterion is much more conservative than other common criteria, such as an increase of 6 % in K_I accepted by ASME CC-N-848 for quasi-laminar flaws or an increase of 10 % in K_I accepted by the French RSE-M code /116/.

The required material properties, particularly the fracture toughness characterising the matrix of the flawed region, were assessed and summarized /94/. The loading conditions were taken from the reassessed and updated standard PTS analyses /173/ (see Chapters 6.1 and 6.4). The local reference temperatures derived from local fluence data as well as local stresses were used in these calculations.

In addition, Axpo analysed a flaw model where all indications found in one of the EAs are grouped into one very large flaw /31/.

All these flaw models were shown to be acceptable by code based criteria, demonstrated in a stepwise approach using acceptance standards, analytical flaw evaluations, numerical flaw evaluation and crack arrest conditions.

ENSI review

The construction code for the Beznau-1 NPP and especially for its RPV was ASME section III. Therefore, the flaw evaluation was based on the rules of the ASME code, in particular section XI.

Since the ASME code rules for grouping of flaws tend to be too conservative for large numbers of closely spaced flaws, as found in the Beznau-1 RPV, Axpo applied specialized grouping rules described in /99/ to facilitate the assessment. Axpo’s validation of the specialized grouping rules by a numerical simulation /100/ was independently verified and accepted by the Fraunhofer Institute for Mechanics of Materials IWM /190/ on behalf of ENSI.

ENSI assessed and accepted the material properties used as input for SC and SIA, as detailed in Chapter 5, ENSI also assessed and accepted the local fluence distribution /175/. However, ENSI has expressed in Section 6.1 its reservations on the local loading conditions selected by Axpo for the analyses.

ENSI takes note of the reported margins. Since the thermo-hydraulic loadings have not been validated, it regards these results as indicative, but not fully demonstrated. The margin assessment will have to be revised within the scope of the periodic safety review of 2018.

7.5.3 Technical measures to increase the safety margins

Safety case description

In the process of the flaw assessment, Axpo carried out an investigation to determine which additional operational measures could be applied to further increase the safety margin of the Beznau-1 RPV during the governing PTS loading /27/. Some of the analysed technical measures were judged non-feasible. This concerns especially the recovery annealing of the RPV. Success of the RPV heat treatment depends on the RPV design and the verification and qualification of the process. Furthermore, there is a risk to induce residual stresses in the vessel.

Only one measure could bring a significant benefit, i. e. the increase of the temperature of the water inventory stored in the accumulator tanks /27/, which would be used for emergency core cooling in the event of a loss-of-coolant accident. In 2017, Axpo implemented measures to increase the water temperature in the accumulator tanks to over 30 ^{o}C by heating the room in which the accumulators are located.

ENSI review

ENSI considers the implemented heating of the accumulator tanks as an appropriate improvement to increase the safety margins.

7.6 ENSI conclusions on the structural integrity assessment

In the assessment of flaws not covered by the material properties investigation program, all indications that are probably also alumina oxide agglomerates, but which may possibly be associated with cracks have been analyzed. The procedures and requirements of Section III and Section XI of the ASME Code formed the basis for the analysis. The flaw assessment is conservative with respect to the NDE input data, the flaw evaluation models, the loadings and the material properties.

The fracture toughness criteria for protection against failure as described in ASME XI App G are met. The pressure-temperature (p-T) curve evaluated to describe the domain in which the Beznau-1 RPV can be safely operated is confirmed.

For emergency and faulted conditions, the PTS conditions is conservatively assessed by deterministic procedures.

ENSI considers that the local loading conditions used for some margin calculations have not been exhaustively demonstrated yet and expects the margin assessment to be revised in the context of the periodic safety review of 2018.

8 Documentation of the safety case

The different and extensive investigations by Axpo to establish the nature of the indications and to justify the structural integrity of the RPV were developed during a 2.5-year period and resulted in more than 100 reports. Some of the studies and investigations were performed in parallel, which required the definition of a set of working assumptions by Axpo. As these assumptions were confirmed or invalidated by evidence and/or further analytical considerations, the technical reports on the SC needed to be revised accordingly. This revision process of the SC documentation was not completed in a coherent way by Axpo.

For example, the assessment procedure for the HAI, as summarized in the preamble of the safety case report and documented in special technical reports, is missing in the associated chapters of /31/ and /34/, nor is it explained in a logical chain of arguments and referenced. The TSOs mandated by ENSI also identified contradictory statements in different reports that need clarification and verification.

ENSI will verify if the technical documentation regarding the RPV SC has been up-to-dated in the context of the periodic safety review of 2018.

9 Safety case assessment by the International Review Panel

ENSI appointed an International Review Panel (IRP) of experts for independent review of the Axpo SC and to advise ENSI, first on the completeness and adequacy of the roadmap, and, second, on the reports demonstrating the SC. The duty of the IRP was to assess the SC reports in an independent manner, within a defined scope, and to identify any deficiencies in Axpo's justifications for structural integrity.

The IRP submitted a report on the adequacy of the roadmap of Axpo /6/ to ENSI in January 2016. This report addressed observations and recommendations, and the independent expert advice was considered for the ENSI assessment of the Axpo roadmap /14/.

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.

The report on the IRP assessment /191/ was submitted to ENSI in February 2018.

The Discussions and Conclusions of the IRP are:

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 behaviour 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***

10 Summary

Assessment and review process

After ultrasonic inspections on the base material of the reactor pressure vessels (RPV) of the Belgian nuclear power plants (NPP) Doel-3 and Tihange-2 revealed numerous flaws, the Swiss Federal Nuclear Safety Inspectorate (ENSI) requested supplementary ultrasonic inspections of the base material of all forged RPVs in Switzerland.

The ultrasonic inspections in Beznau NPP Unit 1 (Beznau-1) were carried out in June 2015. These inspections reported a large number of indications, which required justification and a detailed reassessment of the structural integrity of the RPV. To support the review of the Axpo Safety Case in an independent and critical manner, ENSI appointed an International Review Panel, a group of seven internationally recognized experts, who since 2015 have been closely following the developments in the Safety Case.

The whole assessment process lasted two and a half years and can be summarized as follows:

- August 2015: ENSI requires an overall project plan (Roadmap) for the RPV assessment
- November 2015: Axpo submits the Roadmap.
- March 2016: ENSI issues a review statement on the Roadmap
- November 2016: Axpo submits revision 1 of the Safety Case
- December 2016: ENSI and the IRP perform a review of revision 1 of the Safety Case and require additional information and material tests.
- December 2017: Axpo submits revision 2 of the Safety Case including the required additional information and material tests.
- February 2018: ENSI and the IRP issue their respective final review statements on revision 2 of the Safety Case.

ENSI review

The investigations by Axpo to establish the nature of the indications and to justify the structural integrity of the RPV resulted in more than 100 technical documents. Based on the review of these documents ENSI reaches the following conclusions:

- **The ultrasonic testing procedures used are reliable and able to detect all flaws that might significantly affect structural integrity.**

  Based on the data provided by Axpo and the reviews and assessments of the Swiss Association for Technical Inspections (SVTI) and Vinçotte, ENSI confirms that all relevant flaws in the Beznau-1 RPV have been properly detected. The majority of them are of quasi-laminar character parallel to the inner surface of the vessel wall with an average size comparable to the beam size.

  The assessment of the limitations of the NDE showed that there are no significant defects in the RPV other than those which are considered in the Safety Case.

  Based on the correlation between UT indications and metallographic findings in the replica material, Axpo demonstrated that the detection limit of the UT examination is 2 mm for sufficiently dense inclusions and that the appropriate sizing procedures were used for the alumina agglomerates.

  Some UT indications have higher UT amplitudes than most of the other indications (higher than -6 dB) and were thus labelled as high amplitude indications (HAI). Moreover, some of the HAI produced 45°SW reflections, which were not observed for UT indications with a lower reflectivity.

ENSI agrees with Axpo`s conclusion, that it is plausible that the HAI are caused by alumina agglomerates. However, a different type of flaw cannot be completely ruled out. Since the HAI were conservatively considered as planar flaws in the SIA (see 6.2.2), the aforementioned uncertainty has no impact on the conclusions of the SC.

However, ENSI considers a follow-up UT inspection of the regions with UT indications to confirm stability of HAI as essential and requires it in 2022.

- **The UT indications are caused by agglomerates of alumina inclusions, formed during manufacturing.**

  Axpo assessed all plausible root causes of imperfections that might arise in RPVs during fabrication or in-service and narrowed down the possible origin of the UT indications. Agglomerates of alumina inclusions originating in the sedimentation cone with negative segregations were identified as the only likely cause for the UT indications.

  To confirm this root cause, a replica of the RPV Shell C was fabricated based on the original manufacturing documentation. The Replica C is representative of RPV Shell C with respect to the chemical composition, microstructure and material properties and shows very similar UT indications.

  On the basis of analyses of Replica C material it was demonstrated, and ENSI agrees with Axpo’s conclusion, that the UT indications are caused by agglomerates of alumina inclusions originating from the sedimentation cone at the centre bottom of the ingot.

  In addition, it is confirmed that the locations of the machined test specimens within the Replica C are sufficiently representative to cover the observed UT indications. The HAI mentioned above are an exception, however, they have no impact on the conclusion of the Safety Case, because they were conservatively considered as planar cracks in the Structural Integrity Assessment (SIA).

- **Alumina inclusion agglomerates do not significantly affect the materials properties relevant for the structural integrity assessment or the irradiation sensitivity.**

  By using Replica material it was possible to show that the agglomerates of alumina inclusions present in the Beznau-1 RPV do not significantly affect the fracture toughness in the ductile-to-brittle transition and upper shelf regions. This could also be shown for the tensile strength, the crack growth rate as well as the microstructure near and between Al_2O_3 agglomerates. Furthermore, it was demonstrated by micro-hardness measurements and chemical mappings by energy dispersive X-ray analysis (EDX) that the alumina agglomerates present in the Beznau-1 RPV do not affect irradiation sensitivity.

  Both Shell C and Replica C materials show inhomogeneity of the fracture toughness depending on position within the wall. Due to an unresolved size effect of the acceptance test material of Shell C and the inhomogeneity of the fracture toughness, which is less pronounced using large specimens, the application of Method II-A of guideline ENSI-B01, which permits determination of T_0 from small SE(B)-10 mm (pre-cracked Charpy V notch) specimens is potentially not conservative. ENSI therefore requires the application of Method II-B of guideline ENSI-B01, which uses 25 mm CT specimens to determine T_0 of the unirradiated material and classical Charpy tests to derive the temperature shift.

  In view of the results of the application of Method II-B of guideline ENSI-B01, ENSI confirms that the limits specified by the DETEC criteria for the provisional shutdown of nuclear power plants are not reached for the long-term operation of Beznau-1 up to 54 effective full power years.

- **A fracture mechanics assessment of the flaws, using highly conservative assumptions, demonstrated that the case is robust.**

  In the SIA, a fracture mechanics assessment, all HAIs which are probably also alumina agglomerates, but for which other formation mechanisms and morphologies cannot be excluded with certainty, were analysed according to the procedures and requirements of Section III and Section XI of the ASME Code.

The flaw assessment is conservative with respect to the NDE input data, the flaw evaluation models, the loadings and the material properties. The fracture toughness criteria for resistance against failure as described in ASME XI App G are met. The pressure-temperature (p-T) curve evaluated to describe the domain in which the Beznau-1 RPV can be operated safely is confirmed. For emergency and faulted conditions the pressurized thermal shock (PTS) is conservatively assessed by means of deterministic procedures.

Beyond the demonstration of structural integrity Axpo reported additional safety margins. ENSI takes note of the reported margins. Since the thermo-hydraulic loadings have not been validated, it regards these results as indicative rather than fully demonstrated.

The margin assessment will have to be revised in the context of the periodic safety review of 2018.

ENSI overall conclusion

On the strength of the arguments mentioned above, ENSI considers that the Axpo Safety Case is acceptable. Hence there are no more reasons preventing the recommissioning of Beznau-1. ENSI has one remaining reservation that results in the following, which however can be addressed after the recommissioning of Beznau-1:

Request 1: In 2022 Axpo has to repeat the UT inspections of the base material of RPV Shell C in the area of indications with amplitudes higher than REF-6 dB in.

In its independent review he IRP also came to the conclusion that the safety case is acceptable. In agreement with ENSI review results, the IRP recommends that $RT_{ref,ART}$ be determined using ENSI-B01 Method II Variant B.

11 References and submitted documents

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Recommendation in connection with flaw indications found in Belgian reactors

/2/ ENSI letter, dated 21 January 2013
Kernkraftwerk Beznau, Block 1 und 2, Herstellungsfehler im Grundmaterial der RDB von Doel-3 und Tihange-2, Stellungnahme zum Nachweis der Qualität des RDB

/3/ Westinghouse report WENX-13-48, Rev.1, dated October 2013
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/4/ ENSI letter, dated 31 August 2015
Kernkraftwerk Beznau, Block 1, Projekt BEFLAW, Sicherheitsnachweise für die Integrität des RDB von Block 1 unter Berücksichtigung der aktuellen Ultraschallanzeigen

/5/ ENSI document, dated 25 September 2015,
Rules of Procedure of the International Review Panel on Beznau Reactor Pressure Vessel

/6/ International Review Panel report, Rev. 1, dated 29 January 2016
Assessment of the Axpo Power AG Roadmap for the development of the safety case for the RPV of the Beznau NPP Unit 1

/7/ Axpo letter, dated 30 November 2015
Kernkraftwerk Beznau, Block 1, Projekt BEFLAW, Sicherheitsnachweis für die Integrität des Reaktordruckbehälters (RDB) von Block 1, Einreichung des Gesamtprojektplans (Roadmap)

/8/ Axpo block diagram, Rev. 0, dated 30 November 2015
Road map for the safety case NPP Beznau, Unit 1

/9/ Axpo technical document TM-531-P 15001, Rev. 0, dated 30 November 2015
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Preliminary Assessment of Documents Submitted by Axpo to the Second IRP Workshop Held in May 2016

/16/ Axpo letter, dated 08 April 2016
Project BEFLAW, Submission of documents for the expert meeting in May 2016

/17/ Axpo letter, dated 19 April 2016
Project BEFLAW, Submission of documents for the expert meeting in May 2016

/18/ Axpo document, Rev. 0, dated 03 May 2016
Time Schedule BEFLAW

/19/ Axpo letter, dated 14 November 2016
Project BEFLAW, Proof of Safety for the integrity of RPV Unit 1 - Submission of Safety Case (SC)

/20/ Axpo letter, dated 30 November 2016
Project BEFLAW, Proof of Safety for the integrity of RPV Unit 1 - Submission of references to Safety Case (SC)

/21/ Axpo letter, dated 20 December 2016
Project BEFLAW, Proof of Safety for the integrity of RPV Unit 1 - Submission of Safety Case (SC) version after 3rd Expert Meeting in December 2016

/22/ Axpo letter, dated 24 January 2017
Project BEFLAW, Submission of technical Reports with reference to requests from ENSI/IRP after 3rd Expert Meeting in December 2016

/23/ Axpo letter, dated 28 February 2017
Project BEFLAW, Integrity of RPV Unit 1 - Submission of Safety Case (SC) Revision 1 and reports related to ENSI / IRP requests of 21st December 2016

/24/ Axpo letter, dated 04 April 2017
Project BEFLAW, Axpo reply to ENSI feedback of the SC documents Revision 1, March 9th and to ENSI feedback of the SC documents Revision 1, March 17th 2017 - Submission of supplements

/25/ Axpo letter, dated 21 April 2017
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Project BEFLAW, Integrity of RPV Unit 1 - Submission of Safety Case (SC), Revision 2 and Reports Related to the Final Safety Assessment Concept

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/28/ Axpo letter, dated 13 January 2018
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/29/ Axpo letter, dated 18 January 2018
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/30/ Axpo letter, dated 02 February 2018
Project BEFLAW, Submission of Revised Technical report TM-530-MQ17052

/31/ Axpo technical document TM-530-MQ16047, Rev. 2, dated 04 December 2017
Safety Case RPV Beznau Unit 1

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Inspection of PWR vessels, Beznau unit 1- In-service inspection device CMM - Inspection of the base material of the vessel shells with regard to the detection of hydrogen-related defects

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KKB – 1 – Results of the Inspection looking for planar defects in the Extended Area above the RPV Circumferential Weld RN5

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Inspection of the base metal of the vessel shell, Evaluation of extended are no. 740 down to noise level

/44/ Axpo technical report KKB580D0352, Rev. 2, dated 23 September 2016
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/45/ Axpo inspection report KKB580D0355, Rev. 4, dated 18 April 2017
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Fractographic Examination of Selected Fracture Mechanics Specimens from Beznau 1 and 2 RPV and Replica Shell C (CT12,5, T-L orientation), Material: 1.2MD07

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