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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

28. February 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 assigned 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), after the qualification process of the non-destructive testing procedure, the ultrasonic inspections of the RPV were carried out during the planned outage in 2015. These inspections resulted in a series of indications, which require 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 has been adequately demonstrated. The IRP should assess new or non-standard procedures for suitability for use in the safety case, and identify aspects of the case that are not sufficiently justified.

In November 2015, Axpo submitted a package of four documents describing the overall project plan and constituting the Roadmap /7/. This package 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 as well as the IRP, ENSI and further experts on the regulatory side.

The review process of the IRP and ENSI included five workshops within 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 review concluded that there was insufficient data on the effect of the inclusions on material properties as well as incomplete UT validation. This resulted in ENSI request for Axpo to extend the materials characterization program and to submit an updated safety case. Axpo submitted the final report on the SC (revision 2) in December 2017 /31/. Based on ENSI feedback /187/ additional explanations and revised reports have been filed subsequently 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 to the Beznau-1 Safety Case have been 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/, ENSI requests in /14/, and supplementary judgements in case of new knowledge resulting from the SC revision 2 report package.

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 falsified 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 7).

ENSI therefore limited the scope of its review on the relevant technical justifications for the demonstration of structural integrity and regulatory compliance of the Beznau-1 RPV. Other statements and conclusions by Axpo, which 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/, any requests or obligations in the present report are the sole responsibility of ENSI.

1.4 Content of the present report

Chapters 2 to 6 of the present report cover the review performed by ENSI of the documents submitted by Axpo concerning the SC. Each technical chapter starts with a description of the part of the 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 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 such Replica C. Material properties of the Beznau-1 RPV as confirmed on the Replica C are the subject of Chapter 5, while Chapter 6 covers the structural integrity assessment of the whole vessel. In Chapter 8, the results of the IRP assessments are summarised briefly.

In conclusion Chapter 9 summarizes ENSI review results and sets the request(s) to be fulfilled by Axpo after recommissioning for a continued operation of Beznau-1.

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 flaws were found in RPV Unit 1 with the highest number in Shell C. Most indications were situated in the first 50 mm of depth (starting from the wet cladded surface) and in the lower part of the ring /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 indications could not directly be compared between Beznau-1 and 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 that was applied in Doel-3/Tihange-2.

Because of the missing qualification of the DEKRA method in the depth range between the wet cladded surface and 10 mm depth and 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 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 straight beam techniques in the depth range 0 to 50mm varies from 3 to 5mm (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 10mm).

The standard resolution of the raster scanning (during detection phase) is 2mm, 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 time-of-flights.

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

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

The average size of the indications in axial or circumferential direction is about 3 to 5 mm which is comparable with or smaller than beam size (depending on the depth position). The extension in radial (depth) direction is negligible (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 delivered a strong argument to believe that the observed indications in the Beznau-1 RPV shell forgings were no hydrogen flakes /46/.

The indications in Shells B and C showed comparable amplitude distribution. Most of the indications are located near the bottom of the rings in a depth range starting from the inner side (cladding interface) up to about one fourth of the thickness (from wetted surface: 5 mm to depth of approx. 30 mm, 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 some areas, termed “Extended Areas” (EA) the density of the indications was so high that the individual indications could not be resolved anymore 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 also within these EA all individual indications above the reporting threshold could be properly assessed.

Extended area 600 was identified as the leading area in terms of UT results (spatial distribution of indications, amplitudes, size of indications).

The reportable indications are not evenly distributed over the entire volume of the most effected 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 noise (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 inspection techniques 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 /159/ were found. 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 testing 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 (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 on 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. It should be noted that 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, based on simulation results, the conclusion was drawn, that the hemispherical curvature of Shell E is expected to have no significant influence on amplitude and sizing /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 data assessment of non-grinded cladding surfaces /48/, /49/.

The distributions of the UT indications in Shell E were slightly different from Shell C, including an insignificant shift towards larger sizes. The latter 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. In particular that:

- The laminar indications have been detected and sized appropriately.
- Planar indications (perpendicular to the inner surface) have not been detected.
- Radial connections between the numerous small laminar indications were not detected.
- The overall cladding integrity in Shell C and D was 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 the consistency with formal requirements is confirmed by the TSOs.

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 /1/.

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 between the ligaments. Since the HAI were conservatively considered as planar flaws in the SIA (see 6.2.2), the above mentioned uncertainty has no impact on the conclusions of the SC.

Inspection of Shell E

Although the quality of the DEKRA procedure applied to Shell E does not completely achieve the performance of the Intercontrôle procedure, the NDE results can be accepted as input for the SIA. Shell E contains only isolated indications with high amplitudes (>REF-6 dB), which are considered in the SIA (see Chapter 6.2.3). 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 on 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 geometrical form of the ring) and 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, which corresponds to the beam size of the applied 0° L probe. Axpo compared the amplitude of the UT measurement with the reflectivity of a modelled smooth, continuous, laminar orientation flaw with a size of 3.6 mm and concluded that such flaws would cause significantly higher UT amplitudes. This is consistent with the RCA results that the indications are coming from subcomponents of Al_2O_3 inclusions, which are not ideal reflectors.

Within this context, Axpo further discussed scenarios where the inclusion morphology might preclude detection. 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 (see Chapter 2.4) have revealed such flaws. Axpo stated that in agreement with the RCA, the shaping influence of the forging process should exclude the formation of such difficult-to-detect, strongly tilted, continuous large flaws. Concerning 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, tilted with a significant angle related to subcomponents of Al_2O_3 inclusions 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. This was done by experimental evidence, as well as by simulation results /57/.

No measurable back wall drops were observed in the RPV and also not in the Replica C. In total 33 measured configurations were analysed in which shadowing could be suspected (indications with identical X and Y coordinates, but situated at a different depth Z). It was observed that in about as many cases the amplitude of the smaller-depth indications was lower than the amplitude of the larger-depth indications, as there were cases in which the opposite was true. If shadowing were relevant, it would most likely have resulted in the larger-depth indications being statistically lower in amplitude than the smaller-depth indications. This was however not observed.

Axpo concluded that a relevant shadowing effect can be excluded due to the discontinuous character of the conglomerates. This character allows much of the ultrasound to go right through the agglomerates.

ENSI review

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

2.3.4 Cladding effects

Safety case description

Axpo discussed the cladding influence on the detection and sizing capacity. 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 literature for this type of cladding and measurement configuration.

The necessity to determine the cladding effects comes from the fact that the RPV is cladded and most parts of the Replica C were not. 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 on a statistical 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.

It was concluded that the average influence of the cladding on the amplitude for the MER probe is well addressed 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 aluminium oxide inclusions and not by hydrogen flakes. For this kind of flaws no qualified UT method existed. Therefore, a validation process was required to confirm that the applied UT inspection procedure is able to adequately detect and size the agglomerates of aluminium oxide inclusions /32/, /82/.

2.4.1 Detection capacity

Safety case description

For the UT validation, no structural flaw was predefined. The aluminium oxide agglomerates have extensions between a few micrometres up to several millimetres. The objective of the validation of the detection capacity 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 focused on examinations of selected blocks of the Replica C (see Chapter 3.2). The replica blocks have been 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 the metallographic findings on the specimens. At first Axpo has correlated the alumina agglomerates visible on fracture surfaces of broken C(T) specimens with UT indications above reporting threshold /50/. A limited correlation was found for significant number of samples /69/. Several factors were discussed that prevent the results of this direct correlation from being quantitatively considered for the validation process /59/, /60/, such as the accuracy of superimposing the test specimen with the position of the UT indication, the influence of a deformed fracture surface due to the mechanical tests and the coalescing of neighbouring agglomerates on the surface.

The validation results are based therefore on a destructive evaluation on a cube with a size of 30 x 30 x 30 mm^3 containing an area with high density of UT indications /50/, /113/. This cube was grinded with 0.5 mm increments to ensure a precise correlation of UT findings and the metallographic results.

Axpo developed a qualitative red-orange-green coding system to characterize and size the metallographic findings /50/. A red indication is defined as dense agglomerates with highest inclusion density. An orange indication is defined as conglomerates with medium inclusion density separated by the steel matrix and finally a green conglomeration is described as lines of clouds of small agglomerates separated by the steel matrix.

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

133 red-coded events were observed on the 61 metallographic image slices and 99 UT indications were reported in the 30x30x30mm^3 volume. In a very detailed study, a correlation between the UT indications and the superimposed metallography images was documented.

It was shown that red conglomerations 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” to the noise level off approx. REF-36 dB.

Reducing the UT threshold for reporting, the number of very small flaws of the same nature will increase as well as the number of possible false UT calls due to acoustic interactions. Axpo stated therefore, that the applied UT threshold is well chosen and not limiting the structural integrity assessment taking also the material testing programme into account.

ENSI review

ENSI has requested a sound correlation between UT indications and metallographic findings. Based on the metallographic findings in a 30x30x30mm cube made out of replica material ENSI agrees with the main conclusion, that the Intercontrôle UT examination guarantees detection of red-coded inclusions with a length at least 2mm. For indications with a red-coded length below 2mm the rate of detection was about 60%. Since the detectability of all red-coded events 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 recognised some inconsistencies in the documentation, which mainly relate to the utilisation of the semi-automated image processing used for characterising the multiple metallographic events 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 inspection data 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, y, z) defining the dimension of the 3D-UT box. Limiting is the scanning step (measurement increment), namely for the CIVAMIS inspection data 1.1 mm in circumferential (X) and 1.2 mm in axial (Y) direction.

The sizing capability was validated by comparison of UT sizing measurements to destructive measurements on test blocks taken from the Replica C supported by extensive UT modelling studies /50/, /122/.

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

Axpo stated that the theoretical maximum under-sizing error could be 2 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 inclusions.

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 destructively determined size on selected specimen in the Replica C. The results indicate a systematic oversizing for most indications when applying a 6 dB drop.

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 overall statement has also been confirmed by the IRP and TSOs.

The sizing of the indications has been 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/. Dense group of HAIs in EA600 in Shell C was conservatively enveloped and assessed by a SIA.

2.5 Stability of flaws

Safety case description

In the frame of the RCA, the UT indications detected in 2015 were confirmed to be caused by manufacturing-induced alumina agglomerates. Axpo carried out a literature survey of potential damage mechanisms that may lead to changes of the alumina inclusions 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 a 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. 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 cracking between the ligaments. 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

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 2022.

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 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 the identified limiting factors can be neglected based on the results of the UT validation.

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 and the HAI.

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

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, when looking at the peculiarities of the process parameters and comparing them to known measures to avoid certain types of imperfections, a higher probability for formation of non-metallic inclusions could be assumed. This is particularly the case when reviewing the process parameters of Shell C (high ingot mould-height-to-diameter ratio, smaller piercing diameter /64/). In the record of Shell C /81/, curiously, the comment ‘air pouring’ has been added while vacuum pouring is also mentioned on the same file page. Axpo claims that the comment of air pouring should be understood as a remark for a non-optimal vacuum quality. This peculiarity is important in the context of the root cause analysis in 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 only one single volumetric defect for Shell C was reported for stage III /81/, described as a “pin-point”. A comparison of the UT technique applied at that time shows that the technique used in 2015 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 discard are required by ASTM Specification SA-508 in order to avoid the occurrence of flaws related to these process parameters, e.g. 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 confirms that the manufacturing practice based on steelmakers’ internal expertise was able to avoid such indication clusters at that time, even if the Beznau-1 RPV was one of the first vessels fabricated.

The manufacturing documentation confirms that also the manufacturer of Beznau-1 RPV was aware of the need to sufficiently discard the segregated parts 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 not cut out sufficiently.

It is plausible for ENSI that there are indications in the manufacturing documentation of RPV Beznau-1 leading to a higher probability for the formation of non-metallic inclusions, in particular regarding the fabrication parameters of Shell C.

3.2 Root cause analysis

Safety case description

The objective of the Root Cause Analysis (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 of the highest amount of UT indications, but its result was also double-checked with the UT indications detected in the other shells.

At first, a screening of possible formation mechanisms of certain flaws causing the detected UT indications was done considering both the formation during fabrication and during service /81/. The list of possible flaw formation mechanisms was reduced by excluding non-plausible formation mechanisms. Axpo summarises all possible formation mechanisms while providing a specific reason for excluding most of them /31/.

Even if hydrogen flakes, located in positive macro-segregation zones, were excluded in the screening process, they are assessed in more detail, because Doel-3 and Tihange-2 RPVs and the rejected Beznau-2 Shell D have shown that it was a probable formation mechanism at the time of manufacturing. Furthermore, hydrogen flakes were the initial inspection target for the UT inspection applied to 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, which was rejected 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 is not critical for hydrogen flaking.
- Manufacturing documentation confirms a tailored heat treatment 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 to be 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. The 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. With the results of the Replica C investigations, Axpo concludes 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 for Shell B, the spatial distribution of the UT indications is very similar to Shell C, but to a much lower quantity /31/. The UT indication size distribution of Shells C, B, and E is very similar, which strongly suggests that the origin of UT indications for Shells B, C and E is of the same type.

However, Shell E is discussed in detail in the RCA due to the different manufacturing process. The manufacturing documentation states that Shell E1 containing the highest amount of UT indications (among these three shells) was taken from the middle of the ingot. This location does not coincide with the negative sedimentation cone. Axpo explains 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 assumes that the original blank positions in the ingot were E2, E3, E1 from the metallurgical top.

ENSI review

Axpo assessed all plausible root causes of imperfections which might arise in RPVs during fabrication (casting, forging, heat treatment, cladding) or in-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 UT indication characteristic of the Beznau-1 RPV, the manufacturing review, and state-of-the-art knowledge about the metallurgy of large steel forgings.

Based on the arguments provided, it is plausible for ENSI that the origin of the UT indications are caused by alumina inclusion agglomerates originating from the sedimentation cone at the centre bottom of the ingot.

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

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

3.3 Confirmation of the root cause by the Replica C

Safety case description

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

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

In the frame of the UT validation process, the UT indications of Replica C were correlated to the corresponding findings in the metallographic investigations. It was found that the UT indications are caused by agglomerates of alumina inclusions within the range of some millimetres.

Micro-chemical energy dispersive X-ray (EDX) analyses demonstrated that the UT indications consist of alumina inclusion agglomerates. The alumina inclusions themselves are filled with small, loose grains of alumina, which were partly removed during the preparation of the test specimens.

Based on the findings in the Replica C investigation /82/, Axpo concluded that it was shown and confirmed that alumina inclusion agglomerates 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 predicted type of flaws in the expected lower part of the shell. The UT responses characteristics of the indications in Shell C and the Replica C turned out to be very similar using the same UT equipment and technique.

With the tailored modifications in the replica fabrication process (ingot piercing, bottom cropping and the final machining process) it is plausible for ENSI, that the Replica C contains a higher amount of residual material with the expected type of inclusions.

Based on 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 to the RCA result.
- Al_2O_3 inclusion agglomerates and conglomerates were identified to be the source of the measured UT responses in the Replica C. The UT characteristics match with the morphology of the alumina inclusion agglomerates.
- Taking into account the unremoved 30 mm thickness layer in the Replica C (no machining of the inner layer), the location of the UT indications in depth orientation is comparable to the location in Shell C.
- No hydrogen flakes or other type of flaws were found in the Replica C.
- On the micrographs multiple manganese sulphide inclusions were identified without producing any UT response. With reference to the RCA, no other type of flaws were found in the process of the metallographic and fractographic investigations.
- The measured carbon content shows a slight decrease in the zone with UT indications, which confirms the assumption that the alumina inclusion agglomerates causing the UT indications are embedded in a zone with partially negative segregations.
- 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 how Axpo proceeded in the root cause analysis (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.

Based on the provided arguments in the frame of the replica investigations, ENSI confirms that the UT indications detected in 2015 are caused by alumina inclusion agglomerates originated 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

The Fabrication of the Replica C was carried out at Sheffield Forgemasters (SFEL) in summer 2016 based on the information from manufacturing documentation of Beznau-1 RPV Shell C and recommendations of involved experts. The Replica C fabrication aimed at reproducing the same type of UT indications in the same ingot zone in a sufficient quantity.

The replica fabrication procedure at SFEL followed the Le Creusot practice in 1965-1967 for the manufacturing of the Beznau-1 RPV Shell C as closely as possible. It goes without saying that the applied 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) extracted from the manufacturing documentation have been taken into account. In addition, contrary to modern practice, no argon shielding was used in the transfers of molten steel between ladles, which resulted in an increase the oxygen level in the steel.

The only major deliberate deviations from the Le Creusot practice of the 60s were in the piercing (solid instead of hollow punch), cropping and final machining of the inner surface with the aim to increase the probability for the occurrence of zones with 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 examinations of the Replica C exhibit a homogenous ferritic-bainitic microstructure comparable to the microstructure found in the acceptance test ring material 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 are originated in the sedimentation cone with negative segregations at the bottom of the ingot. This is confirmed by the measurement of a slightly lower carbon content for the matrix around the alumina inclusion agglomerates.

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

- The yield and tensile strength of Replica C material at room temperature is slightly higher but comparable to those properties 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 have been confirmed with the metallographic investigations on the Replica C material.

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

4.2 UT indications in Replica C

Safety Case description

The size and spatial distribution 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 comparable amplitude distribution if a cladding attenuation of 6 dB is applied to data from the un-cladded blocks of the 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 closer than 30 mm to inner surface (maximum depth 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

Based on 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 test specimens. 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 Technical Support Organisation (TSO) on behalf of Axpo.

Axpo has 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 the cumulated C-Scan images of the test specimens were compared with the C-Scan image of the RPV with identical cumulated thickness. The non-presence of cladding on the replica was compensated and a Distance Amplitude Correction (DAC) was applied as well.

For a 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 on the basis of 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. In fact, 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 based on various definitions on 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 are 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 based on the five categories A to E is a robust and engineering-based tool to select test specimens for different areas of the RPV Shell C. Within the comprehensive documentation for each test specimen, the position of the UT indications are visualized and compared to a corresponding category in the RPV Shell C.

In addition, ENSI requested a verification of the real positioning of the test specimens by a measurement of the extent 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 correlates with 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 6.2.2).

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. The production was based on the Le Creusot practice in 1965-1967 for the manufacturing of the Beznau-1 RPV.

All relevant NDE and mechanical testing steps related to the replica C were supervised by Technical Support Organisations (TSO) on behalf of ENSI. This includes the NDE data acquisition on the replica C, sampling and machining of probes, and execution of the mechanical tests.

ENSI confirms that Replica C is representative of RPV Shell C regarding the 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.

Moreover ENSI confirms, that the location of the machined test specimens within the Replica C are sufficiently representative to cover all indications, except the HAI in the RPV Shell C, which were hence addressed 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/. 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 mostly equivalent to SA-508 steel, grade 3, class 1 (earlier: SA-508 class 3). The weld deposit of the submerged-arc welding weld joint between forgings Shell 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 investigations show that in all examined specimens the same inclusion types, shapes, and orientations were found. Three different types of non-metallic inclusions were observed mainly: elongated MnS inclusions, elongated Al_2O_3 inclusions, and MnS inclusions in combination with Ca and fine globular Al_2O_3 inclusions. All specimens show 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. No Al_2O_3 inclusion agglomerates were found.

At the broken halves of the C(T) specimens no significant UT indications have been found. However, no material pieces were available from the inner surface area of the acceptance test Shell C, which is close to the area where most of the indications inside the Beznau-1 Shell C were found. The results of hardness measurements show in all positions comparable values of 197 HV5 up to 243 HV5 typical for the low-alloy RPV steel 1.2MD07. It was noted by Axpo that all of these features and properties have contributed to the material behaviour during the previous mechanical testing.

ENSI review

Metallographic investigation 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. 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/.

5.1.2 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 chemical analyses (more than 600 Scanning Electron Microscopy SEM point measurements, several EDX mapping measurements, and 41 Spark Discharge Optical Emission Spectroscopy SD-OES measurements) were carried out /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.

Hardness HV10 at different axial positions was measured over the full thickness of the Replica C material, micro-hardness HV0.5 was obtained near Al_2O_3 inclusion agglomerates and in the base material. In all positions, comparable hardness values between 192 HV10 and 210 HV10 were measured over the complete thickness

/61/. Low-force HV0.5 hardness measurements were carried out between two separate positions with Al_2O_3 inclusion agglomerates. Micro-hardness values of 195 HV0.5 up to 213 HV0.5 were obtained /61/, which are in the same range as the HV10 hardness values. The chemical mapping investigations were performed with a special focus 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 are detected anywhere on 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 with UT indications of the Beznau-1 RPV 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 at different axial positions were performed over the complete thickness of the Replica C material in areas with both small and large inclusions. There was no significant difference in hardness beyond the expected scatter range, for the results both with and without inclusions. In all positions, a homogeneous distribution of all base material elements in the vicinity of inclusions as well as away from inclusions could be detected by EDX mapping measurements. 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 as well as the amount of trace elements such as Titanium, Vanadium, Chromium, Cobalt, Nickel and Copper in the vicinity of inclusions are typical for low-alloy RPV steels and are not influenced by the presence of these Al_2O_3 inclusion agglomerates.

5.2 Fracture toughness of unirradiated material

Fracture toughness expressed in terms of reference temperature RT_{ref} is the relevant material property for fracture mechanics assessment 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 the embrittlement assessment using the guideline ENSI-B01 /165/ and US-NRC Regulatory Guideline 1.99 Rev. 2 /168/.

5.2.1 RPV Shell C

Safety case description

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

In all cases, the orientation was T-L. A large difference in the Master Curve reference temperature T_0 was found between the C(T)-25 mm specimens (T_0= -35.5ºC) tested in 2009 /92/ and the specimens extracted from the broken 25 mm specimens halves: C(T)-10 mm specimens (T_0= -81ºC) /148/ and SE(B)-10 mm specimens (T_0= -91ºC) tested in 2012 /147/. The difference is so large that it cannot be explained by 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 is relatively high (T_0 = -35.5 °C), a zone of lower fracture toughness should be assumed for the area in the wall centre. More precisely, it should be lower than in the ¼ and ¾ depth positions where the surveillance samples are taken.

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

ENSI review

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

Due to the unresolved size effect of the acceptance test Shell C material 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 agrees that the MC transition temperature T_0= -35.5ºC obtained from standard C(T)-25 mm specimens is conservative for the unirradiated conditions.

5.2.2 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 coverall 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 is 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 from Replica C material were extracted. The data was analysed using the standard MC method to determine the transition temperature T_0 for different sets, based on the size of inclusions in the process zone at the fracture surface. All sets show T_0 values within a ±2.5ºC deviation. The statistical uncertainty (1σ) is of the order of 5ºC. Thus with a 95% confidence level, the average toughness is the same in all cases. 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 /189/ provides a screening criterion to determine when the data set may be representative of a macroscopically inhomogeneous material. 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 for the specimens. 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. The data does not indicate a lower toughness of the Al_2O_3 inclusions compared to the matrix. If this effect existed, the specimens with inclusions should be scattered to lower values compared to specimens with no inclusions. This is not the case, however. With the exception of the layer closest to the surface, the other layers indicate homogeneous material 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 small and large inclusions, but is still similar for each data set. Thus, the existence and size of inclusions in the process zone at the fracture surface has no negative effect on T_0 determined by standard MC analysis. Only the set without inclusions shows a strong inhomogeneity, which is likely to be a similar depth effect as observed for the T-L specimens. The Al_2O_3 inclusions show no negative effect on T_0. As is normally the case for forgings, the results showed that specimens in the T-L orientation have a lower fracture toughness than the L-T orientation.

For the S-L orientation 24 C(T) specimens were tested. Because only two specimens with no 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 was observed. 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.

In 100 C(T) fracture toughness tests performed on Replica C material in the transition range 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, as shown by fractographic investigations of the specimens /61/. Most of the specimens examined show crack initiation sites macroscopically far away from Al_2O_3 inclusions. However, in some specimens, the crack initiation sites are located in the area of Al_2O_3 inclusions. At higher magnification the scanning electron microscope reveals that in the area of Al_2O_3 inclusions ductile fracture characteristics are present and microscopically the crack initiation sites are located in the area of cleavage fracture in a certain distance of the inclusions /61/.

Cleavage fracture of low-alloy RPV steels is generally initiated on carbides. In RPV steels, titanium carbonitrides 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 an amplifier of the local stress favouring the cleavage initiation in their vicinity. However, 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 concludes 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 Scanning Electron Microscopy (SEM).

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°C (T_0+50°C). 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/. Due to only 4 specimens without inclusions, the specimens with no and small inclusions were combined.

Type T-L	Number	T_0 [°C]	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°C in T-L orientation. IH = inhomogeneous, H = homogeneous.

The MC transition temperature values T_0 vary with a deviation of ±6°C. 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, verifying 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 apparent 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 shows 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 from 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 concludes that it is not unusual and does not rule out the application of the test standard ASTM E1921 that fracture toughness data points fall below the 2% failure probability curve of the MC.

Based on the results of all 130 fracture toughness tests Axpo finally claims that there is no negative effect of Al_2O_3 inclusions and Al_2O_3 inclusion agglomerates on the brittle fracture toughness. Fractographic investigation showed that in all specimens cleavage fracture characteristics are present 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, though this was shown to be unrelated to the Al_2O_3 inclusions and rather due to depth effects and statistical uncertainties.

ENSI review

In the first phase of fracture mechanics and microstructural investigations on the possible influence of Al_2O_3 inclusion agglomerates on fracture toughness and MC transition temperature T_0, 10 specimens without UT indications (E0), 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. To confirm that Al_2O_3 inclusion agglomerates 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 have been tested at -30°C. The data points are 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 are 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 the 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 reliable deduction of the possible impact of zones characterised by Al_2O_3 inclusion agglomerates on fracture toughness. ENSI requested from Axpo, by letter dated 21 December 2016 /179/, that complementary material tests be carried out on Replica C material and that grouping criteria for samples be defined, based on features of the process zone on the fracture surface.

Subsequently, Axpo tested a large number of 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. These specimens all meet the validity criteria for the process zone for the groups "no inclusions", "small inclusions" or "large inclusions" defined by Axpo 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

Sample selection was performed in such a way as to ensure their representativeness for the UT results in the extended area EA600 of Beznau-1 RPV Shell C regarding density of UT indications and UT amplitude. ENSI has reviewed the representativeness of the samples and the validity criteria for the grouped fracture toughness assessment. It confirms the suitability of this approach for reliably investigating the impact of Al_2O_3 inclusion agglomerates on fracture toughness and MC transition temperature T_0. High amplitude indications (HAI: amplitude ≥ REF-6 dB) are not covered conservatively by the samples tested and are assessed separately and their acceptability is assessed by means of SIA.

In addition to the fracture mechanics tests, Axpo has 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 Al_2O_3 inclusion agglomerates were performed on Replica C material, to investigate potential changes of the microstructure by the Al_2O_3 inclusion agglomerates.

The results of these supplementary fracture mechanics and microstructural investigations performed in 2017 permit Axpo to construct a simpler and more consistent safety case by proving unaltered material properties for the areas with inclusions. Excluded from this are HAI, whose acceptability has to be proven by means of fracture mechanics.

The evaluation of the C(T)-12.5 mm specimens result in the following values for the mean MC transition temperature T_0 for all samples with and without Al_2O_3 inclusion agglomerates: -83°C for the T-L orientation, -94°C for the L-T orientation, and -56°C for the S-L orientation, each one with a standard deviation of 5°C. There were no significant differences for 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 is smaller on average than T_0 for the T-L orientation, i.e., fracture toughness is higher and needs no special consideration in the SIA.

In S-L orientation, the samples lie radially inside the vessel wall and crack propagation is in circumferential direction. As expected, the value for T_0 is higher than in T-L orientation. However, it is 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.

According to the SINTAP procedure, signs of inhomogeneity are only present in the datasets without Al_2O_3 inclusion agglomerates at the orientations T-L and L-T. This is assumed to be a location effect due to the different depths from which the samples were taken. Al_2O_3 inclusion agglomerates do therefore not preclude application of the standard MC method according to ASTM E1921.

The results presented by Axpo provide no indication that Al_2O_3 inclusion agglomerates affect the Master Curve transition temperature T_0. Results were strongly reinforced by fractographic examinations performed at 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 show, that no case of crack initiation from an Al_2O_3 inclusion was observed.

Additional investigations of the C(T)-25 mm specimens at the upper limit temperature of -30 °C for the MC method in T-L orientation 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. Similar to Shell C material, the Replica C material shows a relevant size effect in the T_0 determination using MC, although less pronounced.

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

Three results with low fracture toughness values lie below the 2 % MC failure probability curve. This result has to be interpreted as an expression of higher variance of the measured values at higher test temperature and local 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 the other samples with higher fracture toughness. Al_2O_3 inclusion agglomerates present in the process zone have no effect on crack initiation in these samples.

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

5.3 Fracture toughness on the upper shelf

Safety case description

For the upper shelf energy, 15 fracture toughness tests with C(T)-12.5 mm specimens in T-L orientation at 75ºC, 100ºC and 300ºC have been performed according to ASTM E1820-15a. Results are documented in /109/.

Fractographic investigations show that all specimens contain a significant number of inclusions in the process zone on the fracture surfaces. Among these specimens, 7 showed large inclusion agglomerates of up to 8.5 mm length on the fracture surface. However, the inclusions did not act as crack initiators. At a test temperature of 100ºC, the mean $k_{Jc0.2BL}$ value from specimens with large inclusions was 9 % lower than that of the small inclusions specimens. At 300ºC, the trend is reversed, with small inclusions showing a 10 % lower mean $k_{Jc0.2BL}$ value than the large inclusions. Axpo claims there is no significant effect of the inclusions on the fracture toughness in the ductile region. From the results of the ductile fracture toughness tests, conclusions can be drawn on the impact of inclusions on the Charpy upper shelf energy (USE). The results indicate that Al_2O_3 inclusion agglomerates 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 characteristic for ductile fracture behaviour. Only small differences were found for the ductile fracture initiation parameters according to ASTM E1820-15a. In the fracture process zone of the examined samples there is 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 are characterised by ductile fracture behaviour between the Al_2O_3 inclusion agglomerates. The areas for crack initiation in all samples lie outside the Al_2O_3 inclusion agglomerates, which therefore do not significantly affect the fracture process.

ENSI accepts the conclusion of Axpo that the alumina 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).

5.4 Tensile properties

Safety case description

The first tensile tests were performed using small round tensile specimens (d = 5 mm) at a wide range of temperatures (-196ºC to 300ºC). 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 Al_2O_3 inclusion agglomerates on yield strength ($R_{p0.2}$) and ultimate tensile strength (R_m) was observed, but ductility (A_g, Z) was reduced with increasing inclusion density. Even with the lower inclusion density (E3), the elongation at maximum force (A_g) was reduced to below 10 % at both 23°C and 300°C. At these temperatures, the reduction in cross section area (Z) was 61 % and 32 % respectively, but in the higher-density material, the corresponding values were 24 % and 6 %.

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

Tensile test specimens were subjected to fractographic investigations, which showed that the specimens contain a significant number of large inclusions at the fracture surface. The scatter of yield strength vs. number of inclusions and maximum length of inclusions was analysed: the scatter was within the usual 5 % and no correlation was observed.

Axpo explains the low ductility of the small tensile specimens with the relative proportions 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 5 mm diameter tensile specimens cover inclusion areas of approximately 2 mm^2 (10 % of the specimen area), up to 18 inclusions on the fracture surface, and up to an inclusion length of approximately 3 mm.

Axpo claims that the inclusion agglomerates 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 -196ºC and +300ºC using small 5 mm and standard 12.5 mm diameter specimens, both with and without UT indications. Axpo showed that the measured values of yield strength and ultimate tensile strength for both the 5 mm and 12.5 mm specimens are within scatter band for all temperatures. The examination of fracture surface characteristics for the 5 mm and 12.5 mm tensile specimens at different temperatures and different inclusion sizes shows no significant influence of the Al_2O_3 inclusion agglomerates on the observed material properties (yield and tensile strength). ENSI confirms that Al_2O_3 inclusion agglomerates present in the Beznau-1 RPV do not significantly affect tensile properties.

The applicable ASME materials 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 considers the low ductility values observed for the small tensile specimens at 23°C and 300°C as a structural effect. Specimens with a diameter of 5 mm with 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.

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

5.5 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 survey of potential damage mechanisms that may lead to changes of the alumina inclusions during operation. Axpo claims that fatigue damage due to thermo-mechanical loading is the only potential mechanism that may influence the inclusions. Axpo has estimated the effect of inclusions on fatigue crack growth from the fatigue pre-cracking 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 Al_2O_3 inclusion agglomerates 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 alumina inclusion agglomerates 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 of 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 Al_2O_3 inclusion agglomerates present in the Beznau-1 RPV do not significantly affect the fatigue crack growth rates.

5.6 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, develop models and 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 survey 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 that they would influence the irradiation embrittlement of the surrounding matrix.

Neutron embrittlement of RPV steel becomes significant for neutron fluences exceeding 10^{17} cm^{-2} (E > 1 MeV). There is increasing hardening and embrittlement of the steels with increasing neutron fluence, which results in a higher ductile-to-brittle transition temperature (T_o from Master Curve 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 has to be expected.

To support the results from literature, investigations on materials from Shell C and Replica C have been performed.

5.6.1 RPV Shell C

Safety case description

In a first step, SEM/EDX, micro-hardness, and chemical element mapping measurements around the alumina inclusions were conducted on two selected specimens: one unirradiated, broken specimen SE(B) in T-L direction from 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 agglomerates 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 inclusion agglomerates 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 agglomerates. 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 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, chemical element mapping, and EDX measurements. Areas in the vicinity of Al_2O_3 inclusion agglomerates and between agglomerates were analysed.

None of these tests on unirradiated and irradiated acceptance test Shell C material showed any unusual enrichment of Copper, Nickel and Phosphorus or increased micro-hardness zones in the vicinity of Al_2O_3 inclusion agglomerates, between them 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.

From this, Axpo concluded that the theoretical expectation is adequately confirmed.

ENSI review

The micro-hardness measurements, chemical element mapping, and energy dispersive X-ray (EDX) analysis in the vicinity of alumina inclusions performed, did not show any significant differences between the irradiated and unirradiated specimens. ENSI therefore supports Axpo's conclusion, that the theoretical expectation is adequately confirmed.

However, the alumina agglomerates present in the specimens of Shell C are relatively small and not representative in size and density for the alumina agglomerates found in most affected zones of Shell C. Furthermore, no investigation on the surrounding matrix between single or large Al_2O_3 inclusion agglomerates was carried out.

To remedy this, 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).

5.6.2 Replica C

Safety case description

At ENSI request, Axpo extended the investigations to Replica C material with Al_2O_3 inclusion agglomerates 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 Al_2O_3 inclusion agglomerates, the full thickness of the Replica C as well as different planes and orientations. Results are given in /113/.

Based on these results Axpo claims that neither the micro-hardness nor the chemical mapping shows any abnormality. The chemical elements found in the vicinity and between the inclusion agglomerates are in full compliance with the material specification.

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.

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 Al_2O_3 inclusion agglomerates, between them and in the surrounding matrix.

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

5.7 Fracture toughness of irradiated material

Historically, adjusted reference temperature for indexing the ASME lower bound toughness curve (k_{IC}) has been determined based on RT_{NDT}. This parameter is based on the combined results from Charpy V notch and drop-weight nil-ductility transition temperature tests as defined in the ASME Code for the unirradiated condition. 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 case of forgings and plates, this indexing parameter is overly conservative relative to the real toughness of low-alloy RPV steels.

The Master Curve (MC) fracture toughness method with tests by 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 more technically sound than the RT_{NDT} approach and uses the statistical nature of measured fracture toughness properties including direct tests of surveillance materials.

The Master Curve method 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 quality 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 them. Using T_0 instead of RT_{NDT} leads to a reduced degree of scatter in fracture toughness data. This can be observed also 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 irradiation sample set is derived from classical Charpy test results.

5.7.1 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 fluence impact 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 Master Curve 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 on Shell C material is higher than for Shell D. 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 uses these reference temperatures as a function of fluence for deterministic PTS- analysis.

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

For a planned operating lifetime of 60 years, Axpo carried out an assessment of irradiation embrittlement of the Beznau-1 RPV based on 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 have been 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. Due to the unresolved size effect of the acceptance test Shell C material 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 however agrees that the MC transition temperature T_0= -35.5ºC 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 irradiation sample set is derived from classical Charpy test results, ENSI considers that this procedure is conservative and requires application of Method II-B for the SIA of the Beznau-1 RPV Shell C.

5.7.2 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 93ºC in 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 without imperfections. After completion of the surveillance program in 2012, results for the reference temperature $RT_{ref,ART}$ at location of maximum fluence (azimuthal angle 0º) for 54 EFPY and the Charpy upper shelf energy can be summarised as follows:

- $RT_{ref,ART}$ using method II-B: inner-surface 89ºC, ¼ wall thickness 83ºC;
- 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 (10ºC for the reference temperature and 45 J for the Charpy upper shelf energy).

5.8 ENSI conclusions on material properties

Using Replica C material Axpo was able to show that the alumina inclusion agglomerates 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 crack growth rate as well as the microstructure near and between Al_2O_3 agglomerates /57/. Furthermore, Axpo has shown by micro-hardness measurements and SEM/EDX chemical mappings that the alumina agglomerates present in the Beznau-1 RPV do not show features 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. Due to the unresolved size effect of the acceptance test Shell C material 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 larger 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.

6 Structural integrity assessment

The purpose of the structural integrity assessment (SIA) is to verify that the structural integrity of the RPV is maintained under all operating and accident conditions, given the presence of inclusions, when assessed by a conservative flaw model.

The SIA was performed for all governing loading conditions according to the applicable rules of the 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 pressurized thermal shock analysis: assessment of the resistance against pressurized thermal shock events according to KTA standards.

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

6.1 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 with the Axpo “Hauptstudie 2016”/173/.

The governing operating conditions (normal and upset) consider:

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

The governing emergency and faulted conditions consider:

- Loss-of-coolant accident inducing a pressurized thermal shock (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 sufficiently been demonstrated by the applied NDE according to the KTA standard /83/ (see Chapter 2). As such it is credited in the structural integrity assessment.

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

ENSI review

The governing operating and accident conditions concerning thermal hydraulic transients have been reviewed by ENSI within the frame of the Long Term Operation (LTO) verification /175/. The ENSI review was supported by an expert approval /174/. In this review, the determination of the leading accident transients has been confirmed, based on 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/. Further 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 is expected to be demonstrated by Axpo every year, based on 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 have been addressed and verified in separate reports /173//174//175/.

When local loadings are used in the flaw assessments, in case of PTS-relevant locations ENSI confirms that all potentially relevant design transients are covered in the SC. The thermo-hydraulic analysis and the stress state of the vessel have been checked and confirmed by GRS /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 is missing as well as references of third–party reviews (see Chapter 5.1 of /14/). It should be noted however, that the flaw assessments which are crediting not-yet-validated loadings, are used only to demonstrate margins. They are not relevant to demonstrate structural integrity (see Chapter 6.5.2).

6.2 Flaw assessment

Axpo decided to perform a flaw assessment in line with the ASME XI procedures. 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 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.

6.2.1 Primary stress limits assessment

Safety case description

The allowable local area reduction of the cross section is calculated following the procedure of ASME III NB-3324.1. Based on the allowable primary stress limit Sm derived from the material properties for material with indications /98/ /94/, the minimum required wall thickness has been determined for Shells A, B, C and E. The minimum required wall thickness allows the calculation of the acceptable area reduction of the cross section according to primary membrane stresses, which can 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 have been taken into account. A possible fatigue crack growth of the flaws has been considered. The flaws have been sized conservatively using enveloping boxes.

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

A supplementary numerical elastic-plastic analysis has been 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 is covering 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 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.

The primary stress limits of NB-3000 are required to be satisfied by IWB-3610 in combination with an analytical flaw evaluation assuming a local area reduction 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 no influence on strength variation, and the remaining indications are covered by general acceptance standards for fabrication flaws. However, all indications have been enveloped by UT boxes, which results in local area reductions of the cross sections. The reservation regarding possible under sizing of some few flaws in /172/ is well compensated in this process. ENSI confirms the conservatism of the process to calculate the area reduction. This conservative approach demonstrated margins compared to the required safety factor defined by the code.

In addition to the conservative analytical demonstration of primary stress limits, numerical elastic-plastic analyses have been performed which 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 is not documented in a verifiable manner /95/.

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

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

6.2.2 Assessment of the HAI in Shell C

Safety case description

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

As the investigations by material test specimen of Replica C did not completely represent amplitude distributions above REF-6 dB as found in the RPV Shell C, a small number of high-amplitude indications was evaluated 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). Therefore, 20 indications recorded by the Intercontrôle NDE system (all with amplitudes higher than REF-6 dB and located in Shell C) were assessed.

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

Cladding integrity is confirmed by NDE for Shell C. 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.

Considering the cladding-base metal interface proximity rules of IWA-3000, 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 as well as based on a less conservative combination of ASME XI with a specific AREVA procedure /98/. The more conservative IWA-3300 procedure resulted in three groups of axial and circumferential flaws respectively.

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

A group of closely spaced HAI within EA600 has been 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 has been 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/ .

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

For the closely spaced HAI in EA600 a conservative procedure with respect to the recommendation for modified sizing in /172/ was provided by Axpo /205/. In the new approach the flaws are represented by an area of 7.3 mm x 43 mm followed by enveloping this area by an underclad crack of 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. Also the comparison with already approved allowable flaws for PTS transients /175/ corroborated the acceptability.

6.2.3 Assessment of indications in Shell E

Safety case description

For Shell E, the NDE results are based on a different inspection method and for conservatism all indications were considered in the flaw assessment /145/ based on two methods /98/.

In the first method, a pre-calculated allowable flaw size from a previously conducted generic flaw assessment /98/ has been used for comparison with an enveloping region containing 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 cladding interface.

The second method according to the code procedure described in /98/ 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 is based on conservative boundary conditions. Enveloping loading conditions inside a plume and at the height of the upper weld seam were considered as well as crack growth for another 20 years of operation.

The material reference temperature is based conservatively on RT_{NDT} and resulted in a enveloping 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 orientation, which is representative for material with inclusions as found in Shell C and would result in a $RT_{Ref,ART}$ = -40.5°C.

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

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

ENSI review

There are no concerns regarding sizing or flaw type expressed by the reviewing experts /171/, /172/, /191/ for Shell E. Getting all these flaws included in the flaw assessment of Shell E regardless of whether they were covered by the material investigations is a conservative approach. The assessment was done to cover uncertainties with respect to the fabrication documentation as discussed in Chapter 3.2.

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

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

The application of the specialized grouping rules for the assessment was accepted by ENSI (see Chapter 6.5.2). Crack growth according to specified transients with respect to another 20 years of operation is marginal but nevertheless considered before grouping.

The material reference temperature established for Shell E is in conclusion conservative.

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

6.3 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 applied 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 has to 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 new p-T curve is enveloped by the OMS 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 alumina inclusion agglomerates 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 due to a potential influence of alumina inclusion agglomerates on irradiation embrittlement (see Chapter 5.6), 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 5.7).

6.4 Deterministic PTS analysis

Safety case description

Axpo finished in 2017 an update of the standard PTS assessment for LTO regarding actual methodology, applied software versions of RELAP and KWU-MIX and relevant boundary conditions /173/.

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

Axpo credited the integrity of the cladding based on 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 as 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, where some indications are conservatively sized, enveloped 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 12 mm x 72 mm.

6.5 Demonstration of conservatism and of the margins of the SIA

6.5.1 Conservatism of the integrity assessment

Safety case description

In the synthesis report of the SIA /34/, Axpo gives attention to the following conservatism aspects of the integrity assessment:

Conservatism regarding 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 Al_2O_3 inclusion agglomerates that are smaller than the beam size are assumed to be equal to the beam size. This applies to the majority of the indications. Ligament between inclusions is therefore generally underestimated.

The HAI are not covered conservatively by the samples tested and are assessed separately and their acceptability is assessed by means of SIA. Conservatively, the interconnected HAI areas of the EA600 were geometrically combined into one enveloping area and evaluated as a single flaw /205/. The acceptability was demonstrated by analytical evaluations.

Conservatism regarding the flaw model

The applied model, projecting the flaws into both axial and circumferential planes perpendicular to the maximum principal stresses (crack opening mode), is very conservative. The projected flaws are planar flaws although the inclusions can be considered as laminar flaws. Following the principles of fracture mechanics, all flaws were considered as cracks despite the non-crack-like shape of the alumina inclusion agglomerates. Due to the interaction of closely spaced defects, adjacent flaws were combined. The conservatism of the applied grouping rules was demonstrated and confirmed.

Conservatism in 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 overpressure mitigation system 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 to be conservative, as the conservativism provides protection against statistical variability and unknown factors. The total conservatism in a SC for the RPV must be sufficient to give an extremely low probability of failure. This 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 model, 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 volumetric shape (voids) without relevant 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 a conservative procedure with respect to the recommendation for modified sizing in /172/ was applied by Axpo /205/. 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 followed by enveloping this area by 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.

6.5.2 Margin discussion

Safety case description

The material tests showed that most of the indications 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 have been 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 exemption. 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 have been provided in /98/, differing 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 % is defined as grouping criteria for the current case. This criterion is much more conservative than other common criteria like an increase of 6 % in K_I as accepted by ASME CC-N-848 for quasi-laminar flaws or an increase of 10 % in K_I as accepted by the French RSE-M code /116/.

The required material properties, particularly the fracture toughness characterising the matrix of the flawed region, has been 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 performed SIA analyses regarding all indications found in one of the EAs as one very large flaw /31/.

It was shown that all flaws are acceptable by code based criteria, demonstrated in a stepwise approach using acceptance standards, analytical flaw evaluations and numerical flaw evaluation with considerable margins.

ENSI review

The construction code for the Beznau-1 NPP and especially for its RPV was ASME section III. Therefore, the flaw evaluation has been 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.

The material properties have been assessed and accepted by ENSI as detailed in Chapter 5 of this report, as well as the local fluence distribution /175/. On the use of local loading conditions ENSI has expressed its reserve in Chapter 6.1.

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. Within the frame of the periodic safety review of 2018, the margin assessment will have to be revised.

6.5.3 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 determined not to be 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.

The only measure evaluated to have a significant benefit is 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 realised measures to increase the water temperature in the accumulator tanks to over 30ºC 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.

6.6 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 analysed based on the procedures and requirements of Section III and Section XI of the ASME Code. The flaw assessment is conservative as concerns 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 loss-of-coolant accident (PTS) is conservatively assessed by deterministic procedures.

ENSI considers that the local loading conditions used for some margin calculations were not exhaustively demonstrated yet and expects, within the frame of the periodic safety review of 2018, the margin assessment to be revised.

7 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 falsified 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.

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/, and neither explained in its logical argumentation chain nor referenced. The TSOs mandated by ENSI also identified contradictory statements in different reports that need clarification and verification.

Within the frame of the periodic safety review of 2018, ENSI will verify if the technical documentation regarding the RPV is up-to-date.

8 Safety case assessment by the International Review Panel

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

9 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 closely followed the developments in the Safety Case since 2015.

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 demand for additional information and material tests.
- December 2017: Axpo submits revision 2 of the Safety Case including the demanded 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 as well as 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 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 have been 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 to be essential.

- **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. Alumina inclusion agglomerates originating in the sedimentation cone with negative segregations were identified to be 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 regarding 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 alumina inclusion agglomerates 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. Exceptions are the HAI mentioned above. Said exceptions have nonetheless no impact on the conclusion of the Safety Case because the HAI 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.**

  Using Replica material it was possible to show that the alumina inclusion agglomerates 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 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 hypotheses cannot be excluded with certainty, have been analysed according to the procedures and requirements of Section III and Section XI of the ASME Code.

The flaw assessment is conservative regarding 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 loss-of-coolant accident (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.

Within the frame of the periodic safety review of 2018, the margin assessment will have to be revised.

ENSI overall conclusion

Based on the abovementioned arguments 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 request, which however can be addressed after the recommissioning of Beznau-1:

> **Request 1:** 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 2022.

The IRP came in its independent review also 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.

10 References and submitted documents

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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

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Project BEFLAW, Submission of technical Reports with reference to requests from ENSI/IRP after 3rd Expert Meeting in December 2016

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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

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