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TECHNICAL REPORT

COMPARISON OF RULES-MAKING AND PRACTICES

CONCERNING REACTOR PRESSURE VESSEL INTEGRITY ASSESSMENT

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CONTENTS

1 INTRODUCTION

The Reactor Pressure Vessel (RPV) is one of the most important components in nuclear power plants. With the exception of the upper head it is considered irreplaceable, which means that it can be the life-limiting component of the nuclear power plant, if its mechanical properties are degraded to such an extent that RPV integrity cannot be proven for all operational and accidental situations of the plant. As neutron irradiation degrades the fracture toughness of the beltline of the lower part of RPV during operation of the plant, the integrity of the beltline has to be proven by fracture mechanical analyses that are the main subject of this report.

Moreover, in the frame of the defence-in-depth approach, the failure of the RPV is not assumed in the original design basis of the plants in operation today. This means that there are no measures which could ensure accident mitigation in case of RPV gross failure except for those plants that implemented measures to cope with this failure, *i.e.* new plants that included RPV gross failure in their design basis and some existing plants that implemented suitable backfitting measures. Yet, for most plants in operation today, this application of the assumption of break preclusion to the RPV therefore requires ensuring a very low probability of RPV failure by strengthening the first two levels of the defence-in-depth approach. This is performed by defining stringent regulatory requirements in the design, procurement, manufacturing, in-service inspection, surveillance program, and more globally in the structural integrity assessment of the RPV.

Most of the regulatory requirements related to the RPV structural integrity defined in the different ETSON countries are based on similar principles, but their approaches may differ significantly. In the frame of the activities of the ETSON Expert group "Mechanical Systems", it has been decided to compare regulatory requirements for RPV fracture mechanical assessment in ETSON member states, particularly in Belgium, Czech Republic, France, Finland, Germany, Russia, Slovakia, Switzerland and Ukraine.

This report provides a synthesis of this comparison. The abbreviations, predictive formulae for the irradiation induced changes of the material toughness and standard fracture toughness curves used in the participating countries are described in annex 1 to this report. Details of the regulatory requirements are given in the comparative table attached as annex 2 to this report. The main objective is to improve the mutual understanding of the different approaches and the identification of differences as well as possible evolutions of the regulations. However, in general, this report will neither provide direct comparisons nor recommendations, as these are already available in different international publications, *e.g.* in the OECD report on the PTS ICAS project /OEC 99/ or the IAEA report on good practices for PTS assessment /IAE 10/.

2 APPROACH FOR INTEGRITY ANALYSES

2.1 General approach

The general approach for the integrity analysis of the RPV is basically the same in all participating countries. The most severe loading of the RPV is analysed for different categories of operating conditions or service levels (*i.e.* normal operation, abnormal operation, accidents and testing conditions; or service levels A, B, C, D according to ASME /ASM III/, article NCA-2142). Thermo-hydraulic analyses of the different transients (including accident scenarios) and the following evaluation of the heat transfer to the RPV will result in time dependent temperature distributions within the RPV. The temperature gradients within the RPV create a stress field analysed by structural mechanic codes mostly using finite elements. These stresses are superimposed to those created by the internal pressure in the vessel.

As the existence of defects in the RPV cannot be excluded with absolute certainty and to show some defect tolerance, cracks as the most detrimental kind of defects are postulated at the most adverse location and orientation. The loading of the crack during the transient in terms of a stress intensity factor $K_I(t, T)$ is then compared to the fracture toughness of the material $K_{Ic}(T)$. If the loading is lower than the fracture toughness then no crack initiation will occur. Showing this is mandatory in most countries. Graded safety factors are applied for the different categories of operating conditions, *i.e.* larger safety factors are required for more frequent operating conditions. Major differences between the requirements in the participating countries exist in the choice of the boundary conditions and applied safety factors. This approach is a deterministic one in all countries.

Probabilistic approaches are applied as supplemental plant specific analyses in many countries. In Switzerland the application of probabilistic fracture mechanics (PFM) is under investigation with the aim to establish PFM for the assessment of RPVs and piping. Beside these plant specific analyses, a simplified procedure based on generic probabilistic analyses following the US-American regulations is applied in Belgium.

2.2 Fracture toughness and Ductile-Brittle Transition

All ferritic steels undergo a transition from brittle behaviour at low temperature (*i.e.* the "lower shelf" with low fracture toughness) to ductile behaviour at higher temperatures (*i.e.* the "upper shelf" with much higher fracture toughness), see figure 1 for illustration. The temperature range of the transition between both levels is relatively narrow (in the range of 50 to 100 K) and it is generally indexed by a ductile-brittle transition temperature (DBTT). In the traditional approach a generic fracture toughness curve K_{Ic} (T) can be adjusted on the temperature axis by this transition temperature, *i.e.* it has the form K_{Ic} (T - DBTT). Close to the upper shelf, where some plastic deformation takes place before fracture, fracture toughness is referred to as K_{Jc}. Next to this curve K_{Ic} (T) based on data for crack initiation, some mechanical codes consider a similar curve based on crack arrest data K_{Ia} (T). As crack arrest takes place at lower K_I -values than initiation the K_{Ia} (T) -curve is below the K_{Ic} -curve. The K_{Ia} (T) -curve is also referred to as K_{IR} (T) being a common lower bound to all fracture toughness data.

Neutron irradiation leads to a degradation of the fracture toughness of the materials within the beltline of the RPV. This degradation can be represented by a shift of the DBTT to higher temperature, see figure 1. In the fracture mechanical analyses this is considered by predicting the shift of the DBTT and hence of the K_{Ic} (T - DBTT) curve with respect to the temperature T until the end of plant life. This prediction is done by an equation where the shift of DBTT, *i.e.* ΔDBTT, is a function of the fast neutron fluence and a factor that depends on the material. This predictive equation is an empirical formula based on experimental data. This prediction for design purposes is then validated by test results of surveillance specimens made of materials representative for the beltline materials and subject to accelerated irradiation within the RPV.

Historically, this curve K_{Ic} (T - DBTT) was created as a lower bound curve to a large number of fracture toughness data K_{Ic} (T) by testing rather large specimens, mostly of CT-type. This type of specimens is considered too big to be integrated into the RPV surveillance program. Therefore these fracture toughness data were correlated with the DBTT of the same materials determined by testing small specimens (mostly Charpy type; Pellini tests were only performed with unirradiated material, see below) that are also used for acceptance tests and that also serve as surveillance specimens to be installed in the RPV.

2.3 Definitions of Ductile-Brittle Transition Temperatures

In different countries the fracture mechanical assessment of reactor pressure vessel is based on different definitions of the DBTT, *i.e.* RT_{NDT}, T_0 or T_k. There are significant differences of the approaches determining these DBTT. Different criteria are used to define the different index temperatures such as:

- T_{NDT}: Nil-Ductility-Transition-Temperature defined by the Pellini test (specimen breaks at this temperature, but does not break at T_{NDT} + 5K, *i.e.* the initiated crack is arrested before reaching the edge of the specimen.)
- T_{xyJ}: temperature where the Charpy impact energy mean curve reaches level of xy J.
- $T_{0.9mm}$: temperature where the lateral extension curve of the Charpy impact test reaches 0.9 mm.
- $T_{50\%}$: temperature corresponding to 50% shear fracture appearance of broken Charpy specimens (also called FATT50).

A combination of these index temperatures is used to define DBTT in the unirradiated state, *i.e.* RT_{NDT}

$$RT_{NDT} = \max\{T_{NDT};\ T_{68J} - 33\ K;\ T_{0.9mm} - 33\ K\}$$

The DBTT used for assessment of VVER RPVs, *i.e.* the critical temperature of brittleness Tk, is based on the Charpy impact tests only. Tk definitions slightly differ in different VVER codes (/PNA 86, RD 12a/, /VER 08/, etc.). For example, the Charpy impact energy level for establishing Tk is dependent on yield stress in /PNA 86, RD 12a/, *e.g.* for typical RPV steels

T_k=max {T_{47J}; T_{70J} - 30°C}.

According to /PNA 86, RD 12a/ this criterion is used for unirradiated as well as irradiated specimens, while in /VER 08/ Charpy impact energy value of 41 J is used for establishing ΔT_k. This measure of $\Delta T_k = \Delta T_{41J}$ is consistent with the measure of shift in most countries using RT_{NDT}, where $\Delta RT_{NDT} = \Delta T_{41J}$.

All these traditional index temperatures have to be correlated to a K_{Ic} curve based on fracture toughness measurements. RT_{NDT} is correlated to the ASME K_{IC}-reference curve for the steel types used in Western countries. T_k is correlated to similar curves that depend on both the material type (different for base and weld metals for VVER 440 or 1000 reactors) and in some countries also the category of operating conditions, as the safety factor is integrated into these curves for normal and abnormal conditions while it may be as low as 1 for emergency conditions. These correlations were established experimentally using CT specimens.

More recently, a new index temperature, the reference temperature T_0 of the Master curve, was proposed based on direct fracture toughness measurements. It is based on the facts that the statistical distribution (or scatter) of the fracture toughness data in the transition region is similar for all ferritic steels and can be described mathematically. Furthermore, the shape of the fracture toughness vs. temperature curve in the transition range is virtually identical for all ferritic steels. The only difference between steels is the absolute position of this curve on the temperature axis that can be indexed by T_0. T_0 is defined as the temperature at which the median fracture toughness is 100 MPa √m for a 25 mm thick specimen. The temperature dependence of median toughness in the ductile-brittle transition region can be defined as:

$K_{Jc(median)} = 30 + 70\exp[0.019(T - T_0)]$ (MPa √m and °C).

Instead of using T_0 and the Master Curve (or its 2% or 5% fractile[1]), T_0 may also be used in some countries as an alternative to RT_{NDT}. While RT_{NDT} in the unirradiated state is constituted by a combination of Pellini and Charpy impact test results, no Pellini tests are performed to establish T_0 or T_k. In fact T_{NDT} determines RT_{NDT} of RPV base materials in most cases in the unirradiated state. Therefore T_0 and T_k might be significantly lower than RT_{NDT} for base metals. This effect is particularly pronounced for T_0. Therefore, if T_0 shall be used as an alternative to RT_{NDT} as an index temperature for the ASME K_{IC}-reference curve an additional shift and a margin shall be used as described in ASME Code Case N-851 /CC 851/ and in /KTA 3203/:

$RT_{T0} = T_0 + 19{,}4K + \text{Margin}$.

Here the margin shall consider the influence on T_0 of the specimen type and size, the number of tests performed, and of the material type (weld or base metal) and its inhomogeneity.

Finally the irradiation induced shift of the DBTT that is generally based on the shift of the Charpy impact energy mean curves may be measured at different energy levels, *e.g.* as ΔT_{39J}, ΔT_{41J} or ΔT_{48J} or ΔT_{56J}, resulting in slightly different values of shift. In general, the shift of the Charpy impact energy mean curves at higher energy level is a little larger than at lower level and ΔT_0 tends to be a little larger than ΔT_{41J}.

Therefore, these differences should be considered, when comparing different values of DBTT. A direct comparison of individual results may only be done by comparing the detailed results of the tests. In contrast to RT_{NDT} and T_k, T_0 is based on directly measured fracture toughness (in the irradiated or unirradiated state) assuming a statistical distribution of test results that is not consistent with a "lower bound curve". Therefore T_0 and the probabilistic Master

1 *The fractiles are defined so that statistically only 2% or 5% of the data fall below these curves for a large number of specimens.*

curve concept are not directly comparable to the deterministic concepts using RT_{NDT} or T_k.

Nevertheless correlations of RT_{NDT} or T_k and T_0 are used in some countries in order to use the standard “lower bound” fracture toughness K_{IC} curve that is based on a large number of historical K_{IC} test results indexed to RT_{NDT} or T_k and allowing to use a deterministic concept. As there is no simple transformation formula between different DBTT, any correlation results in large scatter. This requires the introduction of additional margins to assure a conservative result.

Direct measurement of fracture toughness, *e.g.* of three point bend or CT specimens may be used to prove that the material toughness prediction is still conservative. While the lower bound curve shall not be corrected for specimen size (*i.e.* crack length), when using a fractile curve of the Master Curve approach instead of a lower bound curve, the appropriate size corrections have to be applied. So far all participating countries use the lower bound curve, as they want to maintain the deterministic historical approach.

2.4 Normal and abnormal operation

Normal operation typically contains plant heat up or cooldown at a limited rate, stepwise increase or decrease of power at a limited rate, steady state fluctuations. Abnormal operation includes conditions like fast heat up, fast cool down, loss of offsite power, loss of feedwater, loss of main heat sink. Testing conditions include hydraulic pressure tests.

Besides proving the adequate selection of the material, the design encompasses an analysis against fast fracture, which leads to establish the heat up and cooldown (p-T) limit curves for normal operation. This analysis requires a reference curve of the critical stress intensity factor (*i.e.* fracture toughness) as a function of temperature [K_{Ic} (T) or K_{IR} (T) -curve, see Annex 1], a postulated crack in the ferritic base or weld metal and a K_I expression.

Unstable propagation of a crack is assumed to occur when the value of K_I reaches the K_{Ic} (T) reference curve. Therefore the loading K_I (t, T) is compared to the K_{Ic} (T) -curve in most countries, while Belgium uses the more conservative K_{IR} (T) -curve. The resulting p-T limit curves have to be regularly updated during operation as a consequence of the impact of the embrittlement due to neutron irradiation on the K_{Ic} (T) or K_{IR} (T) reference curve.

The postulated crack used in the p-T curve analysis is generally of semi-elliptic shape, but differences exist between countries on the postulated size. For example, on the one hand in France, the design calculations consider a crack depth equal to ¼ of the wall thickness, whereas calculations performed during operation consider a crack depth based on the limitations of the NDE equipment used for in-service inspection (ISI). On the other hand, in Germany and Belgium, the same approach is used for the design and operation calculations, using a crack depth equal to ¼ of the wall thickness on either side of the RPV wall. For some other countries (Czech Republic, Slovakia, Ukraine), the postulated crack size is always based on the NDE limitations. In Russia the crack depth is fixed at 0.07 times the wall thickness /RD 12b/.

Differences also exist on the safety factors that are applied in the proof of integrity and on the way they are applied (increasing the load, reducing the allowable stress intensity factor or increasing the size of the postulated crack. These many differences render a generic comparison quite difficult. Such a comparison could only be done using for example a benchmark analysis.

2.5 Accidental conditions

For design basis accidents (emergency conditions or levels C and D according to ASME nomenclature/ASM III/) similar analyses are performed, yet with smaller safety factors as the probability of occurrence of these conditions is much lower. These conditions also include pressurized thermal shock (PTS) scenarios that are most important for RPV brittle fracture analysis.

In most participating countries the postulated crack sizes for the fast fracture analyses are based on the specified limit of the NDE equipment used for ISI that have to be multiplied by a safety factor in some countries. In Russia the crack depth is fixed at 0.07 times the wall thickness /RD 12b/.

2.6 Selection of PTS scenarios

In all countries performing PTS analyses the most detrimental transients have to be selected by analysing different groups of transients: small, medium, large LOCA, secondary leaks, primary to secondary leaks, inadvertent ECCS actuation.

There are some plant type specific transients for VVER plants like flooding of RPV from outside. The transients initiated by inadvertent opening of the pressurizer safety valve (PRZ SV) including re-closure that represents one of the severe transients to be considered for VVER plants appears to be under discussion in some countries operating Western type PWRs. If and how these transients have to be considered depends on their probability of occurrence. This is a question of the reliability of the PRZ SV under all operating conditions and may be subject to backfitting measures.

2.7 Prognosis of irradiation induced changes

In any case a prognosis of irradiation induced changes of the DBTT is used in the design phase of the plant. This is always based on a predictive formula using the power function of neutron fluence with the exponent between 0.28 and 0.6 and a second factor that may be a constant (*i.e.* a fixed value for some specified material) or based on the concentration of some chemical elements of the RPV material promoting irradiation embrittlement, *e.g.* Cu, P, Ni and Mn.

As these different predictive formulae were developed experimentally on the basis of data obtained from vessels of a few manufacturers and specifications, respectively, they should not simply be transferred to the vessels of other manufacturers or specifications.

2.8 How is the prognosis used for safety demonstration?

France, Belgium: The predictive curve is used for the safety assessments of the RPV and the surveillance data are used only for validation of the prediction. For the unirradiated state the measured value of RT_{NDT} might be used, while in France the specified value is usually taken.

Czech Republic, Russia, Ukraine, Slovakia, and Switzerland: If there is a sufficient number of data, the curve established on the basis of surveillance data can be used for the assessment with a margin added. Otherwise, the design curve has to be used.

Germany: There is a value of RT_{NDT} (EOL) = 40°C that is an upper bound to all surveillance data of German plants in operation. Either this value or the result of the surveillance program may be used for safety assessments.

3 SCOPE AND TECHNIQUES OF NDT

3.1 Inspections during manufacturing

Regarding the inspections during manufacturing, it seems that there are only minor differences in the general NDT requirements among the countries. In all cases the forgings, welded joints and cladding have to be covered to 100% by UT. Other techniques like PT or MT may apply for surfaces and testing of intermediate welding layers.

3.2 Pre-service inspections

While all parts of the RPV are subject to 100% inspections during manufacturing, the pre-service inspections mainly serve as a baseline for the ISI. The coverage of the pre-service inspections of the RPV show significant differences, as in some countries the whole vessel is covered (Czech Rep., Slovakia, Ukraine; in Germany this is not required by the code but was current practice), while in other countries the inspections are restricted to the welds and surroundings (France, Belgium) that are also covered by the standard ISI.

3.3 In-service inspections

Regarding ISI there are some differences:

In PWR plants in Western countries ISI of the RPV is focussed on welds and their surroundings and the inner surface of the cladding. All inspections are done from the inside of the vessel. In France the area under the cladding is checked in addition for underclad defects in the beltline zone. The UT probes with straight beam included in the system are considered to detect laminar defects in the depth range up to 80 mm. The latter type of inspection was also performed in Belgian plants once. Inspection periods are generally 10 years for those countries following ASME, 5 years in Germany.

Also in VVER vessels ISI of the RPV is focussed on welds including the inner surface of the cladding and the BM in the surrounding of the welds. In addition some inspections of some part of the BM in the beltline are performed in some countries, *e.g.* in Slovakia a section of 600 mm height of the base metal in the centre of the core is inspected by UT every 8 years. Besides, inspections are performed from the inside and the outside that may be performed in an alternating manner. Inspection periods were initially 4 years, they were extended to 6 or 8 years in some cases.

The inspection strategies in the participating countries appear to be adequate. Nevertheless operating experience may have to be taken into account by special inspections. In the frame of LTO a change of inspection intervals or scope of the inspections may be considered.

4 CONTENT AND SCOPE OF IRRADIATION SURVEILLANCE PROGRAMS

4.1 Type of specimens

The type of specimens included in the surveillance programs is almost the same in all countries (tensile, Charpy and fracture toughness). There may be some differences in the number of sets and the amount and kind of fracture toughness specimens.

The surveillance programs of VVER 440 RPVs may also include specimens (or inserts from Charpy specimens already broken for testing) to assess the effect of annealing and re-embrittlement.

4.2 Specimens from cladding

In general there are no specimens made of cladding material included in the surveillance programs. Yet, the cladding thickness of VVER 440 vessels is particularly thick (9 mm nominal) and RPV fluence rather high. Therefore some VVER 440 units have some cladding specimens in their program, *e.g.*:

- in Slovakia there are also specimens included made of austenitic steels (archive base metal and cladding from Greifswald). They serve as surveillance specimens for the ageing of cladding and RPV internals;
- in the Czech Republic cladding specimens (Charpy size for J-R curve and tensile) are included in a supplementary program for LTO.

4.3 Specimens from HAZ

HAZ specimens are no longer required to be tested in the irradiated state in some countries (Germany, Finland, Switzerland) based on the experience that it does not show higher irradiation induced changes than the BM. Besides, test results for HAZ usually show large scatter because the cracks tend to deviate from the HAZ if the material in the neighbourhood exhibits lower toughness.

4.4
Lead factors required and realized

The lead factors, *i.e.* the ratio of fast neutron flux at the specimen and at the inner surface of the RPV, differ significantly between the plant types, reflecting different surveillance philosophies and assumptions (possible flux effect versus early results allowing for flux reduction as mitigative action): Lead factors are rather low (in the range of 1 to 2) in most VVER 1000, about 2 for Temelin and French 1,300 MW plants; about 3 for French and Belgium 900 MW plants, in the range of 3 to 6 in German plants, larger than 10 in the original VVER 440 surveillance programs. In most VVER 440 plants the original surveillance program was later replaced by a "supplementary" surveillance program with lead factors in the range of 2 to 6.

4.5
Extension of the surveillance program for LTO

In the Czech Republic and France some extra sets of specimens are foreseen to cover LTO. In some cases the design fluence will not be exceeded during LTO due to flux reduction measures such as low-leakage-core loading (*e.g.* Switzerland, France, Ukraine). In Belgian plants the surveillance programs cover 50 years of operation. In Germany, no LTO is foreseen.

The question of the coverage of an “extended beltline” (*i.e.* materials that exceed the regulatory limit for materials to be included in the surveillance program due to LTO) cannot be answered. There might be no material available of the extra weld or forging to be covered.

The possible embrittlement of RPV support structures may also be addressed as they have rather low operating temperatures, *e.g.* in VVER 1000 some support structures are close to the core. In Ukraine and Czech Republic these structures are subject to evaluation for LTO.

4.6
Fracture toughness specimens and tests

In Finland blanks are in the sets to be machined to three-point-bend specimens after withdrawal to test for T_0.

In the Czech Republic, Slovakia and Ukraine, the T_K value is established based on Charpy specimens only; Pre-cracked Charpy size inserts for fracture toughness tests are included in the surveillance program to establish T_0.

France and Belgium use only the RT_{NDT} approach. Small size CT (0.5 inch) specimens are included to validate the approach.

Small punch tests are not used for surveillance so far. It is still subject of research programs.

5 SPECIFIC ASPECTS OF FRACTURE MECHANICAL ANALYSIS

5.1 Application of T_0 and the Master Curve (MC)

While the MC is not applied in France, discussions are going on to introduce it in the RCC-M code as an alternative method to be used in countries where the safety authorities approved the application of the MC.

T_0 may be used in Germany, yet it is correlated *via* RT_{T0} with the classical K_{IC} lower bound curve using $RT_{T0} = T_0 + 19.4°C + M$. The value of the margin M is not defined in the code, yet reference is made to IAEA Guideline TRS 429 /IAE 05/ and ASME Code Cases 631 /CC 631/ and 851 /CC 851/.

A sufficient margin may be 10 to 15 K when using other than CT25 specimens and 15 K for pre-cracked Charpy V-notch specimens. The margin may even have to be larger if there are uncertainties of the fluence or if the material is not the same or inhomogeneous.

In Switzerland neutron embrittlement of RPV steels (BM and WM) has to be assessed based on surveillance specimens, whereas the fracture toughness is calculated as a function of temperature by

$$K_{Ic}(T) = min\left\{36.5 + 22.8 \cdot exp\left[0.036 \cdot \left(T - RT_{ref}\right)\right]; \sqrt{\frac{J_{Ic} \cdot E}{1-\nu^2}}\right\}.$$

Here the square root term defines the upper limit of the fracture toughness at high temperatures (*i.e.* the upper shelf).

The reference temperature adjusted to the fluence RT_{ref} = ART may be determined according RG 1.99 Rev. 2 (method I) /REG 88/ or based on the Master-Curve concept using T_0 (method II). Method II allows two options for the determination of T_0 described in ASTM E 1921 /AST 17/. In option A T_0 is determined directly from irradiated material, whereas in option B T_0 is determined from unirradiated material and its shift ΔT_{41J} or ΔT_{68J} is calculated as in method I.

In RT_{ref} margins have to be applied depending on the specimen type and material type (BM or WM). The margins are described in the guideline (ENSI B01) /ENS B01/.

In Belgium T_0 is tested only for additional information to show consistent behaviour.

In the Czech Republic and also in Finland surveillance specimens are regularly tested for T_0 and it is recommended to use the MC approach for RPV lifetime re-assessment in the future. Size correction and different margins have to be applied. From the surveillance results obtained so far, the shift ΔT_0 was larger than the Charpy shift in some cases.

Therefore, care has to be taken when mixing T_0 and Charpy concepts as the Charpy shift ΔT_{41J} and the shift of the MC, *i.e.* ΔT_0, tend to be different. This has to be kept in mind if a mixture of RT_{NDT} and T_0 is used to define a reference temperature (as *e.g.* in CH, DE).

As mentioned in chapter 4, some participating countries using T_0 correlate it with the classical lower bound K_{Ic} curve and do not apply the full MC concept with a probabilistically defined Master Curve, as they want to maintain the deterministic historical approach. According to /VER 08/ for application of Master curve approach, using the 5% fractile of the K_{Ic} curve is prescribed.

5.2 Differences in requirements for strength, ductility, fracture toughness

The level of strength and ductility of RPV steels appears to be similar in most cases with slightly higher values for yield strength of the VVER materials. Differences in DBTT are mainly reflecting the progress in manufacturing technology in the last decades. The requirements for older plants in some countries tend to allow higher transition temperatures at BOL while requirements for plants manufactured more recently are more restrictive. In some countries more stringent requirements for the DBTT at BOL apply to the beltline materials, because they are subject to irradiation embrittlement. A federal decree in Switzerland /UVE 08/ does not allow the adjusted reference temperature to exceed 93°C in a depth of 1/4t (this relates to the US criterion of 200°F for new plants, see RG 1.99 Rev. 2 /REG 88/) and the upper shelf Charpy energy (USE) should not fall below 68 Joule.

RT_{PTS} and the screening criterion of the US 10CFR 50.61 /CFR 50/ is applied in Belgium (RT_{PT} ≤ 132°C for BM and ≤ 149°C for circumferential welds), *i.e.* no plant specific PTS analysis has to be performed if that criterion is met.

5.3 Postulated crack sizes and locations in the ferritic material

The assumptions for the generic postulated cracks are related to the qualification of the NDE equipment in most countries. ISI by UT is effectively performed in all cases. Different aspect ratios are assumed for the geometry of postulated cracks. In general the generic postulated crack size should cover any defect considered possible, *i.e.* that might have escaped its detection by the NDE performed. Cracks are postulated separately for WM and BM at the most adverse location and orientation assuming material conditions corresponding to the highest fluence in the beltline. In case larger defects were detected, these have to be justified separately using the local conditions (fluence, temperature, stress). The requirements for the justifications are the same for postulated cracks and detected defects.

5.4 Consideration of cladding

In general the thermal effect and the elastic-plastic behaviour of cladding are considered in the analyses of temperature and stress distribution for postulated and real cracks. Yet regulations do not always give guidance how to apply these effects in the analyses.

In France for underclad cracks two criteria are assessed at the interface: resistance against unstable ductile tearing of the cladding and against brittle fracture of the BM (in addition to the brittle fracture assessment of the BM at the deepest point of the crack). For these analyses irradiation induced changes of cladding properties are taken into account. So far, these criteria have always been met. Furthermore, the fracture of the first layer of the cladding is postulated as an internal defect and analysed. (So far, no initiation is predicted by the calculations.)

In the Czech Republic, Slovakia and Ukraine the approach is similar as in France regarding underclad cracks, yet 1 mm penetration of the underclad crack into the cladding is assumed. No defect within the cladding is assumed as a separate postulate.

5.5 Consideration of residual stresses

Residual stresses are assumed in the cladding in some countries, yet in other countries it is assumed that the stresses are low or zero at operating temperature. In some countries the stresses to be assumed are not prescribed. Residual stresses of the welds are assumed only in some countries, in other countries the stress relief heat treatment is regarded as sufficient to assure rather low residual stresses that can be neglected in the fracture mechanical analyses.

5.6 Use of crack arrest

In most countries it has to be proven that there is no crack initiation, yet in some countries the integrity might also be proven based on crack arrest (Czech Rep, Slovakia, Finland). In the Czech Republic the crack arrest approach was not used so far while it is only applied in a few cases like LB LOCA in Finland.

5.7 Use of warm pre-stressing (WPS)

While the existence of the WPS effect is generally accepted, it is codified only in the German KTA 3201.2 /KTA 3201/ and also in the current version of VERLIFE /VER 08/. Yet it was also applied in some cases in several countries. The exact boundary conditions to be observed, in the frame of WPS application, in particular the question if WPS can also be applied for non-monotonically decreasing stress during cooling, are still under discussion.

5.8 Adjustments for different constraints, shallow cracks

These topics are not addressed in the national regulations. So far they are only a matter of research projects.

6 PREVENTIVE AND MITIGATIVE MEASURES

Fluence reduction by low-leakage core loading schemes is applied in many countries (also in Germany for economic reasons). Besides, heating of the emergency core cooling water is a measure taken in some plants to reduce maximum stresses and increase the final temperature in the RPV wall in the late phase of the PTS transients. Also improving emergency operating procedures can mitigate the potential PTS. In some VVER 440 plants the core weld of the RPV was annealed to restore its fracture toughness.

7 CONCLUSIONS

The investigation results prepared by the ETSON Expert group “Mechanical systems” are presented in this Report with the objective to improve mutual understanding of different approaches and identification of differences as well as possible evolutions in the regulations for the assessment of safe operation of the RPV.

The regulatory requirements related to the RPV structural integrity in force in Belgium, Czech Republic, Finland, France, Germany, Russia, Slovakia, Switzerland and Ukraine were considered in this investigation, namely the US-American ASME BPVC /ASM III/, /ASM XI/ and CFR /CFR 50/ applied in Belgium, the international VERLIFE /VER 08/ followed in Czech Republic and Slovakia, the Finnish YVL guidelines /YVL E.4/ and /YVL A.8/, the French RCC-M /RCC M/ and RSE-M /RSE M/, the German KTA /KTA 3201/, /KTA 3203/, the Russian Guidelines /RD 12a, RD 12b/, the Swiss ENSI guidelines /ENS B01/, the PNAE of the former Soviet Union /PNA 86/, and the Ukrainian MT-D /MTD 09/.

The main focus of the comparison was on the fracture mechanical analysis of PTS transients. The aspects related to thermo-mechanical loading, postulated crack size, prognosis and validation of irradiation embrittlement were addressed.

At the initial stage, the participants agreed that a direct comparison of rules applied to RPV integrity in those ETSON member states represented within the “Mechanical systems” Expert Group is impossible due to significant differences in detail between the approaches. Nevertheless, as the function and the design of the RPV are rather similar and as the design basis of all existing plants does not consider gross failure of the RPV, the engineering approaches are globally very close. This is also reflected by the different national regulations that all have some common features, *i.e.* they all require high quality materials with high toughness and ductility, sufficient margins against brittle and ductile failure during operational states and postulated accidents, and the ability to fully inspect the whole vessel during manufacturing and at least all welds in-service. ETSON members take part in the process of updating national and international regulations considering the best international practice and knowledge. Therefore, all aspects presented in this report may be used by ETSON members for updating regulations and in their evaluation of specific safety assessments.

Most of the regulatory requirements related to the RPV structural integrity defined in the ETSON countries represented by the participants are based on similar principles, but their approaches may differ significantly in detail. The following common features and differences in regulations mentioned above have been identified based on the comparison of the regulatory requirements performed by the Expert group:

- the level of strength and ductility appears to be similar with somewhat higher strength of the VVER steels. Differences in DBTT are mainly reflecting the progress in manufacturing technology in the last decades. Yet, a direct comparison of data from different countries is hampered by different definitions of the DBTT;

- different formulae were developed to predict the irradiation induced shift of the DBTT. As these are based on experimental data from vessels of a few manufacturers and specifications each, they should not be transferred to the vessels of other manufacturers or specifications;

- the types of specimens included in the surveillance programs are almost the same in all countries (tensile, Charpy and fracture toughness). There may be some differences in the number of sets, as well as the amount and kind of fracture toughness specimens;

- the lead factors for surveillance specimens differ significantly between the plant types due to different positions of the capsules in the RPV. These also reflect different surveillance philosophies and assumptions (possible flux effect, reliability of predictions versus early results allowing for flux reduction as mitigative action);

- concerning inspections during manufacturing, there appear to be only minor differences in the general NDE requirements among the countries. In all cases the forgings, welded joints and cladding have to be covered to 100% by these inspections;

- the assumptions for the size of generic postulated cracks in accidental conditions are related to the qualification of the NDE performed at the component in most countries. ISI by UT is effectively performed in all cases. Different aspect ratios are assumed for the geometry. In general, the generic postulated cracks should cover any possible real defects. In case of larger defects detected, these have to be justified separately using the local conditions (fluence, temperature, stress). The requirements for the justifications are the same for postulated cracks and real defects;

- according to all regulatory requirements, the KI calculated for existing or postulated cracks should be compared with the predicted K_{IC} values of the material but differences relate to different points of the postulated crack (in some cases comparison should be done at the deepest point and in other cases at all points of the crack front) in the framework of fracture mechanical analysis;

- in all participating countries it is shown that there is no initiation of the postulated or real cracks during all operating conditions including design basis accidents. Crack arrest after a postulated initiation may be shown as an additional level of defence in depth. Crack arrest as the only means of proving RPV integrity is not applied in practice although in principle accepted in VERLIFE /VER 08/, that is used *e.g.* Czech Republic, Slovakia and Finland;

- different safety factors are applied in the assessment of the integrity of the RPV in different countries and they are applied in different ways: increasing the load or reducing the allowable stress intensity or increasing the size of the postulated crack. Therefore a generic comparison of the safety factors is not possible. It may only be done using an example like a benchmark analysis.

It is also necessary to pay specific attention to Warm Pre-Stress (WPS) aspects. WPS is codified only in the German KTA 3201.2 /KTA 3201/ and in the current version of VERLIFE /VER 08/. It was also applied in practice in some cases in several countries operating VVER reactors. Their experience demonstrates that WPS application allows extending design lifetime of the RPV significantly. Details of the application of WPS for non-monotonically decreasing stress intensity factor during cooling are still under discussion.

8 REFERENCES

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  ASME Boiler and Pressure Vessel Code, Section III
  Rules for Construction of Nuclear Facility Components, Division 1,
  Subsection NB, Class 1 Components
  ASME, New York

- /ASM XI/ American Society of Mechanical Engineers (ASME):
  ASME Boiler and Pressure Vessel Code, Section XI
  Rules for Inservice Inspection of Nuclear Power Plant Components
  ASME, New York

- /AST 17/ ASTM E1921 (2017) ASTM E1921-17a, Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range, ASTM International, West Conshohocken, PA, 2017

- /CC 631/ ASME Code Case N-631: Use of Fracture Toughness Test Data to Establish the Reference Temperature for Pressure Retaining Materials Other Than Bolting, Class 1 Vessels; Approval Date: 24. September 1999

- /CC 851/ ASME Code Case N-851: Alternative Method for Establishing the Reference Temperature for Pressure Retaining Materials;
  Approval Date: 5. November 2014

- /CFR 50/ US Code of Federal Regulations, title 10, part 50:
  Appendix G, Fracture toughness requirements,
  Appendix H, Reactor Vessel Material Surveillance Program Requirements,
  50.61, Fracture toughness requirements for protection against pressurized thermal shock events

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  Part 4: In-service Inspections and Operational Monitoring

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- /OEC 99/ Comparison report of RPV Pressurized Thermal Shock International Comparative Assessment Study (PTS ICAS), OECD NEA/CSNI/R(99)3, Paris 1999

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- /RCC-M/ Design and construction rules for mechanical components of PWR nuclear islands, AFCEN, Edition 2016

- /RD 12a/ RD EO 1.1.2.09.0789-2012: Guideline for Determination of Fracture Toughness using Test Results of Surveillance for Strength Analysis and Residual Life of VVER-1000, Rosenergoatom, Russian Federation, 2012

- /RD 12b/ RD EO 1.1.3.99.0871-2012: Guideline for Calculation of Brittle Fracture Resistance of Reactor Pressure Vessels for VVER 1000, Rosenergoatom, Russian Federation, 2012

- /RSE-M/ In-Service Inspection Rules for Mechanical Components of PWR Nuclear Islands, AFCEN, Edition 2010

- /UVE 08/ Verordnung des Eidgenössischen Departements für Umwelt, Verkehr, Energie und Kommunikation (UVEK 732.114.5) über die Methodik und die Randbedingungen zur Überprüfung der Kriterien für die vorläufige Ausserbetriebnahme von Kernkraftwerken, Mai 2008

- /VER 08/ Unified Procedure for Lifetime Assessment of Components and Piping in VVER NPPs "VERLIFE", ver. 2008, 6th Framework Program of EU, Project COVERS, Contract N° 12727 (FI60), report COVERS-WP4-D4.10

- /YVL E.4/ Strength Analyses of Nuclear Power Plant Pressure Equipment (Guide YVL E.4), 15 Nov. 2013. Radiation and Nuclear Safety Authority (STUK), Helsinki, Finland

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9 CONTRIBUTORS TO THE REPORT

The following members of the Expert Group EG2 "Mechanical Systems" contributed to this report:

- François Balestreri — IRSN/France
- Vincent Deledicque — Bel V/Belgium
- Peter Hermansky — VUJE/Slovakia
- Uwe Jendrich — GRS/Germany
- Alexander Kryukov — SEC NRS/Russia
- Markus Niffenegger — PSI/Switzerland
- Vladislav Pistora — UJV/Czech Republic
- Tapio Planman — VTT/Finland
- Oleksiy Shugaylo — SSTC NRS/Ukraine

ANNEX 1

ABBREVIATIONS, PREDICTION FORMULAS, AND STANDARD CURVES

CONTENTS

1 ABBREVIATIONS USED IN THE REPORT AND/OR TABLE

A_{CV} [J]	Absorbed energy at Charpy test
A_F [1]	Irradiation embrittlement factor
AOT	Abnormal operating transients (corresponding to service level B)
ART [°C, °F]	Adjusted reference temperature
ASME	American Society of Mechanical Engineers
A_5 [%]	Elongation at fracture
BM	Base metal
BOL	Begin of Life
CFR	Code of Federal Regulation (USA)
CT	Compact tension (specimen)
Cu	Mass % of copper (in the metal)
DBTT	Ductile-Brittle Transition Temperature
ENSI	Swiss nuclear safety authority
EC	Emergency conditions (corresponding to service levels C/D)
ECCS	Emergency core cooling system
EOL	End of life
ET	Eddy current testing
F [n/m^2]	(fast neutron) Fluence
HAZ	Heat affected zone
HT	Hydro(-static) test (Pressure test)
ISI	In-service inspection

KTA	Kerntechnischer Ausschuss (German Nuclear Safety Standards Commission)
K_{Ia} [MPa ·m$^{1/2}$]	Fracture toughness for crack arrest
K_{Ic} [MPa ·m$^{1/2}$]	Fracture toughness for (brittle) crack initiation
K_{Jc} [MPa ·m$^{1/2}$]	Fracture toughness for (ductile) crack initiation
L	Longitudinal (orientation of specimen)
(LB) LOCA	(Large break) Loss of coolant accident
LE [mm]	Lateral expansion (of Charpy V-notch specimen after testing)
LTO	Long-term operation
MC	Master Curve
MT	Magnetic particle testing
Ni	Mass % of nickel (in the metal)
NOC	Normal Operating Conditions (corresponding to service level A)
P	Mass % of phosphorous (in the metal)
PT	Penetrant testing
PTS	Pressurized Thermal Shock
NDT	Non-destructive testing
NRC	Nuclear Regulatory Commission (USA)
PCCV	Pre-cracked Charpy V-notch (specimen)
PRZ SV	Pressurizer safety valve
p-T	Pressure-temperature (curve)
PTS	Pressurised thermal shock
PWR	Pressurized water reactor
RCC-M	Design and construction rules for mechanical components of PWR nuclear islands (French code)
RG	Regulatory guide (US NRC)
R_m [MPa]	Ultimate strength of material
RPV	Reactor pressure vessel
$R_{p0.2}$ [MPa]	Yield strength of material
RT	Radiographic testing
RT_{NDT} [°C, °F]	Reference temperature of Nil Ductility Transition
RT_{PTS} [°C, °F]	Reference temperature for PTS (Screening criterion for PTS, USA)
RSE-M	In-Service Inspection Rules for Mechanical Components of PWR Nuclear Islands (French code)
SF	Safety factor
T	Transverse (orientation of specimen)
T_k [°C]	Critical temperature of brittleness
T_{k0} [°C]	Critical temperature of brittleness at BoL

TOFD	**Time of flight diffraction**
T_0 [°C]	**Master curve reference temperature**
T_{41J} [°C]	**Brittle-ductile transition temperature based on Charpy energy 41 J**
UCC	**Under clad cracks**
USE	**Upper shelf energy (at Charpy test)**
UT	**Ultrasonic testing**
VERLIFE	**Unified Procedure for Lifetime Assessment of Components and Piping in VVER NPPs during Operation**
VT	**Visual testing**
VVER	**Water-water energy reactor**
WPS	**Warm pre-stressing**
WM	**Weld Metal**
Z [%]	**Reduction of area (of tensile specimen at fracture)**

2 FORMULAS FOR THE PREDICTION OF THE BDTT

This section describes the formulas used to predict the irradiation induced shift of the BDTT of the beltline materials of the RPV in the different participating countries.

2.1 Belgium

In Belgium, the irradiation induced shift of the reference temperature RT_{NDT} of different plants is determined according to different trend curves:

The US Reg. Guide 1.99, Rev. 2 is used for Doel 1 and Doel 2 where the limiting material is the circumferential weld with a relatively high Cu content:

- $\Delta RT_{NDT} = CF \cdot F^{(0.28 - 0.1 \cdot \log F)}$ with:
  - CF = chemical factor that depends on Cu and Ni only. Values are tabulated for WM and BM separately for concentrations of $0 \leq Cu \leq 0.40\%$ and $0 \leq Ni \leq 1.20\%$;
  - F = neutron fluence in units of $10^{19} n/cm^2$, E>1MeV.

The "adjusted reference temperature" ART is then defined with a margin to be added, *i.e.* $ART = RT_{NDT} + \Delta RT_{NDT} + M$ with the margin $M = 2 (\sigma_I^2 + \sigma_\Delta^2)^{1/2}$ which is based on the standard deviations of the initial value σ_I and its shift σ_Δ.

For Tihange 1, Tihange 3 and Doel 4, the French FIS formula is used and conservatively envelops the surveillance results. This formula was selected because these RPVs are very similar to those of the French 900 MW series. It has the form:

- $\Delta RT_{FIS} = 8 + (24 + 1537 (P - 0.008) + 238 (Cu - 0.08) + 191 Ni^2Cu) F^{0,35}$.

For Tihange 2 and Doel 3, the FIS formula was used until 2015. A specific formula has then been developed in the framework of the Safety Cases to justify the restart of the units following the discovery in 2012 of hydrogen flakes in the RPV core shells. This formula was based on the more recent trend curve of the French RSE-M code (see chapter 2.3 for France) with an additional term covering the potential effect of hydrogen flakes.

The PTS screening criterion, *i.e.* the value of the reference temperature RT_{PTS} for the vessel beltline material above which the plant cannot continue to operate without justification is defined in 10CFR §50.61:

- RT_{PTS} = 270°F (132°C) for plates, forgings and axial welds;
- RT_{PTS} = 300°F (149°C) for circumferential welds.

2.2 Czech Republic

If there are insufficient surveillance test results, the shift due to irradiation embrittlement ΔT_F is determined in accordance with the following procedure:

- $\Delta T_F = A_F \cdot (F \cdot 10^{-22})^n$
  - where F = neutron fluence in units of n/m², E > 0.5MeV.

Plant type	Material	AF [°C]	n [-]
VVER 1000	BM 15Kh2NMFAA	23	0.333
VVER 1000	WM Sv-12Kh2N2MAA	20 *)	0.333
VVER 440	BM 15Kh2MFA(A)	8.37	0.43
VVER 440	WM Sv-10KhMFT(U)	800·(1.11·P+0.064·Cu)	0.29

*) Valid for Ni content lower than 1.5 mass %; weld metals with Ni content larger than 1.5 mass % must be evaluated separately.

Besides, there are more sophisticated formulae in a Czech NTD ASI standard, where the shift depends also on Ni, Mn, Si. They should be integrated in a future revision of VERLIFE.

2.3 France

According to the French RSE-M the following formula shall be used for the prediction of the irradiation induced shift:

- $\Delta RT_{NDT} = A\,[1 + 35.7\,(P - 0.008) + 6.6\,(Cu - 0.08) + 5.8\,Ni^2Cu]\,F^{0.59} + 2\sigma$
  - where F = neutron fluence in units of 10^{19}n/cm², E>1MeV.

This formula is supposed to be an upper bound of the data by adding 2σ. The formula is the same for BM and WM, only the term A and the scatter (σ) are different.

2.4
Germany

A limit curve bounding the existing surveillance data was introduced in 2001 in /KTA 3203/. It has the form:

- $RT_{NDT}^{j} = RT_{limit}$ $= 40°C$ for $F \leq 10^{19} n/cm^2$

  $= [40 + (F - 1)10]°C$ for $F > 10^{19} n/cm^2$

  - where F = neutron fluence in units of $10^{19} n/cm^2$, E>1MeV;
  - $RT_{NDT}^{j} = RT_{NDT} + \Delta T_{41}$ is the adjusted reference temperature after irradiation.

As the design fluence for most German plants (*i.e.* the 1300 MW units) was as low as $0.5 \cdot 10^{19} n/cm^2$, the absolute shift values are low and the relative scatter quite large. Therefore the former predictive curves were replaced by this limit curve. RT_{limit} shall be used for the integrity analyses of the RPV and validated by the surveillance program.

2.5
Russian Federation

In the Russian Federation the prediction of the shift of TK for WWER-1000 RPV steel is determined in accordance with /RD 12a/:

Equation 2.5-1

- $\Delta T_K = \Delta T_t(t) + \Delta T_F(F) + \delta T_K$, where:
  - $\Delta T_t(t)$ = DBTT shift due to thermal ageing only;
  - $\Delta T_F(F)$ = DBTT shift due to radiation only;
  - δT_K = temperature safety margin;
  - F = neutron fluence (E>0.5 MeV), n/cm^2;
  - t = time.

In the formula for ΔT_K the radiation induced shift of DBTT is calculated according to:

Equation 2.5-2

- $\Delta T_F(F) = A_F \cdot (F/F0)^m$, where:
  - A_F = coefficient of radiation embrittlement, °C;
  - m = 0.8;
  - $F_0 = 10^{18} n/cm^2$ (E>0.5 MeV).
- For base metal A_F = 1.45°C and
- for weld metal $A_F = \alpha 1 \exp(\alpha_2 C_{eq})$, with

- ☐ $C_{eq} = C_{Ni} + C_{Mn} - \alpha_3 C_{Si}$ if $C_{Ni} + C_{Mn} - \alpha_3 C_{Si} \geq 0$
- ☐ $C_{eq} = 0$ if $C_{Ni} + C_{Mn} - \alpha_3 C_{Si} < 0$
- ☐ and the parameters $\alpha_1 = 0.703$; $\alpha_2 = 0.883$; $\alpha_3 = 3.885$.

This formula for the coefficient A_F for weld metal is valid in the following ranges of concentrations:

- 1.00 ≤ CNi ≤ 1.90 %;
- 0.40 ≤ CMn ≤ 1.10 %;
- 0.20 ≤ CSi ≤ 0.40 %.

In equation 2.5-1 the shift due to thermal ageing $\Delta T_t(t)$ of VVER 1000 RPV materials is calculated according to (see figure A1-1 for illustration):

- $$\Delta T_t(t) = \left(\Delta T_t^{\inf} + b_T \exp\left(\frac{t_T - t}{t_{OT}} \right) \right) \cdot th\left(\frac{t}{t_{OT}} \right)$$ Equation 2.5-3

Where the parameters in the following table apply:

Material	b_T [°C]	t_{OT} [h]	t_T [h]	ΔT_t^{inf} [°C]	δT_K [°C]
BM	26.2	32,700	40,700	2	38
WM with C_{Ni} ≤1,3%	26.2	32,700	40,700	2	20
WM with C_{Ni} >1,3%	10.1	23,200	40,900	18	20

Here;

- b_T, t_{OT}, t_T are material constants resulting from the statistical treatment of the surveillance data;
- ΔT_t^{inf} is the T_k shift due to thermal ageing after an infinetely long exposure time;
- $\delta T_K = 2\sigma$; σ = standard deviation (see equation 2.5-1).

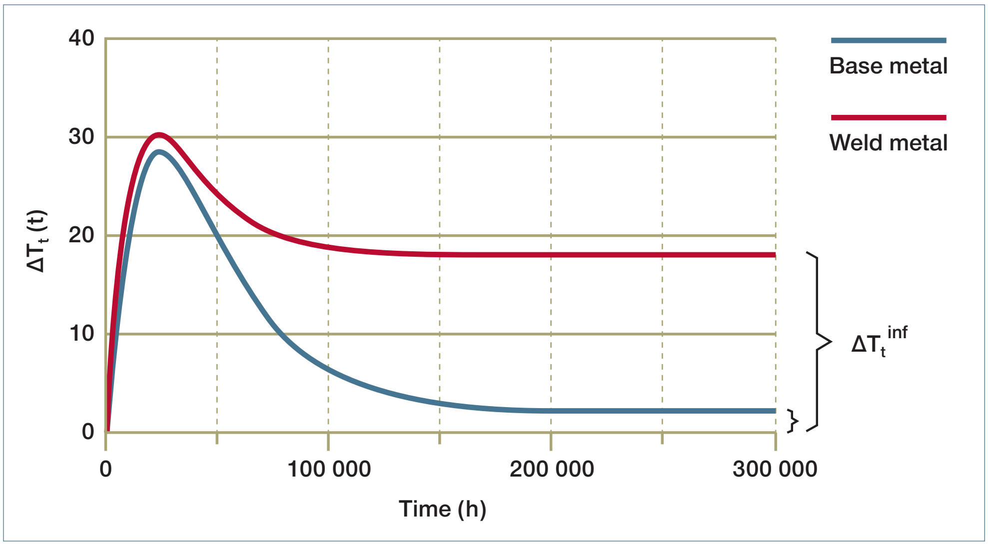


Figure A1-1
Development of the shift ΔT_t due to thermal ageing in service of VVER 1000 RPV materials according to equation 2.5-3.

2.6
Slovakia

T_K is predicted for the whole design life by the equation:

- $T_K = T_{K0} + \Delta T_N + \Delta T_T + \Delta T_F$

where T_{K0} is the critical temperature of brittleness at the beginning of operation, the last three components represent the increments of the critical temperature of brittleness caused by fatigue (ΔT_N), thermal ageing (ΔT_T) and irradiation damage (ΔT_F).

ΔT_F is described by the semi-empirical equations. Applicable equations are given in the regulations PNAE G-7-002-86 of the former Soviet Union and in VERLIFE 2008.

The equation in PNAE G-7-002-86 is as follows:

- $\Delta T_F = A_F (F \cdot 10^{-22})^{1/3}$

where F = neutron fluence with E > 0,5 MeV in the range $10^{22} n/m^2 \leq F \leq 3 \cdot 10^{24} n/m^2$ and

- for VVER 440 (irradiation temperature 269°C): A_F =12 for BM and A_F=15 for WM;
- for VVER 1000 (irradiation temperature 290°C): A_F=9 for BM and A_F=12 for WM.

The equation in VERLIFE 2008 for irradiation temperature 270°C is as follows:

- $\Delta T_F = A_F (F \cdot 10^{-22})^n + \sigma$
  - with A_F=8.37°C, n=0.43, σ=21.7°C for BM
  - and A_F= 800 (1.11·P +0.064·Cu)°C, n=0.29, σ=22.6°C for WM.

2.7
Switzerland

The irradiation induced shift of the reference temperature RT_{NDT} is determined according to US Reg. Guide 1.99, Rev. 2, as described in chapter 2.1 for Belgium.

2.8
Ukraine

The general approach to evaluate the critical temperature after irradiation according to the Ukrainian MT-D.0.03.391-09 starts with the formula:

- $T_K = T_{K0} + \Delta T_F + \Delta T_T + \Delta T_N$ with
  - ΔT_F = transition temperature shift due to radiation damage;

- ☐ ΔT_T = transition temperature shift due to thermal ageing;
- ☐ ΔT_N = transition temperature shift due to fatigue, defined in PNAEG-7-002-86.

T_{K0} shall be taken from RPV passport; if these are not available, data from PNAE G-7-002-86 may be used. Given values depend on material and specification used.

For ΔT_F and ΔT_T surveillance results shall be taken; if these are not available, data from PNAE G-7-002-86 may be used specifying ΔT_T = 0°C for beltline materials.

In case of Ni content > 1.3% ΔT_F shall be defined according to a specific methodology.

For beltline BM and WM it is possible to define T_K by the formula

- $T_K = T_{K0} + \Delta T_F$
- $\Delta T_F = A_F (F/F_0)^{1/3}$;
  - ☐ F = fluence of neutrons with energy E > 0.5 MeV, $F_0=10^{22}$ n/m^2

This formula is supposed to be an upper bound curve. No margin has to be added for use in the brittle fracture assessments.

According to PNAE G-7-002-86 the values for T_{K0} and AF depend on the material, the irradiation temperature and the specification used, *e.g.* for

- VVER 440 with irradiation temperature 270°C:
  - ☐ Base metal 15Kh2MFA-A: T_{K0} = 0°C and A_F = 12
  - ☐ Weld metal T_{K0} = 20°C. A_F is determined from A_F =800(P+0.07 Cu)
- VVER 1000 with irradiation temperature 290°C:
  - ☐ Base metal 15Kh2NMFA-A: T_{K0} = -25°C and A_F = 23
  - ☐ Weld metal: T_{K0} = 0°C and A_F = 20.

3 FRACTURE TOUGHNESS CURVES

This section describes the fracture toughness curves applied for the safety analysis of the RPV against non-ductile failure using postulated flaws in the different participating countries.

3.1 Belgium

The fracture toughness curves corresponding to ASME XI, Appendix G (1998 or earlier editions[2]) are applied in Belgium, see figure A1-2, *i.e.*

- for NOC: $K_{IR} = K_{Ia} = 29.4 + 13.675 \exp [0.026(T - RT_{NDT})]$
- for EC and faulted conditions: $K_{Ic} = 36.5 + 3.1 \exp [0.036 (T - RT_{NDT} + 55°C)]$.

The latter is approximately equivalent to the formula used in later versions of ASME XI, appendix G: $K_{Ic} = 36.5 + 22.783 \exp [0.036 (T\text{-}RT_{NDT})]$, also used in Germany and Switzerland.

3.2 Czech Republic

The following fracture toughness curves from VERLIFE 2008 are applied:

In the T_k approach:

- for normal conditions: $[K_{Ic}]_1 = 13+18\cdot\exp [0.02(T\text{-}T_k)]$;

2 *In later editions only the less conservative KIc-curve is applied in ASME XI, Appendix G.*

- for upset conditions: $[K_{Ic}]_2$ = 17+24·exp[0.018(T-T$_k$)];
- for emergency conditions: $[K_{Ic}]_3$ = 26+36·exp[0.02(T-T$_k$)]. This is the same curve used as lower bound for all materials in Ukraine, see also figure A1-3.

In the T_0 approach:

- for normal conditions: $[K_{Ic}]_1$ = 12.6+18.3·exp[0.019(T-T$_0$)],
- for upset conditions: $[K_{Ic}]_2$ = 16.8+24.4·exp[0.019(T-T0)],
- for emergency conditions: $[K_{Ic}]_3$ = 25.2+36.6·exp[0.019(T-T$_0$)].

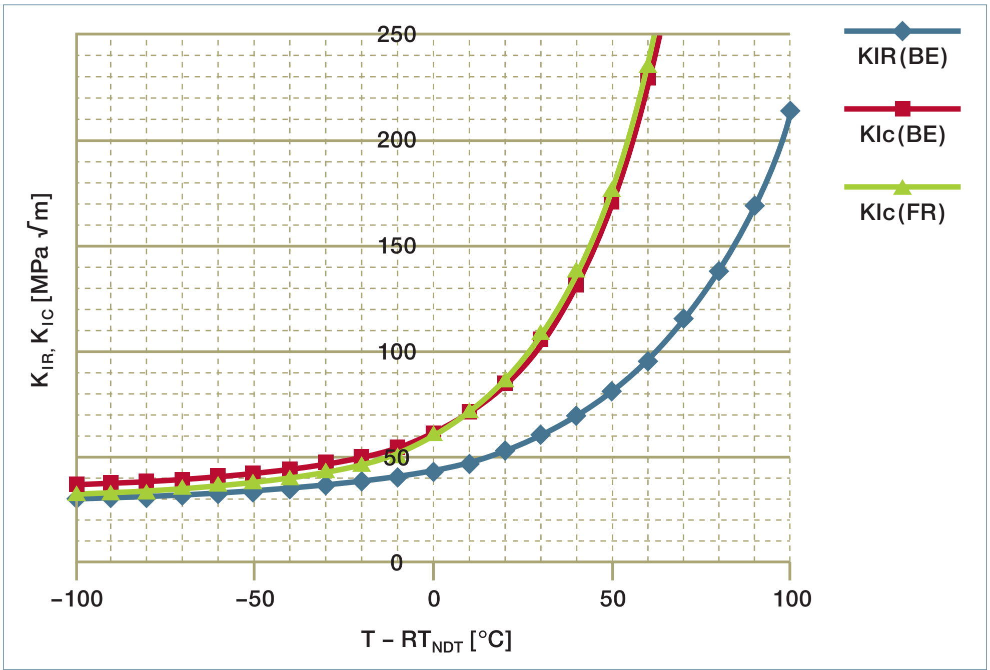


Figure A1-2
Fracture Toughness Reference Curves according to Belgian and French regulations. Germany and Switzerland use practically the same K_{IC}-curve as Belgium.

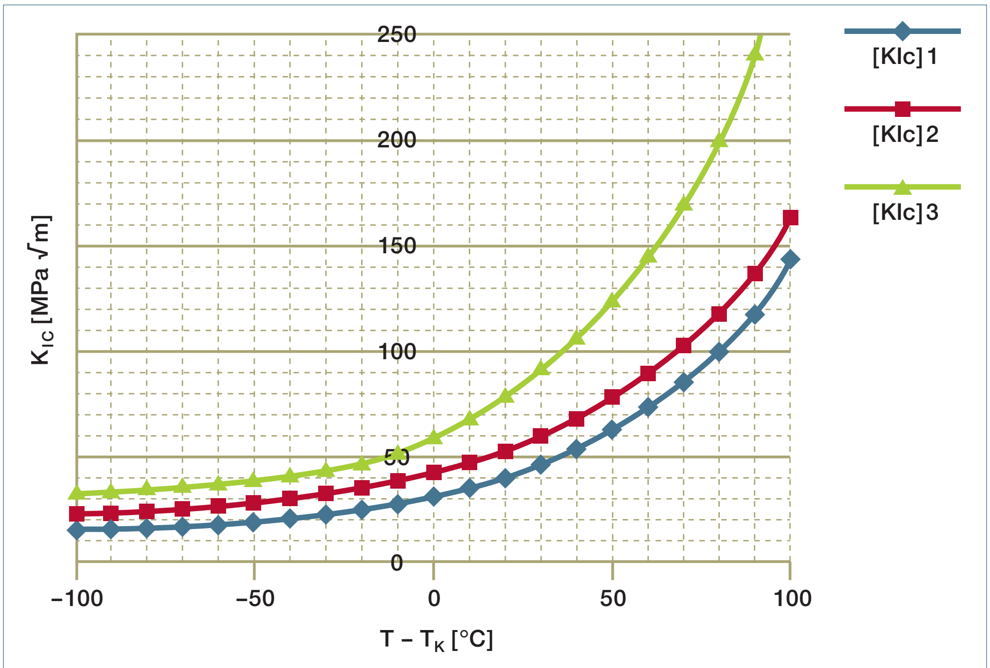
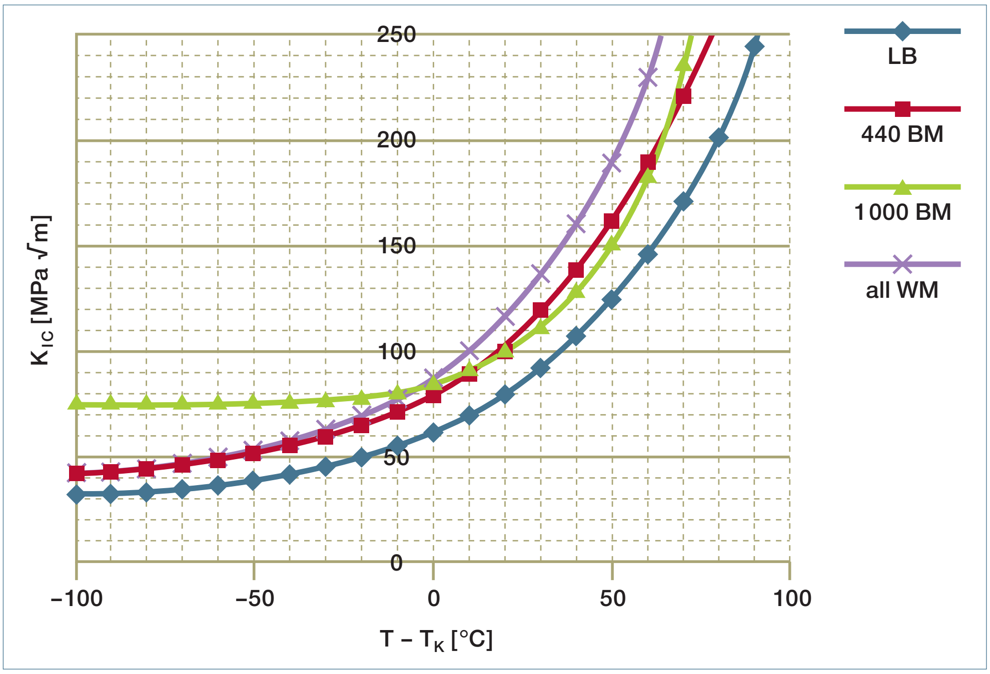


Figure A1-3
Fracture Toughness Reference Curves for different operating conditions according to the Czech regulations. The [KIC]3-curve is identical to the lower bound curve in the Ukrainian regulations, see figure A1-4.

Figure A1-4
Fracture Toughness Reference Curves for different materials under emergency conditions (*i.e.* n = 1) according to the Ukrainian regulations. The lower bound (LB) curve is identical to the [K_{IC}]3-curve in the Czech regulations, see figure A1-3.



3.3
France

- $K_{Ic} = 40 + 0.09\,(T\text{-}RT_{NDT}) + 20{\cdot}\exp\,[0.038\,(T\text{-}RT_{NDT})]$

This curve has no plateau at low temperature, see figure A1-2. At high temperature there is no specified value (the old limit of 220 MPa $m^{0.5}$ was removed), but RCC-M provides values of the resistance to onset of crack extension K_{JC} that can be used.

3.4
Germany

The formulas provided in /KTA 3201.2/ are practically the same as in ASME XI (except rounding, compare chapter 3.1 for Belgium and figure A1-2 and consider that $RT_{NDT} + \Delta T_{41}$ is the adjusted reference temperature after irradiation). They are given in the following form:

- $K_{Ic} = 36.5 + 22.8 \exp\,[0.036\,(T - RT_{NDT} - \Delta T_{41})]$

- $K_{Ia} = 29.5 + 13.7 \exp\,[0.026\,(T - RT_{NDT} - \Delta T_{41})]$.

In the latest edition of KTA 3201.2 from 2013 the K_{Ia}-curve is still described, yet not used any more for fracture assessments of the RPV. Instead the less conservative K_{Ic}-curve is applied. This is similar to the development in ASME XI, Appendix G.

3.5
Russian Federation

In accordance with /RD 12a/ the Unified Curve method is used in the Russian Federation. The calculated dependence of fracture toughness on temperature T for crack front length B=150 mm is described by the following formulae and illustrated in figure A1-5:

- $$K_{JC}^{design}(T) = k \cdot \left[K_{JC}^{shelf} - K_{min} + \Omega \cdot \left(1 + th\left(\frac{T - \delta T_{type} - 130}{105} \right) \right) \right] + K_{min}$$

Equation 3.5-1

where:

- k = 0.33;
- K_{JC}^{shelf} = 26 MPa m$^{1/2}$;
- K_{min} = 20 MPa m$^{1/2}$;
- T = temperature [°C];
- Ω = material parameter controlling the degree of material embrittlement;
- δTt_{ype} = margin depending on type of specimen, *i.e.*
  - for specimen type SEB-10: δTt_{ype} = 15°C;
  - for specimen type CT-0.5: δTt_{ype} = 0°C;

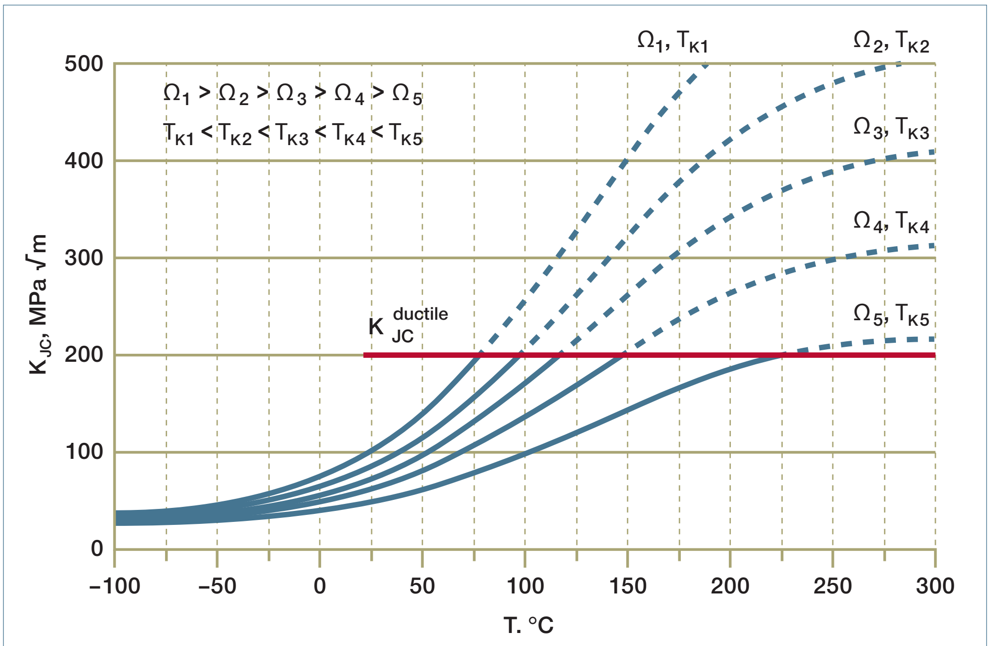


Figure A1-5
The Unified Curve $K_{JC}^{design}(T)$ according to Russian regulations (equation 3.5-1) for different degrees of embrittlement represented by different values of Ω and T_K.

The dependence $K_{JC}^{design}(T)$ on specimen thickness B for B≠150 mm is:

$$\frac{K_{JC}^{X} - K_{min}}{K_{JC}^{Y} - K_{min}} = \left(\frac{B_Y}{B_X}\right)^{1/4}$$

Where K_{JC}^{X} and K_{JC}^{Y} is the fracture toughness for specimens with thickness B_X and B_Y.

/RD 12a/ predicts the $K_{JC}(T)$ curve shape for WWER-1000 RPV integrity assessment on the basis of trend curves or/and surveillance results. Using the trend curves the parameter Ω characterizes the slope of the $K_{JC}(T)$ curve and is calculated by the formulae:

- $$\Omega = (\Omega_0 - \Omega_{min})\exp\left[-\left(C_T(t) + C_F\left(\frac{F}{F_0}\right)^m + C_{\delta Tk}\right)\right] + \Omega_{min}$$

where:

- Ω_0 = value of Ω for material in initial condition;
- Ω_{min} = 37 MPa $m^{1/2}$;
- m=0.8;
- $C_T(t) = (2/105°C) \cdot \Delta T_t(t)$
- $C_F = (2/105°C) \cdot A_F$
- $C_{\delta TK} = (2/105°C) \cdot \delta T_K$

The value of Ω_0 can be obtained from fracture toughness test results of the material in the initial condition, *i.e.* the slope of the experimental $K_{JC}(T)$ curve, or calculated by the formulae:

- $$\Omega_0 = \frac{74}{1 + \mathrm{th}\left(\frac{T_{K0} - 168}{105}\right)}$$

3.6 Slovakia

The following Fracture toughness curves from VERLIFE 2008 are applied for the different operating conditions:

- NOC: $K_{Ic}(T) = \min[13 + 18 \cdot \exp(0.02.(T - T_k)); 100]$
- AOT and HT: $K_{Ic}(T) = \min[17 + 24 \cdot \exp(0.018.(T - T_k)); 120]$
- EC: $K_{Ic}(T) = \min[26 + 36 \cdot \exp(0.02(T - T_k)); 200]$

These are the same curves as those used in the Czech Republic, see figure A1-3, however, with cut-off values of 100, 120, or 200 MPa $m^{1/2}$, respectively, for the different operating conditions.

3.7
Switzerland

The fracture toughness curve for K_{Ic} provided in ASME III, Appendix G and ASME XI, Appendix G can be used, *i.e.* practically the same curve as the one used in Germany for all conditions and in Belgium for EC and faulted conditions, see also chapter 3.1 for Belgium and figure A1-2.

- $K_{Ic} = 36.5 + 22.783 \exp [0.036 (T-RT_{NDT})]$

As an alternative, also the Master Curve approach with the failure probability P_f can be applied using the following formula:

- $$K_{IC} = 20 + \left[ln\left(\frac{1}{1-P_f}\right)\right]^{0.25} \{11 + 77exp^{[0.019(T-T_0)]}\}$$

3.8
Ukraine

The static fracture toughness in MPa $m^{1/2}$ with crack front length 150 mm and fracture probability of 0.05 is given as:

- $K_{Ic} = 23 + 48 \cdot \exp [0.019 (T - T_k)]$.

According to PNAE-G-7-002-86 the fracture toughness curves under emergency conditions (safety factor n=1) are as follows, see also figure A1-4:

- for VVER 440 base metals: $[K_I]_3 = 35 + 45 \exp [0.02 (T - T_k)]$
- for VVER 1000 base metals: $[K_I]_3 = 74 + 11 \exp [0.0385 (T - T_k)]$
- for weld metals: $[K_I]_3 = 35 + 53 \exp [0.0217 (T - T_k)]$
- general lower bound curve: $[K_I]_3 = 26 + 36 \exp [0.02 (T - T_k)]$ for all pearlitic and Chromium steels with $R_{p0.2}(20°C) < 600$ MPa. This curve is identical to the one used in Czech Republic for all materials under EC.

ANNEX 2

COMPARISON OF REQUIREMENTS APPLIED FOR RPV FRACTURE MECHANICAL ASSESSMENTS FOR PWR PLANTS

COUNTRY CODES

BE	BELGIUM
FR	FRANCE
DE	GERMANY
CH	SWITZERLAND
CZ	CZECH REP.
UA	UKRAINE
SK	SLOVAKIA
RU	RUSSIA
FI	FINLAND

For abbreviations used, see annex 1.

BE	FR	DE	CH	CZ / SK	UA	RU	FI
Design requirements for mechanical properties of materials in beltline / off-beltline according to regulations and standards							
Tensile properties: Requirements are the same for beltline and off-beltline BM & WM as given in ASME II, Part D, supplemented by some specific requirements in ASME III NB-2000 A508 Grade3/ Cl.1: $R_{p0.2}$ > 345 MPa R_m: 550-725 MPa	**Tensile properties:** According to RCC-M M2111 or M2111bis $R_{p0.2}$ > 300 MPa R_m: 497-700 MPa	**Tensile properties:** Requirements are the same for beltline and off-beltline BM & WM. $R_{p0.2}$ > 390 MPa R_m: 560-700 MPa (L & T orientation) A_5: > 19% Z: > 45%	**Tensile properties:** Requirements according to KTA or ASME code, depending on plant designer, see Germany and Belgium The plant cannot continue to operate without justification if RT_{NDT} > 93°C in a depth of ¼ wall thickness or if USE < 68 J.	**Tensile properties:** Requirements are the same for beltline and off-beltline. **WWER-440:** $R_{p0.2}$ > 432 MPa R_m > 540 MPa A_5: > 14% Z: > 50% **WWER-1000:** $R_{p0.2}$ > 490 MPa R_m > 608 MPa A_5: > 15% Z: > 55% Values for BM at room temperature.	**Tensile properties:** Requirements are the same for beltline and off-beltline regions as stated in technical specifications for RPV materials and generalized in PNAE G-7-002-86, see Czech Rep.	**Tensile properties:** Stated in technical PNAE G-7-002-86. **WWER-1000:** Values for BM see Czech Rep.; Values for WM at room temperature: $R_{p0.2}$ > 422 MPa R_m > 539 MPa A_5: > 15% Z: > 55%	**Tensile properties:** ASME III, mandatory requirements set in NB 3200 and NB 3650 and in sections NF and NG apply if no specific requirements have been set.
Fracture toughness: A_{CV} and LE at Charpy V-notch test shall meet ASME III, NB-2300, and 10 CFR Part 50, Appendix G, Section IV: At BOL beltline materials must have USE ≥ 102J (T orientation for BM and L for WM) and USE ≥ 68J at EOL. No specific requirements for RT_{NDT}.	**Fracture toughness:** KV > 130 J RT_{NDT} (BOL) < -20°C for all materials.	**Fracture toughness:** off beltline RT_{NDT} < 0° beltline at BOL: RT_{NDT} < -12°C		**Fracture toughness:** **WWER-440:** Beltline : BM – T_{k0} ≤ 0°C, WM - T_{k0} ≤ +20°C Off-beltline: BM - T_{k0} ≤ 0°C, WM - T_{k0} ≤ +40°C **WWER-1000:** Beltline : BM – T_{k0} ≤ -25°C, WM - T_{k0} ≤ 0°C Off-beltline: BM - T_{k0} ≤ 0°C, WM - T_{k0} ≤ 0°C	**Fracture toughness:** See Czech Rep.	**Fracture toughness:** **WWER-1000:** Beltline : BM – T_{k0} ≤ -12°C, WM - T_{k0} ≤ 0°C Off-beltline: BM - T_{k0} ≤ 0°C, WM - T_{k0} ≤ 0°C	**Fracture toughness:** ASME reference curves may be used when appropriate, primarily T_0-analysis, T_0 analysis required for beltline materials. Safety margin requirement against worst case transient.

BE	FR	DE	CH	CZ / SK	UA	RU	FI
Prognosis of irradiation induced changes (see Annex 1 for formulas)							
Formulae for the shift of RT_{NDT} given by - Reg. Guide 1.99 - French FIS/ FIM (function of P, Cu, Ni and Fluence) depending on the plant designer.	Formulae for the shift of RT_{NDT} given by RSE-M (FIM) (function of P, Cu, Ni and Fluence).	There is no prognosis as the fluence values are low: F(EOL)< 5. 10^{18}n/ cm^2 and therefore scatter relatively large. Surveillance results shall show RT_{NDT} (EOL) < 40°C	Formulae for the shift of RT_{NDT} given by Reg. Guide 1.99	**In SK:** formulae given in VERLIFE 2008/IAEA **WWER-440:** ΔTk function of F, Cu, P for WM, function of F for BM **In CZ:** formula also given by NTD ASI, Section IV for **WWER-440:** ΔTk function of F, Cu, P for WM **WWER-1000:** ΔTk function of F, t, Cu, P, Ni, Mn, Si	Formulae for the shift of T_k given by MT-D.0.03.391-09 (see annex 1). In case Ni > 1,3% ΔT_F shall be defined according to specific methodology.	**WWER-1000:** formulae for the shift of T_k given by Guideline / RD 12a/ (see annex 1). For BM: ΔT_k function of F and t, for WM: ΔT_k function of F, t, Ni, Mn, Si with different parameters for high Ni/Mn welds.	Prognosis relevant for the alloy and impurity contents. Alternatively, curve fit to surveillance fracture toughness data vs. fluence or ASME approach based on Charpy surveillance data.

BE	FR	DE	CH	CZ / SK	UA	RU	FI
Scope and techniques of NDT during manufacture and service (ISI)							
Manufacturing: RT, UT (straight and angle beam technique for whole forgings), MT, PT	**Manufacturing:** UT (whole semi-products, whole RPV before hydro-test), RT, MT, PT, ET dimensional optical	**Manufacturing:** 100% of the forged rings: UT with straight and angle beam (from the inside and outside, top and bottom). In addition, sampling of back wall loss. Surface of forgings: MT, PT, After cladding: UT for detachments and underclad cracks, PT, VT of surface During and after welding: PT, MT, UT.	**Manufacturing:** according to KTA or ASME code, depending on plant designer, see Germany and Belgium.	**Manufacturing:** UT of whole semi-products, whole RPV before and after HT: RT, MT, PT, ET, VT, delta-ferrite.	**Manufacturing:** 100% of forgings and welds (RT, VT, UT, MT, PT) 100% Cladding (VT, UT, PT) 100% Cladding inside DN 850 nozzles (RT, VT, UT, PT).	**Manufacturing:** see Ukraine.	**Manufacturing:** UT, scope according to ASME.
Pre-service : inspections in conformity with ASME III and **ISI** in conformity with ASME XI. Following the detection of hydrogen flakes in the shells of two RPVs, the forged parts of all RPVs have been examined with UT techniques on the entire volume.	**Pre-service & ISI:** welds and surroundings, nozzles (UT), optical, BMI (UT), beltline region: VT of cladding, UT for underclad and laminar defects, every 10 years.	**Pre-service:** UT, VT of whole RPV, as baseline for ISI **ISI:** All units: UT with angle beam of all welds ±50 mm. PWR units: UT from the RPV inside every 5 years. BWR units: UT from the RPV outside. VT and UT may be applied to show the integrity of the cladding.		**Pre-service:** UT (whole RPV), VT & ET of cladding. **ISI:** all welds and their surrounding by UT (echo-method + TOFD) from both sides according to the possibilities of access in intervals of 6 (VVER 1000) or 8 (VVER440) years. RPV surface of beltline region: welds and their surrounding and nozzles by ET and VT from both sides. Majority of volume of the BM of beltline and parts of adjacent rings by UT for laminar defects. Underclad cracks potentially penetrating the cladding shall be checked by UT (echo method + TOFD) in WM and majority of BM.	**Pre-service:** UT (whole RPV), VT & ET of cladding. **ISI:** welds and surroundings (±50 mm), and nozzles by UT; beltline region: ET and VT of cladding every 4 years. Underclad cracks potentially penetrating the cladding shall be checked by qualified UT.	**Pre-service:** see Ukraine. **ISI:** see Ukraine. Yet the inspection intervals were changed to 3-7-10-10-7-3 years.	**Pre-service:** UT **ISI:** UT, ET, VT UT: Qualification for crack sizes based on PTS-analyses for beltline. VT for cladding.

BE	FR	DE	CH	CZ / SK	UA	RU	FI
Content and scope of irradiation surveillance program							
Standard program: surveillance program carried out according to 10 CFR 50 Appendix H and ASTM E 185. Charpy, Tensile, Compact Tension specimens. The Charpy-V-Notch specimens represent BM, WM, HAZ material. The tensile and compact tension specimens represent BM and WM.	**Standard program:** BM, WM, HAZ – tensile, Charpy, fracture toughness (1/2 CT) + reference material. **Extended program for LTO:** **2 additional** sets of archive materials were inserted between 2000 and 2006: BM, WM, HAZ material - tensile, Charpy, Compact Tension specimens.	**Standard program:** 2 sets for irradiation: BM, WM, HAZ – tensile, Charpy, (fracture toughness of different types are included in most plants, yet not required). Testing of irradiated HAZ specimens no longer required; fracture toughness optional (recently mainly pre-cracked CV for T_0). T_0 according to ASTM E 1921-09a and ASME code cases N-631 and N-851 may be used, applying appropriate safety margins, *e.g.* according to IAEA TRS 429. BM of the second beltline ring has to be included if F(EOL)>$10^{19} n/cm^2$ (not applicable to German plants in operation).	**Standard program:** according to German or US code, depending on plant designer, see Germany and Belgium.	**Standard program:** for VVER440 – BM, WM, HAZ – tensile, Charpy, fracture toughness. **Supplementary program:** for VVER440 – BM, WM, cladding (layers ss-1, ss-2, HAZ), JRQ – tensile, Charpy, fracture toughness; effect of annealing and re-embrittlement – BM, WM, cladding. **In SK: Modernized program for VVER440** BM, WM, HAZ –tensile, Charpy, fracture toughness, small punch specimens. Monitoring of environmental influence on the RPV internals material (austenitic steel 08Ch18N10T). **In CZ: Extended program for LTO in Temelin:** BM, WM, cladding HAZ, JRQ material – Charpy, fracture toughness.	**Standard program:** BM, WM, HAZ – tensile, Charpy, fracture toughness. **Supplementary program:** BM, WM, cladding (layers ss-1, ss-2, HAZ), JRQ – tensile, Charpy, fracture toughness; effect of annealing (VVER 440 only) and re-embrittlement – BM, WM, cladding. **Modified program for VVER 1000 for LTO:** re-arrangement of specimens and re-constructed Charpy specimens. **Integrated Program in Temelin** includes Ukrainian archive material.	**Standard program:** BM, WM with max. P and Cu content, HAZ – tensile, Charpy, fracture toughness (SEB, CT-0.5). 6 irradiated sets 4 thermal sets 2 control sets. Guideline /RD 12a/ predicts the KJC(T) curve shape for WWER-1000 RPV integrity assessment on the basis of trend curves or/and surveillance results.	**Standard program:** scope so that prognosis of irradiation embrittlement can be ensured to be conservative. **Supplementary program:** for RPV annealing acceptability of DBTT shifts under re-irradiation has to be demonstrated (Loviisa NPP).

BE	FR	DE	CH	CZ / SK	UA	RU	FI
Fracture mechanical analysis							
K_I calculated for existing or postulated cracks, compared with K_{IC} or K_{Ia} adjusted to RTNDT (ART). T_0 is only tested for additional information. ASME XI (in particular IWB-3600, Appendices A and G).	K_I calculated for postulated cracks, compared with K_{IC} at the interface to cladding and the deepest point of the crack. Highest value is selected. No application of Master Curve.	K_I calculated for postulated cracks, compared with K_{IC} at all points on crack front. No crack arrest evaluation.	K_I calculated for postulated cracks, compared with K_{IC} at the interface to cladding and the deepest point of the crack. Highest value is selected.	K_I calculated for postulated cracks, compared with K_{IC} in all points on crack front. Evaluation should be based on either T_K or T_0 (when T_0 approach is used, "integral approach" is allowed: integral along the crack front).	K_I calculated for postulated cracks, compared with K_{IC} at points on crack front with highest loading. Crack arrest may only be used for evaluation for flaws found during ISI.	Guideline / RD 12b/ considers two approaches: "simple" approach: $n_i K_I \leq K_{JC}$; and the "integral approach" considering the distribution of K_I and K_{JC} along the crack front.	K_I calculated for postulated cracks, comparison to highest loading, elastic-plastic analysis applying T_0, crack arrest considered.
Consideration of cladding for underclad cracks (UCC) and cracks within cladding							
	For UCC instability against ductile tearing of the cladding is assessed at the interface.	Cladding considered for UCC. No cracks postulated within the cladding.		Resistance of cladding against ductile tearing during PTS is assessed for UCC. No cracks postulated within the cladding.		For UCC Ductile crack growth during PTS + fatigue crack growth during operation must not exceed half the cladding thickness. Otherwise a through clad crack has to be assumed. No cracks postulated within the cladding. Guideline /RD 12b/ provides critical J-integral J_C (F, T) for cladding.	Cladding considered for UCC. No cracks postulated within the cladding.

BE	FR	DE	CH	CZ / SK	UA	RU	FI
Use of crack arrest							
Crack arrest is not accepted. K_{Ia} = $_{KIR}$ -curves used for p-T curves at level A, B.	Crack arrest is not accepted. No use of K_{Ia}.	Crack arrest is no longer accepted as the only proof of RPV integrity. $K_{Ia} = K_{IR}$ -curves still represented.	Crack arrest is not accepted.	Crack arrest is also accepted in VERLIFE but not applied yet. The crack arrest curve is shifted with respect to the initiation curve by 30°C.	Crack arrest is not accepted.	Crack arrest is also accepted but not applied yet.	Crack arrest is accepted for LB-LOCA.
General approach for normal operation and transients (including PTS) (see Annex 1 for fracture toughness curves)							
$K_{Ia} = K_{IR}$ (T) (for level A, B) or K_{IC} (T) (for level C, D) depending on transient-adjusted to RT_{NDT}. For normal operation, p-T curves are determined. For PTS the RT_{PTS} is defined based on RT_{NDT} with some margin. RT_{PTS} has to be smaller than the screening criterion defined in 10CFR 50.61.	K_{IC} (T) (ASME lower bound curve) adjusted to RT_{NDT}. No specified limits. Safety factors are used on all loads or $RT_{NDT} < RT_{NDT}^{limit}$, limit determined by a plant specific assessment. For the service levels B, C, and D safety factors are defined for the transition regime ($T-RT_{NDT} \leq 60$°C): SF= 2; 1,6; 1,2 and the ductile regime ($T-RT_{NDT} > 40$°C): SF= 1.5; 1.3; 1.1. For $T-RT_{NDT}$ between 40 and 60°C both criteria have to be fulfilled.	K_{IC} (T) (ASME lower bound curve) adjusted to RT_{NDT} or RT_{T0}. $K_{IC} > K_I = K_{I,mech} + K_{I,\ thermal} + K_{I,residual}$ Implicit safety factors due to crack size (see below).	K_{IC} (T) (ASME lower bound curve) adjusted to RT_{NDT} or RT_{Ref}. The latter is determined on the basis of T_0 and ΔRT_{NDT} with defined margins according to ENSI-B01.	Specific K_{IC}-curves with different safety factors prescribed for normal and for emergency conditions. For normal operation – p-T curves are determined based on linear-elastic calculation for postulated surface crack; for emergency conditions – maximum allowable transition temperature is calculated. Moreover, p-T curves determined for emergency conditions based on elastic-plastic calculation and underclad cracks, p-T curves for cooling after emergency events also elaborated for support of emergency procedures.	For Fracture toughness the same condition has to be fulfilled with different safety factors for different plant conditions for the points on the postulated crack front: $(K_I)_i = n_i K_I \leq K_{IC}$ The SF are defined: for NOC: n_1=2 for HT: n_2=1.5 for AOC: n_3=1.25 for EC: n_4=1. In addition, there shall be a 30K margin for NOC and AOC, *i.e.* KI (T) ≤ KIC (T-30K)	For fracture toughness the same condition has to be fulfilled with different safety factors for different plant conditions for the points on the postulated crack front: $(K_I)_i = n_i K_I \leq K_{JC}$ The SF are defined: for NOC: n_1=2 for HT: n_2=1.5 if core outside; if core inside: n_2=2 for AOC: n_3=1.25 for EC: n_4=1.	p-T –curves applied for normal operation. For PTS, T_0 with a MC lower tolerance bound (usually 5% fractile) and a margin or the ASME XI approach may be used.

BE	FR	DE	CH	CZ / SK	UA	RU	FI
Selection of transients							
ASME III NCA-2140. No specific PTS analyses are performed as long as the PTS criterion is fulfilled.	Selection for each category of the most detrimental transients. Lowest margins appeared for small break LOCA in emergency conditions. Preselection with simplified analyses, detailed analyses of most severe transients.	Grouping of transients: small, medium, large LOCA, secondary leaks, primary to secondary leaks, inadvertent ECCS actuation. Preselection with simplified analyses and engineering judgement, detailed analyses of most severe transients.	At least Large (*e.g.* 450 cm^2), Medium (*e.g.* 70 cm^2) and Small break LOCA (*e.g.* 3 cm^2) in hot leg are analysed. The real spectrum of transients is plant specific.	Procedure given in VERLIFE, Appendix VI. Essential PTS groups are analysed: LOCA, large secondary leaks, leaks from primary to secondary circuit, PRZ SV opening (including reclosure), inadvertent actuation of ECCS, flooding of RPV from the outside.	All groups of events must be considered: 1. LOCA (Pressurizer steam leak, leak of primary to secondary circuit), 2. Increase of primary coolant (non-intentional actuation of ECCS, Failure of the primary circuit feed and bleed system), 3. Increase of heat removal (main steam collector rupture, main steam line rupture, non-intentional actuation of steam valves (BRU-A, BRU-K, SG SV), feed water line rupture). 4. Cooling of RPV from the outside (reactor cavity flooding, *e.g.* by spray system actuation).	Primary small LOCA and Primary to secondary leakage shall be considered.	Large scale of LOCA, opening/ reclosure of pressurizer safety valve, cold over-pressurisation, external emergency cooling.
Use of DBTT (RT_{NDT}, T_{41J}, T_K, T_0) and fracture toughness curves (see Annex 1 for formulas and curves)							
RT_{NDT} and shift of RT_{NDT} measured by ΔT_{41J} from surveillance program. **Fracture toughness:** Curves from ASME III or XI, Appendix G.	RT_{NDT} and its shift are used. The fracture toughness curve is extracted from the RCC-M code. This curve has no plateau at low temperature.	Mostly RT_{NDT} and its shift are used to correlate K_{IC} (T) curve (ASME lower bound curve, see Belgium). RT_{T0} may also be used in the same manner. K_{IA} (T) generally no longer needed.	K_{IC} (T) curve (ASME lower bound) is used adjusted to RT_{NDT}. See ENSI Guideline B0.1	VERLIFE: T_k, T_0 (T_0 not applied yet). **Fracture toughness:** Curves for emergency conditions from VERLIFE 2008. Master curve (5% fractile) is also accepted.	**Fracture toughness:** Curves for the BM of VVER 440 and 1000 and their WM recommended for calculations are given in the code as a function of T and T_K.	T_{47J}, T_{70J} and fracture toughness curves are used (see report).	T_0-temperature from surveillance data, 5% Master Curve for lower bound, T_{41J} shift based on surveillance data.

BE	FR	DE	CH	CZ / SK	UA	RU	FI
Postulated crack sizes and locations							
Sharp surface defect oriented circumferentially or axially, depending on the orientation of the weld. For normal and upset conditions p-T-curves are defined using crack depth of ¼ of section and length of 1 ½ times of section thickness. Defects postulated at both the inside and outside surfaces. ASME III and XI, Appendix G No PTS evaluations have to be performed as long as the PTS criteria are met.	Different postulated flaws are studied. Inside cladding: elliptical 4 x 60 mm, both axial and circumferential crack orientation. Under the cladding: semi elliptical 5 x 25mm (full length). Both axial (beltline zone) and circumferential (in weld) crack orientation. Several detected flaws are also studied at their location.	Semi-elliptical crack with aspect ratio a/c = 0.3 at most adverse location and orientation. - normal and upset: Depth a = ¼ t (at inside and outside) - emergency conditions: a = Twice the crack size that can safely be detected. If integrity of cladding can be shown by NDT, cracks may be postulated as sub-clad only, otherwise through-clad cracks have to be postulated.	Semi-elliptical, Different crack sizes and orientations have to be analysed depending on the plant design code. Through-clad defects may have to be analysed.	Postulated crack depth a is defined based on criteria for NDE qualification: a = Twice the crack size that can safely be detected. Recommended crack depth a= 0.1s (in case of qualified NDE). Underclad semi-elliptic type with penetration into cladding (1 mm) – "VERLIFE type". Aspect rati-os a/c = 0.3 and 0.7 have to assessed. Location in RPV: cylindrical part (beltline zone), main inlet nozzle ("nozzle corner"). Both axial and circumferential crack orientation for cylindrical part of RPV.	Surface cracks and UCC have to be postulated as half-elliptic in axial and circumferential orientation in RPV in critical areas with aspect ratio a/c=1/3. Additionally a/c=1/2 and a/c=2/3 have to be analysed. Their size has to be not less than the size that can be discovered by ISI. If ISI is conducted a = 0.125s can be assumed (s = wall thickness with cladding). Otherwise a = 0.25s has to be assumed.	Surface cracks and UCC have to be postulated as half-elliptic in axial and circumferential orientation in RPV in critical areas with aspect ratio a/c=1/3. Their size is a = scl + 0.07s for surface cracks and a = 0.07s for UCC.	Based on qualified NDE. In Loviisa for PTS: crack size is 15 x 30 mm through cladding with semi-elliptic shape, both axial and circumferential crack orientation.
Consideration of residual stresses							
Yes (including cladding-induced stresses) for flaw assessment. ASME XI Appendix A (non-mandatory)	Yes, only in cladding as proposed by Areva (axial = 200 MPa circumf = 150 MPa in the cold state). Residual stress in Welds due to cladding: under discussions.	Yes. For residual stresses next to welds σ = 56 MPa cos $2\pi x/t$ may be assumed. No proposal is made for residual stresses due to cladding.	No.	Yes, both in welds: σ = 60 MPa cos $2\pi x/t$ and in cladding: stress-free temperature equal to operating temperature. (VERLIFE 2008).	Residual welding stresses (RWS) in BM, WM and cladding are considered while defining stress fields in RPV wall. RWS distribution in BM, WM and cladding are allowed to be assumed in accordance with known literature and reports data.	Residual welding stresses (RWS) in BM, WM and cladding are considered while defining stress fields in RPV wall. Their distribution is given in the guideline /RD 12b/.	Yes.

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Adjustments for different constraint, shallow cracks							
No.	No. No.	Loss of constraint may be assumed if it can be quantified.	No.	Not yet.	Not provided.	Different constraint, the shallow crack effect and biaxial loading are considered in the guideline.	No.
Use of warm pre-stress (WPS)							
Not allowed.	Not yet. Under discussion. There is a proposal by French industry, not yet approved.	According to KTA 3201.2 WPS can be assumed for monotonically decreasing KI and also for non-monotonically decreasing K_I, if $K_I < K_{FRAC}$ $K_{FRAC} = K_{IC}$ at temperature of reloading after WPS.	Yes, according to KTA 3201.2 rule.	Yes. VERLIFE 2008 - WPS only for monotonically decreasing K_I after reaching its maximum, **In CZ:** new version of VERLIFE – WPS can be applied also for non-monotonically decreasing K_I. In any case K_I should be smaller than 90% of its maximal value.	According to PNAE G-7-002-86 and MT-D.0.03.391-09 WPS is not considered but actual calculations include the WPS based on IAEA recommendations.	A procedure for consideration of WPS is given in a guideline /RD 12b/.	Yes, in specific cases.
Mitigative measures applied							
In some plants fluence reduction by core loading. Modification of the ECCS injection path at Doel-1 and -2. Heating the ECCS-water to 35°C at Doel-1 and -2 and to 45°C at Doel-3.	In some plants fluence reduction by core loading. Heating the ECCS-water tanks to 20°C at Tricastin-1, Fessenheim-2, and St Laurent B-1.	No measures necessary for plants in operation.	In some plants fluence reduction by core loading.	In all plants fluence reduction by core loading. Heating to 55°C of high-pressure ECCS tanks (VVER 440 and 1000) and sump tanks (for high, low pressure and spray system) of VVER 1000. Modification of emergency procedures.	In all plants fluence reduction by core loading. Heating of high-pressure ECCS tanks to 20 to 55°C for different units. Possibility of reducing ECCS flow.	Fluence reduction by core loading, heating of high-pressure ECCS tanks up to 55°C and thermal annealing of the core weld of VVER 440 RPV. Annealing is also considered as an option for VVER 1000 in the future.	Loviisa NPP: Core reduction by dummy assemblies, heating of ECCS water in the accumulators and emergency tank, several modifications to instrumentation affecting coolant flow in certain PTS transients. Loviisa 1 RPV was annealed in 1996.

ETSON
EUROPEAN
TECHNICAL SAFETY
ORGANISATIONS
NETWORK

ETSON SECRETARIAT – IRSN
31, avenue de la Division Leclerc
B.P. 17
92262 Fontenay-aux-Roses Cedex
France
www.etson.eu

Association n° W921001929