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Unified Procedure for Lifetime Assessment of Components and Piping in WWER Nuclear Power Plants

(VERLIFE)

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APPENDICES

1. INTRODUCTION

This „Unified Procedure for Lifetime Assessment of Components and Piping in WWER Nuclear Power Plants“ *(Procedure)* provides a methodology for:

a. Lifetime assessment of components and piping in Nuclear Power Plants (NPPs) with WWER type reactors during their operation from point of view of fast failure caused by non-ductile and ductile fracture, fatigue and mechanical corrosion damage under operational conditions.

This Procedure can also be used at:

b. Evaluation of indications found during in-service inspection in components and pipings
c. Elaboration of Periodic Safety Review Reports during NPP operation including assessment of residual lifetime of components and piping
d. Preparation or modification of Plant/Component Life Management

This Procedure is mainly based on former Soviet Rules and Codes applied during design and manufacturing of components and piping of WWER type reactors. It also incorporates some approaches used in PWR Codes and Rules in order to be as consistent with PWR Codes and Rules as possible.

This Procedure is not intended to replace the national legislative documents. However, this document suggests modern, applicable procedures for component integrity assessment and remaining lifetime evaluation for WWER type plants. This Procedure or parts of this Procedure can be used for development of official reports (e.g. Periodic Safety Review Report, Licensing, Life Management Acceptance etc.) only with the acceptance of the cognizant National Regulatory Body.

2. GENERAL STATEMENTS, DEFINITIONS, ABBREVIATIONS

2.1 FIELD OF APPLICATION

2.1.1 This Procedure can be used for evaluation of residual lifetime of components and piping of NPPs with WWER type reactors designed, manufactured, inspected and operated in accordance with former Soviet Rules and Codes.

2.1.2 This Procedure can be used for evaluation of residual lifetime of replacement components and piping of NPPs with WWER type reactors manufactured in accordance with original design specifications.

2.1.3 This Procedure can be used for evaluation of residual lifetime of components and piping of NPPs with WWER type reactors during their operation.

2.1.4 This Procedure can be used for development of Periodic Safety Reports (or similar type of documentation) to demonstrate operational safety and reliability of components and piping during reactor operation.

2.1.5 This Procedure can be used for a definition of conditions for further reactor operation within or beyond the component or piping design lifetime/license validity.

2.1.6 This Procedure is based on a philosophy of operation lifetime and integrity evaluation similar to that used worldwide in codes and standards for PWR type reactors, but it does not exclude further use of results of current research and developments. Thus, this Procedure is harmonised with PWR Codes and rules as much as possible, taking into account original Soviet rules for design, manufacturing and inspection.

2.1.7 This Procedure can be applied to technological parts of NPPs with WWER type of reactors:

(1) metallic parts of pressure boundary components of safety related systems

(2) metallic parts of containments.

2.1.8 Figures and schemes in this Procedure represent only the generic conceptual design of a component and are not intended to provide actual design details.

2.2 LIST OF PRINCIPAL SYMBOLS AND ABBREVIATIONS

2.2.1 Technical symbols

a	depth (minor semiaxis) of a postulated defect, m
c	half length (major semiaxis) of a postulated defect, m
a_{calc}	depth of maximum postulated defect, m
a_{hyp}	depth of hypothetical starting crack, m
a_{arrest}	depth of finally arrested crack, m
E	young modulus, MPa
ν	Poisson ratio, -
G	energy release rate, $J.m^{-2}$
D	fatigue usage factor, -
K_I	stress intensity factor, $MPa.m^{0.5}$
K_{IC}	static fracture toughness under plane strain conditions, $MPa.m^{0.5}$
K_{JC}	static fracture toughness, $MPa.m^{0.5}$
$[K_{IC}]_i$	allowable value of stress intensity factor, $MPa.m^{0.5}$
$[K_{IA}]_i$	allowable value of stress intensity factor for crack arrest, $MPa.m^{0.5}$
n_k	safety factor, -
ΔT	temperature safety factor, °C
s	thickness of component wall, m
p	pressure, MPa
T	temperature, °C
T_t	material transition temperature, °C
T_k	material critical temperature of brittleness, °C
T_0	material reference temperature, °C
RT_0	material reference temperature for integrity evaluation, °C
$[T_h]$	allowable hydrotest temperature, °C
$[T_t]_j$	maximum allowable transition temperature for regime *j*, °C

$[T_t]$	maximum allowable transition temperature, ^{o}C
$[T_A]_j$	maximum allowable transition temperature for crack arrest for regime *j*, ^{o}C
$[T_A]$	maximum allowable transition temperature for crack arrest, ^{o}C

2.2.2 Abbreviations of terms

AOT	anticipated operational transients
EC	postulated accidents (emergency conditions)
HT	hydrotest or pressure test
I&C	Instrumentation and Control system for technological data collection (temperature and pressure of the media, velocity and volume of the flowing media, amounts of chemical admixtures, steam humidity etc.) measured by sensors in accordance with the NPP unit design
MDS	Monitoring and Diagnostic system for collection of supplementary data (temperature of the metal, stress and strain, frequency etc.) necessary for evaluation of the running damage of the material of the component, piping and their supports and for determination of their residual lifetime
NOC	normal operating conditions
NPP	nuclear power plant
QI	quality instructions
QM	quality manual
QP	quality procedures
RPV	Reactor Pressure vessel
SM	Special measurements for temporary collection of data of the same character as the data collected by the monitoring and diagnostic system. The special measurements are usually used to obtain supplemental information on the strain in areas without permanently located MDS sensors
WWER	Nuclear power plant with water-water energy reactor.

Other symbols and abbreviations specific to each chapter are defined and used in the separate chapters. The appendices include their own lists of symbols and abbreviations if necessary.

2.3 GENERAL TERMS

2.3.1 Design Specification. This is a document issued by the developer to ensure the design conforms to the demands of the controlling and regulatory bodies with legal authority for the nuclear power plant.

2.3.2 Limit represents the allowable value of a mechanical or physical quantity of the material, media or the value of load. To assure the required level of safety and compliance with the nuclear safety criteria issued by the State supervising bodies, the limit must not be exceeded.

2.3.3 Operability of the component means the ability of the component to function as designed and is separate from the issue of integrity.

2.3.4 Authorised body (institution, company) is the body holding the Authorisation of the professional qualification issued by relevant national organisation and/or the body employing workers who hold the Certificate of the professional qualification, in compliance with the relevant national legislation.

2.3.5 Verified computational code is the code awarded the Certificate for its use by the competent organisation, after verification its quality and function, by the appropriate commission of the State Regulatory Body

2.3.6 Holder of the authorisation is the natural or legal person in sense of national laws.

2.4 TERMS RELATED TO ASSESSMENT OF RESIDUAL LIFETIME

2.4.1 The terms used in this Procedure for treating assessment or residual lifetime are defined in the following articles.

2.4.2 Reduced stress (stress intensity)

Reduced stress (stress intensity) is defined as two times the maximum shear stress. In another way, the reduced stress is the difference between the maximum principal stress (algebraic value) and the minimum principal stress (algebraic value) in the given point. The tensile stresses are to be taken as positive, the compressing stresses as negative.

Comment: This definition of the reduced stress has no significance for the definition of the reduced stress in the area of fracture mechanics.

2.4.3 Large construction discontinuity (change)

A large construction discontinuity is a change in geometry or material which affects the stress or strain distribution through the entire wall thickness of the component loaded by the inner or outer pressure or the temperature field. Examples of areas where large construction discontinuities may exist include: the bottom head – shell wall interface; the shell flange; couplings with the shell; and transitions between shells of different radius or thickness.

2.4.4 Local construction discontinuity (change)

A local construction discontinuity is a geometry or material change that influences the stress or strain distribution in a small part of the wall thickness. The stress distribution connected with the local change causes only the localised deformation or reshape and has no significant influence on the deformation discontinuities of the shell. Examples include pipes of small radius, notches, small clamps, and welds with penetrations.

2.4.5 Normal stress

Normal stress is the stress component perpendicular to the given plane. The normal stress through thickness of the component is usually not uniform and is considered to consist of two parts: membrane stress and bending stress.

2.4.6 Shear stress

Shear stress is the stress component parallel to the given cross-section area.

2.4.7 Membrane stress

Membrane stress is the component of the normal stress, which is uniform and equal to the mean value of stress through the thickness of the given section.

2.4.8 Bending stress

Bending stress is the variable component of the normal stress described in Article 2.4.5. Bending stress is assumed to vary linearly through the thickness of the section under consideration.

2.4.9 Mechanical stress

Mechanical stresses are stresses initiated by pressure loads such as inner and outer pressure, inertial load, seismic impacts or gravitational effects. The size of such loads will not change due to deformation.

2.4.10 Total stress

Total stress is the sum of stresses of all categories, taking into account also the stress concentration.

2.4.11 Operation cycle

Operation cycle is defined as initiation followed by arising of changed conditions and by return again to the conditions prevailing at the beginning of the cycle.

2.4.12 Stress cycle

Stress cycle is the state in what the stress varies from its initial values through its algebraically maximum and minimum values and returns again to its initial value. A simple operation cycle can be formed by several stress cycles.

2.4.13 Free shift

Free shift represents the relative movements between the rigid bound and the connected wire or piping, in the case that those elements would be separated and permitted to displace.

2.4.14 Deformation (strain)

Deformation of the part of the component represents the change of its form and sizes.

2.4.15 Operational lifetime of the component

Operational lifetime of the component is the total period of operation, during which all prescribed limits are fulfilled in accordance with Article 2.3.2 and operability of the component is ensured.

2.4.16 Design lifetime of the component

Design lifetime of the component is the period given by design of the component (nuclear power plant). All conditions for lifetime of the component given in Article 2.4.15, based on design specification of the component and on ensured properties of materials of the component, have to be fulfilled.

2.4.17 Residual lifetime of the component

Residual lifetime of the component is the period from executed assessment until the end of its design lifetime.

3. GENERAL REQUIREMENTS FOR CALCULATION OF RESIDUAL LIFETIME

3.1 OPERATION CONDITIONS AND LIMITS

3.1.1 Components and systems in nuclear power plants of the WWER type are allowed to operate in service conditions given in the Design specifications after the system safety has been checked and verified. Significance of the operation conditions can be different for different components and their parts. Temperatures, stresses, and mechanical loads can be treated as computational, operation and test loads.

3.1.2 The suitable guidelines for selection of operation conditions that can be of some significance for selection of appropriate computational, operation and test loads and limits of those loads can be derived from the safety criteria for the systems of nuclear power plants. The guidelines can be included into requirements of the regulatory bodies with the legal authority for the nuclear power plants.

3.1.3 The loads given in the Design Specifications are to be used for assessment of residual lifetime of the component, piping and their supports. The load time variation should be corrected in accordance with data measured by the sensors of the Instrumentation and Control System (I&C), Monitoring and Diagnostic System (MDS) and temporary Special Measurement (SM).

In the case that measured data on loading obtained from I&C, MDS, and SM systems are available for the assessed period, utilisation of these data is preferred rather than data from the Design Specification.

3.1.4 For calculation of residual lifetime of the component, the limits established in the Design Specifications are to be used. If the necessary limits are not given in the Design Specifications, the limits given in the appropriate chapters of this Procedure shall govern.

3.2 MECHANISMS OF MATERIAL DAMAGE

3.2.1 Components, piping and their supports experience various degradation mechanisms during operation due to:

(1) fatigue of the material by cyclic loading,
(2) corrosion (pitting corrosion, corrosion cracking under permanent load and corrosion fatigue under accidental cyclic loading),
(3) flow accelerated erosion
(4) cyclic loading induced fatigue crack growth of flaws potentially presented in the material,
(5) radiation damage,
(6) material ageing under elevated temperatures, and
(7) material creep under elevated temperatures.

3.2.2 Nuclear power plant components are typically subjected to several degradation mechanisms simultaneously. In the case that this Procedure does not give suitable guidelines for assessment of interacting damage mechanisms, it is necessary to evaluate each mechanism separately and then sum the individual damage contributions. The total sum of the damage of the material must not exceed the limit value given in this Procedure. The gradual degradation of material properties during the lifetime of the nuclear power plant is taken into account in calculation of the residual lifetime of the components and piping.

3.3 GENERAL PROVISIONS FOR CALCULATION OF RESIDUAL LIFETIME

3.3.1 This Procedure provides the guidelines for:

(1) assessment of residual lifetime from the point of view of resistance against fast fracture,
(2) assessment of residual lifetime from the point of view of resistance against fatigue damage,
(3) assessment of residual lifetime from the point of view of resistance against corrosion-mechanical damage,

(4) assessment of acceptability of flaws found during in-service inspections and assessment of residual lifetime of the component with those flaws,

(5) final assessment of residual lifetime of the component.

3.3.2 This Procedure does not offer the guidelines for assessment of all kinds of material failure. For assessment of material creep at elevated temperatures or material wear, the procedures used should be based on the latest scientific knowledge and accepted by the Regulatory organisations.

3.3.3 The material characteristics of strength, plastic and brittle fracture resistance, referred to in this Procedure or experimentally derived by the accredited or authorised body, are used for calculation of residual lifetime of the component.

3.3.4 For the lifetime calculation, increases in tensile strength and yield point and changes in non-conventional characteristics due to radiation are not taken into account, with the exception of elastic-plastic calculations for fast fracture assessment in accordance with par. 5.2.4. The reduction of plastic characteristics and characteristics of material resistance against fast fracture and fatigue failure is included.

3.3.5 For assessment of gradual fatigue damage to cyclically loaded components, the procedures described in this Procedure are to be used.

3.3.6 For calculation of residual lifetime of the component, the groups of stress categories are to be used, in accordance with this Procedure.

3.3.7 For calculation of stresses and strains, component nominal wall thickness s taken from the design documentation is to be used. The actual wall thickness can be used if it is known and has to be used if it is less than s.

3.3.8 For calculation of stress in the component with cladding or anti-corrosion layer, the temperature effects of the cladding or the anti-corrosion layer and also mechanical properties of the cladding and the anti-corrosion layer are to be taken into account.

3.3.9 The reduced stresses are to be derived in accordance with the maximum shear stress theory. The only exception is calculation of the resistance against fast fracture, where the reduced stress is to be derived in accordance with the maximum normal stress theory.

3.3.10 Calculation of the stress is carried out assuming elastic behaviour of the material in the whole loading range, unless the special cases are studied mentioned in the appropriate Articles of this Procedure.

3.3.11 For calculation of residual lifetime of the component, the limits for allowable values of stress, displacement, and loading, postulated number of repeats of operation transient modes as well as the required operational lifetime are taken in accordance with the Design Specifications. The number of the actual repeats of the operations transient modes is to be taken in accordance with the measurements of the I&C and MDS systems. The number also can be extracted from the Design Specifications, in relation to the current time of operation. The number of repeats of the operation transient regimes during the residual lifetime is considered in accordance with the component Technical Specifications. This is proportional to the assumed period of the subsequent operation of the component.

3.3.12 The limits of allowable values are different in accordance with the type of structure, the character of load, working regime and categories of active stresses, taking into account also the level of importance of the component and effects of its possible failure.

3.3.13 Calculation of residual lifetime of the components and piping in accordance with this Procedure is to be carried out only by the authorised body (company) having the appropriate Authorisation; the employees, who are performing the work, have to be awarded the Certificate required by the relevant legislation. The authorised body is responsible for extraction of the proper input data for calculation of strength from the developer's Design Specifications and from the producer’s technical specification and also for use of the proper data from the measurements of the I&C, MDS and SM systems. The authorised body is responsible also for the choice and proper use of the methods of calculation of temperature fields, strains and stresses, if specific methods have not been prescribed. Nevertheless, the used methods have to consider all computational operation loads for all computational modes and facilitate determination of all necessary groups of stress categories.

3.3.14 The authorised body performing calculation of strength of the component is also responsible for correctness of the results of calculation.

3.3.15 Only computer codes verified in accordance with the relevant legislation can be used for calculation.

3.4 DOCUMENTATION

3.4.1 Calculation of residual lifetime is to be carried out for every single type of structure. Different types of structures can be included into a single report only if the structures are functionally interconnected.

3.4.2 The holder of the authorisation is authorised to adapt, in accordance with the relevant legal provisions, the required extent of calculation of residual lifetime by issuing the relevant requirements. Calculation of residual lifetime has to involve at least the following parts:

(1) technical terms of reference,
(2) justification of the computational model,
(3) calculation of the temperature fields, strains and stresses,
(4) calculation of residual lifetime,
(5) conclusions and recommendation of measures.

3.4.3 The part "*Technical Terms of Reference*" must provide a short description of the type of the component and its use, and the sources of inputs (projects, designs, plans etc.) must be identified. Geometry of the component, the marks of the used materials and the loads in the sites of their actions have to be displayed in figures and sketches. An overview of loads, operation modes and loading blocks including their specific properties, physical and strength characteristics necessary for strength calculation should be also given. The limits for reduction of stresses, strains, cumulative damage etc. have to be also displayed.

3.4.4 In the part "*Justification of computational model*", the choice of the areas in the component and acting loads is to be justified and the methods of schematisation of geometry and acting loads used for computational or experimental model are to be presented.

3.4.5 In the part *"Calculation of temperature fields, strains and stresses*", the methods used for calculation and for experimental measurements have to be justified. Use of the computing codes also must be justified, and the source of their verification (the verifying body, the date of verification, relevant legal provisions for evaluation of the compliance) must be identified. Results of calculations and experimental measurements shall be presented in a clear (graphic) format.

3.4.6 In the part "*Calculation of residual lifetime*", it has to be demonstrated that the calculated strains, stresses and temperatures and defects, if applicable, do not exceed limits established by this Procedure.

3.4.7 In the part *"Conclusions and recommendations of measures"*, the results of calculation of residual lifetime of the component are to be generalised. If necessary, the required verification of in-service measurements and special measurements for a specified operation period are to be specified. If necessary, the storage sites of the surveillance samples for demonstration of changes of the material properties during operation of the component and piping are to be recommended. The storage sites of the surveillance samples must be out of influence of any degradation process. If necessary, the areas of the component or piping, where non-destructive in-service tests have to be carried out, are to be determined or specified. The necessary frequency of non-destructive testing is to be determined. If needed, the period of exchange due to ageing of replaceable parts of the component is to be determined.

3.4.8 An example of the table of contents of the Residual Lifetime Assessment Report is given in Appendix I.

3.5 SYSTEM OF QUALITY ASSURANCE

3.5.1 The System of the quality assurance, in accordance with the relevant legal provisions, has to be established in the body performing calculation of residual lifetime of the component.

3.5.2 The System of the quality assurance has to be demonstrated and documented by the Manual of the Quality Assurance (QM – Quality Manual), the Procedures of the Quality Assurance (QP – Quality Procedures) and the Instructions for Quality Assurance (Quality Instructions – QI). The Quality Assurance Procedures for development and use of computing codes and for performing the residual lifetime calculation of the component (the manual) shall be issued. The Procedures have to involve the declaration of responsibility for application of valid and verified computing codes for the defined computing technique. The requirements for professional qualification of workers who are responsible for activities or execute activities related to development and use of computing codes and performing the calculation of residual lifetime of the component have to be defined. The responsibilities for awarding, maintaining and control of the professional qualification of workers have to be presented.

3.5.3 The Quality Assurance Procedure for identification and recording of disagreements related to the development and use of computing codes and to performing the calculation of residual lifetime of the component and procedures for adoption and inspection of corrective measures shall be issued.

3.5.4 The List of controlled documents with nominal responsibilities for their elaboration and deposition shall be issued.

3.5.5 The Procedure for archiving of controlled documents with responsibilities for their storage, maintenance and access to those shall be issued.

3.5.6 A page containing name of the document, date of its issue, the issue number, the review number, indication if changes shall be sent to the holder and name and signature of the author of the document has to accompany the controlled document, in accordance with the established Quality Assurance System. Also names, signatures and date of signing of the persons who verified, approved and adopted (if applicable) the document have to be added.

3.5.7 The author of the certificates has to prove in the controlled way compliance with all requirements contained in the Design Specification issued by the owner of the component for which calculations of residual lifetime are performed.

3.5.8 The author of the certificates has to take into account all comments to the elaborated calculation of residual lifetime issued by the Inspection authority chosen by the holder of the permission.

3.5.9 The author of the residual lifetime calculation has to issue the List of approved suppliers of computing codes, single parts of residual lifetime calculation and material characteristics. Before enlisting them into the List of approved suppliers, the author has to check the application of their Quality Assurance Systems, ownership and validity of their authorisations and certificates for the required activities. The mentioned systems have to be regularly audited by the author.

If the supplier of services has not established its own Quality Assurance System, then the responsibility for his activities is transferred to the author and the author has to prove the way of the quality assurance of the supplied services.

If the supplier of services does not own the required Authorisation or Certificate, then the author will have to own the necessary Authorisation or Certificate for the supplied services, for example, for measurements of the material characteristics.

3.5.10 The author of calculation of residual lifetime has to own the valid Authorisation and to employ workers with valid Certificates for activities related to performing the residual lifetime calculation for the component of the nuclear power plants (NPP).

4. PROCEDURE FOR ASSESSMENT OF RESIDUAL LIFETIME OF THE COMPONENT

4.1 GENERAL PRINCIPLES

The residual lifetime assessment of the component is usually carried out in four steps described in Articles 4.2-4.5 and in Chapters 5-8.

4.2 ASSESSMENT OF RESIDUAL LIFETIME OF THE COMPONENT FROM THE POINT OF VIEW OF THE RESISTANCE AGAINST FAST FRACTURE ("WITH THE POSTULATED DEFECT")

4.2.1 During the assessment, all environmental effects and operational conditions should be taken into account even beyond design conditions. Assessment represents a check of the project level lifetime assessment and is described in detail in Chapter 5 of this Procedure.

4.2.2 The calculation is based on a "postulated defect" – the surface or underclad semi-elliptical crack. The actual operation conditions are to be used for calculation, including the degradation processes in the material of the component.

4.2.3 The residual lifetime calculation is carried out on the basis of trends of material transition temperature changes established for the designed or assumed component lifetime.

4.2.4 **The criterion of residual lifetime of the component from the point of view of resistance against fast fracture is exclusion of fast fracture from the "postulated defect" during all possible operating condition**. Resistance against fast fracture is assured (for emergency conditions or anticipated operational transients) if the transition temperature of the component material is lower than its maximum allowable value $[T_t]$ or $[T_A]$. In case of reactor pressure vessels, this temperature is usually determined from the worst mode of pressurised thermal shock. For normal operation conditions or hydrotests, so-called [p]-[T] curves (dependence of allowed pressure on the primary coolant temperature), can represent the decisive mode. In such special cases, the allowed range of operation parameters can be so close to the saturation curve (shifted to lower temperatures with the necessary safety margin) that the safe operation of the component is not possible.

4.3 ASSESSMENT OF "FATIGUE LIFETIME" OF THE COMPONENT

4.3.1 Residual lifetime of the component from the point of view of resistance against fatigue damage is to be derived during the whole assumed technical lifetime of the component until initiation of the surface macro-crack of the postulated size equal to 1.0 mm.
Residual lifetime of the component with the macro-crack larger than 1.0 mm is to be derived in accordance with Article 4.5.

4.3.2 The aim of assessment is to determine conditions for potential initiation of the macro-crack on the material originally without any defect due to thermal-mechanical cyclic (fatigue) loading. This is assessment of residual lifetime of the component under the cyclic loading, which is described in Chapter 6 of this Procedure.

4.3.3 The actual operation conditions are taken into account in this calculation in accordance with Article 3.3.11, i.e. the actual operational thermal-stress cycles, their time variations, frequency and series.

4.3.4 **The criterion of residual lifetime of the component from the point of view of resistance against fatigue damage is exclusion of any initiation of the macro-defect of the size 1.0 mm due to the cyclic loading. During the period of the assumed technical lifetime of the component as mentioned, for example, in design, no initiation of the macro-defects (cracks) is admissible. A possibility of the time-limited operation with the detected macro-defect, which arose during operation, has to be assessed in accordance with Article 4.5 of this Procedure.**

4.4 ASSESSMENT OF RESIDUAL LIFETIME OF THE COMPONENT FROM THE POINT OF VIEW OF RESISTANCE AGAINST CORROSION-MECHANICAL DAMAGE

4.4.1 Residual lifetime of the component from the point of view of resistance against corrosion-mechanical damage is defined as the time remaining until initiation of a surface defect (pit, crack) due to corrosion-mechanical loading.

4.4.2 The aim of assessment is to determine the conditions for initiation of the macro-crack sized 1.0 mm on the material originally without any defect due to corrosion-mechanical loading. The procedure of assessment is described in Chapter 7 of this Procedure.

4.4.3 The actual operation conditions are taken into account in this calculation in accordance with Article 3.3.11, i.e. the actual operation thermal-stress cycles, their time variations, frequencies and sequences and influence of fluid chemical additives or influence of adulterants in surface deposits.

4.4.4 **The criterion of residual lifetime of the component from the point of view of resistance against corrosion-mechanical damage is exclusion of initiation of any macro-defect of size 1.0 mm due to a corrosion-mechanical damage. During the period of the assumed technical lifetime of the component as mentioned, for example, in design, no initiation of macro-defects (pit, crack) is admissible. The possibility of a time-limited operation with the macro-defect detected in service has to be assessed in accordance with Chapter 7 of this Procedure.**

4.5 ASSESSMENT OF RESIDUAL LIFETIME OF THE COMPONENT WITH FLAWS DETECTED DURING IN-SERVICE INSPECTION

4.5.1 Residual lifetime of the component with flaws found by non-destructive tests during in-service inspections is to be calculated in accordance with the procedure described in Chapter 8 of this Procedure.

4.5.2 The aim of assessment is to determine the conditions for instability including fatigue crack growth of the flaw detected.

4.5.3 For the calculation, the actual operation conditions are to be taken into account in accordance with Article 3.3.11. Actual operation thermal-stress cycles, their time variations, frequencies and sequences, actual temperature of the metal and also the actual radiation load, radiation damage and thermal ageing of the component material are to be considered. Possible growth of the flaws due to operation conditions during the assumed technical life of the component is to be derived for the flaws schematised in accordance with Appendix X of this Procedure.

4.5.4 The criterion of residual lifetime of the component with flaws determined by non-destructive tests carried out during outages and shutdowns is exclusion of growth of the flaws over the allowed value during the period of the assumed technical lifetime of the component as mentioned, for example, in design.

5. ASSESSMENT OF COMPONENT RESISTANCE AGAINST FAST FRACTURE

5.1 GENERAL CONDITIONS

5.1.1 Assessment of ferritic steel component lifetime based on resistance against fast fracture should be performed in accordance with this Chapter. Assessment is based on stress intensity factor K_I, computation of which is based on either linear-elastic or elastic-plastic fracture mechanics. Selection of components for the assessment is based on national regulatory body requirements.

5.1.2 Assessment of component resistance against fast fracture is performed for all regimes of NOC, HT, AOT as well as EC.

5.1.3 Base materials characteristics for the calculations are static fracture toughness, K_{IC}, and transition temperatures: reference temperature T_0 (based on Master curve approach) and/or critical temperature of brittleness, T_k. Material damage due to operating conditions is expressed in terms of a shift of temperature dependences of static fracture toughness (characterised by reference temperature, T_0) or impact notch toughness (characterised by critical temperature of brittleness, T_k) as a result of different operating stressors.

5.1.4 Resistance against fast fracture is assured if the following condition

$$K_I \leq [K_{IC}]_i, \qquad (5.1)$$

is fulfilled for a postulated crack-like defect, where $[K_{IC}]_i$ is the allowable value of stress intensity factor for a given type of operating condition.

Index **i** indicates different operating conditions:

$i = 1$ - normal operating conditions (NOC),

$i = 2$ - anticipated operational transients and hydrotests (AOT and HT),

$i = 3$ - postulated accidents / emergency conditions (EC).

5.1.5 Values of K_I and $[K_{IC}]_i$ are compared at least for the deepest and surface or near interface points of the postulated defect. (The near interface point is the point just below the interface between cladding and base or weld material in the case of cladded components.) Comparison of those values for all points of postulated crack front is recommended (it is usually possible only for a finite element solution on a model with crack included in the mesh).

5.1.6 This procedure may be applied for component integrity assessment and lifetime evaluation during NPP operation based on resistance against fast fracture. In the case of component assessment during operation, actual material characteristics may be used in calculations if their definition is accepted in advance by Regulatory organisations.

5.2 TEMPERATURE AND STRESS FIELDS

5.2.1 Stress and temperature fields must be calculated for all normal operating regimes, anticipated operational transients and postulated accidents either represented by their design parameters or by parameters calculated from thermal-hydraulic analyses according to the Appendix VI.

5.2.2 Stress calculations must be performed taking into account internal pressure, dead weight, temperature gradients; for EC and AOT, residual stresses (in welding joints and in cladding) must be considered. Residual stresses σ_R in welding joints in absence of measured values can be taken conservatively according to the following formula:

$$\sigma_R = 60 \cdot \cos\left(\frac{2\pi x}{s_w}\right) \quad [MPa], \tag{5.2}$$

where

x is coordinate in weld thickness direction (with its origin in surface point for the case of uncladded component or in interface point for the case of cladded component),

s_w is weld thickness.

Formula (5.2) can be used only in the case when heat treatment of the weld joint was performed after welding. Residual stress in cladding is introduced by choosing the value of stress-free temperature equal to normal operating temperature.

5.2.3 Temperature and stress field must be calculated for different time steps which must be chosen in such a way to catch all local maxima/minima of stress as well as the transient course until stabilised conditions occur or until the time important for the determination of temperature [T_t] is reached (see 5.10.6).

5.2.4 Temperature and stress fields are calculated using temperature-dependent characteristics of base material, weld metal as well as cladding materials. Changes of these properties due to radiation damage may be taken into account if they are reliably known. The proposed thermal-physical properties for materials of WWER 440 and WWER 1000 reactor pressure vessels are presented in Appendix XV. The tensile properties necessary for elastic-plastic calculations should be taken plant-specific.

5.2.5 Calculation of temperature and stress fields must take into account also the existence of austenitic cladding and its plastic behaviour in the case of cladded components.

5.2.6 For elastic-plastic calculations, the following selection of tensile properties (based either on results of surveillance program or on standards) of both base/weld and cladding materials is conservative:

- for the case of surface crack: the upper bound of yield and ultimate strengths and lower bound of uniform elongation,
- for the case of underclad crack: the lower bound of yield and ultimate strengths and upper bound of uniform elongation.

5.2.7 Calculation of temperature and stress fields may be performed using numerical as well as analytical methods if they are accepted by Regulatory organisations. Generally, Finite Element Method is recommended for temperature and stress fields calculations.

5.3 STRESS INTENSITY FACTOR

5.3.1 Stress intensity factor for a chosen postulated defect may be calculated by numerical methods or by simplified engineering methods if they are accepted by Regulatory organisations in advance.

5.3.2 The preferable way for determining the stress intensity factor for both surface and underclad cracks is using Finite Element Method code on elastic-plastic model with crack included in the mesh. In that case the energy release rate G (or J-integral) is usually calculated directly by the FEM code and subsequently the stress intensity factor can be calculated using the following formulae:

for surface points of the crack (plane stress condition):

$$K_I = \sqrt{G \cdot E} \qquad (5.3)$$

for other points of the crack (plane strain condition):

$$K_I = \sqrt{\frac{G \cdot E}{1-\nu^2}} \qquad (5.4)$$

where the Young modulus *E* is determined for the actual temperature of the relevant point on crack tip.

5.3.3 Stress intensity factor for surface cracks for all types of operating conditions may be also determined with the use of procedure given in Appendix IV, based on stresses computed on model without crack. In the case of cladded components, stress values extrapolated from the base/weld material to points located in cladding are used in the formulae from the Appendix IV instead of stresses computed directly in the cladding.

5.3.4 In the case of underclad cracks, specific formulae taking into account the effect of cladding may be used if they are validated.

5.4. TRANSITION TEMPERATURES OF MATERIAL

5.4.1 The following transition temperatures, T_t, may be used for characterisation of material state: reference temperature, T_0, determined from static fracture toughness tests using “Master curve“ approach, as well as critical temperature of brittleness, T_k, determined from Charpy impact tests.

Material state of degradation should be determined according to Appendix III for all assessed points of the postulated crack, as defined in par. 5.1.5.

5.4.2 Reference temperature T_0

5.4.2.1 Reference temperature T_0, increasing during operation, is determined experimentally from surveillance specimens irradiated to required neutron fluence. End-of-life design fluence should be taken as a basis for initial evaluations. Possible thermal and fatigue aging should be also taken into account.

5.4.2.2 Determination of reference temperature T_0 is performed using “Master curve“ approach using multi-temperature approach preferably to the single-temperature one.

5.4.2.3 Reference temperature T_0 is defined from experimentally determined values of static fracture toughness, K_{JC}, adjusted to the thickness of 25 mm. Margin σ is added to cover the uncertainty in T_0 in accordance with Appendix III and for the assessment the value

$$RT_0 = T_0 + \sigma \tag{5.5}$$

is used.

5.4.3 **Critical temperature of brittleness T_k**

5.4.3.1 Critical temperature of brittleness during component operation is determined as:

$$T_k(t) = T_{k0} + \Delta T_F(t) + \Delta T_T(t) + \Delta T_N(t) \tag{5.6}$$

where

$T_k(t)$ - critical temperature of brittleness for time t, ^oC

T_{k0} - initial critical temperature of brittleness, ^oC

$\Delta T_F(t)$ - transition temperature shift due to radiation damage, ^oC

$\Delta T_T(t)$ - transition temperature shift due to thermal ageing, ^oC

$\Delta T_N(t)$- transition temperature shift due to cyclic damage, ^oC

5.4.3.2 Values of T_{k0} are determined from acceptance tests of materials. Values of $\Delta T_F(t)$, $\Delta T_T(t)$ and $\Delta T_N(t)$ are determined from surveillance specimens programme tests, material qualification tests or standards (see also Appendix III).

5.4.3.3 Trends in changes of critical temperature of brittleness are determined taking into account evaluated trends of component operation - from the point of view of number and types of operation regimes as well as neutron fluences and truly determined material properties.

5.5 PROCEDURES FOR DETERMINATION OF RADIATION LOADING OF REACTOR PRESSURE VESSELS

5.5.1 Determination of radiation loading, i.e. values of neutron fluences in different places of reactor pressure vessel, is necessary for precise determination of degradation trends in reactor pressure vessel materials as well as for prediction of reactor pressure vessel residual lifetime.

Determination of radiation loading of reactor pressure vessels is carried out by combining measurements and calculations. Neutron fluences in given reactor pressure vessel points and in surveillance specimens positions are determined by calculating the absolute values. The calculation results are compared with the measurement results in surveillance specimens' positions and on outer reactor pressure vessel wall. All values which are necessary for calculations, interpretation of measurements and comparison of calculated and measured values shall be archived.

5.5.2 Inputs for reactor pressure vessel integrity evaluation must not be only neutron fluences reached during actual operation but also estimation of their trend changes until the reactor end-of-life. These trends must be prepared taking into account planned further operation and potential changes in reactor operation, such as changes in operational cycles, campaigns, types and enrichment of fuel elements, etc.

5.5.3 More detailed procedure of fluence determination is presented in Appendix II.

5.6 ALLOWABLE STRESS INTENSITY FACTORS

5.6.1 Allowable stress intensity factors, $[K_{IC}]_i$, and also allowable stress intensity factors for crack arrest, $[K_{IA}]_i$, depend on material temperature and operating conditions of the component. It is allowed to determine their temperature dependences with respect to the transition temperature according to the formulae in this paragraph. More detailed description is presented in Appendix V.

5.6.2 **Allowable stress intensity factors based on reference temperature T_0**

5.6.2.1 Temperature dependence $[K_{IC}]_i$ based on reference temperature T_0 is defined as lower bound curve of two curves obtained from the 5% tolerance bound of “Master curve”; one curve is calculated using a safety factor $\mathbf{n_k}$ and the other one using a temperature safety factor Δ **T,** i.e. using the formula:

$$[K_{IC}]_i(T\text{-}RT_0) = \min \{ n_k^{-1}.\ K_{JC}^{5\%}(T\text{-}RT_0); K_{JC}^{5\%}(T\text{-}RT_0\text{-}\Delta T) \} \qquad (5.7)$$

where $K_{JC}^{5\%}(T\text{-}RT_0)$ represents a 5 % tolerance bound of “Master curve“ for temperature $(T\text{-}RT_0)$ etc. The denotation $[K_{IC}]_i$ is used here for simplification of the following text even thought it is based on K_{JC}.

Safety factors are defined as follows

for NOC (i=1) :	$n_k = 2;$	$\Delta T = + 30\ ^oC$	(5.8)
for HT and AOT (i=2) :	$n_k = 1.5;$	$\Delta T = + 30\ ^oC$	(5.9)
for EC (i=3) :	$n_k = 1;$	$\Delta T = + 0\ ^oC$	(5.10)

For components made from 15Kh2MFA(A), 18Kh2MFA, 25Kh2MFA, 15Kh2NMFA(A), 22K and 10GN2MFA type steels and their welding joints, the following relation may be used:

$$K_{JC}^{5\%}(T) = \min\{25.2 + 36.6\cdot\exp[0.019\cdot(T\text{-}RT_0)]; 200\} \qquad (5.11)$$

5.6.2.2 Temperature dependence of allowable values of stress intensity factors for crack arrest $[K_{IA}]_3$ based on reference temperature T_0 for materials used in WWER-440 and WWER 1000 reactor pressure vessels may be calculated from the following formula:

$$[K_{IA}]_3(T) = \min\{25.2 + 36.6\cdot\exp[0.019\cdot(T\text{-}RT_0\text{-}60)]; 200\} \qquad (5.12)$$

5.6.2.3 The formulae for $K_{JC}^{5\%}$ (for above mentioned materials used in WWER-440 and WWER 1000 NPPs the formula (5.11) may be used) and for $[K_{IA}]_3$ (5.12) are valid for length of crack front 25 mm. For general value of length of crack front for emergency conditions the size correction has to be applied as follows:

$$K_B = K_{\min} + (K_{25} - K_{\min})\cdot\left(\frac{B_{25}}{B}\right)^{\frac{1}{4}} \qquad (5.13)$$

where

K_B is the value of $K_{JC}^{5\%}$ or $[K_{IA}]_3$ corrected to length of crack front B,

K_{25} is the original value of $K_{JC}^{5\%}$ or $[K_{IA}]_3$ valid for 25 mm,

B is the length of crack front (in mm),

B_{25} is 25 mm,

K_{min} is 20 MPa·m$^{1/2}$.

For cracks postulated according to Chap. 5.7 the length of crack front used in size correction will be taken as the length of main axis of the postulated semi-ellipse, i.e. $B = 2c$ will be taken. The maximum length of crack front used in the correction is the wall thickness.

The size correction is applied only to the "Master curve part" of formulae (5.11) and (5.12), the "upper shelf" value 200 MPa·m$^{1/2}$ remains uncorrected.

5.6.3. Allowable stress intensity factors based on critical temperature of brittleness T_k

5.6.3.1 Temperature dependence $[K_{IC}]_i$ based on critical temperature of brittleness T_k is defined as lower bound curve of two curves obtained from the temperature dependence of static fracture toughness, $\mathbf{K_{IC}^{5\%}}$**;** one curve is calculated using a safety factor $\mathbf{n_k}$ and the other one using a temperature safety factor Δ **T**, i.e. using the formula:

$$[K_{IC}]_i(T-T_k) = \min \{ n_k^{-1}.K_{IC}^{5\%}(T-T_k); K_{IC}^{5\%}(T-T_k-\Delta T) \} \qquad (5.14)$$

where $K_{IC}^{5\%}(T-T_k)$ represents the 5% lower bound curve as a function of $(T-T_k)$ etc. of all experimental data of static fracture toughness of the materials obtained within the qualification and other type tests and values of safety factors $\mathbf{n_k}$ and Δ **T** are given in 5.6.2.

For components made from 15Kh2MFA(A), 18Kh2MFA, 25Kh2MFA, 15Kh2NMFA(A), 22K and 10GN2MFA type steels and their welding joints, the following temperature dependences of allowable stress intensity factors may be used:

$$[K_{IC}]_1(T) = \min \{13 + 18\cdot\exp [0.020\cdot(T-T_k)]; 100\} \qquad (5.15)$$

$$[K_{IC}]_2(T) = \min \{17 + 24\cdot\exp [0.018\cdot(T-T_k)]; 120\} \qquad (5.16)$$

$$[K_{IC}]_3(T) = \min \{26 + 36\cdot\exp [0.020\cdot(T-T_k)]; 200\} \qquad (5.17)$$

The above-mentioned curves are 1% lower bound curves.

5.6.3.2 Temperature dependence of allowable values of stress intensity factors for crack arrest $[K_{IA}]_3$ based on critical temperature of brittleness T_k for materials used in WWER-440 and WWER 1000 reactor pressure vessels may be obtained from the following formula:

$$[K_{IA}]_3(T) = \min \{26 + 36\cdot\exp [0.020\cdot(T-T_k-30)]; 200\} \qquad (5.18)$$

5.6.4 No additional safety margin besides that defined in this paragraph should be applied to $[K_{IC}]_i$ and $[K_{IA}]_3$.

5.6.5. Formulae for allowable stress intensity factors given in this paragraph can be used only if material testing and evaluation of the results is performed in accordance with the appropriate paragraphs or appendices of this Procedure.

5.7 POSTULATED CRACKS

5.7.1 The integrity assessment has to be performed for a set of postulated cracks with depth values varying from the minimum value up to the maximum postulated crack depth a_{calc} defined in next paragraphs. In the case when the whole crack front is assessed, postulation of the crack with only one value of crack depth a_{calc} is sufficient.

5.7.2 If in-service inspections are performed with devices, procedures and personnel qualified according to requirements of Regulatory organisation, the maximum postulated crack depth a_{calc} may be defined on the basis of the plant specific non-destructive testing qualification criteria. In this case the value a_{calc} is taken equal to higher of the two following values:
(i) “high confidence of detection” crack depth with applied safety factor 2,
(ii)“high confidence of sizing” crack depth without applied safety factor (safety factor = 1).
The recommended value corresponding to application of advanced qualified non-destructive testing techniques is $a_{calc} = 0.1$ s.

5.7.3 If the conditions concerning the qualification of non-destructive testing mentioned in the previous paragraph aren’t satisfied, the maximum postulated crack depth shall be defined as:

$a_{calc} = 0.25$ s.

5.7.4 Minimum depth of postulated crack for RPV wall to be assessed is 4 mm for uncladded RPVs or for underclad cracks, and thickness of cladding plus 4 mm for surface cracks in cladded RPVs.

5.7.5 The postulated defects are defined as a semi-elliptical cracks with aspect ratios

a/c = 0.3 and a/c = 0.7.

5.7.6 Two orientations of postulated crack shall be considered: perpendicular to direction of first principal stresses and perpendicular to direction of second principal stresses, i.e. in the case of cylindrical vessel perpendicular to circumferential direction and perpendicular to axial direction.

5.7.7 For the assessment of postulated cracks in weld metal of weldments, all points of crack front are supposed to lie within the weld material (independently of weld and crack actual dimensions and of the crack orientation) taking into account the possible existence of cladding.

5.7.8 The position of the crack within the component wall is defined specifically for individual types of operating conditions in the following paragraphs.

5.8 EVALUATION OF NORMAL OPERATING CONDITIONS (NOC)

5.8.1 Resistance of the component against fast fracture under NOC is assured, if the following condition is fulfilled in points defined in paragraph 5.1.5:

$$K_I \leq [K_{IC}]_1 \qquad (5.19)$$

5.8.2 The postulated defect is defined as a surface crack with further specifications defined in par. 5.7.

5.8.3 Temperature dependence of allowable pressure, i.e. the [p] - [T] curve, can be determined for individual NOC regimes on the basis of condition (5.19) for given transition temperature. The [p] - [T] curve can be constructed in the following way:

For all time steps within the NOC regime, contributions due to thermal loading, K_I^T, to the total stress intensity factor K_I are computed. Contribution due to loading by unit inner pressure, K_I^p, is computed separately. Assuming linear fracture mechanics, the condition (5.19) can be rewritten according to the principle of superposition as follows:

$$p \cdot K_I^p + K_I^T \leq [K_{IC}]_1 \tag{5.20}$$

From the equality in this condition the maximum allowable pressure for the particular time step can be determined. The resulting curve is presented as dependence of maximum allowable pressure on the temperature of the system coolant, the time variation of which is known for the actual NOC regime.

5.9 EVALUATION OF ALLOWABLE HYDROTEST TEMPERATURES

5.9.1 Resistance of the component against fast fracture during a hydrotest is assured, if the following condition is fulfilled in the points of postulated defect as defined in paragraph 5.1.5:

$$K_I \leq [K_{IC}]_2 \tag{5.21}$$

This condition must be fulfilled during the heating-up of the component, pressure increase, holding at maximum pressure and during the following cooling.

5.9.2 The postulated defect is defined as a surface crack with further specifications defined in par. 5.7.

5.9.3 Allowable temperature during hydrotest is then determined from the equality in condition (5.21) for individual parts of the component for given transition temperature for the time of the hydrotest, where similarly as in 5.8.3 contributions due to thermal loading, K_I^T, and due to hydrotest pressure, $p_H \cdot K_I^p$, to the total stress intensity factor K_I are considered:

$$p_H \cdot K_I^p + K_I^T = [K_{IC}]_2 \tag{5.22}$$

Allowable hydrotest temperature, **$[T_h]$**, is the maximum value of all allowable temperatures determined for individual parts for the hydrotest. The temperature of the component during the hydrotest must be greater than or equal to **$[T_h]$.**

5.9.4 Temperature dependence of allowable pressure, i.e. the [p] - [T] curve, during the whole hydrotest can be determined from the condition (5.22) for given transition temperature in similar way as described for NOC in par. 5.8.3.

5.10 EVALUATION OF EMERGENCY CONDITIONS (EC) AND ANTICIPATED OPERATING TRANSIENTS (AOT)

5.10.1 Choice of proper emergency conditions as well as anticipated operational transients must be performed in accordance with the design. Such evaluation is mandatory for reactor pressure vessels. Requirements for selection of the EC regimes of the PTS (pressurised thermal shock) type for reactor pressure vessel and for thermal-hydraulic calculations of the selected regimes are presented in Appendix VI.

5.10.2 Resistance of the component against fast fracture during EC and AOT is assured if the following condition is satisfied respectively

(1) for AOT: $K_I \leq [K_{IC}]_2$ (5.23)

(2) for EC: $K_I \leq [K_{IC}]_3$ (5.24)

for points of the postulated crack front (as defined in 5.1.5). The values of $[K_{IC}]_2$ and $[K_{IC}]_3$ may be based either on T_k or T_0 approach.

5.10.3 The integrity assessment must be performed for a set of postulated cracks with depth values varying up to a_{calc} (or in the case when the whole crack front is assessed it can be performed for only one crack depth a_{calc} — see par. 5.7). The crack is located in the component area with the most damaged material or in the region with the maximum thermal-mechanical impact of the regime evaluated. Postulated crack is defined in the following manner:

5.10.3.1 Uncladded component

The postulated defect is defined as inner surface crack with further specifications defined in par. 5.7 (see Fig. 5.1).

In this case, at least the deepest and surface points of the postulated defect must be assessed.

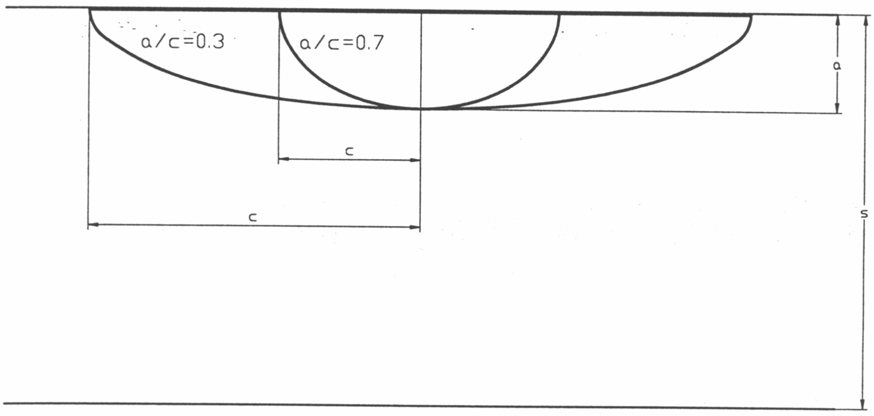

Fig. 5.1. *Semielliptical surface crack, uncladded vessel.*

5.10.3.2 Cladded component, provided that fracture properties of cladding are not known or its integrity is not assured by qualified non-destructive inspections

The postulated defect is defined as inner surface crack going through the austenitic cladding (see Fig. 5.2). Further crack specifications are defined in par. 5.7.

In this case, at least the deepest and near interface points of the postulated defect must be assessed.

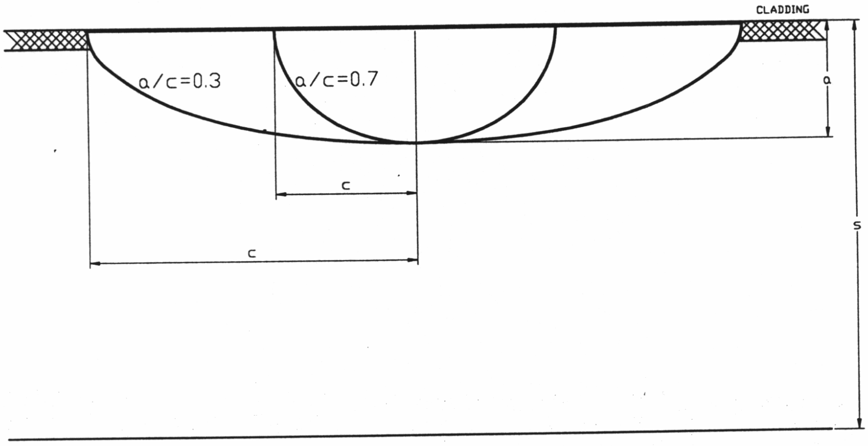

Fig. 5.2. *Semielliptical surface crack, cladded vessel.*

5.10.3.3 Cladded component, provided that fracture properties of austenitic cladding are known and cladding integrity is assured by qualified non-destructive inspections

The postulated defect is defined as underclad crack located just below the cladding (see Fig. 5.3). Further crack specifications are defined in par. 5.7.

In this case, at least the deepest and near interface points of the postulated defect must be assessed.

In this case the integrity of cladding above the postulated defect during the whole AOT or EC regime has to be verified according to specific procedure accepted by Regulatory organisations. This procedure can be based on J-R curve.

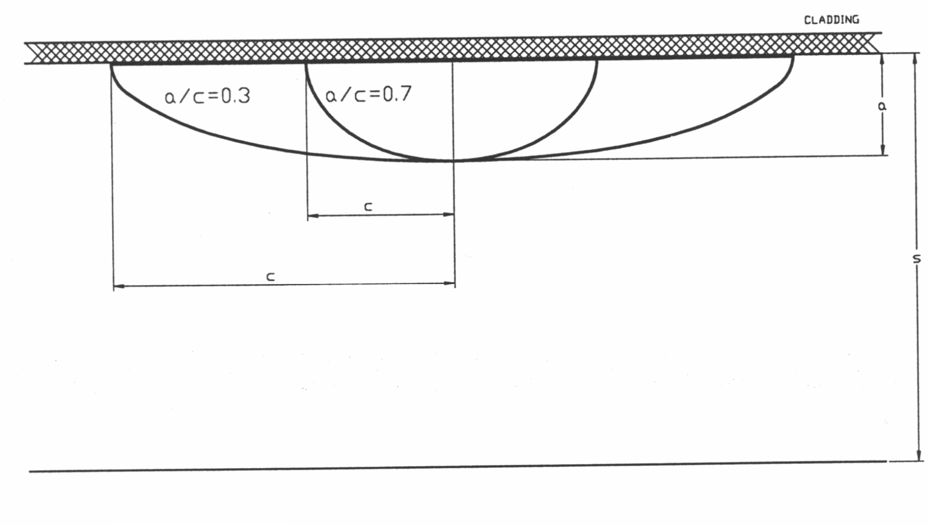

Fig. 5.3. *Semielliptical undercladding crack, cladded vessel.*

5.10.3.4 Components for which cooling from the outer surface can occur (e.g. reactor pressure vessel for the accident with reactor cavity flooding)

The crack is postulated both on the inner and outer surface.

5.10.4 Calculation of stress intensity factors is performed for selected time intervals of selected EC and AOT regimes and for postulated defects of defined shapes and locations and for the assessed points of their fronts in accordance with 5.10.3. Time steps of calculation are chosen in such a way that values of K_I near the time critical for $[T_t]_j$ determination may be calculated in sufficient detail.

5.10.5 Stress intensity factors K_I are compared with allowable stress intensity factors, $[K_{IC}]_2$ or $[K_{IC}]_3$ for all time steps.

5.10.6 Maximum allowable transition temperature for static crack initiation, $[T_t]_j$ is determined for each of calculated regimes *j*. This temperature is determined from condition (5.23) or (5.24) in which equality is reached. This temperature is defined as the value of transition temperature T_t for which the curve of temperature dependence of allowable stress intensity factors $[K_{IC}]_2$ or $[K_{IC}]_3$ is tangent to the envelope curve of temperature dependences of stress intensity factors K_I for all calculated points of all postulated cracks, for regime *j*.

5.10.7 If the tangent point determined according to the previous paragraph is found on continuously decreasing (here "decreasing" means decreasing in time) path of temperature dependence of K_I below 90% of its global maximum value $K_I^{max}{}_j$, temperature $[T_t]_j$ is determined using the value of stress intensity factor equal to 0.9 $K_I^{max}{}_j$ instead of value corresponding to the tangent point (warm prestressing approach).

5.10.8 In the case with reloading, i.e. when the path of temperature dependence of K_I is not continuously decreasing, maximum allowable transition temperature for static crack initiation, $[T_t]_j$ can be determined using the most conservative value from all 90% of local maxima of stress intensity factor K_I.

5.10.9 Maximum allowable transition temperature for static crack initiation, $[T_t]$ is determined from the minimum of all calculated values of $[T_t]_j$ for individual regimes as:

$$[T_t] = \min ([T_t]_j) \qquad (5.25)$$

5.10.10 Crack arrest approach may be also used in the integrity assessment for EC.

5.10.10.1 Using this approach, the crack postulated according to par. 5.7 and 5.10.3 can initiate a non-ductile fast fracture, and it must be proved that it will arrest within the 75 % of component wall thickness. This approach can be used only for cases where reloading is excluded (mainly large or medium LOCA).

5.10.10.2 After crack initiation, the postulated crack is converted to a surface crack of infinite length (then, only the deepest point of the crack is checked for a possible crack arrest). The crack depth is then repeatedly incremented and the depth is searched, for which the arrest condition is fulfilled:

$$K_I = [K_{IA}]_3 \qquad (5.26)$$

where $[K_{IA}]_3$ is allowable value of stress intensity factor for crack arrest for given T_t according to par. 5.6. The formulae from App. IV are not suitable for K_I evaluation for this purpose due to their conservativeness.

5.10.10.3 For the arrested crack, the condition (5.24) is tested for the remaining time of the EC regime. If at any time the condition is not met, another crack initiation is assumed and the above described procedure for crack arrest assessment is repeated. Several crack initiations and arrests (e.g. initiation – arrest – re-initiation – re-arrest) can occur. It is assumed that the component will not fail if the final crack arrest (after which no initiation follows till the end of the whole regime) occurs with the crack depth smaller than 75 % of component wall thickness, i.e.

$$a_{arrest} \leq 0.75 \cdot s \qquad (5.27)$$

For axial cracks postulated in weld metal the crack arrest and re-initiation shall be assessed using fracture properties of the base metal.

5.10.10.4 Maximum allowable transition temperature for crack arrest for EC regime *j*, $[T_A]_j$, is determined as maximum T_t for which the component will not fail (in the sense according to par. 5.10.10.3) during the whole regime *j*, i.e. such T_t for which in the condition (5.27) the equality is achieved for regime *j*. $[T_A]_j$ can be found e.g. by incremental increasing of T_t starting with $[T_t]_j$ and performing repeatedly the whole crack arrest assessment procedure as long as the condition (5.27) is fulfilled. (Simple tangent approach as described in 5.10.6 for $[T_t]_j$ determination cannot be adopted in this case.) If even for $[T_t]_j$ the condition (5.27) is not met, the crack arrest approach cannot be applied for regime *j* and the value $[T_t]_j$ has to be used for the assessment.

5.10.10.5 Maximum allowable transition temperature for crack arrest, $[T_A]$, is determined as minimum (over all individual regimes *j*) of calculated values of $[T_A]_j$ for which arrest of the running crack can be found:

$$[T_A] = \min([T_A]_j) \qquad (5.28)$$

This maximum allowable transition temperature $[T_A]$ may be used as an alternative for temperature $[T_t]$.

5.11 ASSESSMENT OF COMPONENT RESIDUAL LIFETIME WITH RESPECT TO RESISTANCE AGAINST FAST FRACTURE (WITH POSTULATED DEFECT)

5.11.1 Assessment of residual lifetime is performed periodically in intervals required by Regulatory organisations.

5.11.2 The following inputs must be prepared for this assessment:

- trends in operation, i.e. number and sequences of different regimes,
- trends in material changes (shifts of transition temperature) as a function of operational time.

5.11.3 Residual lifetime of the component for normal operational regimes is evaluated from the comparison of calculated temperature dependences of allowable pressure ([p]-[T] curves dependent on the transition temperature of the material - see 5.8) with limit dependences given by thermo-hydraulic conditions for safe operation (saturation curve shifted by some safety margin). Knowledge of trends in materials transition temperature as a function of operational time must be taken into account.

5.11.4 Conditions for hydrotests, i.e. allowable hydrotest temperature [T_h] and subsequent dependences [p]-[T] are determined in accordance with 5.9.

Residual lifetime assessment is based on comparison of allowable dependences [p]-[T] (dependent on material transition temperature) with their limit ones.

Usually neither normal operating conditions nor hydrotests are limiting for the lifetime of a component.

5.11.5 Residual lifetime of the component based on emergency conditions and anticipated operating transients is usually limiting for the whole residual lifetime. For a reactor pressure vessel the most important part is the beltline region.

Evaluation must be performed for all potential regimes of EC and AOT. Residual lifetime is determined on the basis of maximum allowable transition temperature for static crack initiation, [T_t], or maximum allowable transition temperature for crack arrest, [T_A], and from the trend in the change of material transition temperature T_t and from neutron fluence increase during the operation.

6. RESIDUAL LIFETIME OF THE COMPONENT FROM THE POINT OF VIEW OF RESISTANCE AGAINST FATIGUE DAMAGE

The residual lifetime assessment of the component from the point of view of fatigue damage shall be carried out according to standards accepted by national Regulatory Bodies.

6.1 **The residual lifetime assessment of the component** from the point of view of fatigue damage shall be carried out in two steps:

1) Until initiation of the macro-defect of size 1.0 mm for the loading condition according to Article 4.3.4, i.e. up to the criterion of $D \geq 1$.
2) For the phase of potential growth of the "hypothetical crack" which could escape detection by non-destructive testing. The procedure described in Chapter 8 shall be used for this step.

Cumulative fatigue coefficient D shall be calculated according to standards accepted by national Regulatory Bodies.

6.2 **Selection of assessed areas of the component** is based on the calculations included in the associated documentation supplied by the manufacturer of the component, or in accordance with the Pre-Operation Safety Analysis Report. The selection shall be specified prior to operation of the NPP and it should be supported by monitoring using I&C, MDS and SM systems.

Assessment shall be executed at the areas of the component for which the following value of the design cumulative damage coefficient is determined:

$$D \geq 0{,}3 \qquad (6.1)$$

6.3 **For calculation of residual lifetime of the component** from the point of view of resistance against fatigue damage, the actual loads and actual series of operation modes shall be taken into account, in accordance with Articles 3.3.11 and 4.3.3.

For calculation of residual lifetime of component, the usage factor is determined as a sum of individual usage factors calculated for single load blocks created from appropriate operational transients. The usage factor calculated for the load block created from all transients shall not be used.

6.4 **Design calculations may be used** in fatigue assessment if the differences between actual and design parameters of operational modes are not higher than 10 %.
In case that numbers of applied or extrapolated (predicted) modes exceed the design numbers of modes, it is necessary to take this fact into consideration.

In case that historical operational modes cannot be classified (in any case) as design operation modes, it is necessary to perform calculation of fatigue damage with these operational modes.

6.5 **To simplify the calculation,** construction of a "qualified" trend in operation loading is admissible, including the sequences of operational modes and their occurrence, on the basis of the results of the monitoring by I&C, MDS and SM systems. **C**alculation for these operational loads shall be executed in accordance with Article 6.1.

6.5.1 The trend in operation loading including sequences and frequencies of operational modes shall be considered up to next periodic evaluation (or up to the end of design lifetime).

6.5.2 For determination of fatigue damage, conservative assessment from design documentation shall be used (considering actual number of modes).

6.6. **If the calculation executed during operation** of the equipment demonstrates non-fulfilment of the condition

$$D \leq 0{,}8, \qquad (6.2)$$

then following procedure shall be applied:

6.6.1 Perform a conclusive non-destructive test of the mentioned area up to the time of reaching equality in the condition (6.2). If a defect due to fatigue is identified, it shall be schematised and further assessed in accordance with the procedure described in Chapter 8.

6.6.2 If a non-destructive testing of certain area is unfeasible or if no defects were identified, the semi-elliptical “hypothetical starting crack” shall be defined, parameters of which are as follows:

$$a_{hyp} = 0{,}1\ s, \quad a/2\,c = 1/6 \tag{6.3}$$

Assessment of crack admissibility shall be carried out in accordance with Chapter 8, including assessment of crack growth due to repeated mechanical and corrosion-mechanical loading.

6.7 **Assessment of residual lifetime of the component** from the point of view of resistance against fatigue damage

6.7.1 The resistance against fatigue damage during the assumed technical lifetime of the component, as given for example in design basis, is reached when the condition (6.2) is fulfilled in any of assessed areas of the equipment.

6.7.2 If the condition (6.2) is not fulfilled during the whole technical lifetime of the component, then either an assessment of allowed growth of the “hypothetical crack” shall be carried out, or an assessment of allowed growth of the flaw detected by non-destructive testing shall be carried out. This assessment shall be elaborated in accordance with the procedure described in Chapter 8 of this procedure. If allowance of these flaws is proven, it is considered as an evidence of resistance of the component against fatigue damage.

Appendix VII describes recommended good practices in residual lifetime fatigue evaluation.

Appendix VIII describes general recommendations for piping and components temperature measurement.

7. RESIDUAL LIFETIME OF THE COMPONENT FROM THE POINT OF VIEW OF RESISTANCE AGAINST CORROSION-MECHANICAL DAMAGE

7.1 **Assessment of residual lifetime** from the point of view of resistance against corrosion-mechanical-damage is to be carried out in two steps, in accordance with the procedures in Appendix IX.

1) Assessment of resistance against initiation of “pit” type defects (pitting corrosion) or fatigue cracks of the size corresponding to the conditions of stress corrosion.

2) Assessment of acceptability of growth of the flaws in the conditions of stress corrosion. Growth of the flaws can appear under the constant load (corrosion cracking), under the variable loading (corrosion fatigue) and/or under the time dependent combination of both of them.

7.2 **The actual loads** and influence of the actual chemical admixtures are to be taken into account for calculation, in accordance with Articles 3.3.11 and 4.4.3.

7.3 **Stress and strain** are to be derived for the loading in accordance with Article 7.2. If the difference between the stress fields and these loadings is not bigger than 10 % compared to values given in the associated documentation supplied by the producer of the component, then the stress fields from the associated documentation can be used.

7.4 **To simplify calculation**, it is admissible to construct a “qualified” trend of operational loading, including also the series of operation modes and their occurrence, based on results of measurements of the I&C and MDS systems. Then the stress fields and their time changes are to be calculated for the above-mentioned operational loads.

7.5 **If the assessment** executed in accordance with Article 7.1, point 1, demonstrates a possibility of initiation of the defect capable of growth in the stress corrosion conditions already during the assumed technical lifetime of the components (which given for example in the project), it is necessary to perform the following:

7.5.1 Perform non-destructive testing of the area where defect initiation and growth due to stress corrosion cracking is possible.

7.5.2 In the case that the non-destructive test of the area is not feasible or if no flaw was found during non-destructive testing, a “hypothetical initial crack” in the form of an semi-elliptical surface crack is to be assumed, with the following semi-axes:

$$a_{hyp} = 0{,}1\ s; \qquad a/(2c) = 1/6 \tag{7.1}$$

Then assessment of acceptability is to be done for this assumed crack in conditions for stress corrosion in accordance with procedures given in Appendix IX and XII.

The limit value a_{hyp} is to be determined in accordance with the wall thickness s:

$$a_{hyp} = 5\ \text{mm} \quad \text{for} \quad s \leq 50\ \text{mm},$$

$$a_{hyp} = 30\ \text{mm} \quad \text{for} \quad s \geq 300\ \text{mm} \tag{7.2}$$

7.5.3 For the austenitic piping, the “hypothetical initial crack” is to be taken as a semi-elliptical inner surface crack with semi-axes:

$$a/(2c) = 1/6 \tag{7.3}$$

The ratios a/s for different values of wall thickness are given in Table 7.1.

Table 7.1

Wall thickness s [mm]	**a/s** [%]
10	30.0
25	20.0
50	15.0
75	11.7
100 to 300	10.0

7.6 **Assessment of residual lifetime of the component** from the point of view of resistance against corrosion-mechanical damage

7.6.1 Residual lifetime of the component from the point of view of resistance against corrosion-mechanical damage is demonstrated if, during the assumed technical lifetime period (for example, according to design) of the component, no macro-defect capable of growth in stress corrosion conditions originates. The limit value of depth of such a macro-defect is 1.0 mm.

7.6.2 If the requirement of Article 7.6.1 cannot be demonstrated, then assessment in accordance with Article 7.1, point 2), must be performed for a postulated crack in accordance with this chapter. The resistance of the construction against corrosion-mechanical damage is adequately demonstrated if it is shown that conditions necessary for growth of a macro-defect are absent for the whole assumed technical lifetime of the component.

7.6.3 If the requirement of Article 7.6.2 is not fulfilled and growth of a macro-defect in the stress corrosion conditions occurs, then only temporary operation of the component is to be allowed, only for the necessary period and only with the special permission of the supervising body after supplying a supporting justifiable assessment.

8. ASSESSMENT OF ALLOWABILITY OF FLAWS FOUND DURING IN-SERVICE INSPECTIONS AND OF RESIDUAL LIFETIME OF COMPONENT WITH FLAWS

8.1 Any flaw found during in-service inspections is to be schematised in accordance with the procedure shown in Appendix X.

8.2 The flaws in components or austenitic piping schematised in this way are to be compared with the Tables of allowable sizes of flaws, which are given in Appendix XI.

8.3 Flaws which do not exceed the schematised size requirements prescribed in the Tables are allowable, and it is not necessary to continue with their assessment.

8.4 The flaws that do not fulfil some of the requirements prescribed in the Tables must be assessed in accordance with the appropriate Appendix as follows:
flaws in components — Appendix XII,
flaws in austenitic piping — Appendix XIII,
flaws in carbon steel piping — Appendix XIV.

8.5 The parameters of the realised operation modes are to be used in this assessment (pressure, temperature, water chemistry) including their sequences, and for EC also their design courses.

8.6 In calculation of fatigue and corrosion-mechanical growth of the cracks, it is necessary to re-calculate all previously performed (in the frame of the associated documentation or the Pre-Operation Safety Report) nodal computations of the temperature and stress fields by incorporating the following operation conditions:

- actual temperature-pressure course of single operation modes, including the actual water regimes,
- actual sequences of operation modes.

Calculation of possible growth of the flaws is to be performed in accordance with Appendix XII (components) or Appendix XIV (carbon steel piping).

8.7 If the stress fields of the actual operation modes do not differ more than 10 % from the computational fields given in the associated documentation, then it is possible to base the assessment of allowability of flaws on calculation results given in the associated documentation.

8.8 Based on past operation modes, their sequences, operation practices, and computational blocks of modes, the “qualified” trend of operational loading of the component during the whole period of design lifetime is to be prepared. Consequently, assessment in accordance with Appendix XII or Appendix XIV is to be carried out for this trend.

8.9 ASSESSMENT OF RESIDUAL LIFETIME OF THE COMPONENT WITH FLAWS

8.9.1 The residual lifetime of the component with the flaws detected during in-service inspections is ensured either if the determined flaws are smaller than the flaws displayed in the Tables of allowable sizes of the flaws, or if all detected flaws are allowable for all nodes of the component and during the whole design lifetime of the component, taking into account also the possible growth of the flaws.

8.9.2 If the condition given in Article 8.9.1 is not fulfilled, then it is necessary to use the procedures of the appropriate Appendix (Appendix XII, XIII or XIV).

8.9.3 From the point of view of allowability of flaws detected during in-service inspections, the residual lifetime of the component is defined as the period for which the validity of Article 8.9.1 is ensured.

9. COMPLEX (TOTAL) ASSESSMENT OF RESIDUAL LIFETIME

9.1 **The assumed technical lifetime** of a component, given for example by its design, is ensured by the successful completion of the assessments required by Chapters 5-8.

9.2 **Residual lifetime of the component** is to be based on the shortest residual lifetime determined by assessments executed in accordance with Chapters 5-8.

If the period is shorter than the period given, for example, by design, then it is necessary to take the appropriate measures for operation management and maintenance, in accordance with the "Programme for control of lifetime of the component of the production unit of nuclear power plant".