EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2002
KEY ACTION : NUCLEAR FISSION

HTR-M

European Project for the development of HTR Technology - Materials for the HTR

CONTRACT N°
FIKI-CT-2000-00032
&
FIKI-CT-2001-00135

Weldments for Reactor Pressure Vessels. A Guide to Qualification, Quality Assurance and Defect Assessment

By
B.-C. Friedrich

Dissemination level : CO
Document Number: HTR-M-04/10-D-1.8.97

AREVA

Work-Report	Ref. (Department/Year/Language/Serial No.) NGTM/2004/en/0372	Rev. A

Subject/Title

Weldments for Reactor Pressure Vessels
A Guide to Qualification, Quality Assurance and Defect Assessment

HTR-M Deliverable 1.8

Place	Date
Erlangen	2004-10-11

Prepared by	Department	Tel.	Signature
Bernd-Christian Friedrich	NGTM	93839	
Reviewed by			
Reinhard Langer	NGTM	95785	14.12.04 R. L.

Project

High Temperature Reactor

HTR-M Project

Handling Instructions

RESTRIKTIVE

Export Classification (Reports with techn. content)

AL: N ECCN: N

Rainer Hardt — Released by concerned department (content, handling, distribution)

Wolfgang Däuwel — released for external distribution

Proj.-Code	UA	DCC	Contents Code
ZFY116	BN	M BB	

Doc. Ident. No. 0600350253

Pages of Text: 16 Appendices - Pages total: 16

Summary

The requirements for safety and operational availability of nuclear power plants (NPPs) lead to well defined assessments for design, material's suitability, manufacturing process of semi-finished parts, welding, quality control, supervision and documentation of test and examination results. Besides the general suitability qualification of the materials used, the welding is subject to a manufacturer's qualification for the welding process (weld procedure qualification) and a subtle quality assurance guideline including destructive tests of the welds using monitoring specimens and non-destructive examinations. Based on the relation between true defect sizes and signals achieved by ultrasonic examination (UT), the results of fracture mechanic calculations were set in relationship to the results of the UT-examination.
A concept was established comparing the examination results of the examinations after pressure test and results achieved in the in-service inspections to evaluate the plant's safety condition applicable to pressure vessels of LWRs operating up to 370°C.
Generally, this assessment may be transferred to vessels operating in the temperature regime above. Then informations about the material's behaviour for e.g. crack initiation and crack propagation by creep and fatigue is needed.
The examinations shall be assisted by cyclic metallographic examinations of the material's structure (surface) in order to check the "microstructural degradation state". The research activities for high-resolution NDE- methods and relation of examination results to material condition continues.

Distribution

Members of Workpackage WP1 of HTR-M

PVED B. Riou
PVED C. Escaravage
NZ D. Hittner
NFTW G. Merle

NGPS4 G. Brinkmann
NGTM W. Däuwel
NGTM R. Langer

List of revisions

Rev.	Date	Scope of revision	Section/Page
A	2004-10-11	First Issue	

1. Introduction

Within the scope of work package 1 of the European R&D project related to "High-Temperature-Reactor Materials" (HTR-M) several activities on material's database and experience for reactor pressure vessels are performed.
In this frame information about the assessment of weld defects and fracture is scheduled in the work program.

The contents of this report shows up the assessment scheme for LWR-RPVs as an example.

The requirements for safety and operational availability of nuclear power plants (NPPs) lead to well defined assessments for design, materials, manufacturing, quality control and supervision.

During operation the NPPs are subject to periodical control and on-line monitoring.

With respect to welding the following summarizes by an example for the reactor pressure vessel (RPV) the general guide to quality and reliability of welded components based on German specifications /1, 2, 3, /. Other technical rules as ASME and RCC follow a similar assessment scheme.

The focus is set to the welding process and the relation between the examination for defects and the assigned fracture mechanics considerations.

In light of an application as vessels for high temperature reactors (HTRs) further issues are discussed.

2. Quality and Quality Assurance – Basic Issues

2.1 General

By material selection, design calculation and component manufacturing aspects as sufficient toughness level, avoidance of defects and limitation of stresses has to be considered in a general line. By the design of the plants the consequences of defects shall be considered.

The certainty to detect any damage shall be provided by suitable examination processes and examination extent and, by quality assurance during manufacturing.

During plant operation a control of the loads is requested. The plant supervision contains also the evaluation of defects and assessments for plant life time and life time extension capabilities.

2.2 Material

2.2.1 Base Material

Basic requirements for materials are e.g. toughness and brittle fracture resistance, controlled shift of ductile-brittle transition during irradiation and defined level of toughness, weldability and microstructure control.

Therefore, suitable materials for pressure vessels are as an example low-alloyed and fully killed ferritic steels of fine grain size. The manufacturing (melting, casting, forging) and all heat treatments are adjusted to produce material with controlled and reproducible properties.

The materials are subject to a high sophisticated qualification process that includes the determination of all relevant properties by testing and examination.

The examinations include (besides others) melting and segregation behaviour, forging and micro structure and grain size control. The toughness behaviour versus temperature, the level and the shift of the upper/lower shelf are subject to material development by control of e.g. chemical composition and heat treatment.

Changes in microstructure by heat input due to welding are also part of the qualification program. Material altered e.g. by direct welding or by simulation of the heat affected zone (HAZ) is investigated for the properties, change of properties and defects (e.g. reheat cracking, stress-relief cracking), respectively.

Weldability includes both, the manufacturing of butt welds for the pressure vessel and of cladding with stainless steel.

The extent of qualification programs are subject to standards and additional requirements of the authorities or their representatives. Materials and reputation are therefore somewhat different depending on licensing countries.

2.2.2 Weld Material

For weld filler materials generally similar requirements are valid as for the base materials. The properties of the weld filler metal are determined and qualified according to the same prerequisits but, manufacturing in this case is the application by welding and the examination of properties at weld metal.

Certainly, the assessment is a little bit different as properties like surface tension of molten metal, wetting of surfaces, alloying/de-alloying by welding, solidification behaviour etc. as well as the HAZ induced in the beads by welding of subsequent beads is of importance including cracking sensivity.

The properties of the deposited weld materials are also dependend on the type of welding technique (e.g. TIG, SMAW, Narrow-gap wire-TIG etc.).

2.3 Manufacturer's Qualification

For both, the base material product forms and weld metal product forms, a manufacturer-related product qualification is necessary.

This means that the manufacturer of e.g. the forging or the welding electrode of the selected material has to proof, that its process guarantees a product showing the expected material properties.

The manufacturer shows by the manufacturing and detailed examination of real parts or weldments in case of weld metal that it has the ability to provide semi-finished parts in acceptable quality.

The qualification includes also the establishment of quality assurance steps including related technical procedures in order to provide process transparency and reproducibility.

The qualification certificate is issued by a supervision authority or it's representative (e.g. TÜV, ASME etc.).

Depending on the technical standard, the validity duration of the qualification is depended on the manufacturing extent and, a re-qualification may be necessary after a certain period without manufacturing.

3. Quality and Quality Assurance – Production Issues

3.1 Quality Assurance of Materials Used – Welding Procedure Qualification - Certificates

3.1.1 General

Besides the basic qualification and suitability test of the materials and, the individual qualification related to the manufacturer, a defined quality assurance is required for the manufacturing of the parts to be processed.
Specifications have to be available that provide the actions, type of tests/examinations including extent and certificates that have to be performed for each production lot issued.
After product inspection and control of product properties by the manufacturer an inspection certificate is compiled.
The product including the record will be controlled and approved by a supervising authority.

3.1.2 Base Metal

The base metal (example forged ring) will be tested by chemical composition, tensile tests, toughness test, hardness, structure etc.
The entire volume of the material will be ultrasonically examined (UT) acc. to the provisions of the respective specification and also surface crack examination (SCE) will be performed at the entire surfaces.
All tests, examinations and results will be supervised and respective records will be issued.

3.1.3 Weld Metal

In manufacturing of weld filler metal also multiple quality assurance steps are performed in order to provide acceptable properties.
Besides the melting and wire manufacturing process also examinations on coatings for electrodes are performed. The mechanical properties are ranked in less priority but, have also to fulfill minimum requirements for the processing of bars and electrodes. In case of weld metal wire (e.g. diameter 0,8 mm) the forming process is important in order to control the wire's distortion, that might have negative influence during the welding operation.

For weld metals a "welding test" is being performed that provides information about the desired weldability and chemical composition after deposition (includes e.g. reactions with electrode's cover and shielding gas).

3.1.4 Weld Procedure Qualification – Batch Test

For any combination of base metal, weld metal, welding technique and welding parameters the manufacturer has to perform a welding procedure qualification (PQT).
This qualification comprises the general material and welding experience ("basics") and the proof that the selected welding equipment, parameters .... are adjusted in a suitable manner. Generally, a repair welding procedure is included.
For components of major priority this PQT is performed using the exact batch of base material and weld filler metal (batch test) scheduled to manufacture the components.

Preheating, intermediate heat treatment and post weld heat treatment (PWHT) are part of the PQT.

For a PQT a test coupon is welded that represents the dimensions and the weld edge preparation similar to the original component part.
As an example the extent of mechanical specimens and tests required for a RPV-PQT (wall thickness > 100 mm) is shown in Figure 1.

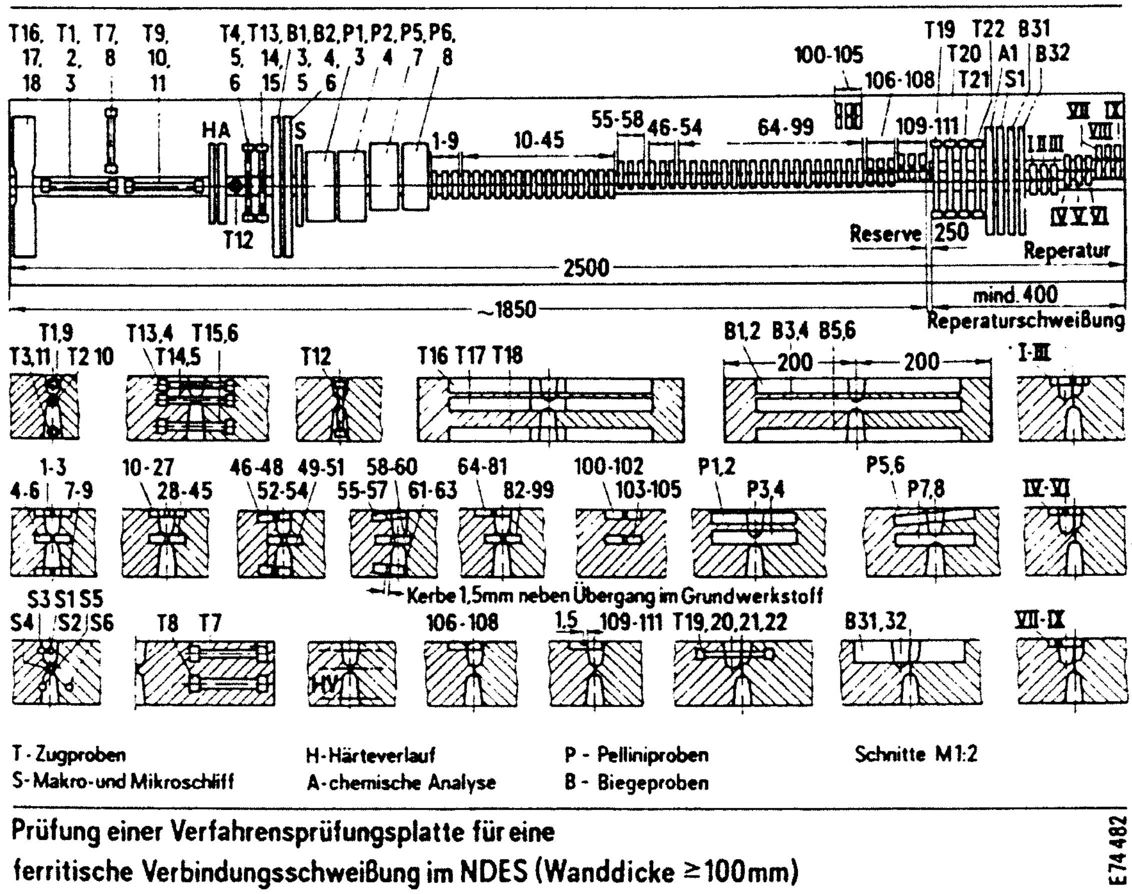


Figure 1: Extent of mechanical specimens and tests required for a RPV-PQT (wall thickness > 100 mm)

All the welds of the PQT will be examined by means of non-destructive examinations according to the same extent and requirements as specified for the component itself.
All PQT work is supervised by the authority or its representative and an approval record will then be released.

In case more than one batch of weld filler metal is needed, batch tests for each lot have to be performed. In the batch test, weld metal is deposited according to the same manner as in the PQT but, the plate's dimensions are somewhat smaller. The properties of the weld filler metal are tested prior to release to application (Figure 2).

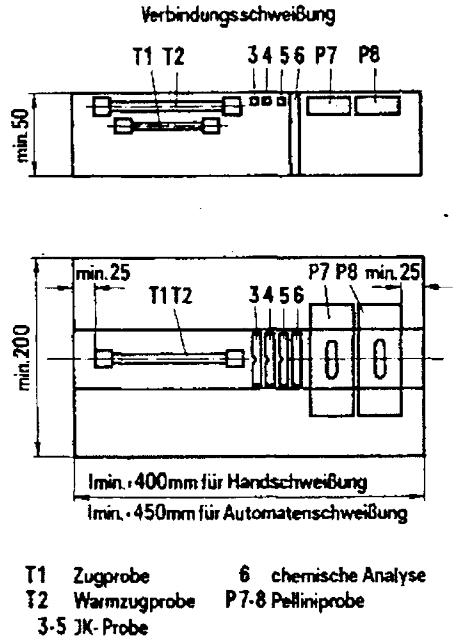


Figure 2: Weld Filler Metal Batch Test Plate For Ferritic Butt Weld

3.2 Welding of Component

3.2.1 General

For information, Figure 3 shows the welds that can occur at a reactor pressure vessel. There are longitudinal welds (shaped plates for vessels made at former times) and circumferential welds (all vessels). The number of welds depends on the design and the number of forgings. Improved forging technique reduces the amount of welds due to less parts.
The wall thickness is in the range of 250-350 mm and the amount of weld filler metal can accumulate to about 10.000 kg (10 tons) for one pressure vessel.

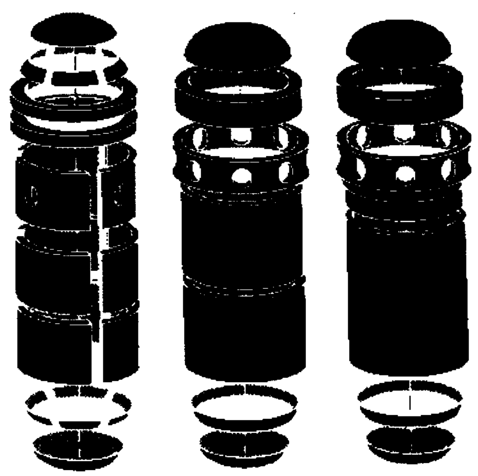
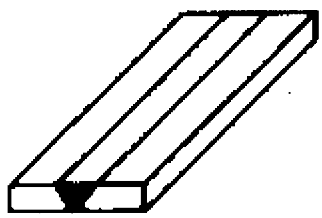
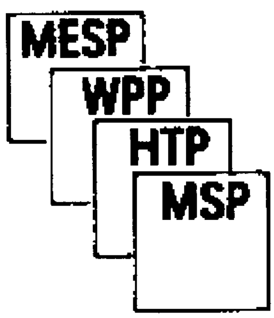
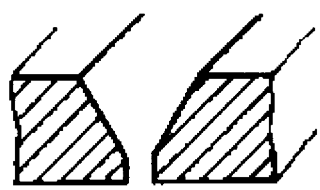
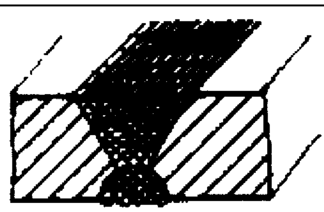


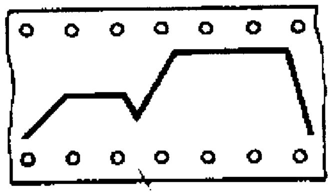
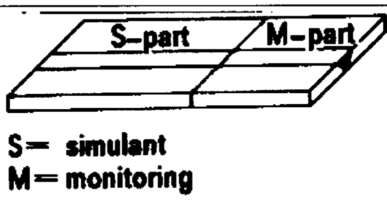
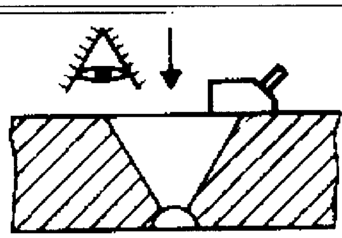
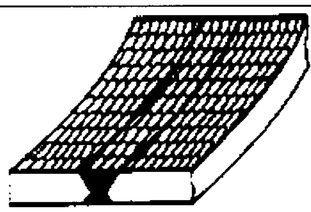
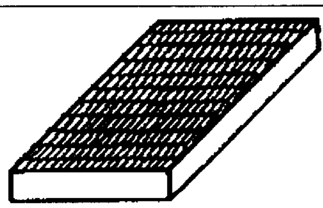
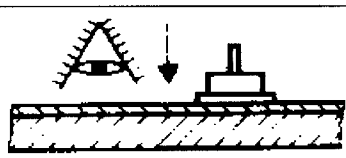
Figure 3: Welds at a Reactor Pressure Vessel.

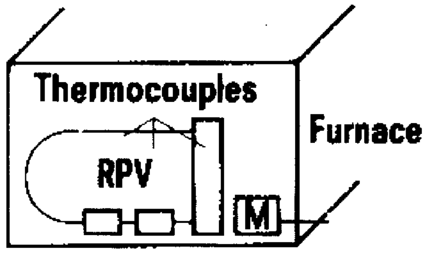
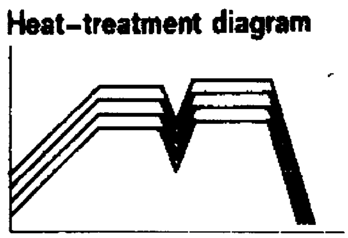
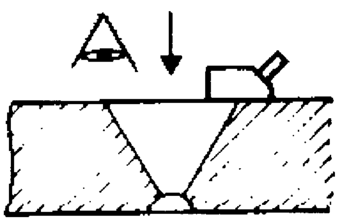
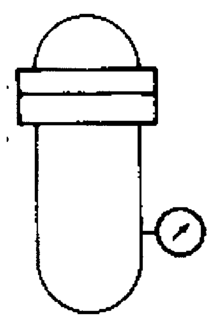
3.2.2 Manufacturing and Quality Steps in the Component Manufacturing Process

A typical LWR-RPV manufacturing process is compiled step by step in TABLE 1.

Besides the welding qualification another prerequisit is the compilation and approval of all manufacturing and QA procedures (Manufacturing and Examination Sequence Plan, MESP).

	Pre-Conditions For Welding		
1		Weld filler metal qualification Welding Procedure Qualification Batch Test of Weld Filler Metal	
2		Approved Documents for Weld And Production Weld Tests Manufacturing And Examination Sequence Plan Welding Procedure Plan Heat Treatment Plan Materials Testing And Sampling Plan (only for production weld test coupons)	
	Weld Preparation		
3		Weld Edge Preparation Surface Crack Examination of Weld Edges Assembly Check by Dimensional Control	
	Welding And Intermediate Heat Treatment		
4		Welding Record Check of Back-gauged Root by Surface Crack Examination or Visually	
5	Weld Repair Cycle (if necessary)	Weld Repair Cycle acc. to the Procedure Established in the PQT	

6		Heat Treatment Diagram For Preheat Temperature And Intermediate Heat Treatment	
	Production Weld Test		
7		Concurrent Welding of Production Weld Test Coupons – Simulated Part And Monitoring Part	
	Intermediate Examinations		
8		Surface Crack Examination Ultrasonic Examination (Weld Metal, Adjacent Base Metal) Examination by Manufacturer, Supervisor and Customer	
	Overlay Cladding of Weld		
9		Overlay Cladding of Weld	
10		Cladding Production Weld Test Coupons	
	Examination And Testing of Overlay Cladding		
11		Ultrasonic Examination For Bonding Defects, Sub-surface Cracks Surface Crack Examination	
12	Non-destructive and Mechanical Examination/Tests of the Weld Procedure Test Coupon	Testing of the Simulated Part of the Weld Procedure Test Coupon	

	Final Heat Treatment		
13		Final Heat Treatment RPV... Reactor Pressure Vessel M... Monitoring Part of Production Weld Test Coupon	
		Final Heat Treatment Heat Treatment Diagram	
14	Non-destructive and Mechanical Examination/Tests of the Monitoring Part of Production Weld Test Coupon	Testing of The Monitoring Part of Production Weld Test Coupon	
	Final Inspection		
15		Surface Crack Examination Ultrasonic Examination (Weld Metal, Adjacent Base Metal) Examination by Manufacturer, Supervisor and Customer	
	Pressure Test		
16		Pressure Test at 1,3 x Design Pressure in Conjunction With Strain Measurement Program	

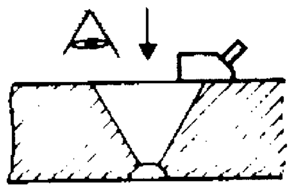
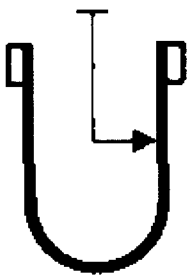
	Examination After Pressure Test		
17		Surface Crack Examination Ultrasonic Examination (reduced extent) Examination by Manufacturer, Supervisor and Customer	
	Examination Base Line And In-Service Inspection		
18		Base Examination Periodic In-Service Inspection Automated ultrasonic examination with the assistance of special examination probes and recording equipment	

TABLE 1: Steps of Typical Manufacturing and Examination Steps for a LWR-RPV

4. Relationship Between Indications by NDE and Fracture Mechanics

4.1 Ultrasonic Examination and Examination Criteria

The extent, the scanning directions, the recording levels and the acceptance criteria are stipulated in the respective specifications.
As an example for a RPV-weld, the German KTA-rule 3201.3 requests in case of nominal wall thickness is above 100 mm that the examination by angle beam scanning to detect longitudinal defects shall be performed with one beam angle and by means of angled pitch-catch technique. For this, the beam's angle shall be selected such that the angles of incidence on the surface are between 35° and 55°.
The examination for transverse defects shall be performed at one beam angle.

The scanning entry positions shall be selected in a manner that defects oriented parallel and transverse to the direction of the weld's progression can clearly be examined. Other defect orientations shall be examined by additional fanning movements of the heads during the examination.
An example for the UT scanning of weld is given in Figure 4.

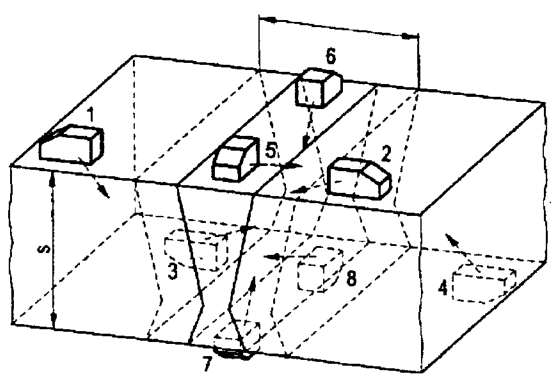


Figure 4: Example for the UT Scanning of Welds

The respective recording limits are given in TABLE 2:

	Diameter of the Respective Circular Disk Reflector in mm		
Nominal Wall Thickness s in mm	Straight beam scanning	Angle Beam Scanning	Angled-Pitch-Catch Technique (Tandemprüfung)
s > 100	3.0	3.0	6.0

TABLE 2: Recording Limits by Ultrasonic Examination

As an example for wall thickness above 120 mm, TABLE 3 lists the permitted number of indications for different length categories, determined by UT examination.

The final quality criterion is given by an equation that limits the maximum defects size by number and length relationship criterion (e.g. "large" number of small defects and "small" number of large defects and a permitted range of "mixed" defect sizes in between).
These criteria are related to fracture analyses and leak before break concept.

Length of Indication Length Category mm	Maximum Number of Indications Ni max Per Meter of Weld	
	Nominal Wall Thickness in mm	
	120 ≤ s ≤ 250	250 < s
≤ 10	25	27
≤ 15	20	22
≤ 20	16	18
≤ 25	14	16
≤ 30	12	14
≤ 35	10	12
≤ 40	8	10
≤ 45	6[1)]	8
≤ 50	5[1)]	7[1)]
≤ 55	4[1)]	6[1)]
≤ 60	3[1)]	5[1)]
≤ 65	2[1)]	4[1)]
≤ 70	1[1)]	3[1)]
≤ 75	-	2[1)]
≤ 80	-	1[1)]
The allowable number of indications per meter of weld is obtained if the following condition has been satisfied		
$\sum N_i/N_{i\,max} = N_1/N_{1\,max} + N_2/N_{2\,max} + \dots N_n/N_{n\,max} \le 1$		
Ni ... Number of indications of equal lengths Ni max ... Maximum allowable number of indications		

TABLE 3: Reference values for the evaluation of indications detected by ultrasonic testing
1) Not permitted for sub-surface layers
Remark: For s > 80 mm, the sub-surface zone is limited starting from the final surface to 20 mm.

4.2 Fracture Mechanic's Assessment

The criteria given in the manufacturing specification are based, besides others, on fracture mechanic's calculations /4, 5/. Based on calculation assessments (stress, gradients, transients, defect types, shapes, sizes, material data) and information of non-destructive examinations, relations between indications by UT-examination and fracture mechanic calculation results could be developed.
Based on fracture mechanics the permitted crack depth (2 a) and depth/length relationship (2a/2c) were determined (see Figure 5, where 2 c is crack length and 2 a is crack depth).

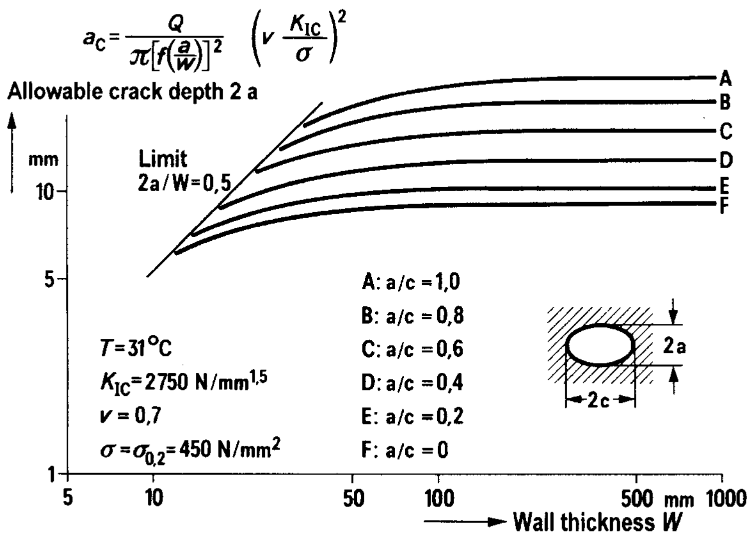


Figure 5: Permitted Crack Depth/Length as Function of Wall Thickness

The calculated permitted defect sizes are transferred by the relationship "Ultrasonic Indication vs True Defect Size" (Figure 6) in permitted UT-echo signal heights above the recording levels (related to crack depth 2 a) and defect length (crack length 2 c).
Depending on the classification of the part's zone, different UT-echo-height – defect length (2 a/2 c) relations are defined (zone I, II, III), Figure 7.

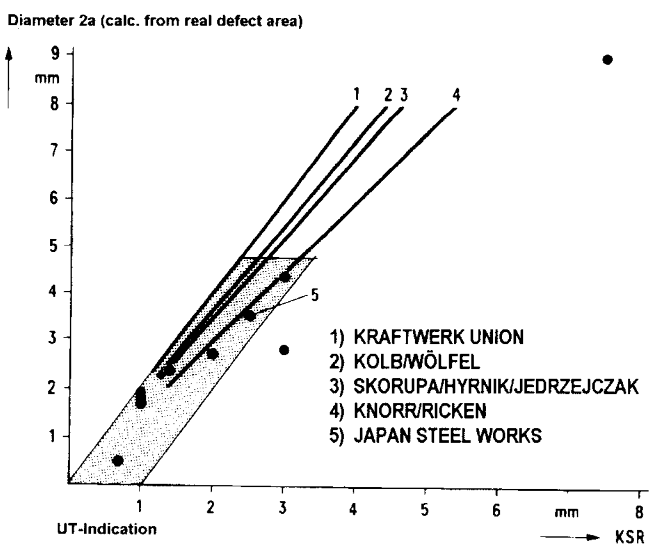


Figure 6: Relation Crack Depth 2a, Calculated by True Defect Area) vs UT-reflector Size Circular Reference Reflector (CRR)

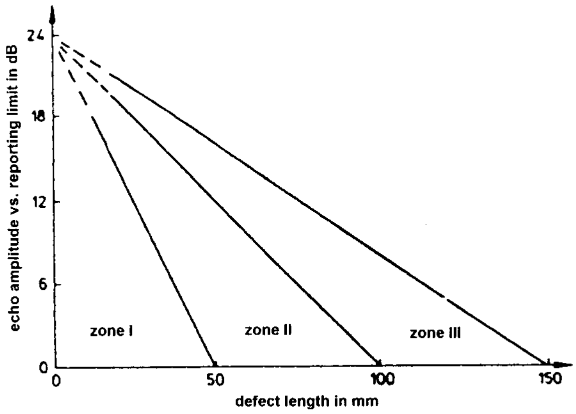


Figure 7: UT-echo-height – Defect Length (2 a/2 c) Relations

For the transformation of the real defect dimensions to the postulated cracks in the fracture mechanics calculations a conservative assessment has been established (Figure 8).

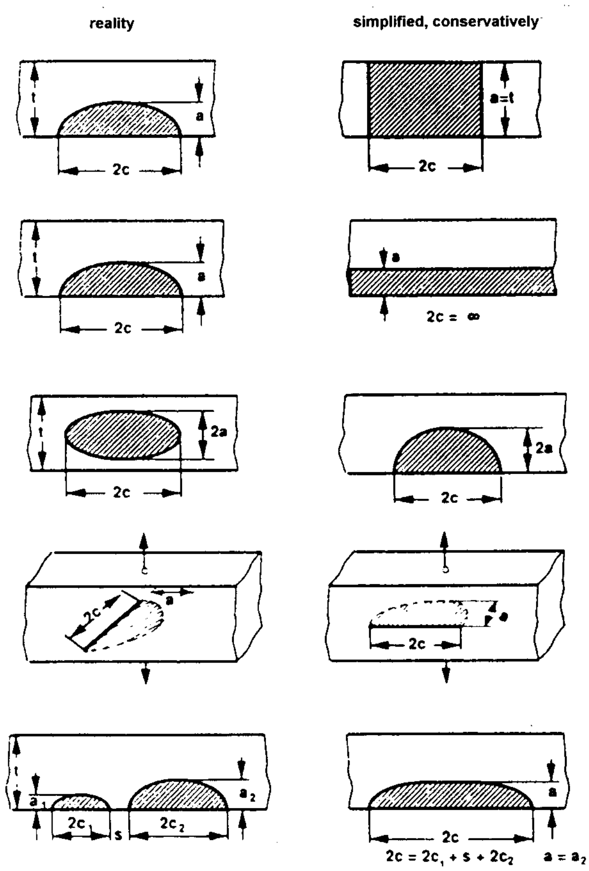


Figure 8: Examples for Simplifications for Conservative Fracture Calculations

The results of the cyclic in-service inspections are assessed by fracture mechanic methods for their relevance considered to plant operation safety /6, 7/.

The general evaluation concept is compiled in Figure 9:

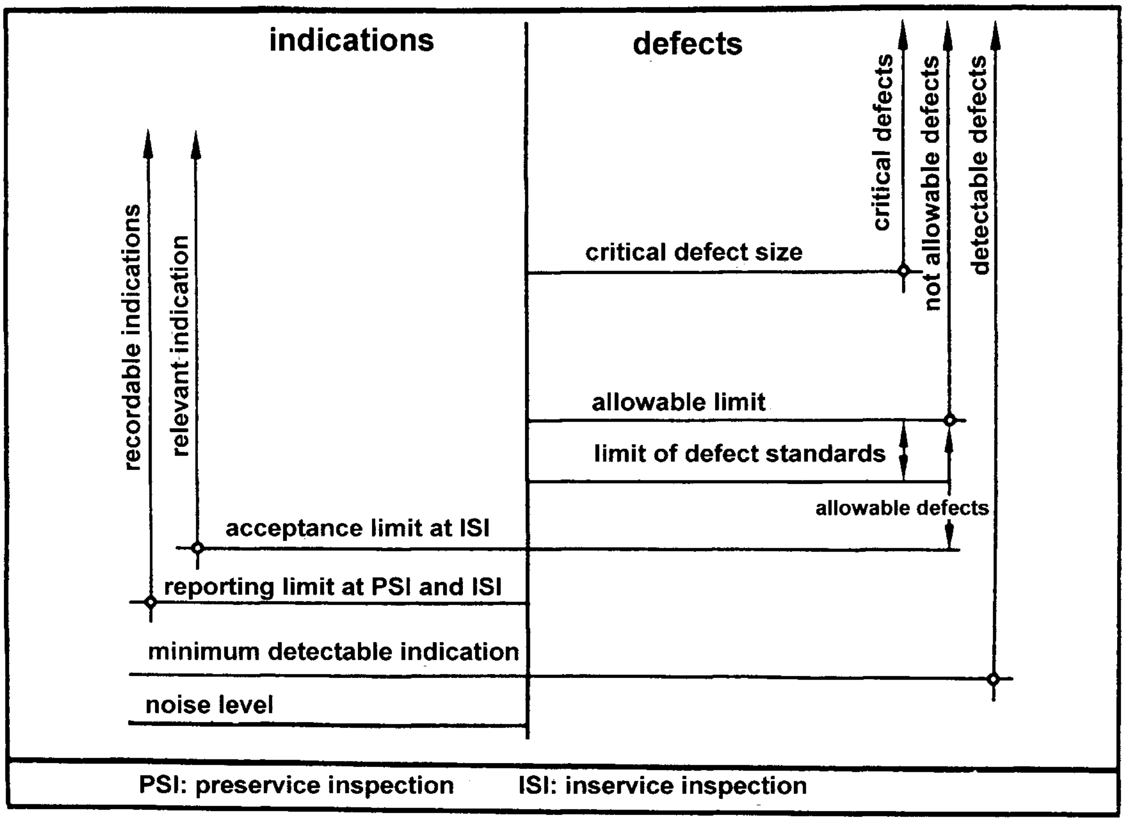


Figure 9: Relation of Indications to Defects

According to these relationships, the indications by UT examination can be evaluated and classified in "permitted/non-permitted" in light of plant life time or, life time extension, respectively.

5. Considerations for HTR/VHTR Components

Generally, the assessment for LWRs is transferable also to the design, manufacturing and safety analysis of components operation at very high temperatures. But, as materials suffer time-dependent degradations, some other aspects shall be considered.

Failure modes as ductile rupture from short-term loadings, creep rupture from long-term loadings, creep fatigue failure, gross distortion due to incremental collapse and ratcheting, loss of function due to excessive deformation, buckling due to short-term loadings and non-ductile rupture due to material embrittlement by ageing effects have to be considered.

Environmental factors for e.g. degradation by corrosion have to be determined and also non-typical material behaviour has to be considered.

Assessments have been made for the components operating in the temperature regime 500 - 760 °C /8/.

In the present state of HTR-design, the reactor pressure vessel is scheduled to operate in the temperature range of up to 370° and the rules for LWRs could generally be applied.

When temperatures exceed this limit, time-dependend degradations cannot be excluded.

Data of material's behaviour in the range above 370°C for creep and fatigue will be needed. This includes also crack initiation and crack propagation information in order to have the data base for a fracture mechanics calculation, as e.g. concepts of elastic-plastic limit may not succeed in suitable predictions.

Based on existing relations of defect sizes and examination results, load- and strain monitoring, acoustic emission and cyclic in-service inspections an information base sufficient to monitor a RPV could be estalblished.

Standards to be applied for conventional vessels includes the definition of a degradation state due to "thermal history" and request therefore, the supervision and recording of related operating data /9/.
The in-service examinations are assisted by periodic metallographic examinations of the material's structure (surface) in order to check the "microstructural degradation state" by evaluation of structure's appearance, micropores, chain-like appearance of micropores, cracks and relates a degree of degradation /10/.

An advanced degree of degradation could be definetely examined by means of e.g. magnetic flux related methods and, may be beyond the limits for NPPs.

The research activities for high-resolution NDE- methods and the relation of examination results to the material condition continues.

6. References

/1/ KTA 3201.1, 1998, Komponents of the Primary Circuit of LWR, Materials....
/2/ KTA 3201.2, 1996, Komponents of the Primary Circuit of LWR, Design....
/3/ KTA 3201.3, 1998, Komponents of the Primary Circuit of LWR, Manufacturing
/4/ Merkblatt DVS 2401 Teil 1, 1982, Bruchmechanische Bewertung von Fehlern in Schweißverbindungen; (Standard Deutscher Verband für Schweisstechnik)
/5/ Bartholomé, G., Erstellung einer Spezifikation für zerstörungsfreie Prüfungen. 18. Sitzung DVM-Bruchvorgänge, Aachen, 18./19.02.1985, S 415 - 430
/6/ KTA 3204.4, 1999, In-service inspections and Operation Monitoring
/7/ KTA 3203, 2001, Supervision of Irradiation Embrittlement of Materials of the Reactor Pressure Vessel of Light Water Reactors
/8/ ASME Boiler & Pressure Vessel Code Division 1 – Subsection NH, 2001
/9/ Technische Regeln für Dampfkessel (TRD), TRD 508, 1978, Prüfung, Zusätzliche Prüfungen an Bauteilen, berechnet mit zeitabhängigen Festigkeitskennwerten
/10/ VdTÜV-Merkblatt Dampfkessel 451-83/6. 3.83, Oberflächengefügeuntersuchung zeitstandbeanspruchter Bauteile gemäß TRD 508