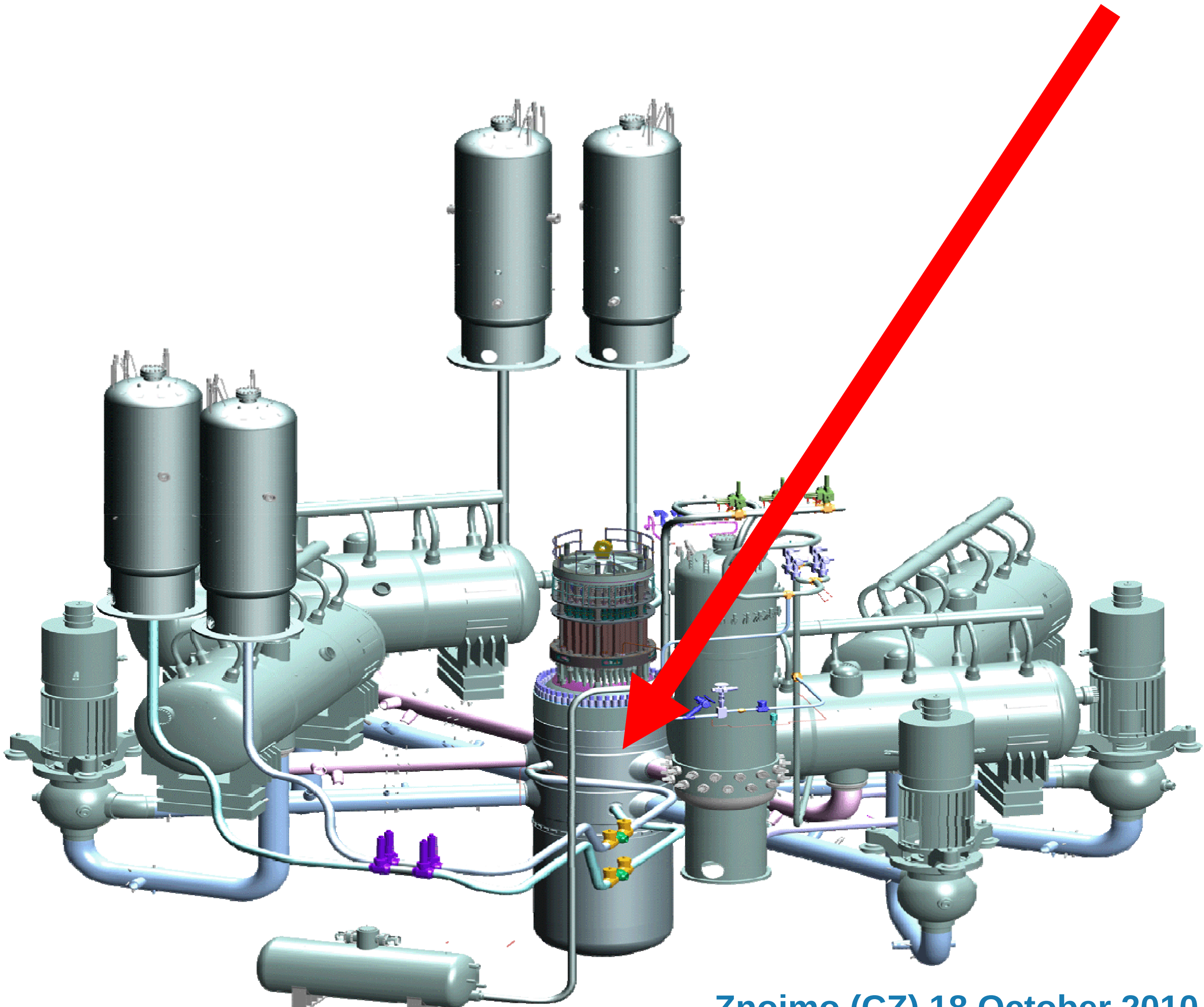
Tutorial
Irradiation Embrittlement and Life Management of RPVs

RPV Design: Materials and Stressors

M. Brumovsky

Znojmo (CZ) 18 October 2010

REACTOR PRESSURE VESSEL



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REACTOR PRESSURE VESSEL

RPV IS A UNIQUE COMPONENT, AS :

- NUCLEAR REACTION IS REALIZED INSIDE RPV
- RPV CONTAINS WHOLE NUCLEAR FISSION MATERIALS
- RPV CONTAINS PRACTICALLY ALL RADIOACTIVELY INDUCED MATERIALS
- RPV CANNOT BE PRACTICALLY COOLED DOWN IF IT RUPTURED, THEN NON-CONTROLLED CORE MELTING TAKES PLACE

REACTOR PRESSURE VESSEL

DUE TO A LARGE VOLUME OF REACTOR ACTIVE CORE TO PRODUCE REQUIRED HEAT OUTPUT,

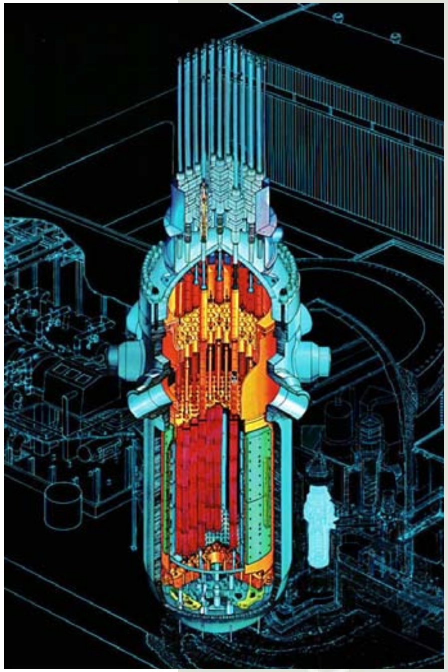
AND DUE TO HIGH OPERATION CONDITIONS:

- RPV IS A LARGE AND HEAVY COMPONENT
- RPV IS PRACTICALLY NON-REPLACEABLE
- MUST BE SAFE DURING WHOLE LIFETIME
- RPV MUST FULFIL THE MOST SEVERE REQUIREMENTS TO MATERIAL QUALITY

REACTOR PRESSURE VESSEL

RPV CONSISTS FROM THE FOLLOWING MAIN PARTS:

- **RPV BODY (LOWER PART)**
  - BELTLINE REGION AS THE MOST DAMAGED BY RADIATION
  - INLET AND OUTLET NOZZLES FOR WATER COOLANT
- **RPV COVER WITH NOZZLES/PENETRATIONS FOR CONTROL ROD MECHANISMS, IN-PILE MEASUREMENTS**
- **BOLTING JOINTS**
- **FREE FLANGE (IN SOME OLD DESIGNS)**



REACTOR PRESSURE VESSEL

RPV MUST ENSURE LONG TERM AND SAFE OPERATION UNDER CONDITIONS OF HIGH PRESSURE, TEMPERATURE AND RADIATION

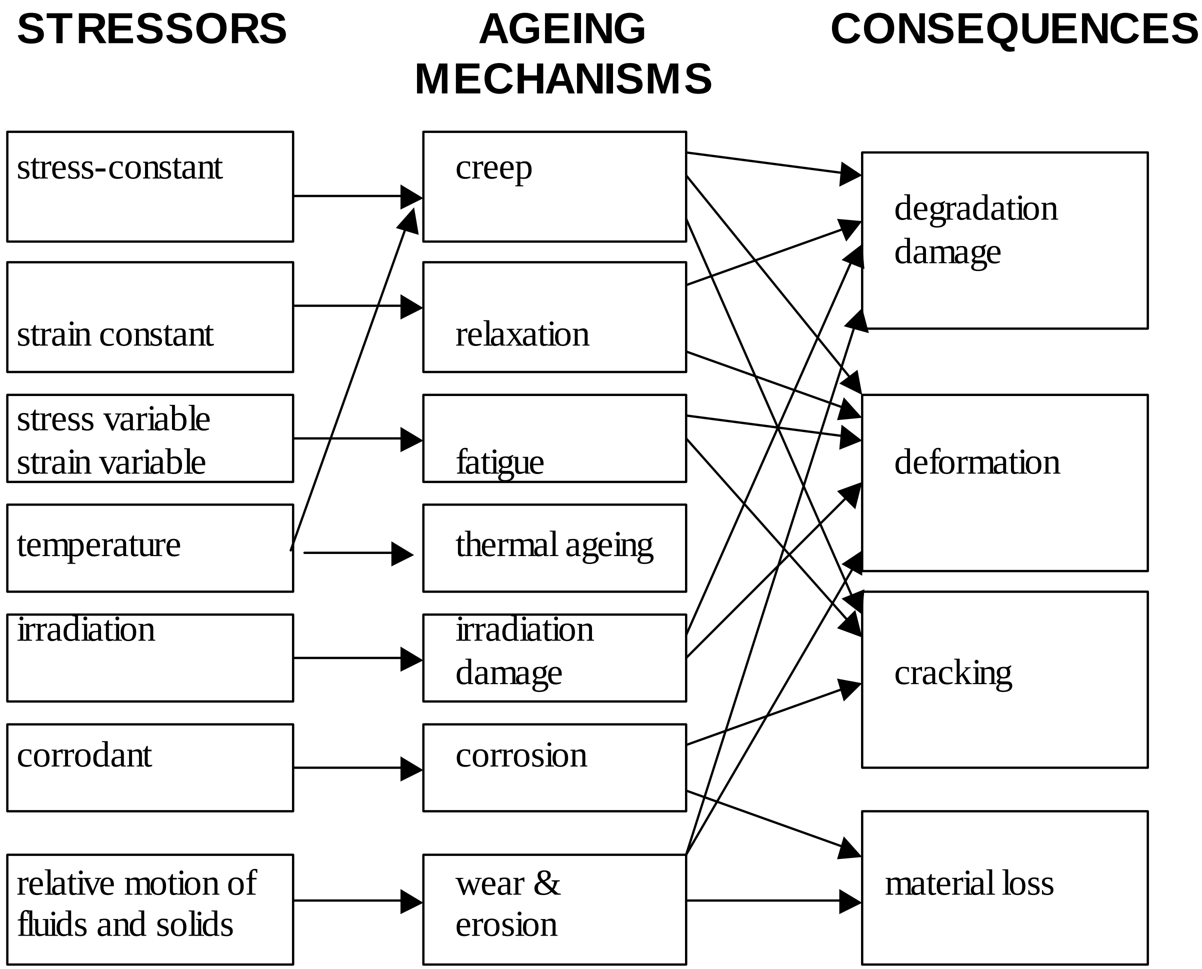
RPV MUST WITHSTAND EFFECTS OF SEVERAL STRESSORS RESULTING FROM OPERATING CONDITIONS

PRESSURE: 12 – 18 MPa

TEMPERATURE: 270 – 325 °C

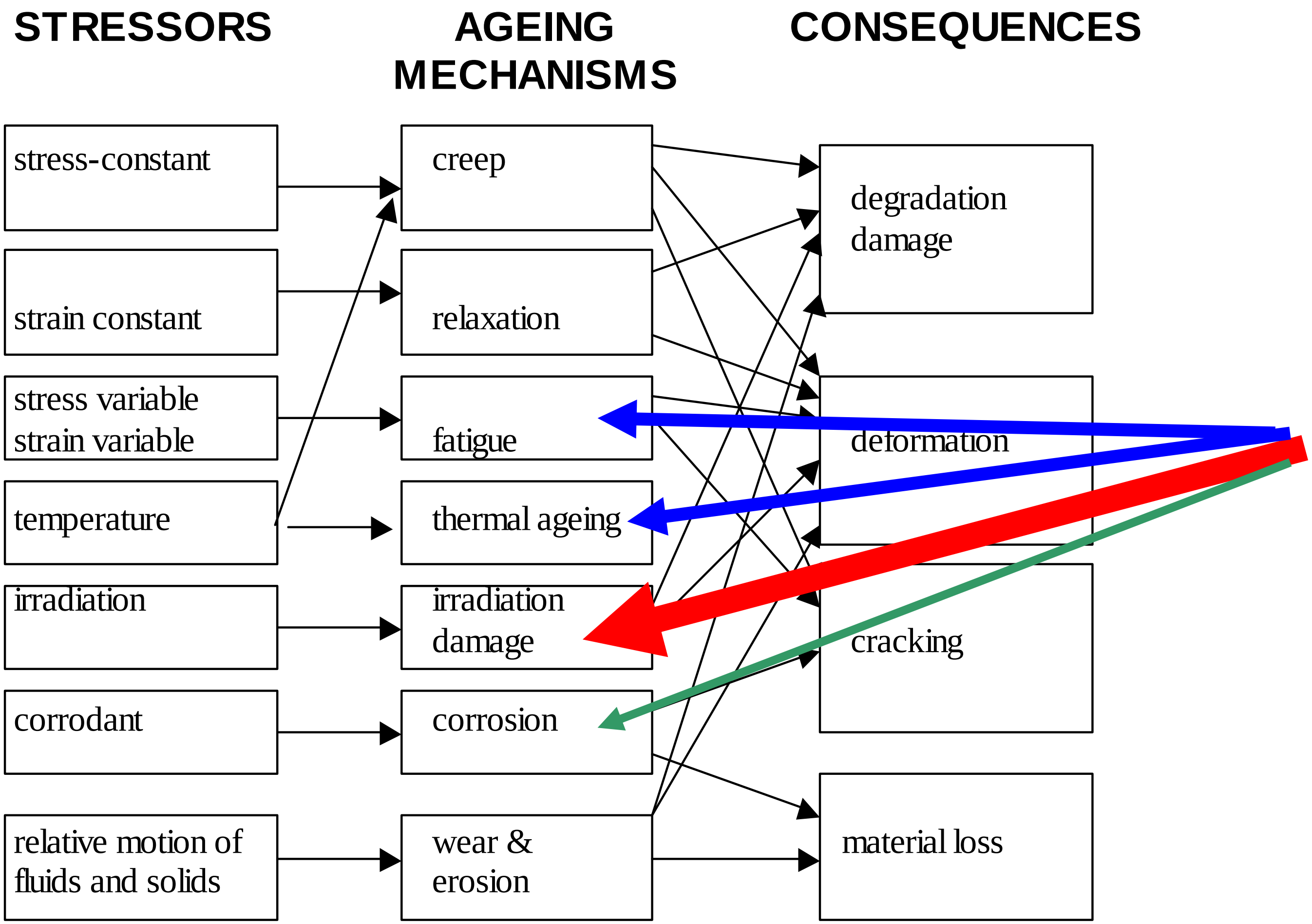
NEUTRON FLUENCE: 10^{18} – $2x10^{24}$ m^{-2} (En > 1 MeV)

RPV STRESSORS



Ageing factors, basic ageing mechanisms and possible consequences. A major stressor in an ageing structure is time itself. (For example, in the embrittlement of rubber and plastic materials in components)

RPV STRESSORS



Ageing factors, basic ageing mechanisms and possible consequences. A major stressor in an ageing structure is time itself. (For example, in the embrittlement of rubber and plastic materials in components)

RPV MATERIALS

RPV MATERIALS GENERALLY MUST HAVE:

- HIGH TENSILE PROPERTIES AT OPERATING TEMPERATURES (Rp0,2 and Rm)
- HIGH RESISTANCE AGAINST NON-DUCTILE FAST FRACTURE IN THE WHOLE RPV THICKNESS (K_{JC})
- HIGH RESISTANCE AGAINST RADIATION DAMAGE AN D THERMAL AGEING AT OPERATING CONDITIONS
- VERY GOOD WELDABILITY
- GOOD TECHNOLOGICAL OPERATION

RPV DESIGN

RPV DESIGN AND MATERIALS ARE DEFINED BY CODES AND STANDARDS, e.g.

PWR : ASME
KTA
RCC-M
JSME

WWER : PNAE-G
= PWR TYPE REACTOR DESIGNED ACCORDING TO RUSSIAN CODES AND STANDARDS

RPV DESIGN

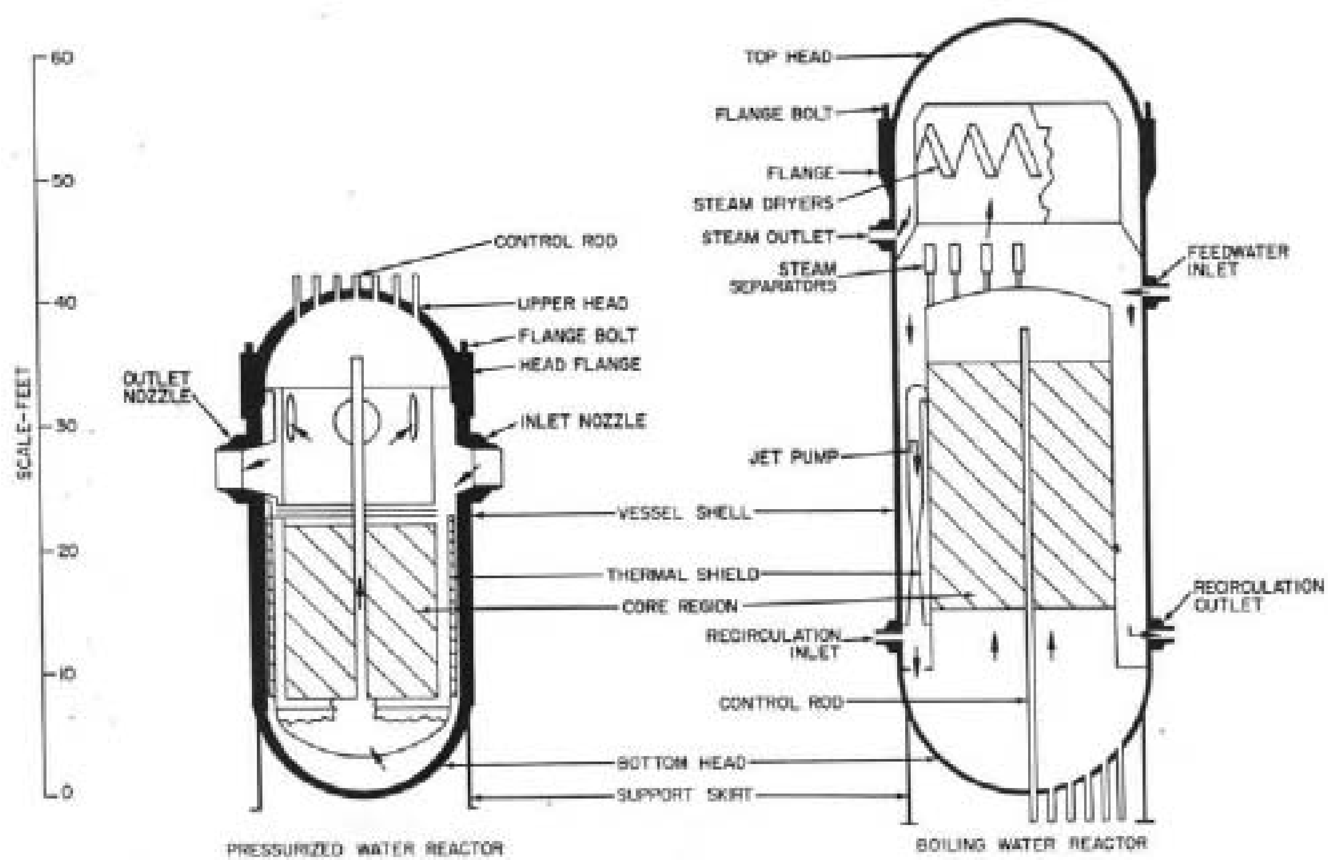
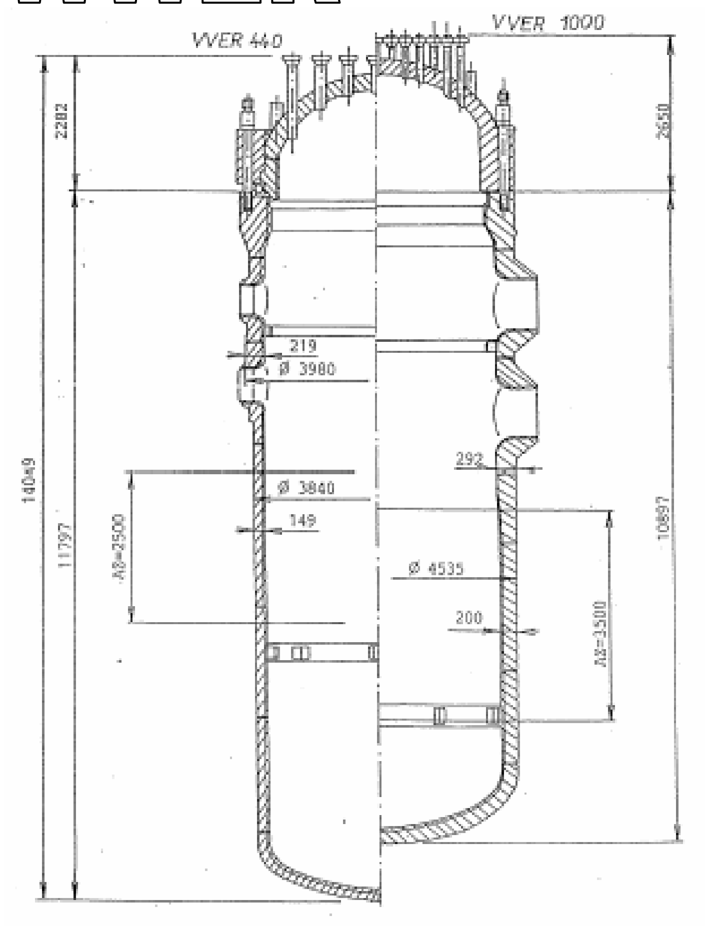
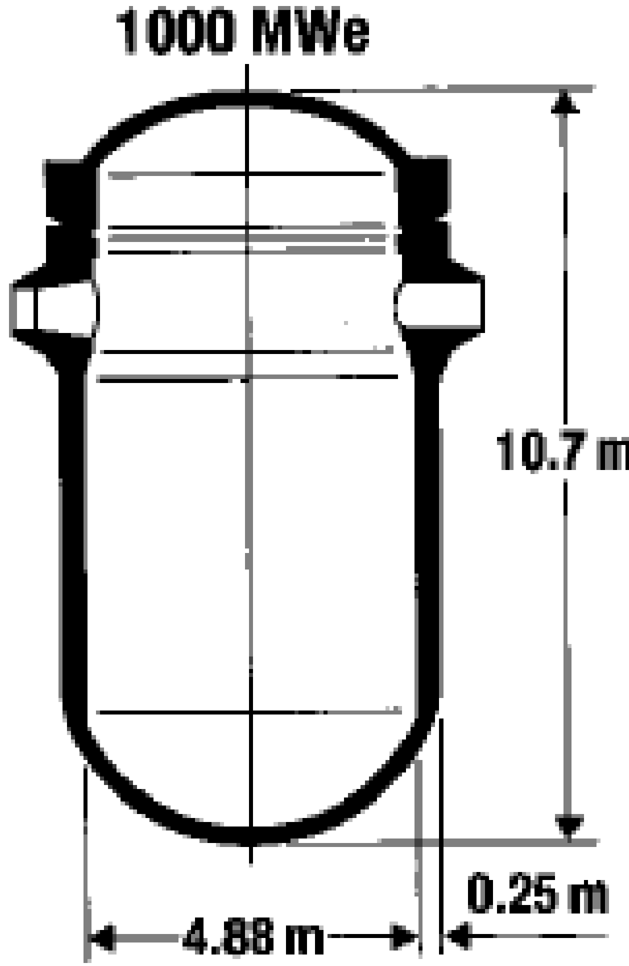


FIG. 6. Comparison of PWR and BWR RPVs with the same output.

RPV DESIGN

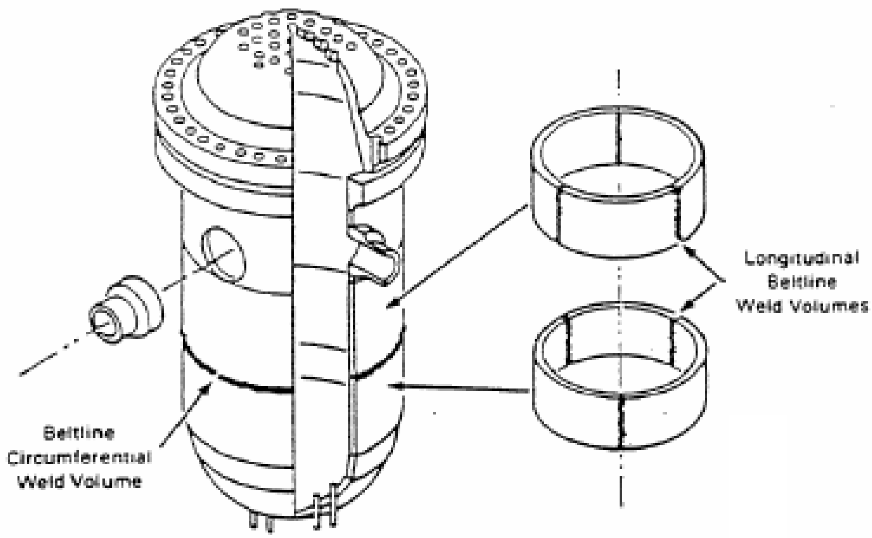
WWER



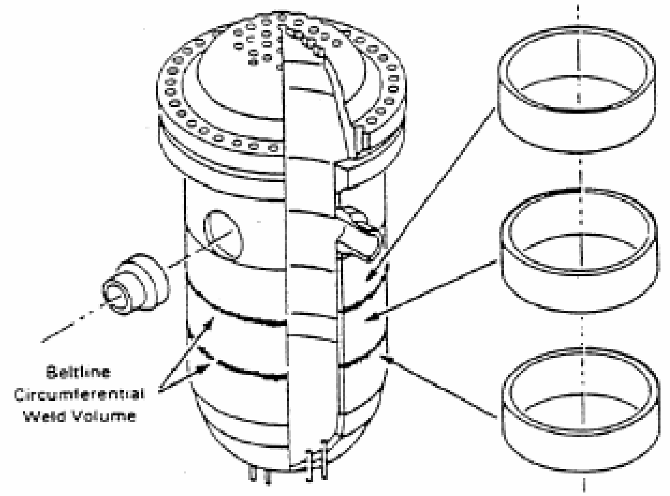


KWU

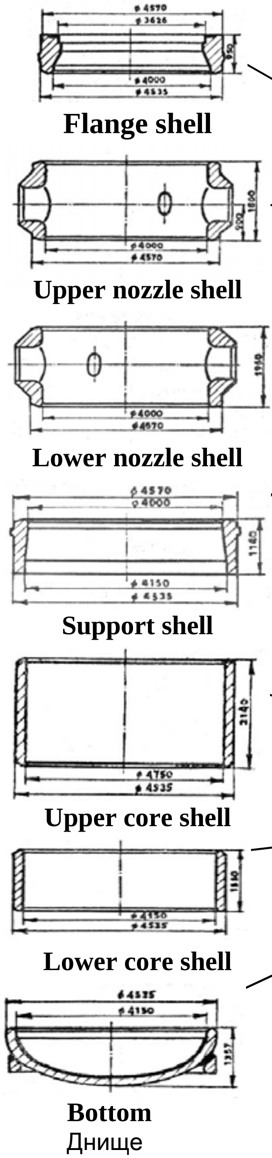
RPV DESIGN



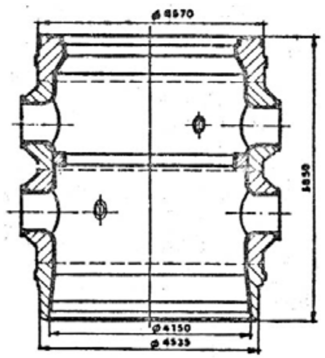
(a) Rolled and Welded Beltline Shell



(b) Welded-Ring-Forging Beltline Shell

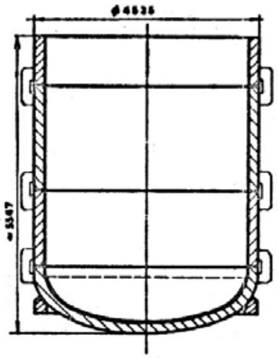


Upper part of RPV



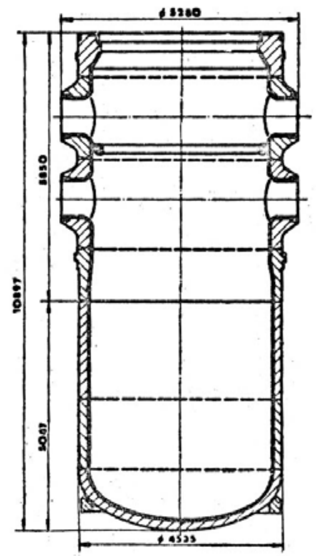
1welding of circumferential welds
2anticorrosive cladding
3mechanical and heat treatment
4quality inspection

Lower part of RPV



1welding of circumferential welds
2anticorrosive cladding
3mechanical and heat treatment
4quality inspection

RPV assembly



1. welding of circumferential weld no.4
2anticorrosive cladding of a zone under weld no.4
3mechanical and heat treatment
4quality inspection

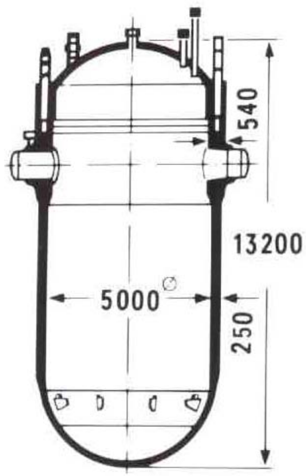
TYPICAL TECHNOLOGY PROCESS FOR WWER-1000 RPV

RPV DESIGN

PWR	VVER
3 – 4 LOOPS	**6 LOOPS – VVER-440** **4 LOOPS – VVER-1000**
1 NOZZLE RING – IN + OUT	2 NOZZLE RINGS RING INLER + RING OUTLET
IN-WELDED NOZZLES	MECHANICALLY MACHINED NOZZLES (VVER-440) NOZZLED HOT FORGED OUT (VVER-1000)
1ST RPV GENERATION – WELDED PLATES 2ND RPV GENERATION – FORGED RINGS LATESTS RPVs – NOZZLE-FLANGE RING (cca 500 t)	ALL GENERATIONS –ONLY FORGED RINGS 1ST RPV GENERATION- SOME WITHOUT CLADDING MAXIMUM INGOT MASS – 195 t
MATERIALS (HISTORICALLY) ASTM A-212 B (C-Mn) ASTM A-302 B (Mn-Ni-Mo) ASTM A-533 B/A 508 (Mn-Ni-Mo)	MATERIALS VVER-440 – 15Kh2MFA (Cr-Mo-V) VVER-1000 – 15Kh2NMFA (Ni-Cr-Mo-V)
ONLY ELECTRIC FURNACES	SM + ELECTRICAL FURNACES
ONE LAYER CLADDING	TWO LAYERS CLADDING
TRANSPORT ON WATER	**TRANSPORT ON LAND**

RPV DESIGN IMPROVEMENTS

- REMOVAL OF AXIAL WELDS
- DECREASE OF NUMBER OF AZIMUTHAL WELDS
- REMOVAL OF WELDS FROM THE BELTLINE REGION



RPV DESIGN

STRESSES IN RPV UNDER NORMAL(STABLE) OPERATING CONDITONS, I.E. ONLY FROM PRESSURE, CAN BE EXPRESSED BY THE SIMPLIFIED EQUATION:

$$\sigma = p \,.\, R \,/\, S$$

WHERE σ – STRESS
p – PRESSURE
R – RPV MEAN RADIUS
S – RPV WALL THICKNESS

RPV DESIGN

STRESS INTENSITIES (I.E. ALLOWED STRESSES) IN RPV UNDER NORMAL OPERATING CONDITIONS ARE USUALLY DEFINED AS:

SI^{PWR} or $[\sigma]^{WWER} = \min(Rp0.2/n_{Rp}, Rm/n_{Rm})$

SAFETY FACTORS n_{Rp} AND n_{Rm} ARE DEFINED BY CODES:

FOR PWR : $n_{Rp} = 3/2$, $n_{Rm} = 3$

FOR WWER: $n_{Rp} = 1.5$, $n_{Rm} = 2.6$

RPV MATERIALS

MATERIAL	USED FROM THE YEAR	STEEL TYPE	HEAT TREATMENT	Rp 0,2 at 20°C (minimum MPa)	Rm at 20°C (MPa)	A5 at 20°C (minimum %)
PLATES						
A 212B	1955	C-Mn	HR or N	262	483-586	22
A 302B	1960	Mn-Mo	Q/T oro N/T	345	552-689	20
A 302B (modifikovaná)	1965	Mn-Mo-Ni	Q/T	345	552-689	20
A 533 Gr.B Class 1	1967	Mn-Mo-Ni	Q/T	345	620-793	18
20MnMoNi55	1974	Mn-Mo-Ni	Q/T	440	590-740	18
15Kh2MFA	1960	Cr-Mo-V	Q/T	431	539-735	14
FORGINGS						
A 105	1955	C-Mn	A or N	248	483 min.	22
A 182	1956	Mn-Mo	A or N/T	276	483 min.	22
A 350-82	1956	Mn-Ni	A or N/T	207	414 min.	22
A 336 (modified)	1965	Mn-Mo-Ni	Q/T	345	550 min.	20

RPV MATERIALS

A 508 Class 2	1961	Mn-Mo-Ni	Q/T	345	550-725	18
A 508 Class 3	1965	Mn-Mo-Ni	Q/T	345	550-725	18
20MnMoNi55	1974	Mn-Mo-Ni	Q/T	440	590-740	18
22NiMoCr37	1980	Mn-Mo-Ni	Q/T	440	590-740	18
16 MN D5	1978	Mn-Mo-Ni	Q/T			
15Kh2MFA	1960	Cr-Mo-V	Q/T	431	539-735	14
15K2NMFA(A)	1975	Cr-Ni-Mo-V	Q/T	490	608	15
15Kh2NMFA Class 1	2000	Cr-Ni-Mo-V	Q/T	490	608	15
15Kh2V2FA	2005	Cr-V	Q/T			
15Kh2MFA-A mod.A	2009	Cr-Mo-V	Q/T			

HR = HOT ROLLED, A = ANNEALED, N = NORMALIZED,
N/T = NORMALIZED AND TEMPERED, Q/T = QUENCHED AND TEMPERED

RPV MATERIALS

Designation	Elements (mass %)													
	C	Si	Mn	P	S	Cr	Mo	Ni	V	Cu	Al	Sn	N	As
ASTM A 302B	max 0.25	0.15 0.30	1.15 1.50	max 0.035	max 0.040		0.45 0.60							
ASTM A 336, Code Case 1236	0.19 0.25	0.15 0.35	1.10 1.30	max 0.035	max 0.035	max 0.35	0.50 0.60	0.40 0.50						
ASME A 508 Cl 2 (1971)	max 0.27	0.15 0.35	0.50 0.90	max 0.025	max 0.025	0.25 0.45	0.55 0.70	0.50 0.90	max 0.05					
ASME A 533 GR B (1971)	max 0.25	0.15 0.30	1.15 1.50	max 0.035	max 0.040		0.45 0.60	0.40 0.70						
ASME A 508 Cl 2 (1989)[a]	max 0.27	0.15 0.40	0.50 1.00	max 0..015	max 0.015	0.25 0.45	0.55 0.70	0.50 1.00	max 0.05	max 0.15				
ASME A 508 Cl 3 (1989)[a]	max 0.25	0.15 0.40	1.20 1.50	max 0.015	max 0.015	max 0.25	0.45 0.60	0.40 1.00	max 0.05					
ASME A 533Gr B (1989)	max 0.25	0.15 0.40	1.15 1.50	max 0.035	max 0.040		0.45 0.60	0.40 0.70						
16 MnD5 RCC-M 2111[b]	max 0.22	0.10 0.30	1.15 1.60	max 0.02	max 0.012	max 0.25	0.43 0.57	0.50 0.80	max 0.01	max 0.20	max 0.040			
18 MnD5 RCC-M 2112 (1988)	max 0.20	0.10 0.30	1.15 1.55	max 0.015	max 0.012	max 0.25	0.45 0.55	0.50 0.80	max 0.01	max 0.20	max 0.040			
20 Mn Mo Ni 5 5 (1983, 1990)[c,d]	0.17 0.23	0.15 0.30	1.20 1.50	max 0.012	max 0.008	max 0.20	0.40 0.55	0.50 0.80	max 0.02	max 0.12[e]	0.010 0.040	max 0.011	max 0.013	max 0.036
22 Ni Mo Cr 3 7 (1991)[f]	0.17 0.23	0.15 0.35	0.50 1.00	max 0.012	max 0.008	0.25 0.50	max 0.60	0.60 1.20[g]	max 0.02	max 0.12[e]	0.010 0.050	max 0.011	max 0.013	max 0.036

[a] Supplementary Requirement S 9.1(2) and S 9.2 for A 508 Cl 2 and A508 Cl 3.
[b] Forgings for reactor shells outside core region. Restrictions for core region (RCC-M 2111): S ≤ 0.008, P ≤ 0.008, Cu ≤ 0.08.
[c] VdTÜV Material Specification 401, Issue 1983.
[d] KTA 3201.1 Appendix A, Issue 6/90.
[e] Cu-Content for RPV (core region) shall be ≤0.10%.
[f] According to Siemens/KWU under consideration of SR 10 (MPA Stuttgart).
[g] For flanges and tube sheets the Ni content shall be ≤1.40%.

RPV MATERIALS

REACTOR PRESSURE VESSELS-3

CHEMICAL COMPOSITION OF WWER FORGING AND WELD MATERIALS (mass%)

MATERIAL	C	Mn	Si	P	S	Cr	Ni	Mo	V
WWER-440 15Kh2MFA	0.13 0.18	0.30 0.60	0.17 0.37	max 0.025	max 0.025	2.50 3.00	max 0.40	0.60 0.80	0.25 0.35
Submerged arc weldSv- 10KhMFT + AN-42	0.04 0.12	0.60 1.30	0.20 0.60	max 0.042	max 0.035	1.20 1.80	max 0.30	0.35 0.70	0.10 0.35
Submerged arc weldSv- 10KhMFT + AN-42M	0.04 0.12	0.60 1.30	0.20 0.60	max 0.012	max 0.015	1.20 1.80	max 0.30	0.35 0.70	0.10 0.35
Electroslag weld Sv-13Kh2MFT + OF-6	0.11 0.16	0.40 0.70	0.17 0.35	max 0.030	max 0.030	1.40 2.50	-	0.40 0.80	0.17 0.37
WWER-1000 15Kh2NMFA	0.13 0.18	0.30 0.60	0.17 0.37	max 0.020	max 0.020	1.80 2.30	1.00 1.50	0.50 0.70	max 0.10
Submerged arc weldSv- 12Kh2N2MA + FC-16	0.05 0.12	0.50 1.00	0.15 0.45	max 0.025	max 0.020	1.40 2.10	1.20 1.90[x]	0.45 0.75	
Submerged arc weld Sv-12Kh2N2MA + FC-16A	0.05 0.12	0.50 1.00	0.15 0.45	max 0.012	max 0.015	1.40 2.10	1.20 1.90[x]	0.45 0.75	-

RPV MATERIALS

RESISTANCE AGAINST NON-DUCTILE (BRITTLE) FRACTURE IS CHARACTERIZED BY so-called TRANSITION TEMPERATURE:

PWR – RT_{NDT} DETERMINED FROM DWT (DROP WEIGHT TEST) AND CHARPY V-NOTCH IMPACT TESTS

WWER – T_{K0} DETERMINED FROM CHARPY V-NOTCH IMPACT TESTS ONLY

RPV MATERIALS

RPV MATERIALS/WELD METALS OF GENERATION I:

- NO REQUIREMENTS FOR COPPER CONTENT
- USUALLY MILD REQUIREMENTS FOR PHOSPHORUS CONTENT :

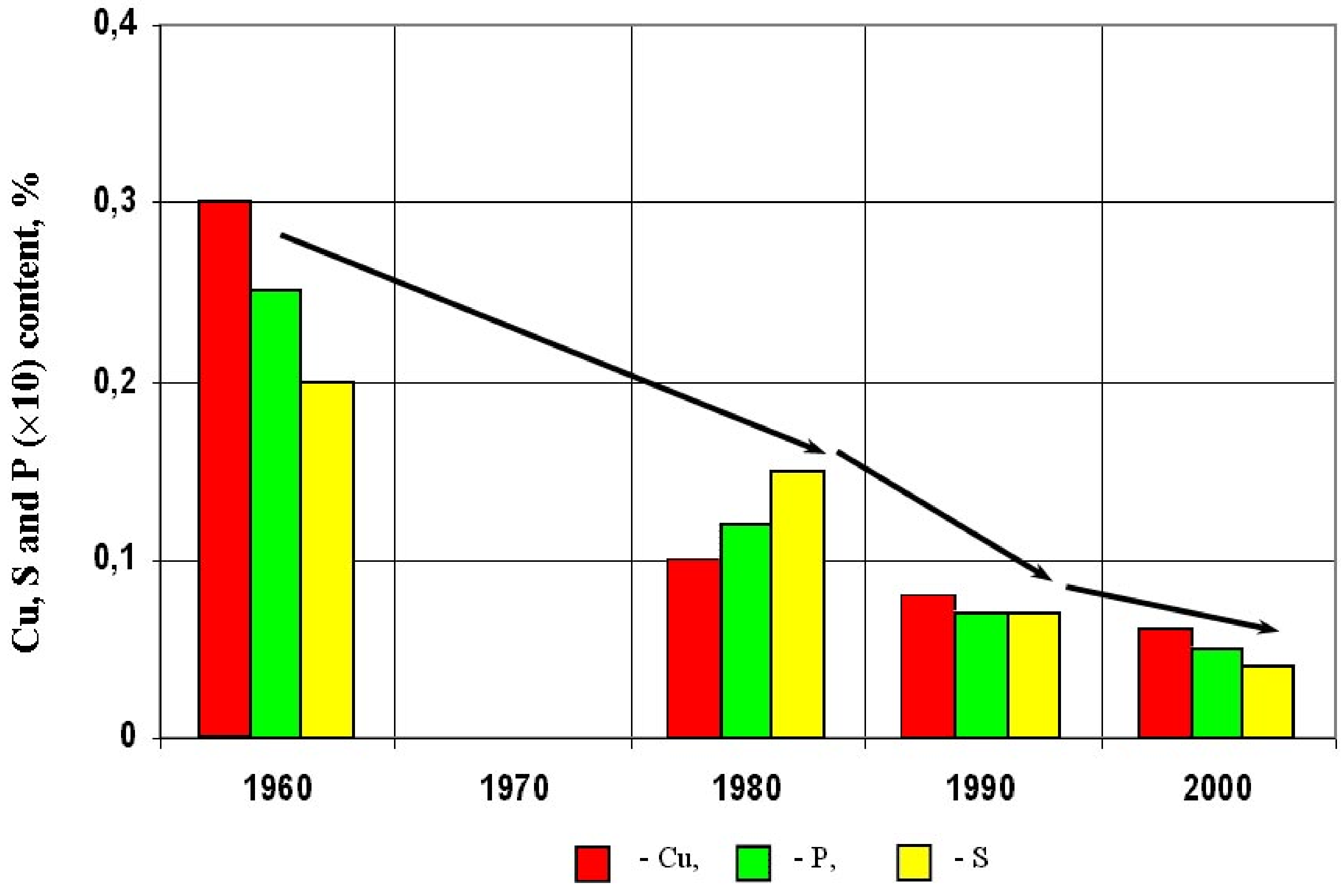
- PWR – WELDMENTS
  - – HIGH CONTENT OF Cu (up to approx. 0.40 mass %),
  - MEDIUM CONTENT OF PHOSPHORUS
- WWER – WELDMENTS
  - HIGH CONTENT OF P (up to approx. 0.040 mass %
  - INCREASED CONTENT OF Cu (up to approx. 0.20 mass %)

RPV MATERIALS

REQUIREMENTS FOR BELTLINE RPV MATERIALS

MATERIAL	P	S	Cu	As	Sb	Sn	P+Sb+Sn	Co
GENERATION II								
15Kh2MFAA	0.012	0.015	0.08	0.010	0.005	0.005	0.015	0.020
15Kh2NMFAA	0.010	0.012	0.08	0.010	0.005	0.005	0.015	0.020
A 533-B, Class 1	0.012	0.015	0.10					
16 MnD 5	0.008	0.008	0.08					
20 MnMoNi 55	0.012	0.012	0.10	0.036		0.011		
GENERATION III								
SA-508 Grade 3 Class 1 SA 533-B	0.010	0.010	**0.03**					
16 MnD 5	0.008	0.008	0.08					
15Kh2NMFAA	0.010	0.012	0.08	0.010	0.005	0.005	0.015	

RPV MATERIALS
trend in decrease of Cu+P contents



ACCEPTANCE TESTS

- REQUIREMENTS FOR ACCEPTANCE TESTS ARE GIVEN IN CODES (GENERALLY) AND IN MANUFACTURING AND DESIGN DOCUMENTATION
- ACCEPTANCE TESTS SERVE FOR PERMISSION TO USE GIVEN MATERIAL/COMPONENT
- RESULTS OF ACCEPTANCE TESTS SERVE AS A BASIS FOR LIFETIME EVALUATION DURING OPERATION
- ACCEPTANCE TESTS MUST CHARACTERIZED REAL PROPERTIES OF USED MATERIALS IN A CONDITION OF RPV START OF OPERATION (i.e. DELIVERY FROM THE SHOP TO THE NPP)

ACCEPTANCE TESTS

ACCEPTANCE TESTS ARE USUALLY PERFORMED IN THE FOLLOWING STAGES OF MANUFACTURING:

- PLATES/FORGINGS AFTER INITIAL HEAT TREATMENT, i.e. AFTER Q+T (OR N+T) FROM ADDITIONS
- WELDING MATERIALS (WIRES, STRIPS, FLUX)
- WELDING JOINTS – ON WELDING COUPONS MADE BY THE SAME TECHNOLOGY AS RPV (USUALLY WITH LIMITED TIME VALIDITY)
- BM AND WM – AFTER FINAL HEAT TREATMENT OF RPV
- SURVEILĹANCE SPECIMENS – AFTER FINAL HEAT TREATMENT OF RPV (FROM WELDING COUPON)

ACCEPTANCE TESTS

SPECIMENS FOR ACCEPTANCE TESTS ARE USUALLY CUT FROM ¼ OF RPV WALL THICKNESS

REASON FOR SUCH LOCATION IS:

- MATERIAL PROPERTIES IN THE MIDDLE PART (BETWEEN ¼ AND ¾ OF WALL THICKNESS ARE PRACTICALLY CONSTANT)
- POSTULATED CRACK DEPTH FOR ASSESSMENT OF RPV RESISTANCE AGAINST NON-DUCTILE FAILURE WAS INITIALLY TAKEN AS ¼ OF WALL THICKNESS

ACCEPTANCE TESTS

SEGREGATION IN INGOT

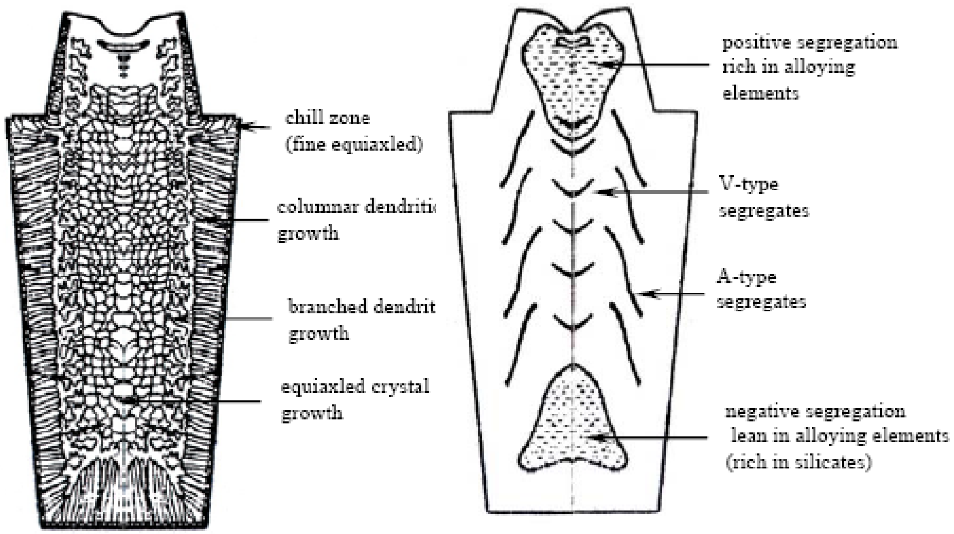
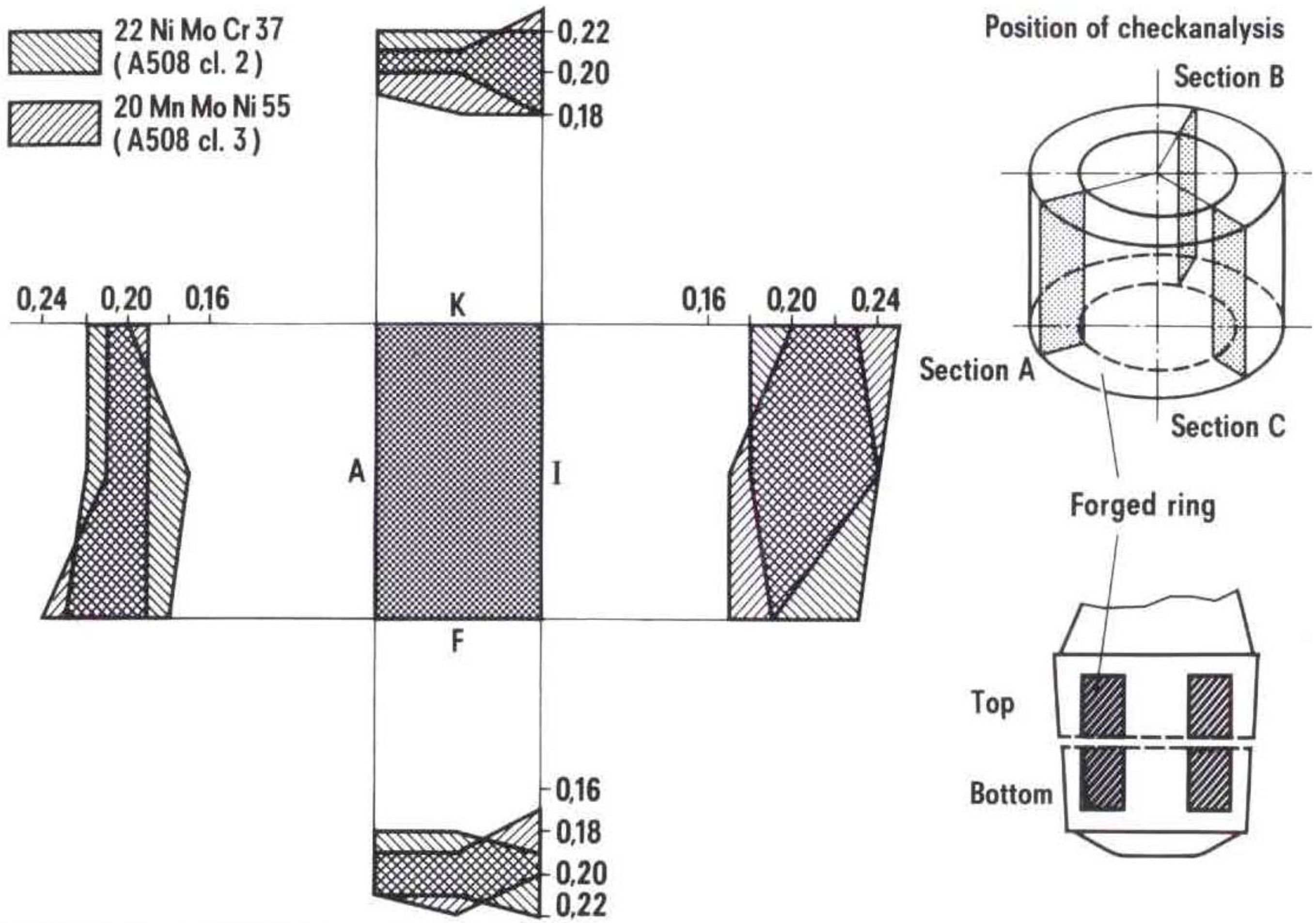


Figure 4-3. Macrostructure of metal in heavy steel ingots:
a – crystallization zones by solidification
b – macro segregation pattern.

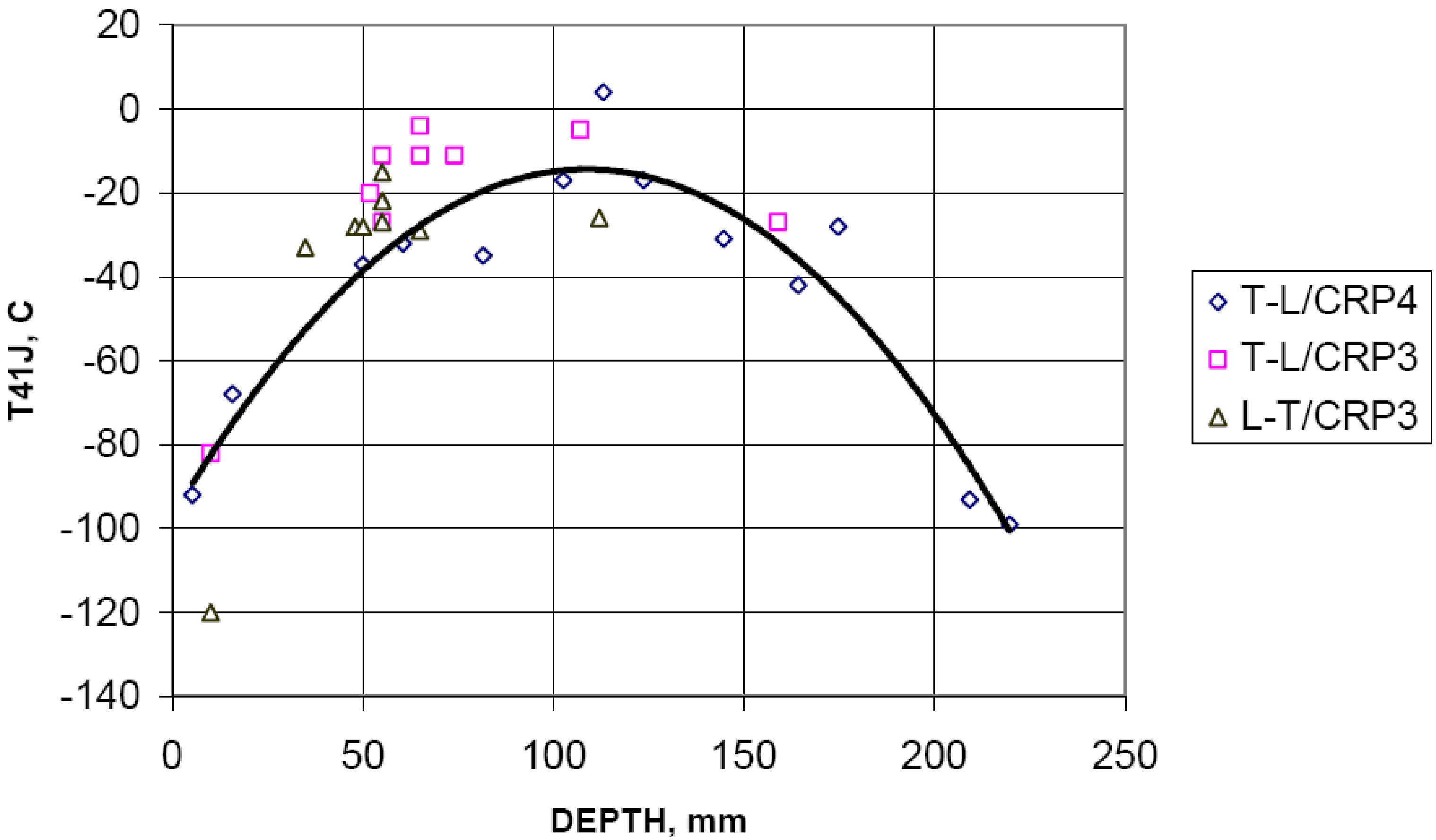
ACCEPTANCE TESTS

SEGREGATION OF C IN FORGED RING



ACCEPTANCE TESTS

TYPICAL DISTRIBUTION OF TRANSITION TEMPERATURE THROUGH WALL THICKNESS OF JRQ STEEL



ACCEPTANCE TESTS

TEST RESULTS DEPEND ALSO ON ORIENTATION OF TEST SPECIMENS

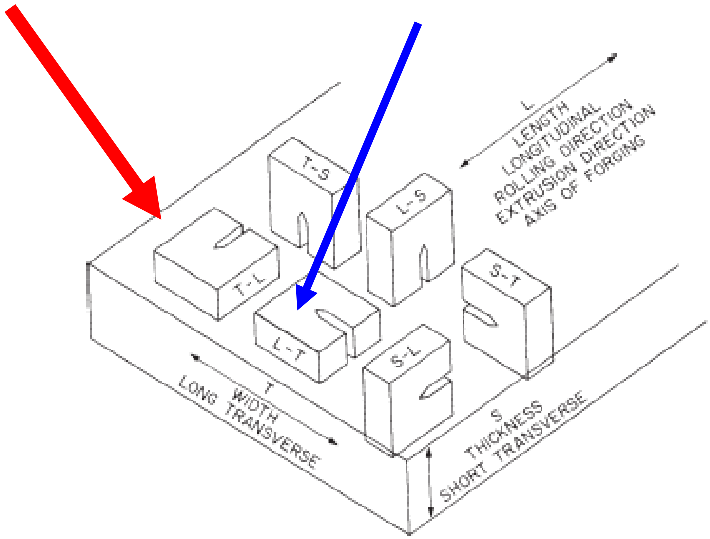


FIG. 1 Crack Plane Orientation Code for Rectangular Sections

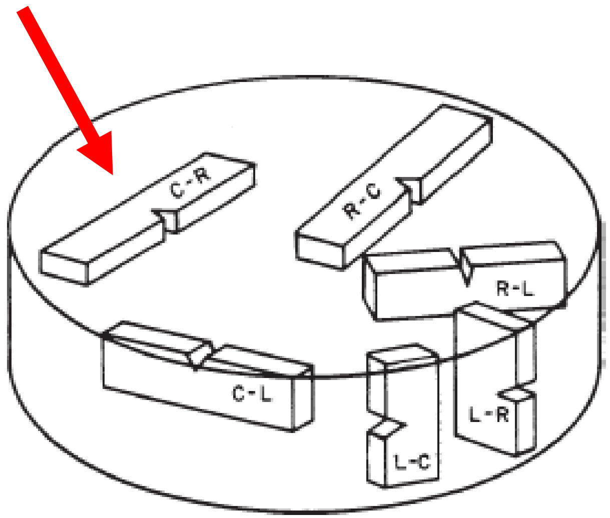


FIG. 3 Crack Plane Orientation Code for Bar and Hollow Cylinder

ACCEPTANCE TESTS

DUE TO LARGE DIMENSIONS OF INGOTS AND LARGE THICKNESS OF FINAL COMPONENTS, NON-HOMOGENEITY EXISTS WITHIN THE COMPONENT

THIS NON-HOMOGENEITY IS NECESSARY TO TAKE INTO ACCOUNT IN RPV LIFETIME AND INTEGRITY ASSESSMENT

VALUES OF SUCH SAFETY FACTOR (REPRESENTING NON-HOMOGENEITY) CAN BE GIVEN IN CODES

MAIN AGEING MECHANISMS

RADIATION DAMAGE

RADIATION DAMAGE TAKES PLACE IN THE BELTLINE REGION

NEUTRON FLUX DISTRIBUTION ON THE RPV WALL DEPENDS ON:

- REACTOR OUTPUT
- ACTIVE CORE GEOMETRY (QUADRATIC- PWR/ HEXAGONAL-WWER)
- THICKNESS OF WATER REFLECTOR
- MOVEMENTS/POSITION OF CONTROL RODES
- FLUX CHANGES IN HORIZONTAL AND AXIAL DIRECTIONS AND ALSO THROUGH RPV WALL

MAIN AGEING MECHANISMS
RADIATION DAMAGE

. OPERATING LIFETIME FLUENCE FOR WWERs, PWRs AND THE BWR

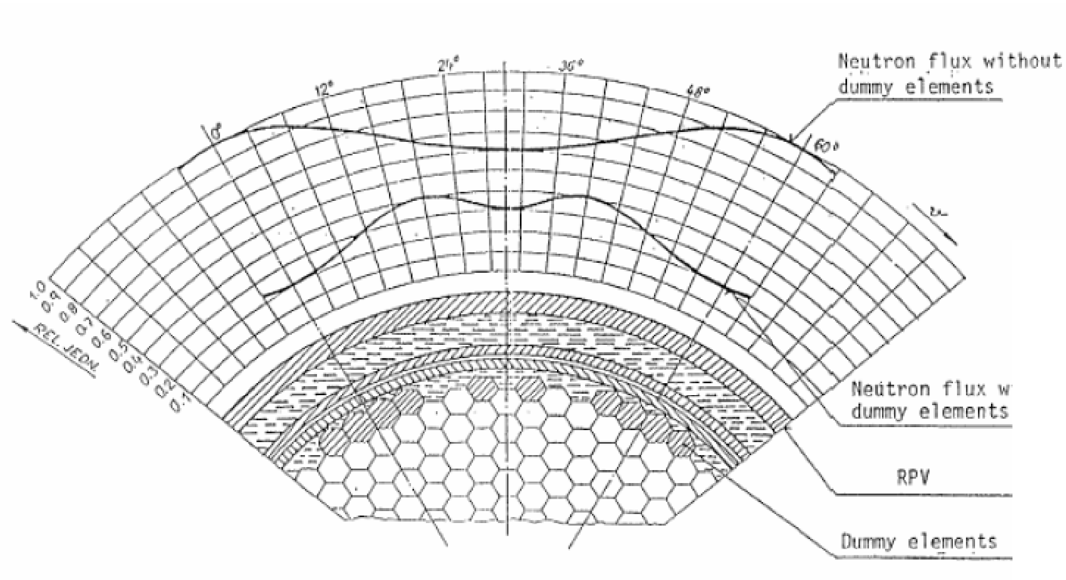
REACTOR TYPE	**FLUX, $n.m^{-2}.sec^{-1}$ (E>1MeV)**	**LIFETIME* FLUENCE, $n.m^{-2}$ (E>1MeV)**
WWER-440 core weld	1.2×10^{15}	1.1×10^{24}
WWER-440 maximum	1.5×10^{15}	**1.6×10^{24}**
WWER-1000	$3\text{-}4 \times 10^{14}$	3.7×10^{23}
PWR (W)	4×10^{14}	4×10^{23}
PWR (B&W)	1.2×10^{14}	1.2×10^{23}
BWR	4×10^{13}	4×10^{22}

MAIN AGEING MECHANISMS
RADIATION DAMAGE

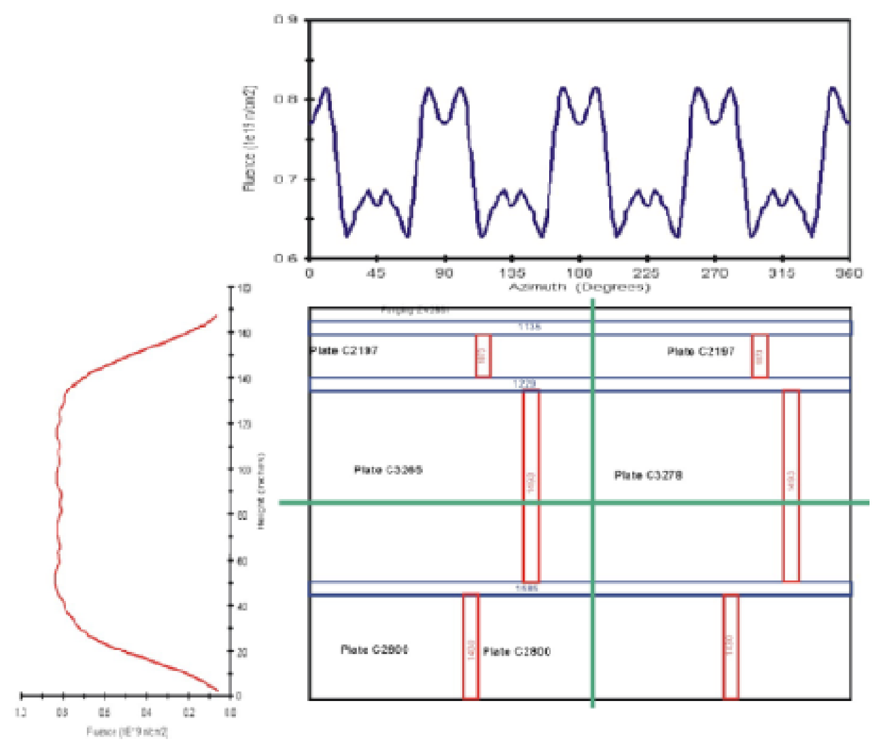
NEUTRON FLUX/NEUTRON FLUENCE ARE DEFINED USUALLY AS:

- **PWR – WITH ENERGIES LARGER THAN 1 MeV**
- **WWER - WITH ENERGIES LARGER THAN 0.5 MeV**
  - THERE IS NO CONSTANT RATIO BETWEEN THESE TWO FLUXES, DEPENDS ON NEUTRON SPECTRUM
  - THUS, DIFFERENT FOR DIFFERENT LOCATION, DIFFERENT REACTORS (POWER vs. EXPERIMENTAL), THROUGH WALL THICKNESS
- **dpa - DISPLACEMENT PER ATOM FOR THE WHOLE ENERGY SPECTRUM**

MAIN AGEING MECHANISMS
RADIATION DAMAGE



After EricksonKirk



MAIN AGEING MECHANISMS
RADIATION DAMAGE

RADIATION DAMAGE IS USUALLY EXPRESSED AS:

- **RADIATION HARDENING**
  - USUALLY NO PREDICTIVE FORMULAE IN CODES
- **RADIATION EMBRITTLEMENT**
  - PREDICTIVE FORMULAE IN CODES DIFFER FOR DIFFERENT MATERIALS/ COUNTRY OF PRODUCTION:
    - US NRC REG.GUIDE 1.99/10 CFR 50.61A/ASTM E 900-2,
    - RCC-M/RSE-M - FIM (BASE METAL), FIS (WELD METAL) – FRANCE
    - KTA 3201, 3203 – GERMANY
    - JEAC 4201-200 – JAPAN
    - PNAE-G 7-002-86, IAEA TECDOC 1442 – WWER-440
    - RD EO 1.1.2.09.0789-2009 – WWER-1000

MAIN AGEING MECHANISMS
RADIATION DAMAGE

TRANSITION TEMPERATURE SHIFT IS DEFINED:

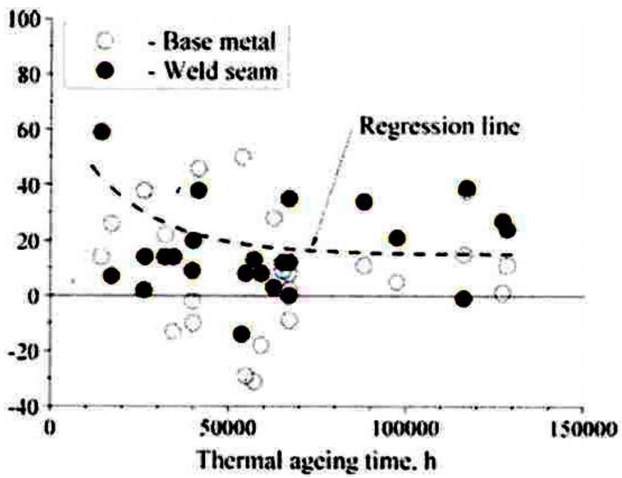
PWR – FOR ENERGY 41 J, ONLY

WWER – FOR ENERGY THAT DEPENDS ON ACTUAL YIELD STRENGTH OF MATERIAL (i.e. WITH INCREASING FLUENCE THIS VALUE IS ALSO INCREASING)

MAIN AGEING MECHANISMS
THERMAL AGEING

DEPENDS ON RPV MATERIAL

- **PWR STEELS**
  - NOT MENTIONED IN CODES, i.e. NOT TAKEN INTO ACCOUNT
- **WWER STEELS**
  - PNAE-G 7-002-86 FOR 15Kh2MFA(A) : ΔTt = 0 °C
  - RD EO 1.1.2.09.0789-2009 FOR 15Kh2NMFA(A): ΔTt = f(t, Ni)

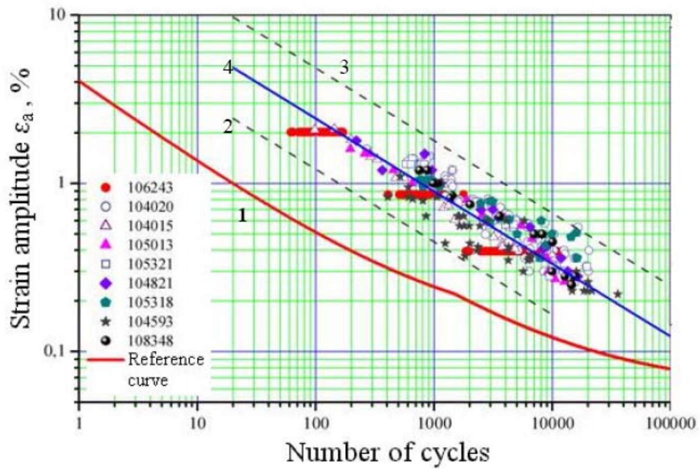


After Yu. Nikolaev

MAIN AGEING MECHANISMS
FATIGUE

FATIGUE IS MOSTLY PRONOUNCED IN:

- NOZZLE REGION (HIGH STRESS CONCENTRATION),
- NOZZLE PENETRATIONS IN COVER
- BOLTING JOINTS (LARGEST DAMAGE, BUT BOLTS ARE REPLACEABLE



MAIN AGEING MECHANISMS

CORROSION

INNER SURFACE OF RPV SHOULD HAVE TO BE PROTECTED BY ANTICORROSIVE LAYER

PRACTICALLY ALL RPV ARE COVERED BY AUSTENITIC CLADDING (ONE OR TWO LAYERS) MADE BY STRIP WELDING UNDER FLUX OR MANUALLY

(ONLY SEVERAL FIRST WWER-440/v-230 TYPE RPVs WERE COVERED ONLY IN NOZZLE REGIONS)

PWR HAVE MOSTLY NON-STABILIZED AUSTENITIC OUTER LAYER

WWER HAVE AUSTENITIC OUTER LAYER STABILIZED BY NIOBIUM

PWR USED Ni-BASED ALLOYS FOR BUTTERING/ DISSIMILAR WELDS

WWER USED ONLY AUSTENITIC STABILIZED STEELS

- Boric acid corrosion of outer surfaces

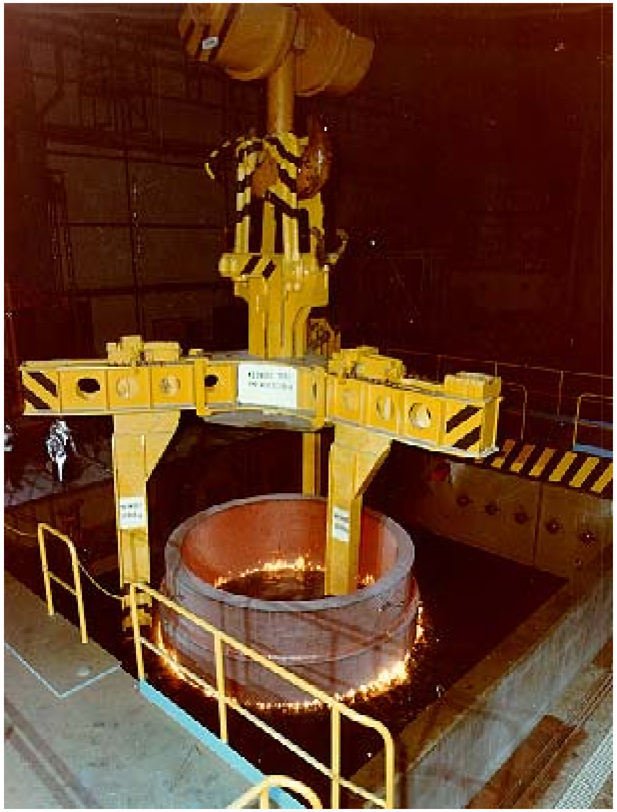
IN-SERVICE INSPECTION

IN-SERVICE INSPECTION IS A MANDATORY PART OF SAFE OPERATION:

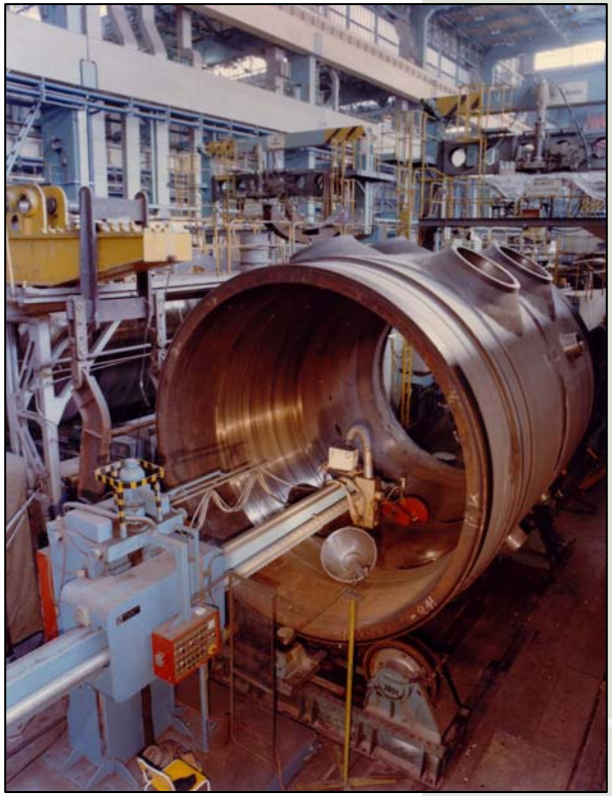
- **PERIODIC**
  - NON-DESTRUCTIVE TESTING DURING OUTAGES
  - SURVEILLANCE SPECIMEN PROGRAMMES (DESTRUCTIVE)
- **CONTINOUS**
  - TEMPERATURE AND PRESSURE MEASUREMENTS
  - NEUTRON DOSIMETRY IN OUTER SURFACE (CAVITY)

TYPICAL RPVs

NOZZLE FORGING



QUENCHING



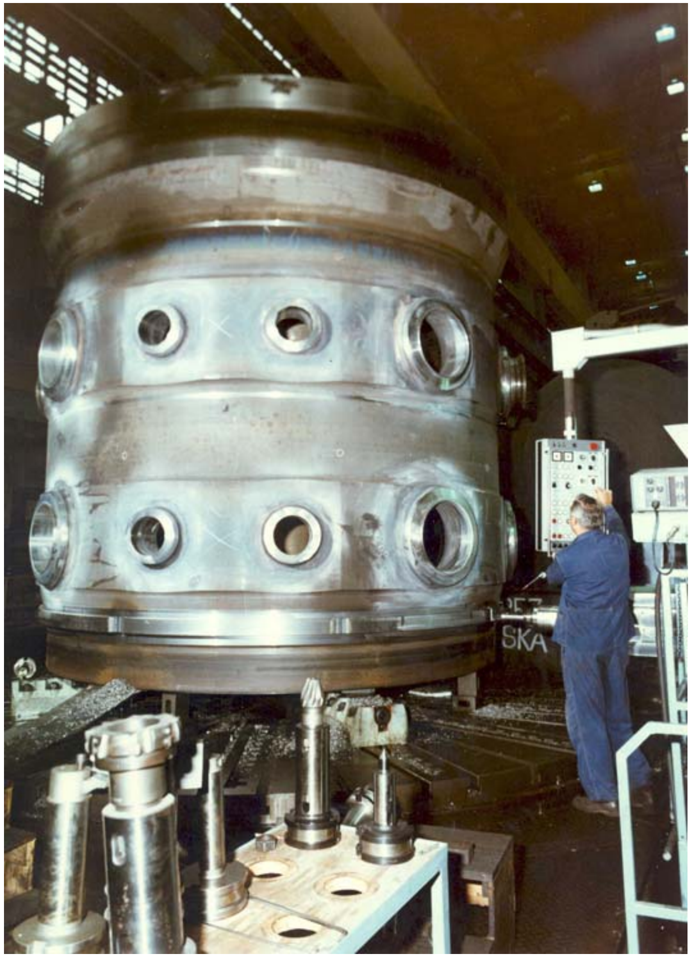
WELDING

TYPICAL RPVs

A 315-TON HOLLOW INGOT PROVIDES STARTING
MATERIAL FOR A LARGE FORGED SHELL RING
(AFTER MIYANA OF KAWASAKI STEEL)

TYPICAL RPVs

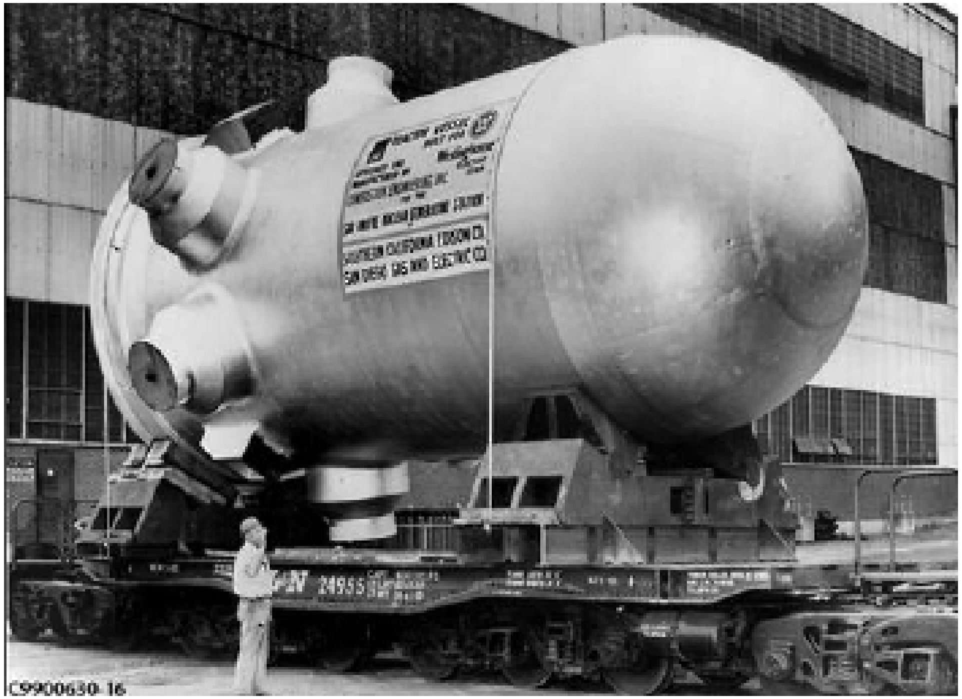
WELDING OF CLADDING



MACHINING

TYPICAL RPVs

TYPICAL PWR RPV



WWER-440 RPV

- Vessels may weigh up to 800t with wall thickness up to ~330mm.

Comparison of III^rd generation RPVs

RPV	AP 1000 Westinghouse (USA)	EPR AREVA (France)	ASE 92 Atomstrojexport (Russian)
Material	**A-508 Grade 3 Class 1 A-533-B**	**16 MND 5** [1)]	**15Kh2NMFA,** [2)] **15Kh2NMFA-A 15Kh2NMFA Class 1**
Concentration of Cu, P, S, As, Sb, Sn in beltline region	**Cu < 0,03 P < 0,010 S < 0,010**	**Cu < 0,08 P < 0,008 S < 0,008**	**Cu < 0,08 P < 0,010** [3)] **S < 0,012 As < 0,010 Sb < 0,005 Sn < 0,005**
Number of circumferential welds in beltline	**0**	**1**	**2**
EOL fluence	**7,0 x 10^{19} n/cm^2 (E > 1 MeV)**	**1,2 x 10^{19} n/cm^2 (E > 1 MeV)**	**3,7 x 10^{19} n/cm^2 (E > 1 MeV)**
Surveillance programme	**Specimens on active core basket**	**Specimens on active core basket**	**Specimens on inner RPV wall**
Lifetime (EOL)	**60**	**60**	**60 + 20**
RPV diameter, length, wall thickness (without cladding)	**4,470 mm, 10,256 mm 200 mm**	**5,385 mm, 13,078 mm 250 mm**	**4,585 mm, 11,185 mm 195 mm**
RPV mass (transportable)	**296 t**	**405 t**	**320 t**
Code	**ASME, Sekce III**	**RCC-M, (ASME)**	**PNAE-G, GOST**
Output	**1100 MWe**	**1600 MWe**	**1000 MWe**

CONCLUSIONS

RPV ARE UNIQUE REACTOR COMPONENTS WITH HIGHEST REQUIREMENTS FOR ENSURING INTEGRITY AND SAFE OPERATION DURING WHOLE LIFETIME UNDER ALL OPERATIONG CONDITIONS/REGIMES

MAIN FAILURE MECHANISM CAN BE NON-DUCTILE/FAST FRACTURE

MAIN DAMAGING MECHANISM IS RADIATION DAMAGE PRONOUNCED AS RADIATION HARDENING AND EMBRITTLEMENT

THANK YOU FOR YOUR VERY KIND ATTENTION