The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2067-11

Joint ICTP/IAEA Workshop on Irradiation-induced Embrittlement of Pressure Vessel Steels

23 - 27 November 2009

RPV design, manufacturing and materials

Milan Brumovsky

Nuclear Research Institute
Rez

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RPV design, manufacturing and materials

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Joint ICTP/IAEA Workshop on Effects of Mechanical Properties and Mechanisms Governing the Irradiation-induced Embrittlement of Pressure Vessel Steels

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CONTENT

INTRODUCTION

- REACTOR PRESSURE VESSELS
  - NUCLEAR REACTION IS REALIZED INSIDE RPV = HEART OF THE NPP
    - THUS, RPV IS THE MOST IMPORTANT COMPONENT OF THE WHOLE NPP
  - RPV CONTAINS ALL NUCLEAR FISSION MATERIALS
    - THEIR PRACTICALLY 100 % INTEGRITY MUST BE ASSURED
  - RPV PRACTICALLY CANNOT BE REPLACED
    - DETERMINED LIFETIME OF THE WHOLE NPP

INTRODUCTION

NEUTRONS	MODERATOR	COOLANT	RPV/TUBES	TYPE
THERMAL	H_2O	H_2O	RPV	PWR VVER
				BWR
	D_2O	D_2O	TUBES	CANDU
	D_2O	CO_2	RPV/TUBES	HWGCR = A1
	GRAFIT	H_2O	TUBES	RBMK
		He	TNR	HTR
FAST	-	Na/Pb+Bi	RV	FBR

VVER = WWER IS PWR DESIGNED IN ACCORDANCE WITH RUSSIAN CODES

WWER = WATER-WATER ENERGETICAL REACTOR

ВОДО-ВОДЯНЫЙ ЭНЕРГЕТИЧЕСКИЙ РЕАКТОР

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CONTENT

REQUIREMENTS TO RPV

- RPV DESIGN MUST BE PERFORMED WITH RESPECT TO:
  - OPERATION CONDITIONS OF REACTOR AND NPP
    - REQUIREMENTS TO DESIGN OF ACTIVE CORE AND ALL NPP
    - OPERATION PRESSURE AND TEMPERATURE
    - REQUIRED LIFETIME
  - CURRENT CODES AND STANDARDS
    - IN PRINCIPLE: ASME (KTA, RCC-M, JSME) - PNAEG
  - TECHNOLOGICAL POSSIBILITIES
    - EXISTING/ALLOWED MATERIALS AND MANUFACTURING BASES
  - TRANSPORT REQUIREMENTS AND POSSIBILITIES
    - LOCATION/SITE OF NPP AND TRANSPORT POSSIBILITIES BETWEEN MANUFACTURER AND NPP

REQUIREMENTS TO RPV

- CALCULATION BASES OF RPV DESIGN:
  - STATICAL STRESS ANALYSIS
  - RESISTANCE AGAINST NON-DUCTILE/BRITTLE FRACTURE
  - FATIGUE STRENGTH
  - RESISTANCE TO SEISMIC EVENTS
  - ASSESSMENT/EVALUATION OF LIFETIME

REQUIREMENTS TO RPV

❑ ASSURANCE OF RPV SAFETY:

- PROGRAMME OF RPV HYDROTESTS
- PROGRAMME OF MONITORING OF OPERATION REGIMES
- SURVEILLANCE SPECIMEN PROGRAMME OF RPV MATERIALS
- PROGRAMME OF NON-DESTRUCTIVE IN-SERVICE INSPECTIONS OF RPV
- PROGRAMME OF MONITORING RPV RADIATION LOADING
- PROGRAMME OF MONITORING VIBRATIONS, ACCELERATION, FREE PARTS etc.

CONTENT

RPV DESIGN

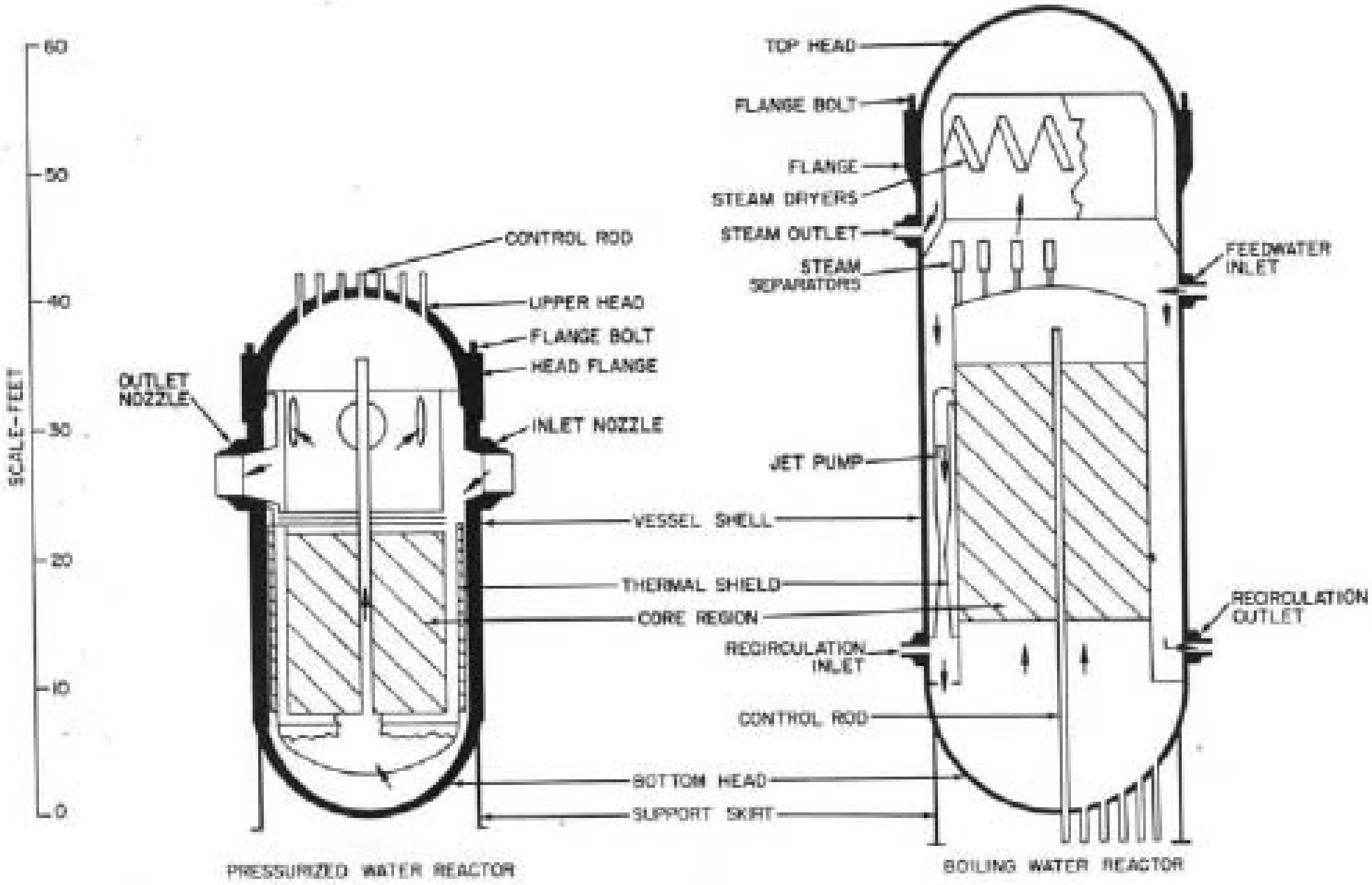

FIG. 6. Comparison of PWR and BWR RPVs with the same output.

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RPV DESIGN

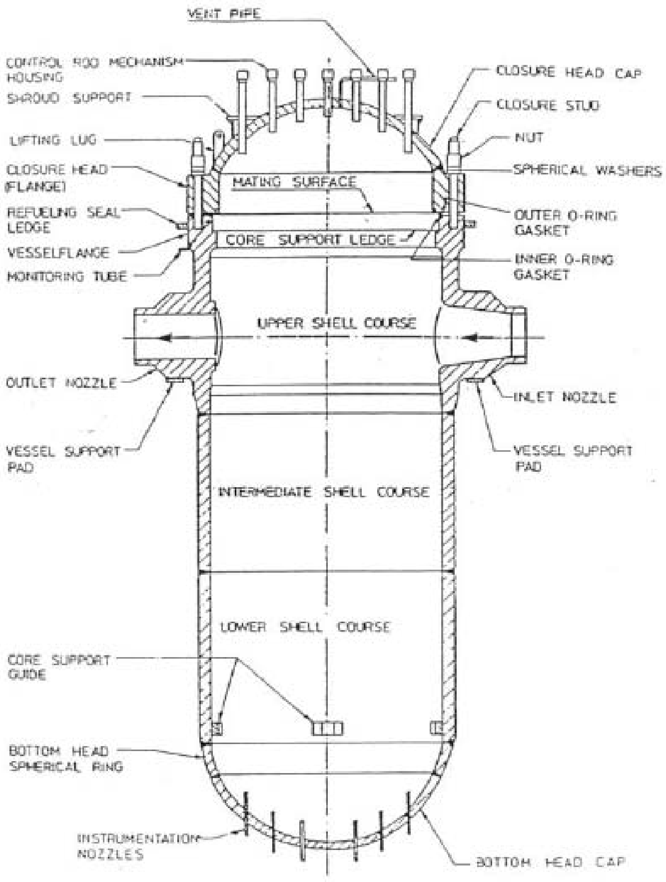


FIG. 2. Typical Westinghouse RPV.

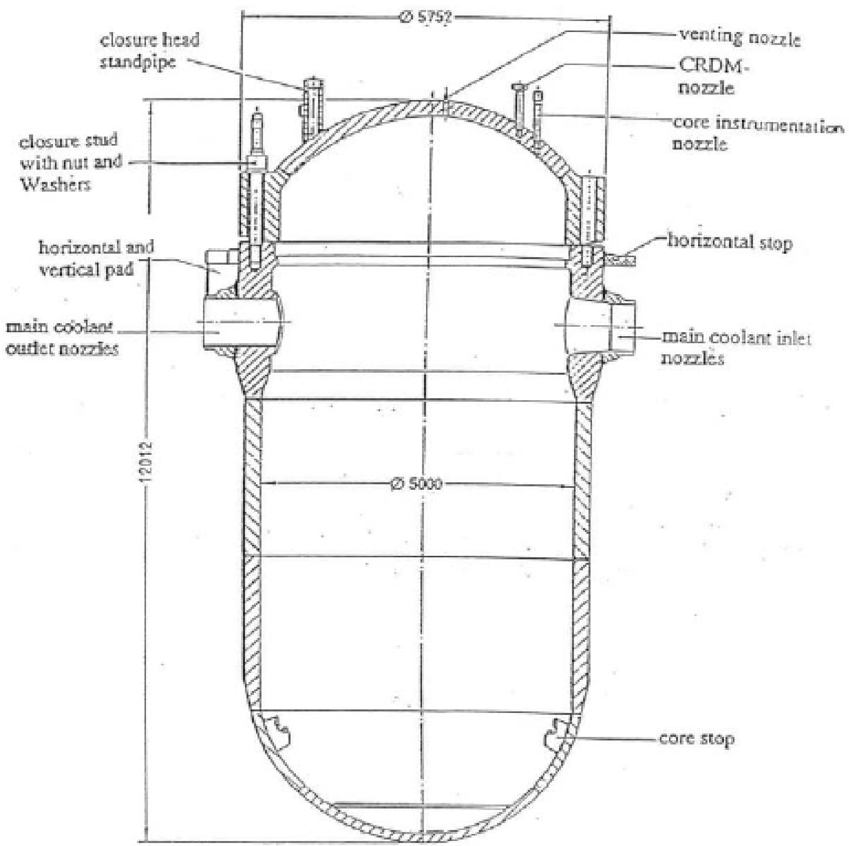
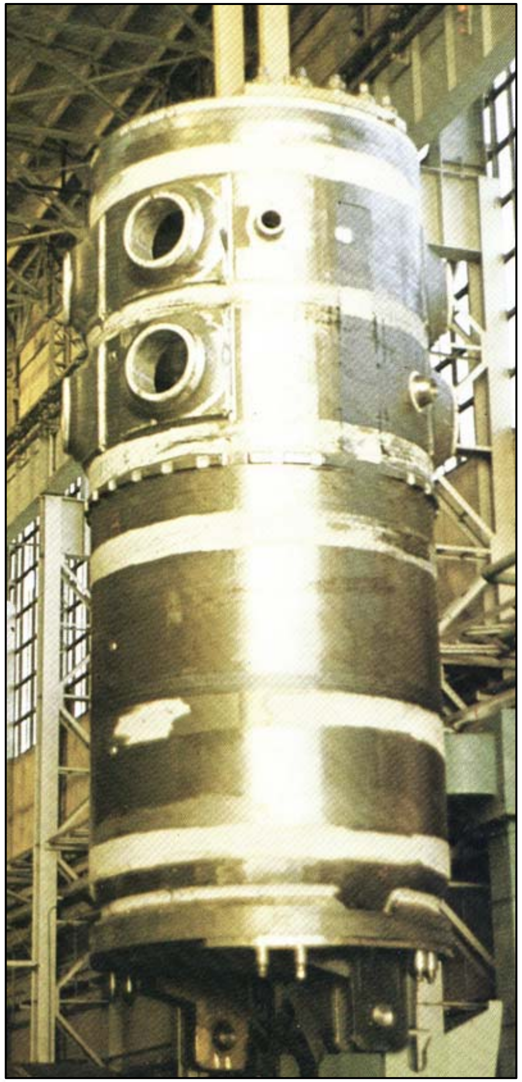
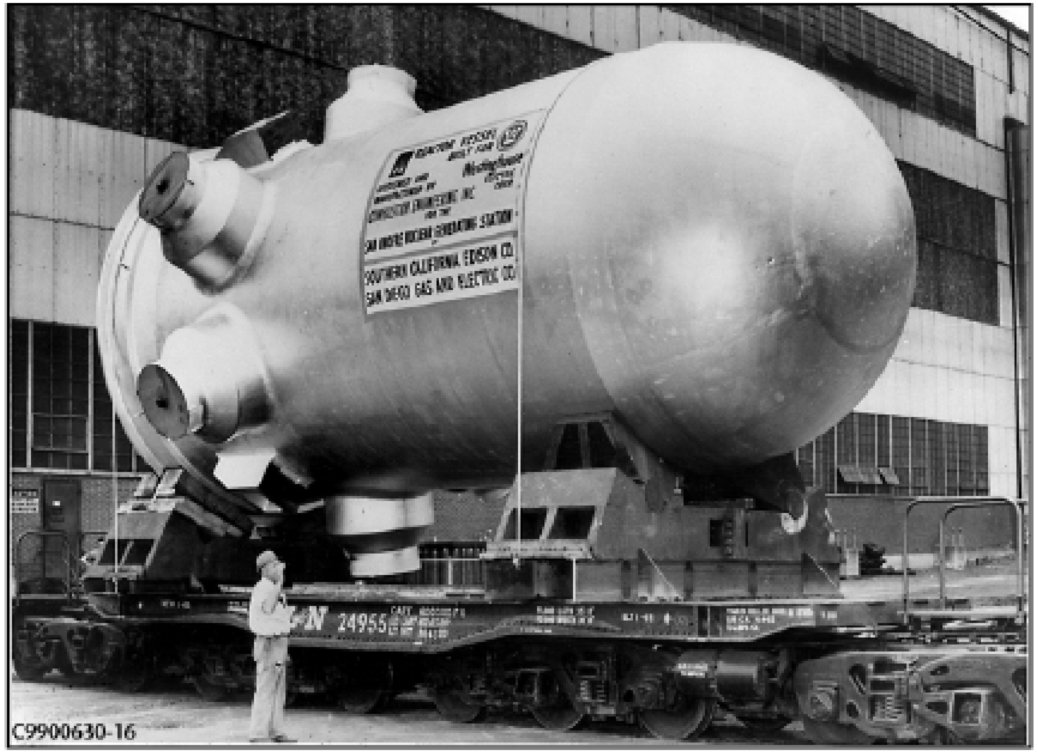


FIG. 4. A typical Siemens/KWU RPV for a 1300 MWe plant.

RPV DESIGN





RPV DESIGN

❑ PRINCIPAL DIFFERENCES BETWEEN PWR AND VVER REACTORS:

- ❑ PWR REACTORS ARE IN PRINCIPLE DESIGNED IN ACCORDANCE WITH ASME, SECTION III AND SECTION XI
- ❑ VVER REACTORS ARE DESIGNED IN ACCODANCE WITH RUSSIAN CODES

- ❑ PWR REACTORS HAVE QUADRATIC GRID OF ACTIVE CORE
- ❑ VVER REACTORS HAVE HEXAGONAL GRID OF ACTIVE CORE

- ❑ PWR REACTORS HAVE VERTICAL STEAM GENERATORS
- ❑ VVER REACTORS HAVE HORIZONTAL STEAM GENERATORS

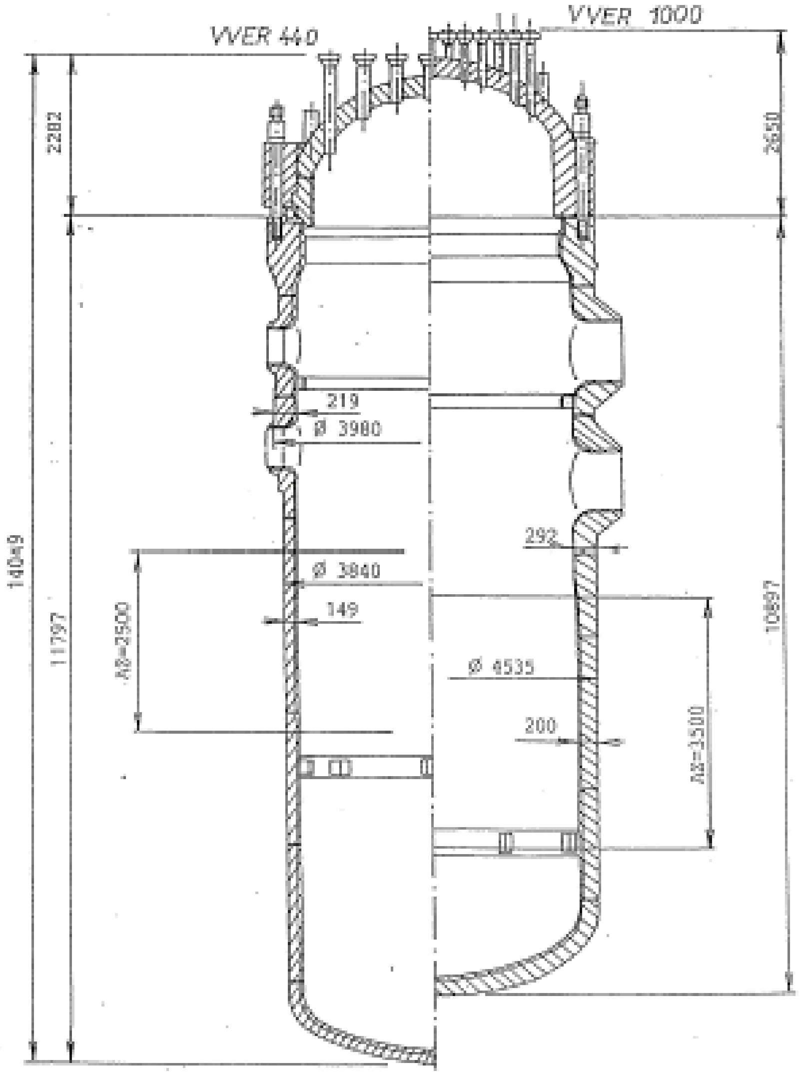
RPV DESIGN

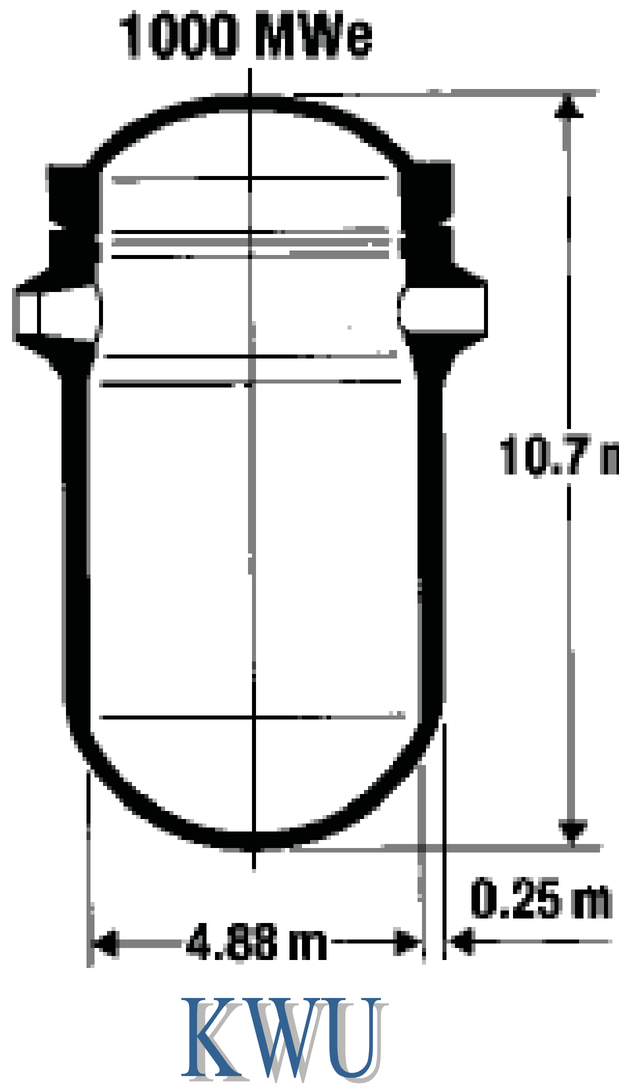
PWR	VVER
3 – 4 LOOPS	**6 LOOPS – VVER-440** **4 LOOPS – VVER-1000**
1 NOZZLE RING – IN + OUT	2 NOZZLE RINGS RING INLER + RING OUTLET
IN-WELDED NOZZLES	MECHANICALLY MACHINED NOZZLES (VVER-440) NOZZLED HOT FORGED OUT (VVER-1000)
1^{ST} RPV GENERATION – WELDED PLATES 2^{ND} RPV GENERATION – FORGED RINGS LATESTS RPVs – NOZZLE-FLANGE RING (cca 500 t)	ALL GENERATIONS –ONLY FORGED RINGS 1^{ST} 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

- CONSEQUENCES OF REQUIREMENTS ON LAND TRANSPORT (TRAIN, TRUCK):
  - SMALLER DIAMETER
    - HIGHER NEUTRON FLUX ON RPV WALL
    - LARGER FLUENCE DURING RPV LIFETIME
    - STRONGER REQUIREMENTS TO RPV MATERIAL RESISTANCE AGAINST RADIATION DAMAGE
  - SMALLER MASS
    - SMALLER RPV WALL THICKNESS
      - HIGHER MATERIAL STRENGTH PROPERTIES

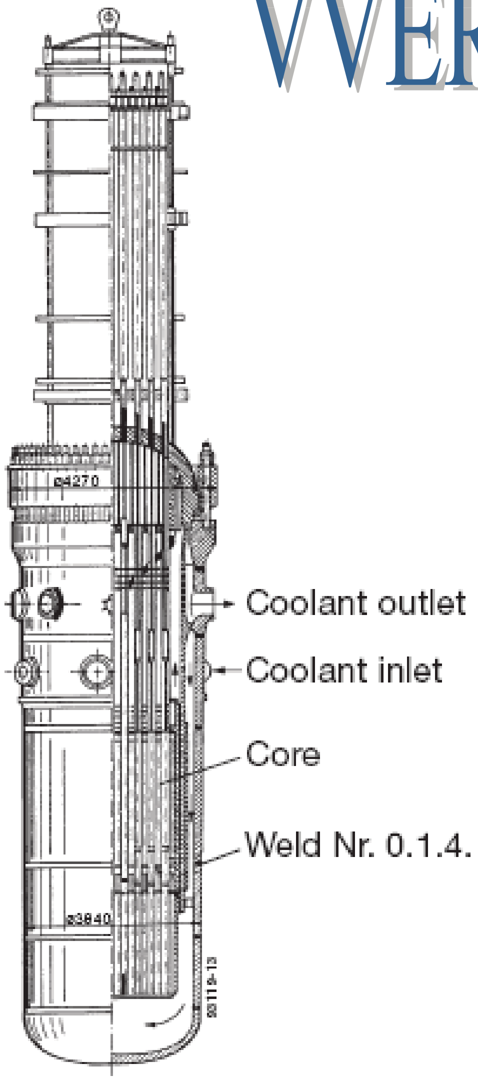
RPV DESIGN


VVER 440
VVER 1000
2282
2650
14049
11797
10897
AB=2500
AB=3500
219
Ø 3980
292
Ø 3840
149
Ø 4535
200

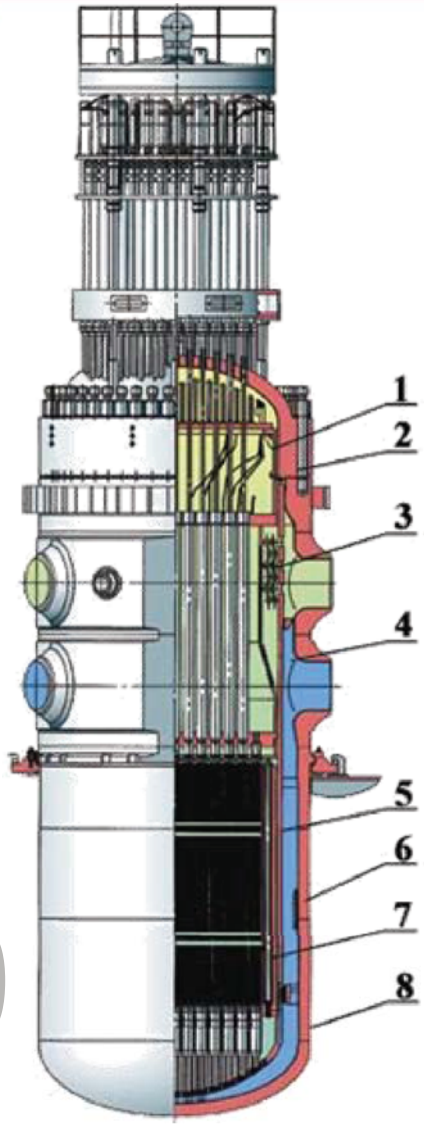

1000 MWe
10.7 m
0.25 m
4.88 m
KWU

RPV DESIGN

VVER-440



VVER-1000



CONTENT

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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%.

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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

REACTOR PRESSURE VESSELS-4

GUARANTEED MECHANICAL PROPERTIES OF LWR RPV MATERIALS*

MATERIAL	20 °C				350 °C				T_{k0}[1] RT_{NDT}[2]
	$R_{p0.2}$	R_m	A_5	Z	$R_{p0.2}$	R_m	A_5	Z	
	[MPa]	[MPa]	[%]	[%]	[MPa]	[MPa]	[%]	[%]	[°C]
15Kh2MFA - base metal	431	519	14	50	392	490	14	50	0[1]
- A/S weld metal	392	539	14	50	373	490	12	45	20[1]
15Kh2NMFA - base metal	490	608	15	55	441	539	14	50	-10[1]
15Kh2NMFAA – base metal	490	608	15	55	441	539	14	50	-25[1]
- A/S weld metal	422	539	15	55	392	510	14	50	0[1]
A 533-B, Cl.1	345	551	18	-	285	-	-	-	-12[2]
A 508, Cl.3	345	551	18	38	285	-	-	-	-12[2]

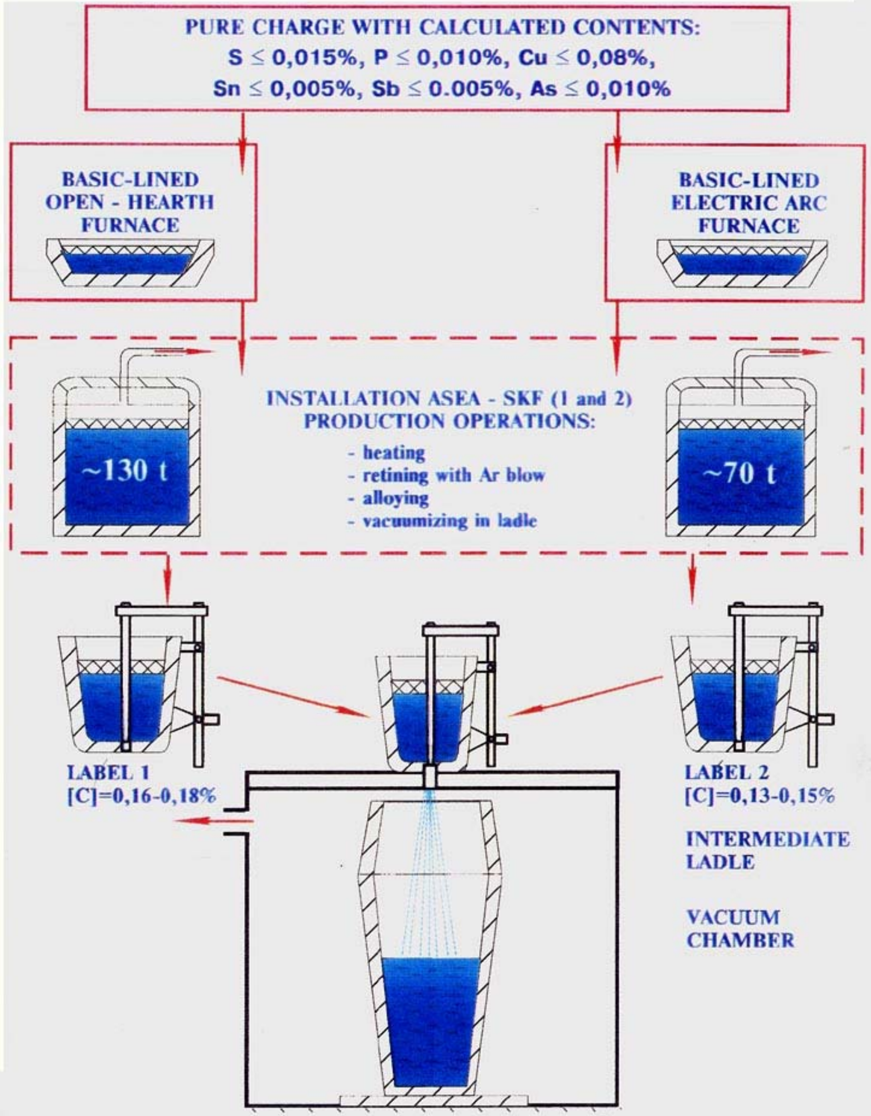
RPV MATERIALS

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	

CONTENT

RPV MANUFACTURING TECHNOLOGY



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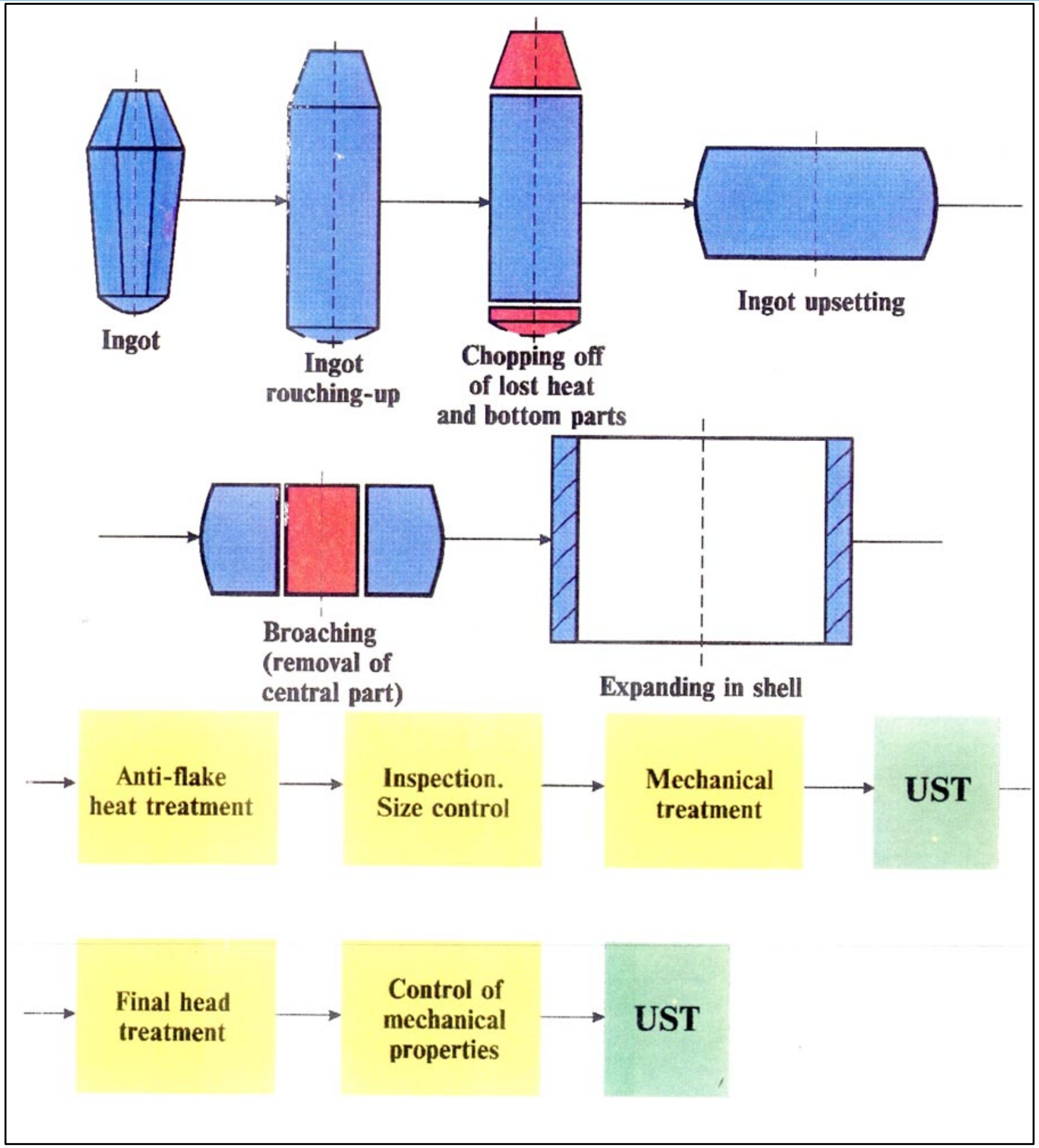


RPV MANUFACTURING TECHNOLOGY

RPV MANUFACTURING TECHNOLOGY

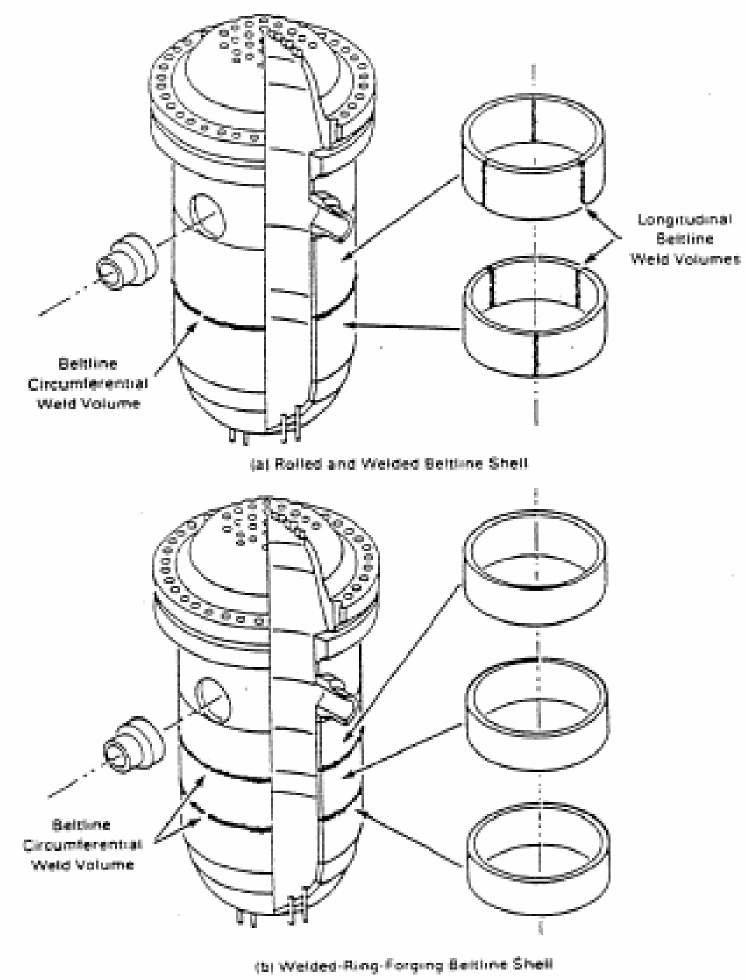
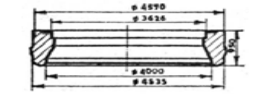
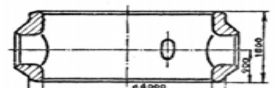


Fig. 9. Fabrication configuration of PWR beltline shells.

RPV MANUFACTURING TECHNOLOGY


Фланцевая обечайка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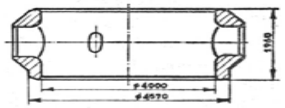
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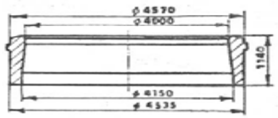
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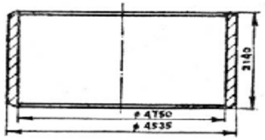
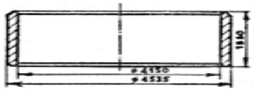

Гладкая обечайка верхняя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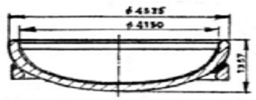
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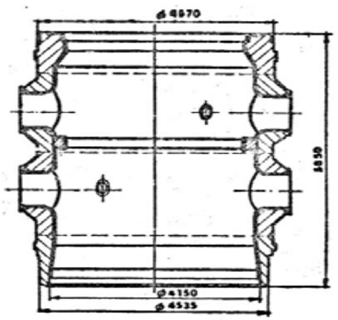
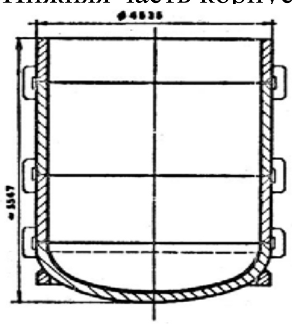
Верхняя часть корпуса



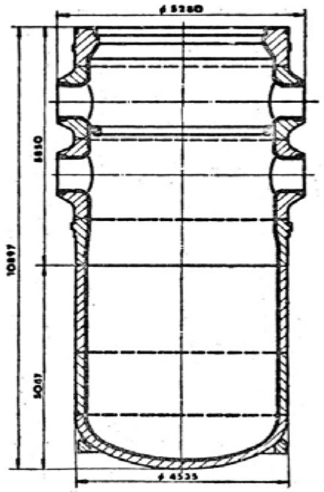
1. сварка кольцевых швов
2. антикоррозионная наплавка
3. механическая и термическая обработка
4. контроль качества

Нижняя часть корпуса



1. сварка кольцевых швов
2. антикоррозионная наплавка
3. механическая и термическая обработка
4. контроль качества

Сборка корпуса



1. сварка кольцевого шва №4
2. антикоррозионная наплавка пояса под швом №4
3. механическая и термическая обработка
4. контроль качества

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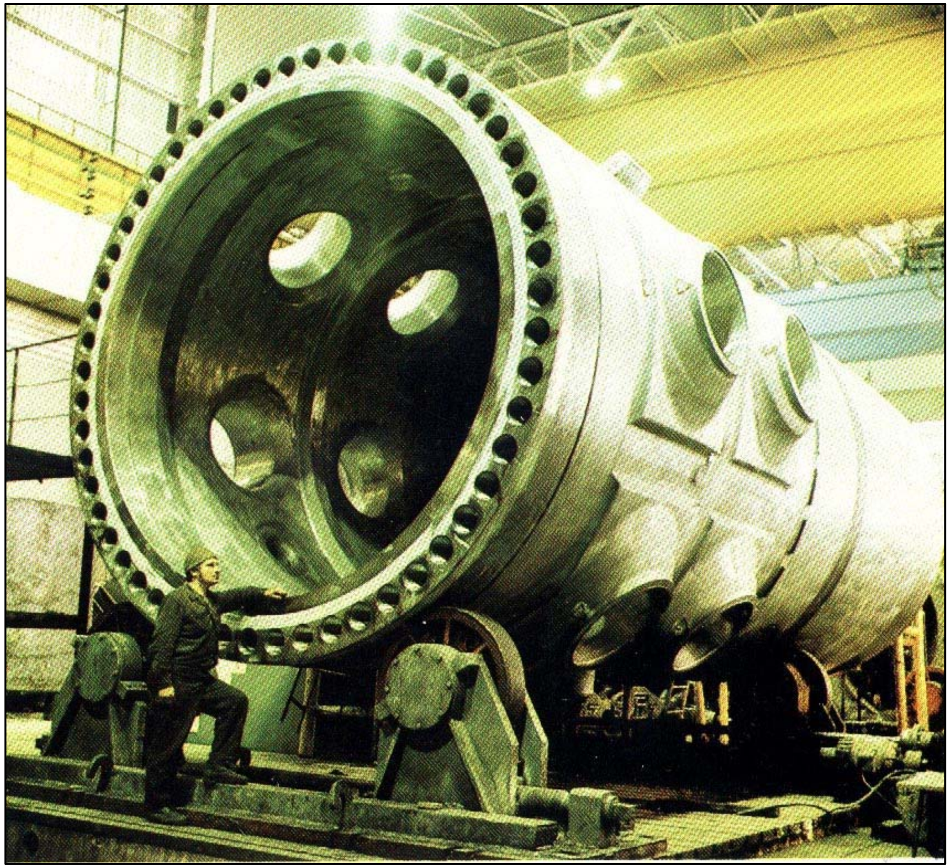

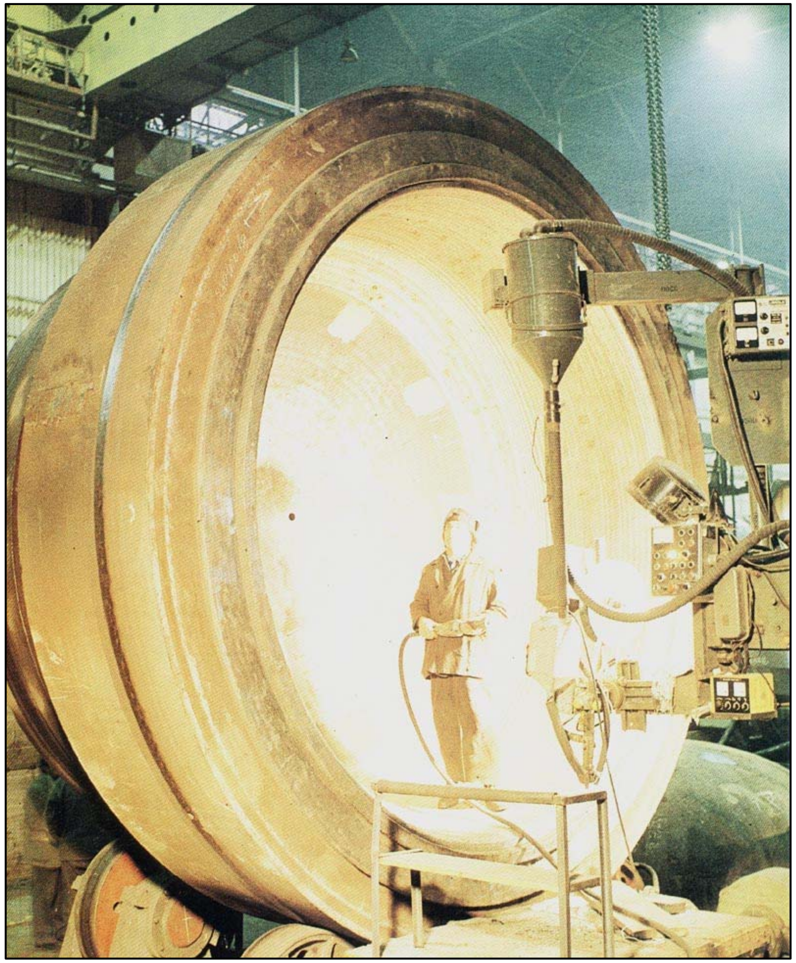

RPV MANUFACTURING TECHNOLOGY

CONTENT

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MONITORING CHANGES IN MECHANICAL PROPERTIES

- MONITORING OF CHANGES IN RPV MATERIAL PROPERTIES IS, IN PRINCIPLE, PERFORMED BY SURVEILLANCE SPECIMEN PROGRAMMES
- IN REACTORS WITHOUT SURVEIKLLANCE SPECIMEN PROGRAMMES (VVER-440/V-230), IT IS NECESSARY TO RELY ON PREDICTIVE FORMULAE AND/OR SPECIMENS CUTTING FROM THE RPV WALL (RPV WITHOUT CLADDING)
- PRINCIPIAL REQUIREMENTS TO SURVEILANCE SPECIMEN PROGRAMMES:
- LWR REACTORS :
  - ASTM E 185 – Standard Recommended Practice for Surveillance Tests for Nuclear Reactor Vessels
- VVER:
  - Pravila ustrojstva i bezopasnoj ekspluatacii oborudovanija i truboprovodov atomnykh energeticheskikh ustanovok, PN AE G-7-008-89

    (Rules for Design and Safe Operation of Components and Piping in Nuclear Power Plants)

MONITORING CHANGES IN MECHANICAL PROPERTIES

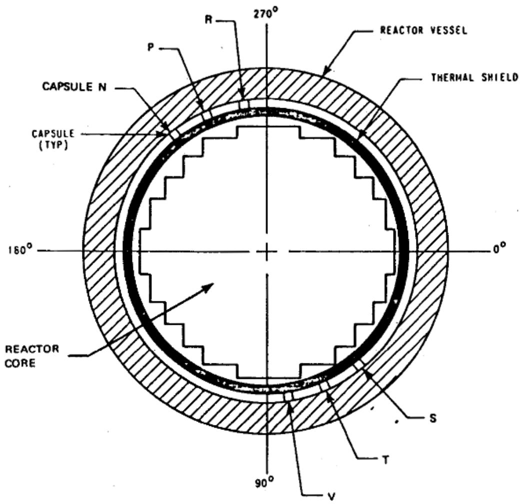
- RPV SURVEILLANCE SPECIMEN PROGRAMMES
- CHOICE:
  - CRITICAL MATERIALS ACCORDING TO GIVEN CRITERIA (CHEMICAL COMPOSITION – CONTENT OF IMPURITIES: P, Cu, …)
  - ONLY ARCHIVE MATERIALS, i.e. HEATS OF BASE METALS, WELDING JOINTS (IDENTICAL WIRE AND FLUX HEATS), IDENTICAL HEAT TREATMENT WITH CRITICAL RPV MATERIALS
- MATERIALS:
  - BASE METAL, WELD METAL, HEAT AFFECTED ZONE) NOT ALWAYS REQUIRED), AUSTENITIC CLADDING (NEITHER REQUIRED NOR RECOMMENDED, ONLY OPTINALLY)
- TEST SPECIMENS:
  - TENSILE TEST
  - IMPACT NOTCH TOUGHNESS (CHARPY V-NOTCH)
  - STATIC FRACTURE TOUGHNESS (MANDATFORY ONLY FOR VVER, RECOMMENDED FOR PWR)
  - LOW-CYCLE FATIGUE (ONLY FOR VVER-1000/V-320)

MONITORING CHANGES IN MECHANICAL PROPERTIES

- SURVEILLANCE SPECIMEN LOCATION
  - INSIDE RPV
  - IN THE RPV BELTLINE
  - LEAD FACTORSMALLER THAN 5
  - PSIBILITY FOR ACCELERATED IRRADIATION (PWR)
- MONITORING OF IRRADIATION CONDITIONS
  - NEUTRON FLUENCE MONITORS (ACTIVATION, FISSION)
  - IRRADIATION TEMPERATURE MONITORS (MELTING ALLOYS, DIAMOND)
  - MEASUREMENT ON OUTER RPV WALL (IN CAVITY)
- WITHDRAWAL TIJME SCHEDULE:
  - MINIMUM 3 SETS FOR DETERMINATION OF FLUENCE DEPENDANCE OF MECHANICAL PROPERTY CHANGES
  - MAXIMUM FLUENCE CORRESPONDED TO DESIGN EOL FLUENCE
  - PROBLEM – EXTENSION BEYOND DESIGN LIFETIME: 60 + YEARS

MONITORING CHANGES IN MECHANICAL PROPERTIES

- TYPICAL PWR WESTINGHOUSE REACTOR



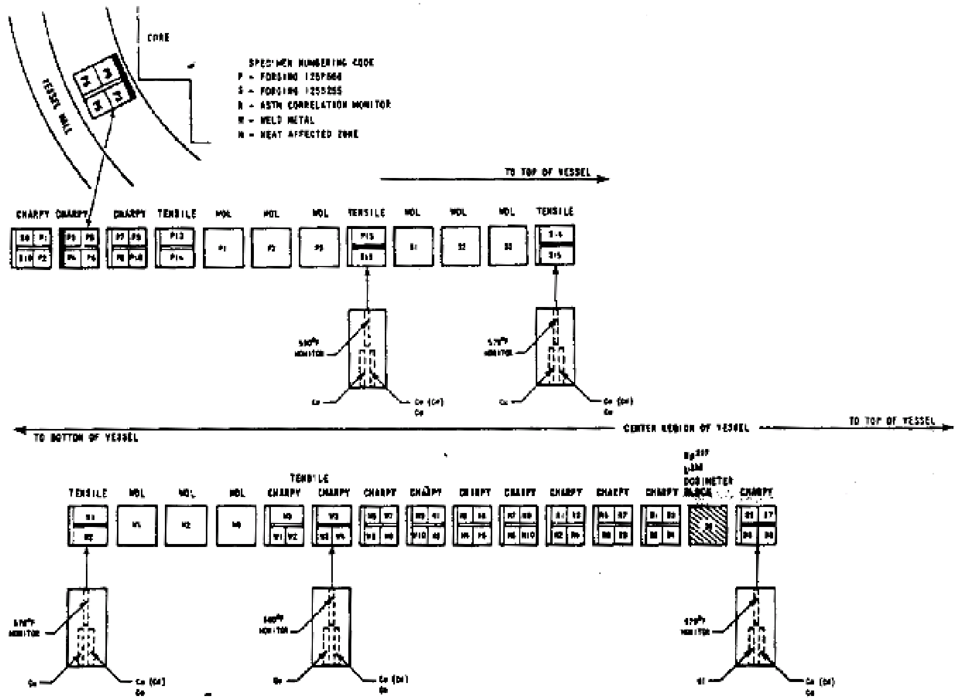


FIG. 5.1—*Typical capsule schematic showing specimens, thermal monitors, and dosimeter placement and orientation with respect to the core and vessel wall.*

MONITORING CHANGES IN MECHANICAL PROPERTIES

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❑ TYPICAL PWR C-E

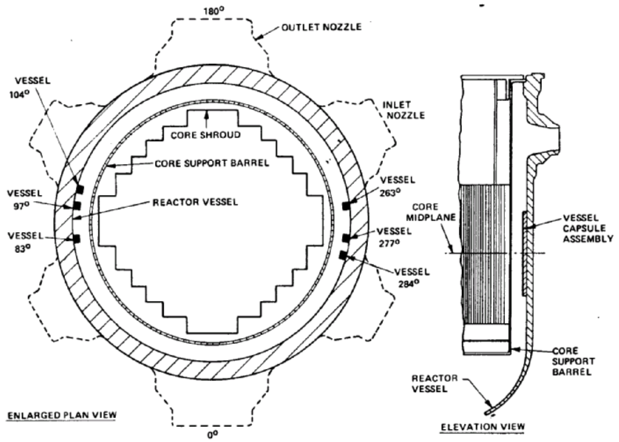


FIG. 3.7—*Location of capsule holders with respect to the peak fluence of the vessel, which occurs at the 90-deg locations. Physical constraints prevent use of the 0-deg and 180-deg positions for this purpose. The elevation of the capsule assembly bisects the geometric centerline of the core.*

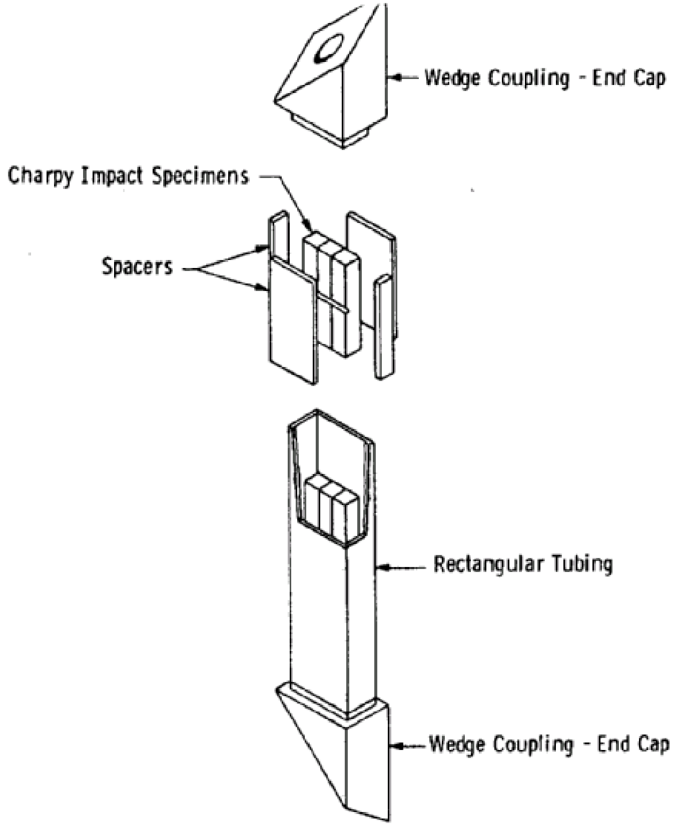


FIG. 3.5—*Typical Charpy specimen compartment containing 12 Charpy specimens in × 3 × 4 array. The notch of each specimen faces the center of the core.*

MONITORING CHANGES IN MECHANICAL PROPERTIES

- NEWER PWR C-E

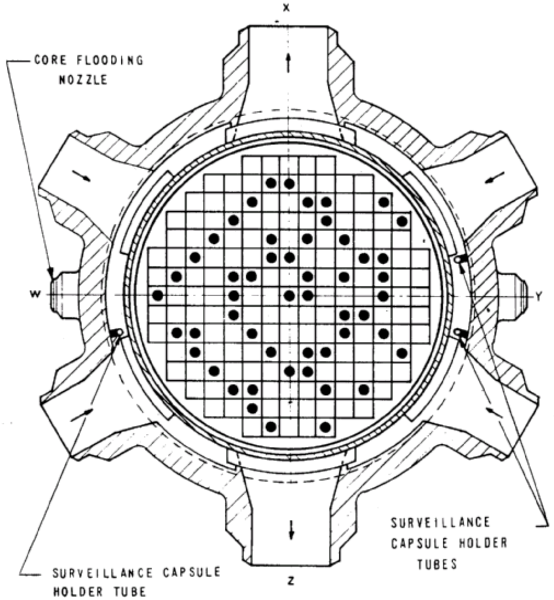


FIG. 2.4—*Reactor vessel cross section.*

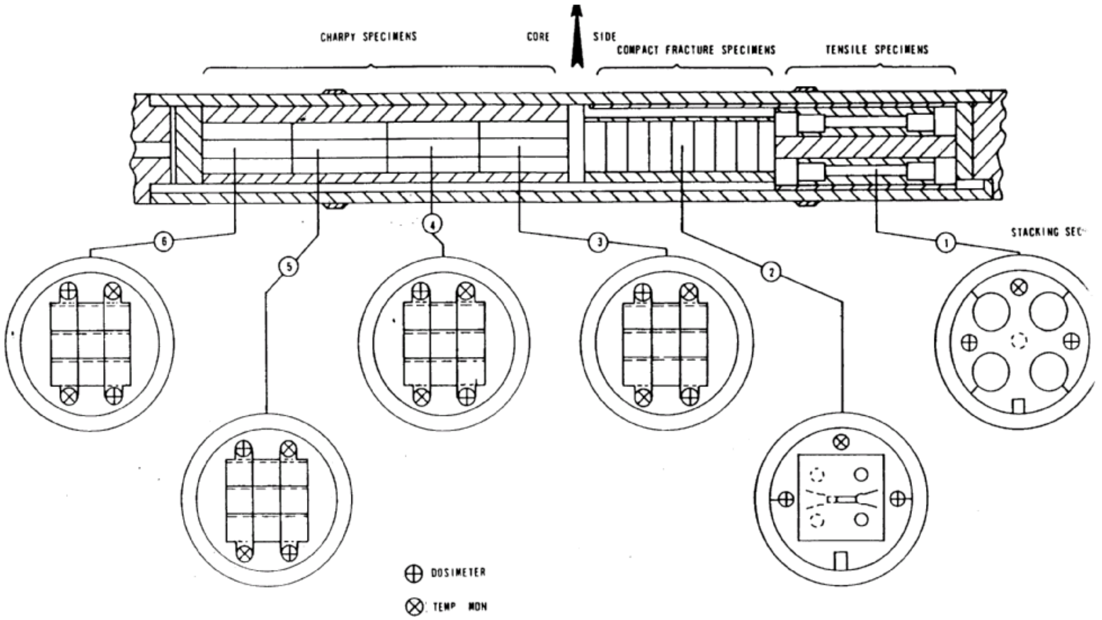


FIG. 2.12—*Typical loading diagram for test specimens in surveillance capsule containing compact and fracture specimens.*

MONITORING CHANGES IN MECHANICAL PROPERTIES

- VVER-440

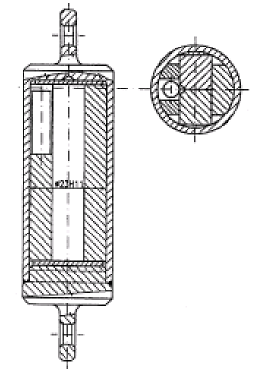


Fig. 1 Scheme of a container from the Standard Surveillance Program

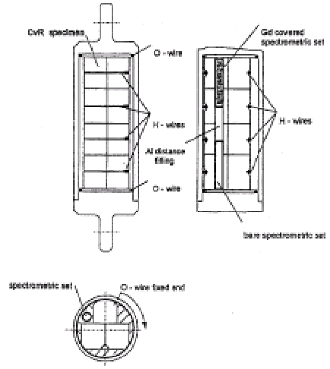
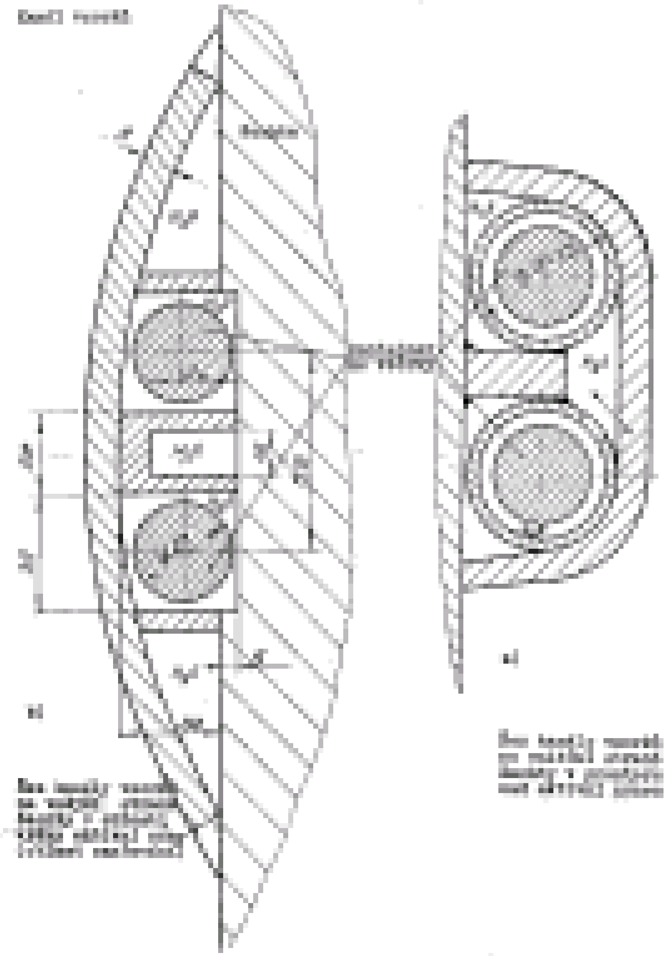
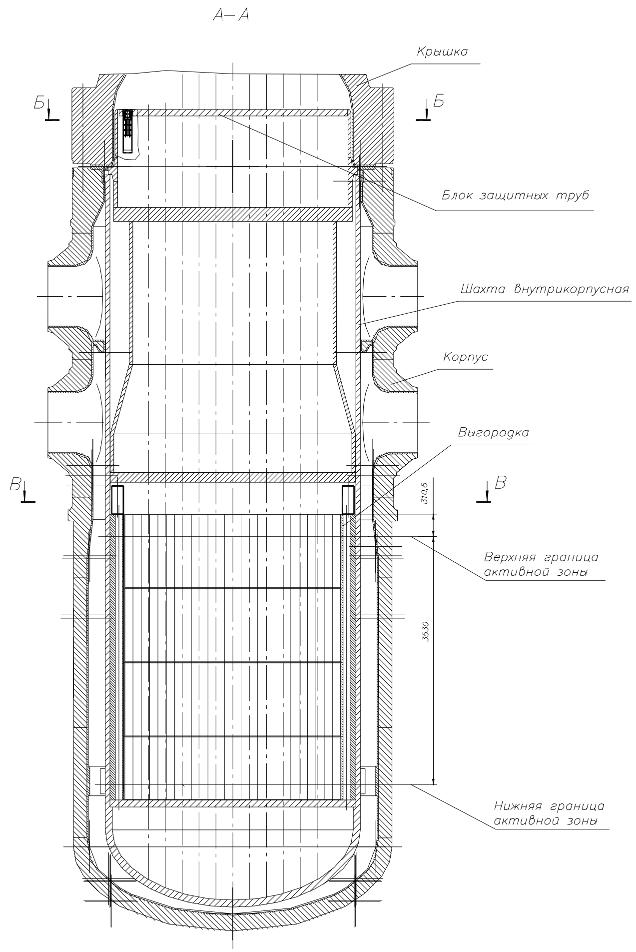


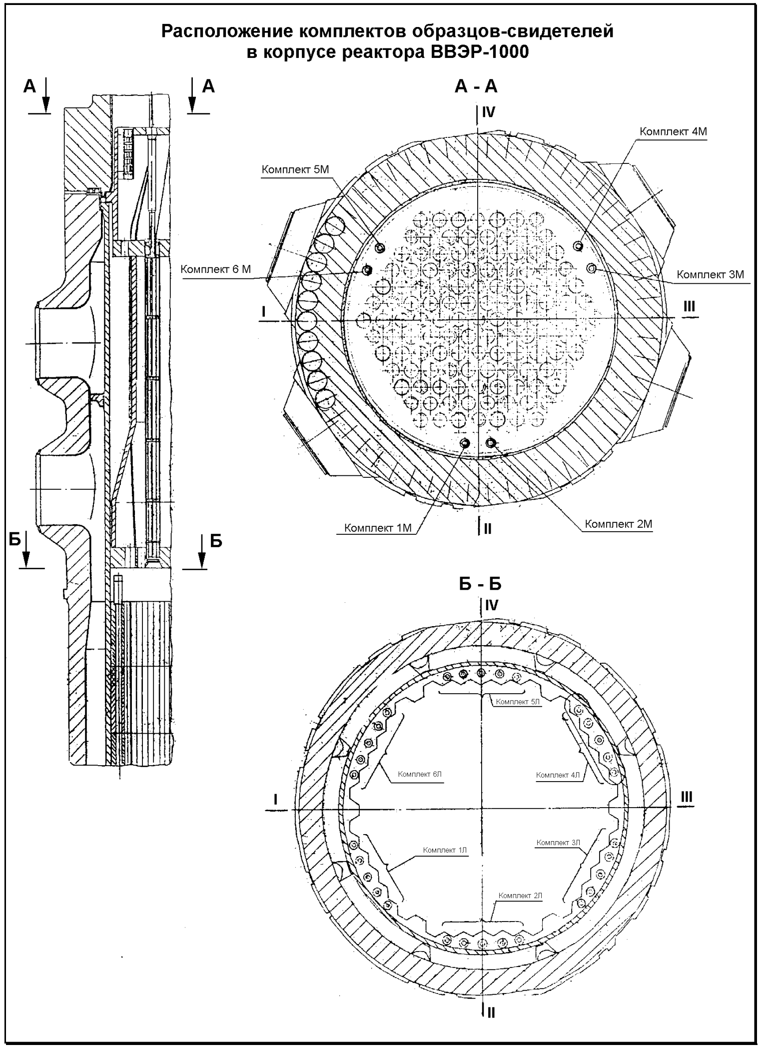
Fig. 2 Scheme of a container from the Supplementary Surveillance Program



MONITORING CHANGES IN MECHANICAL PROPERTIES

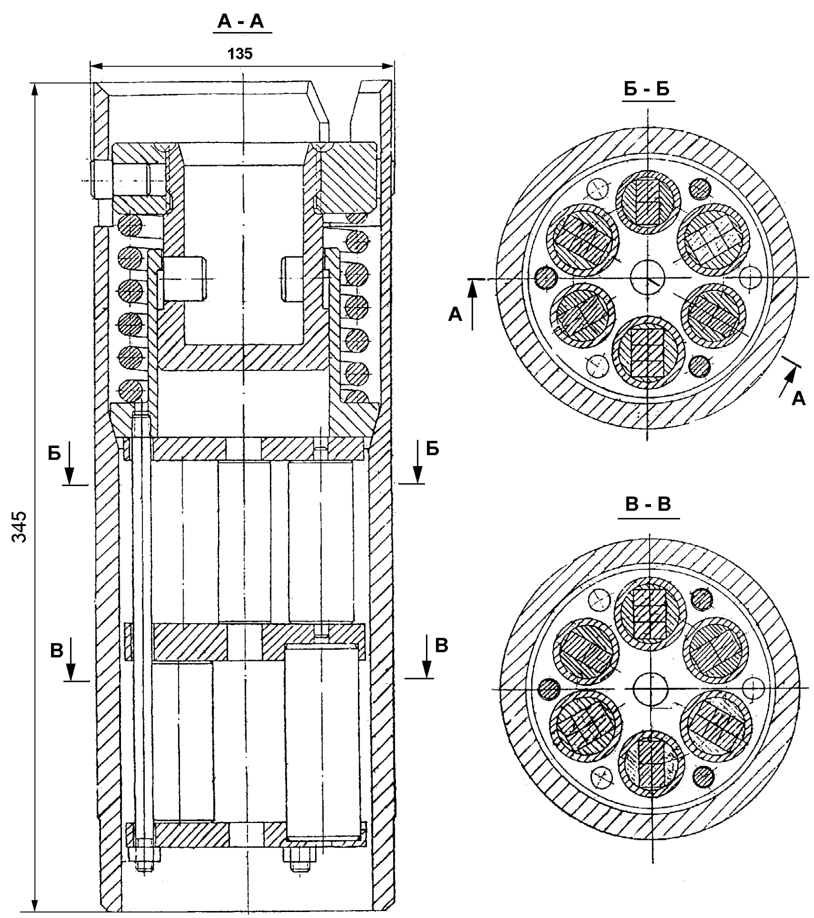
- VVER-1000 – STANDARD PROGRAMME

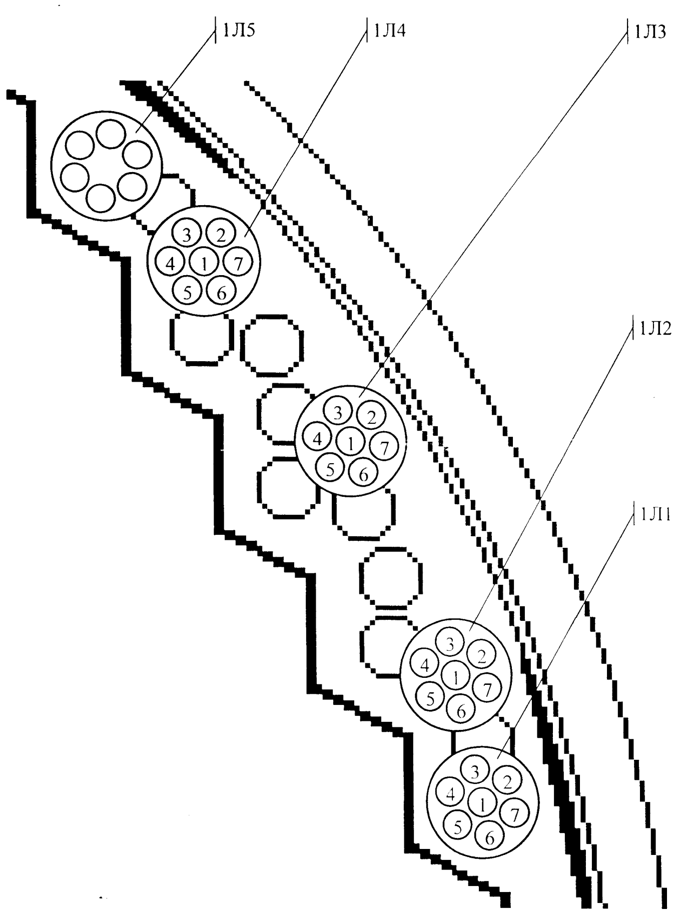




MONITORING CHANGES IN MECHANICAL PROPERTIES

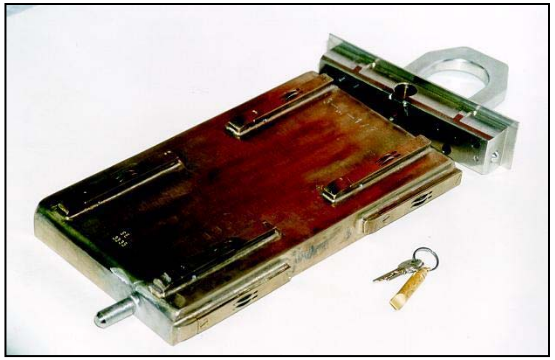
Размещение облучаемых образцов-свидетелей в контейнере

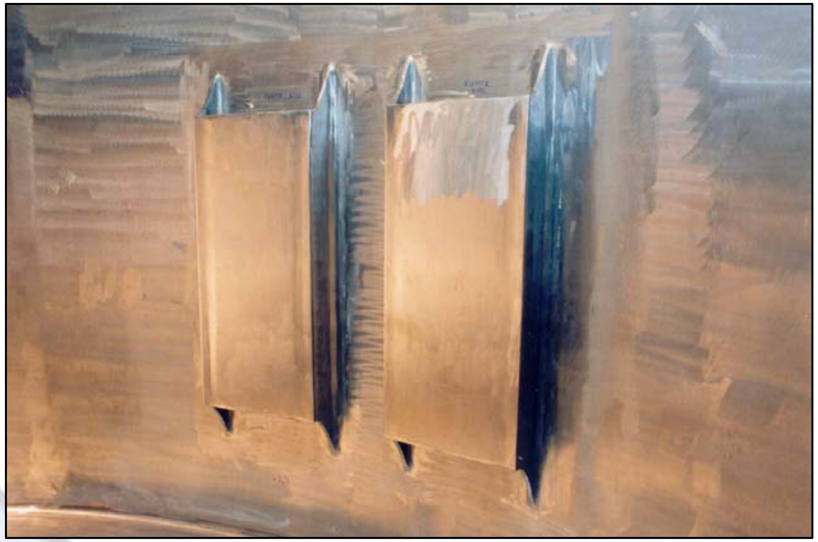




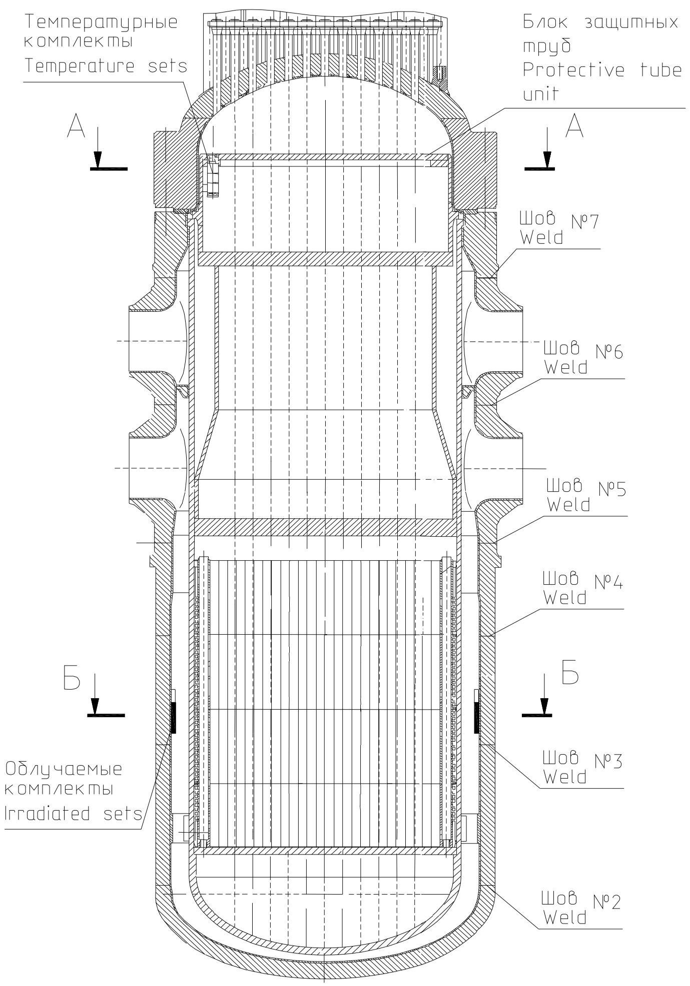
MONITORING CHANGES IN MECHANICAL PROPERTIES

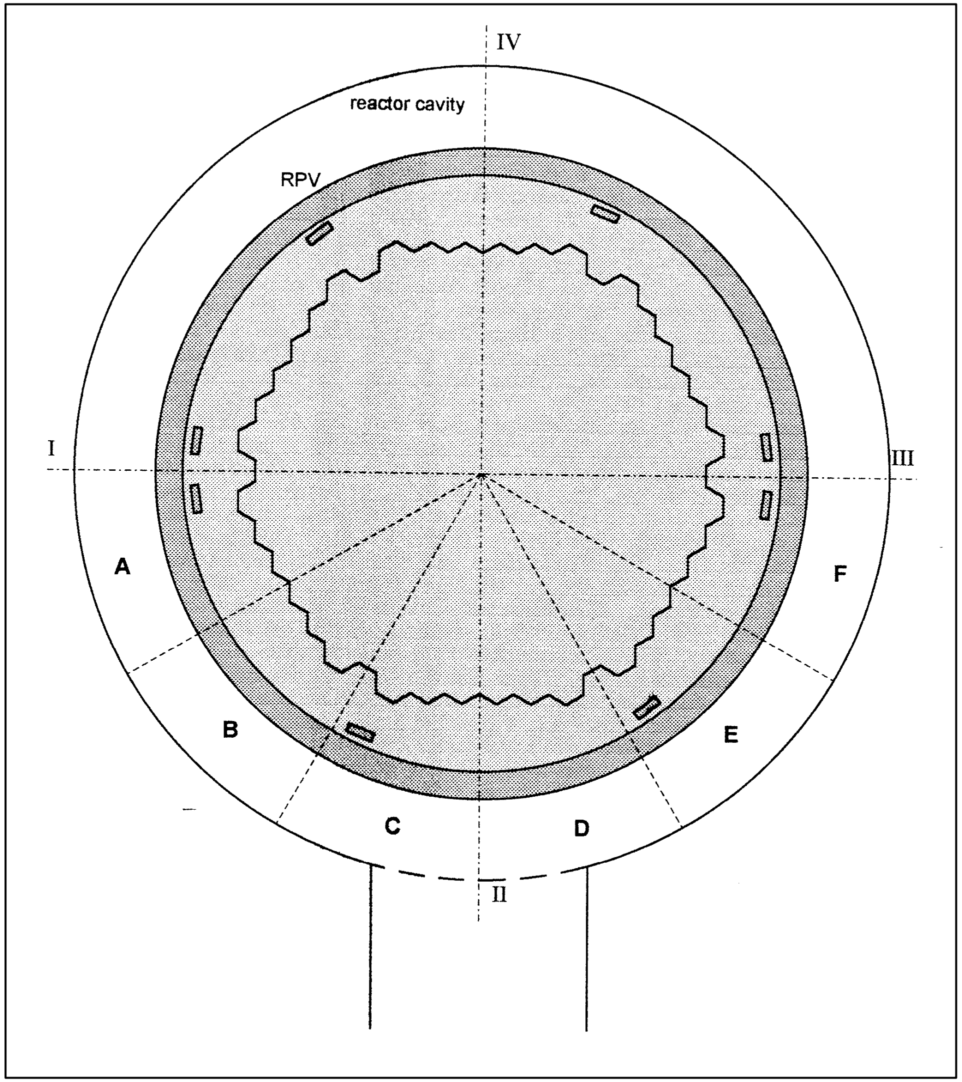
- VVER-1000 – MODIFIED SURVEILLANCE PROGRAMME SKODA





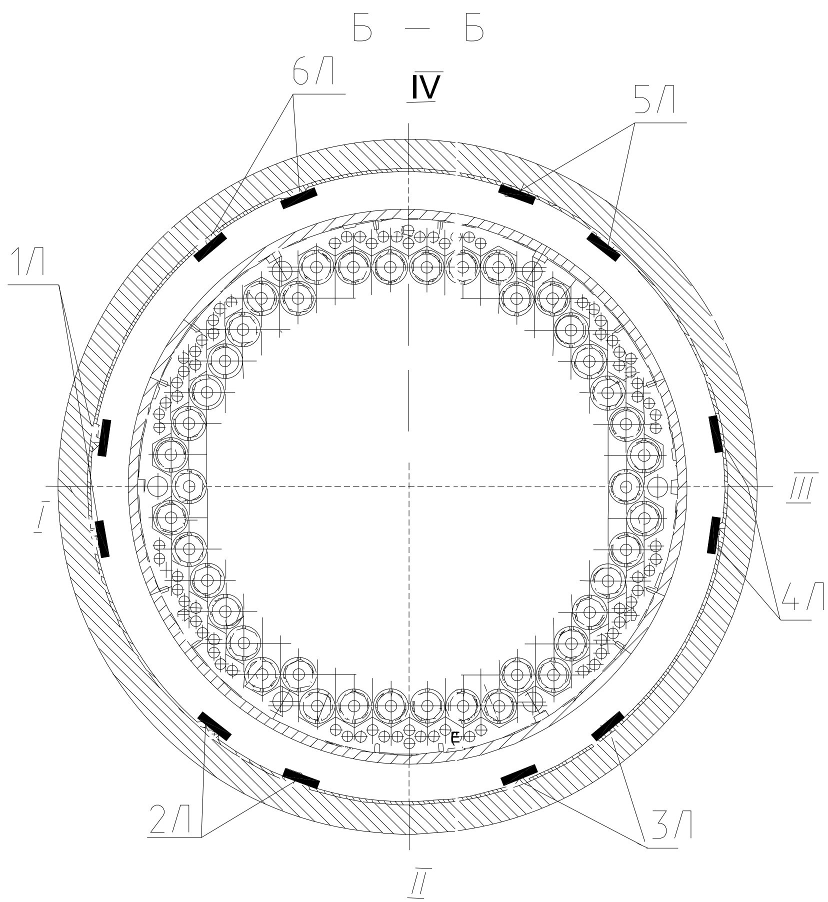
MONITORING CHANGES IN MECHANICAL PROPERTIES

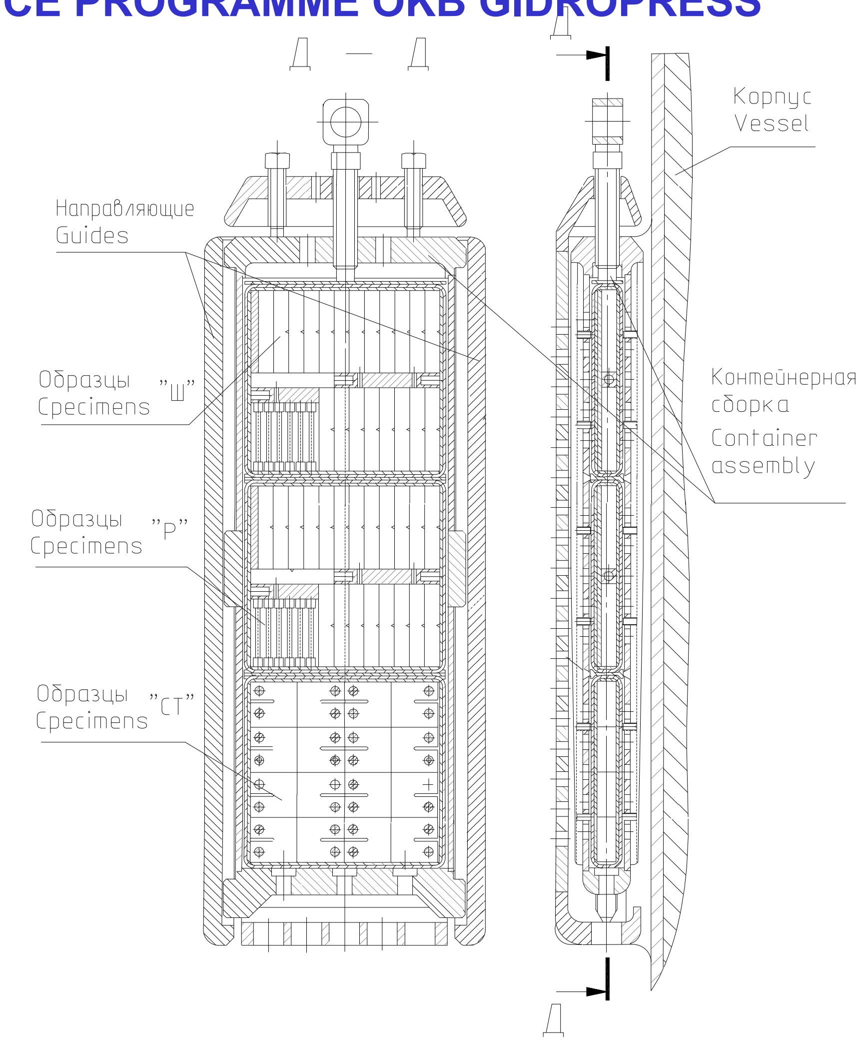




MONITORING CHANGES IN MECHANICAL PROPERTIES

VVER-1000 – MODIFIED SURVEILLANCE PROGRAMME OKB GIDROPRESS





CONTENT

RPV INTEGRITY

- RPV INTEGRITY MUST BE ASSURED FOR ALL OPERATION REGIMES, i.e. FOR
  - NORMAL OPERATION REGIMES (START-UP, STUT-DOWN, DECREASE IN POWER,…)
  - HYDROTEST (PRESSURE AND TIGHTNESS)
  - EMERGENCY REGIMES WITH OR WITHOUT LOST OF COOLANT (APPROX. 70 DIFFERENT REGIMES AND THEIR COMBINATIONS)
- ASSURANCE OF INTEGRITY IS PERFORMED BY CALCULATION OF RPV RESISTANCE AGAINST FAST/NOT-DUCTILE FAILURE
  - DETERMINISTIC WAY (VVER AND MOST OF EUJROPEAN CXOUNTRIES) FOR SO-CALLED POSTULATED/CALCULATED DEFECT (FORMERLY, FOR SURFACE SEMIELLIPTIC CRACK WITRH THE DEPOTH OF ¼ OF THICKNESS, NOW, IF NDE QUALIFICATION HAS BEEN PERFORMED, ONLY UNDERCLAD ELLIPTICAL CRACK WITH DEPTH OF APROX. 0.1 OF THICKNESS
  - PROBABILISTIC WAY (PWR DESIGNED STRICTLY ACCORDING TO ÁSME AND US NRC Reg.Guides) WITH A STATISTICAL DISTRIBIUTION OF DEFECT SIZES

RPV INTEGRITY

- CALCULATION OF RESISTANCE AGAINST FAST/NON-DUCTILE FAILURE ARE CARRIED OUT WITH THE USE OF FRACTURE MECHANICS (LINEAR, IN THE CASE OF RPV WITH CLADDING – NON-LINEAR)
  - BASES FOR THIS CALCULATION IS STATISTICALLY SUPPORTED DESIGN FRACTURE TOLUGHNESS CURVE K_{IC} OR K_{JC}
  - NEW APPROACH IS BASED ON SO-CALLED "MASTER CURVE DLE ASTM
- RESULT OF SUCH CALCULATIONS IS THE MAXIMUM ALLOWABLE TRANSITION TEMPERATURE OF THE RPV MATERIALS

RPV INTEGRITY

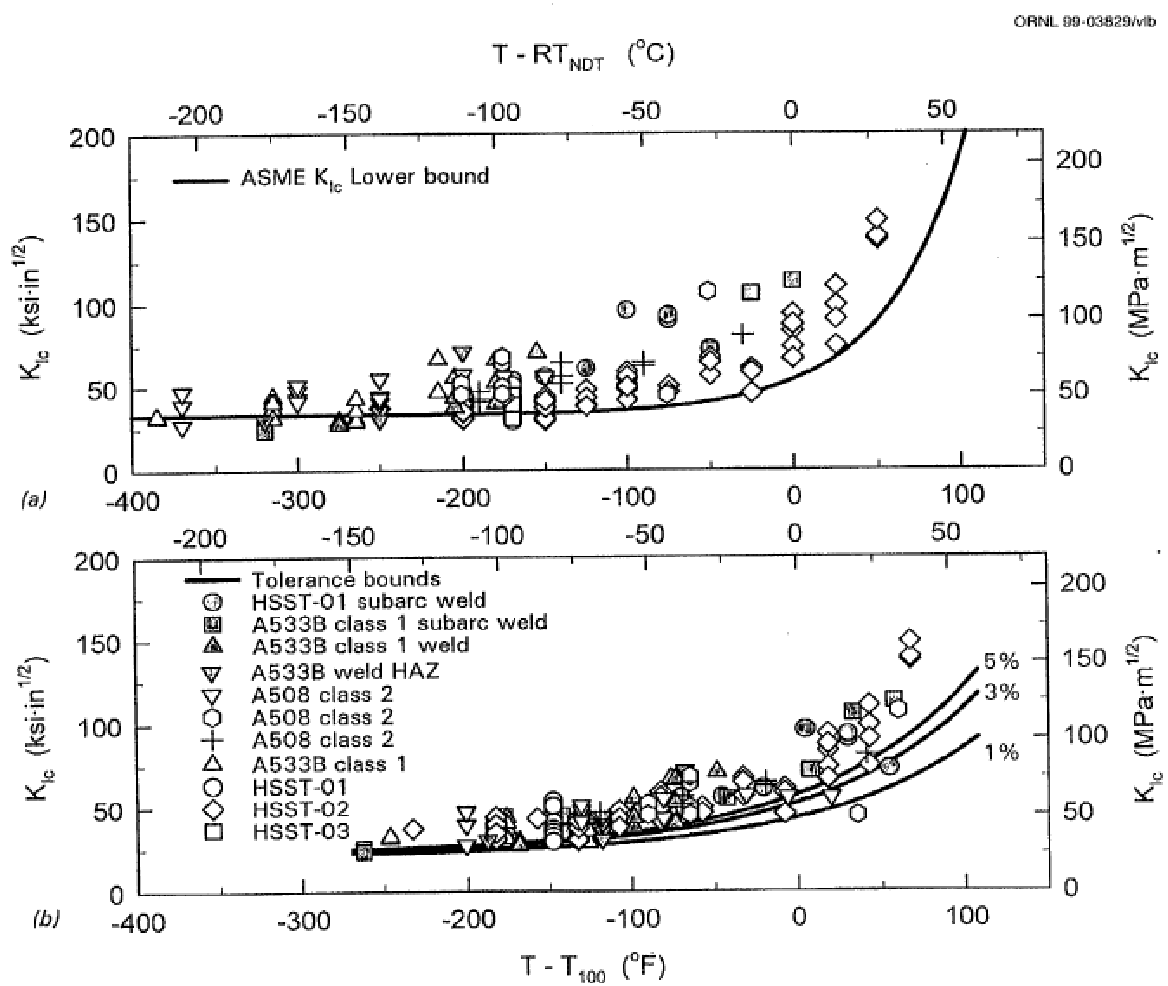
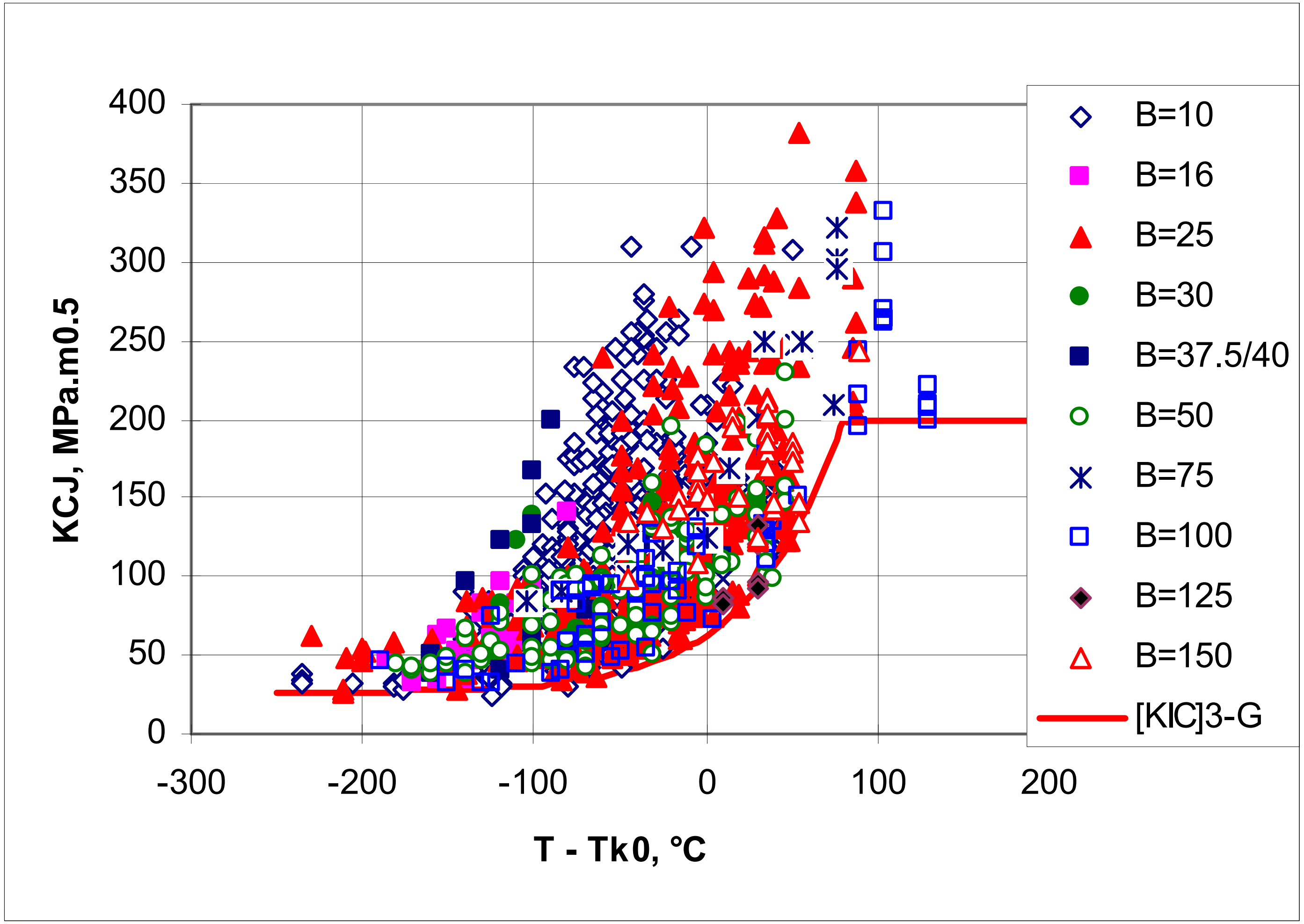


FIG. 7.4 *The ASME K_{IC} Database vs Temperature Normalised by (a) RT_{NDT} and (b) T_{100}* *[**Chyba! Záložka není definována.**].*

RPV INTEGRITY

Temperature dependence of static fracture toughness data of 15Kh2MFA type steel (base and weld metals) for WWER-440 reactor pressure vessel correlated with transition temperature Tk0 (B = specimen thickness, [KIC]3 = generic design fracture toughness curve)



RPV INTEGRITY

- RPV MATERIALS ARE AFFECTED BY SEVERAL AGEING MECHANISMS DURING OPERATION, MAINLY::
  - RADIATION DAMAGE
  - THERMAL AGEING
  - FATIGUE DAMAGE
  - CORROSION-MECHANICAL DAMAGE
  - WEAR etc
- FROM RPV LIFETIME POINT OF VIEW, THE MOST IMPORTANT IS RADIATION DAMAGE, as
  - FATIGUE DAMAGE IS IMPORTANT ONLY FOR AREAS WITH HNIGH STRESS CINCENTRATIONS (NOZZLES) OR FOR REPLACEABLE COMPONENTS (BOLTING JOINTS) WHERE RADIATION IS NEGLIGIBLE
  - THERMAL AGEING IS USUALLY NEGLECTED IN CALCULATIONS (WHILE FOR SOME MATERIALS, LIKE VVER-1000 CAN REACH VALUES UP TO + 40 °C), OR IT IS INCLUDED IN CALCULATIONS FOR UPPER RPV BLOCK/COVER WHERE WALL TEMPERATURE IS GIVEN BY OUTLET WATER

CONTENT

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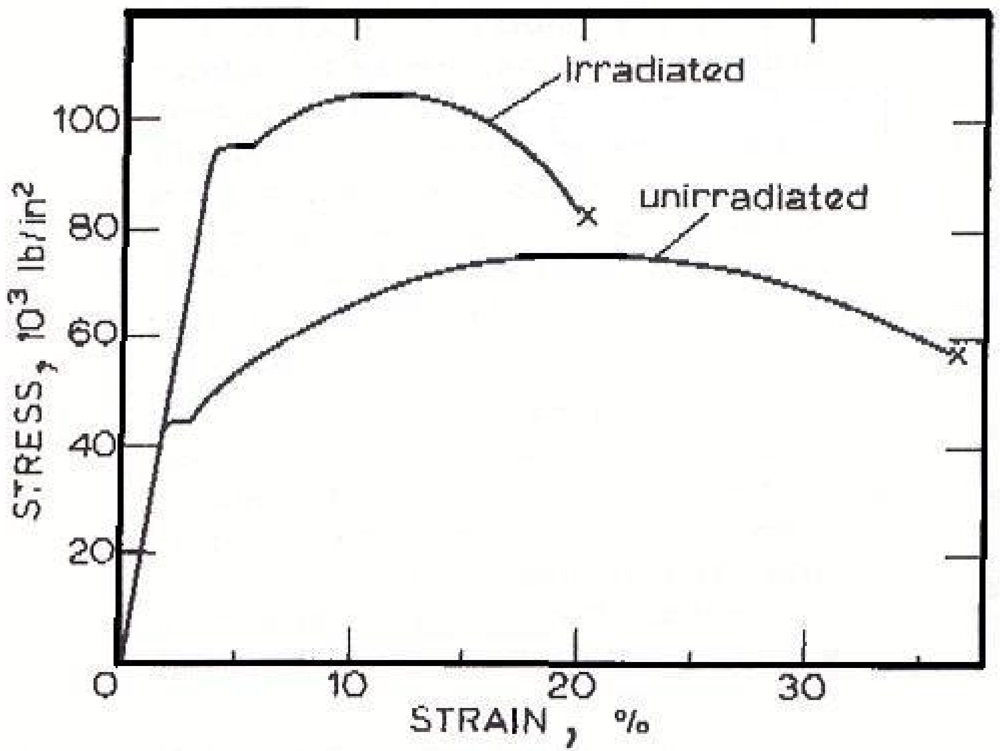
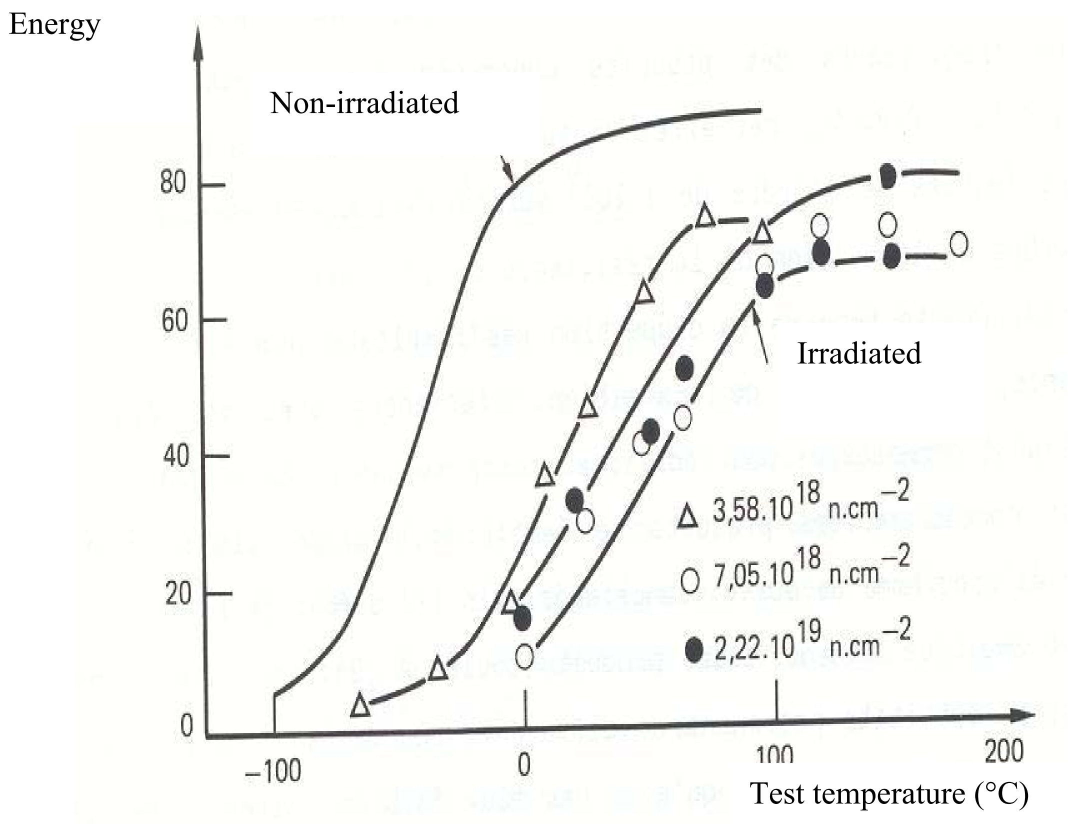
RADIATION DAMAGE

- RADIATION DAMAGE IS THE MOST IMPORTANT AGEING MECHANISM AND RESULTS IN:
  - INCREASE IN STRENGTH PROPERTIES
  - DECREASE IN DUCTILITY AND REDUCTION OF AREA
  - DECREASE IN TOUGHNESS (NOTCH IMPACT AND FRACTURE) THAT RESULTS IN SHIFT OF THEIR TEMPERATURE DEPENDENCE TO HIGHER TEMPERATURES
  - THESE DEPENDENCES ARE CHARACTERIZED BY SO-CALLED TRANSITION TEMPERATURES:
    - RT_{NDT} FOR RPV DESIGNED IN ACCORDANCE WITH ASME
      - RT_{NDT} IS DETERMINED FOR DROP WEIGHT TESTS (DWT – NDT) AND IMPACT NOTCH TOUGHNESS TESTS (CHARPY-V)
    - T_{k0} FOR RPV DESIGNED IN ACCORDANCE WITH PNAEG
      - T_{k0} IS DETERMINED ONLY FROM IMPACT NOTCH TOUGHNESS TESTS (CHARPY-V), CRITERIUM IS GIVEN BY REAL YIELD STRENGTH OF MATERIAL

RADIATION DAMAGE



RADIATION DAMAGE



RADIATION DAMAGE

A533B Cl.1 (JRQ)

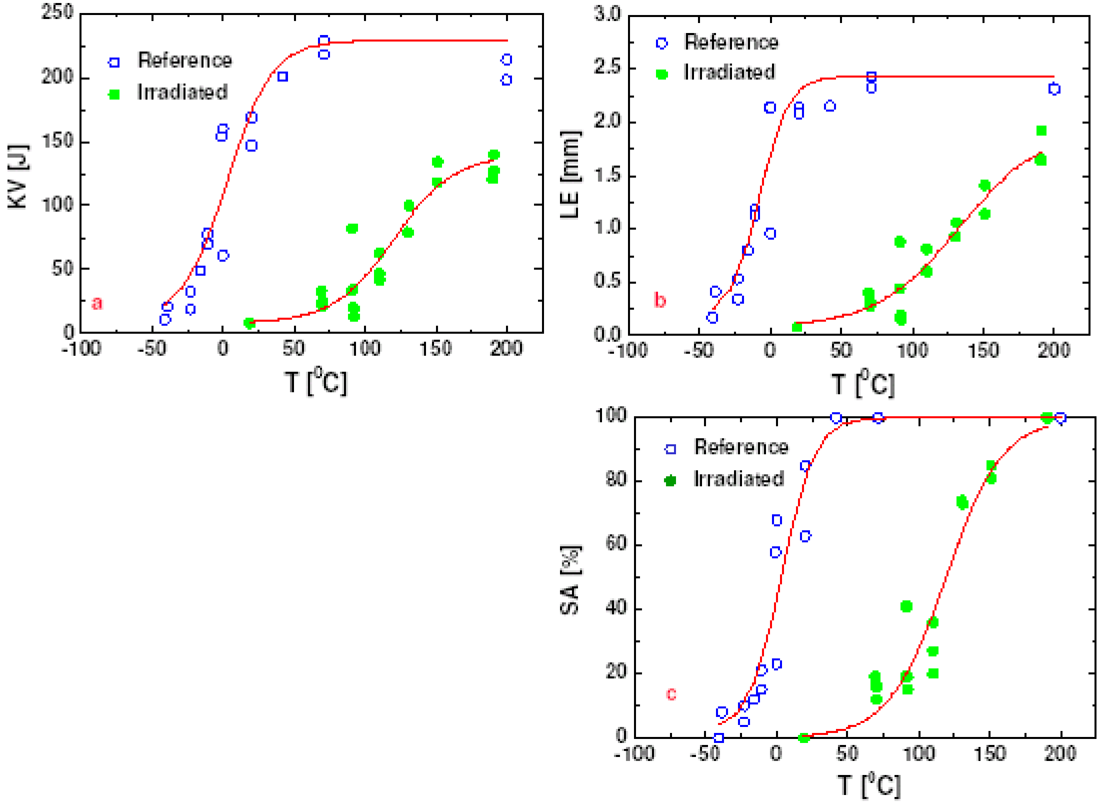


Fig. 3. Typical transition curves measured by CVN energy parameter (a), lateral expansion (b) and fracture appearance (SA), showing effect of embrittlement on curves.

RADIATION DAMAGE

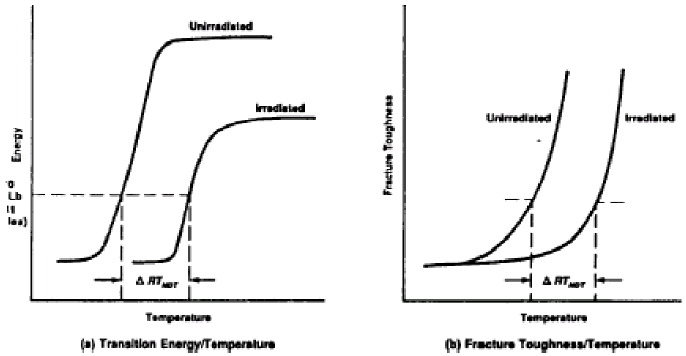


Figure 2.6a and Figure 2.6b.- *Effect of neutron irradiation on transition temperature and fracture toughness properties.*

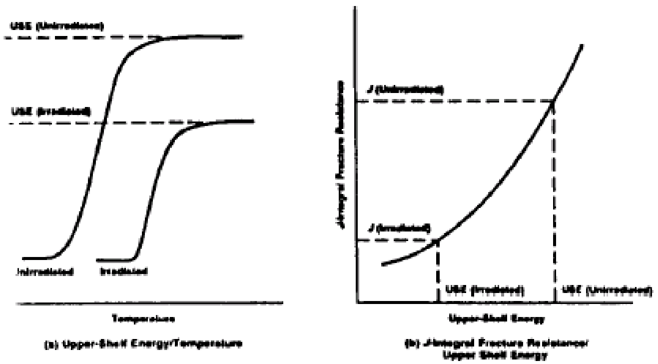


Figure 2.7a and Figure 2.7b.- *Effect of neutron irradiation on the upper shelf energy and J-integral fracture resistance.*

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RADIATION DAMAGE

❑ RADIATION DAMAGE VALUE DEPENDS ON:

- NEUTRON FLUENCE (DEPENDS ON REACTOR OUTPUT AND WATER MODERATOR THICKNESS)
  - THRESHOLD VALUES
    - 0,5 MeV FOR VVER REACTORS
    - 1 MeV FOR PWR REACTORS
- IRRADIATION RATE, i.e. NEUTRON FLUX (FLUX RATE EFFECT)
- IRRADIATION TEMPERATURE
- STEEL TYPE
- CONTENT OF IMPURITIES – P, Cu, …., As, Sb, Sn,…
- CONTENT OF ALLOYING ELEMENTS – Ni, Mn, …

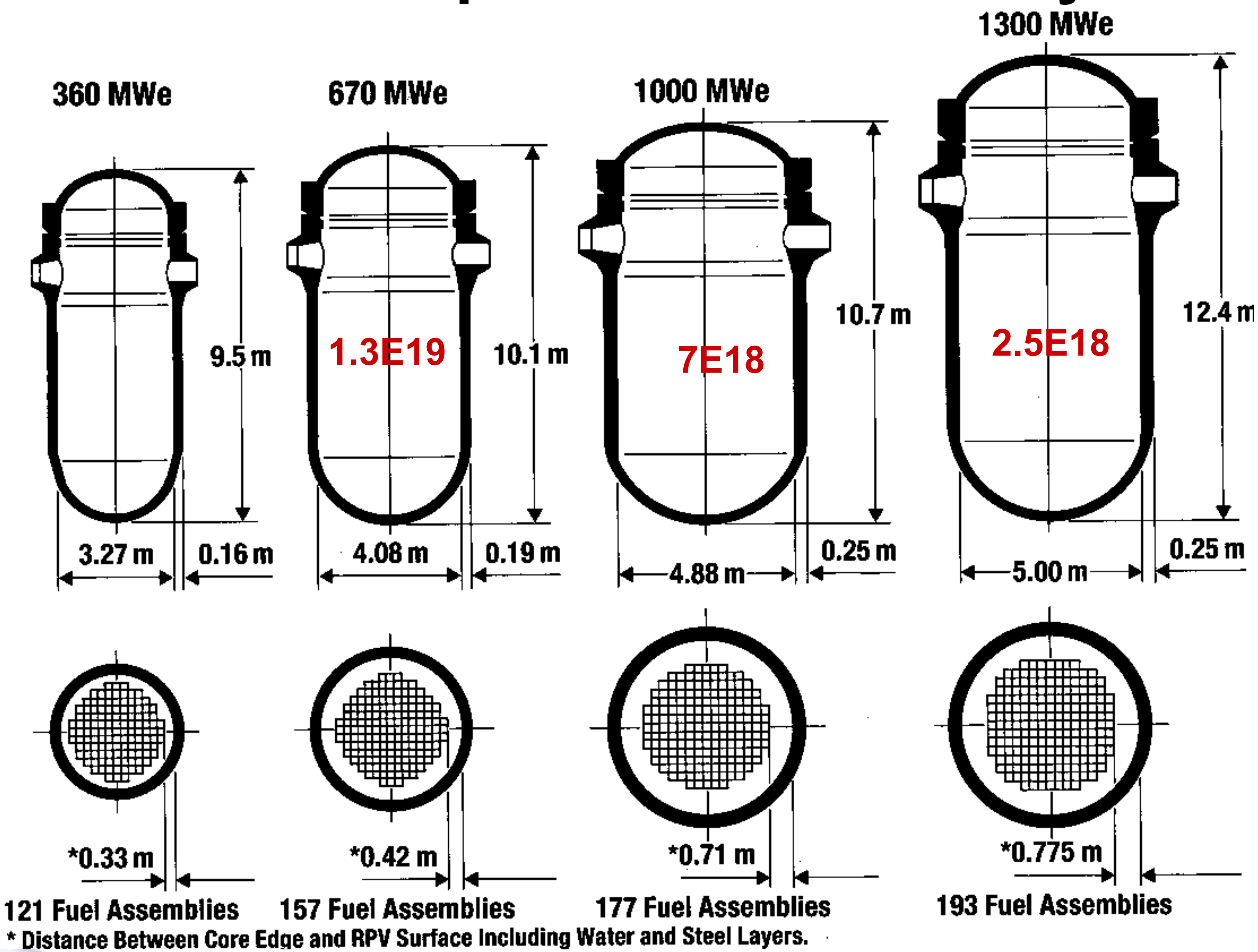
RADIATION DAMAGE

. 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 x 10^{15}	1.1 x 10^{24}
WWER-440 maximum	1.5 x 10^{15}	1.6 x 10^{24}
WWER-1000	3-4 x 10^{14}	3.7 x 10^{23}
PWR (W)	4 x 10^{14}	4 x 10^{23}
PWR (B&W)	1.2 x 10^{14}	1.2 x 10^{23}
BWR	4 x 10^{13}	4 x 10^{22}

RADIATION DAMAGE

PWR under Operation in Germany



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CONTENT

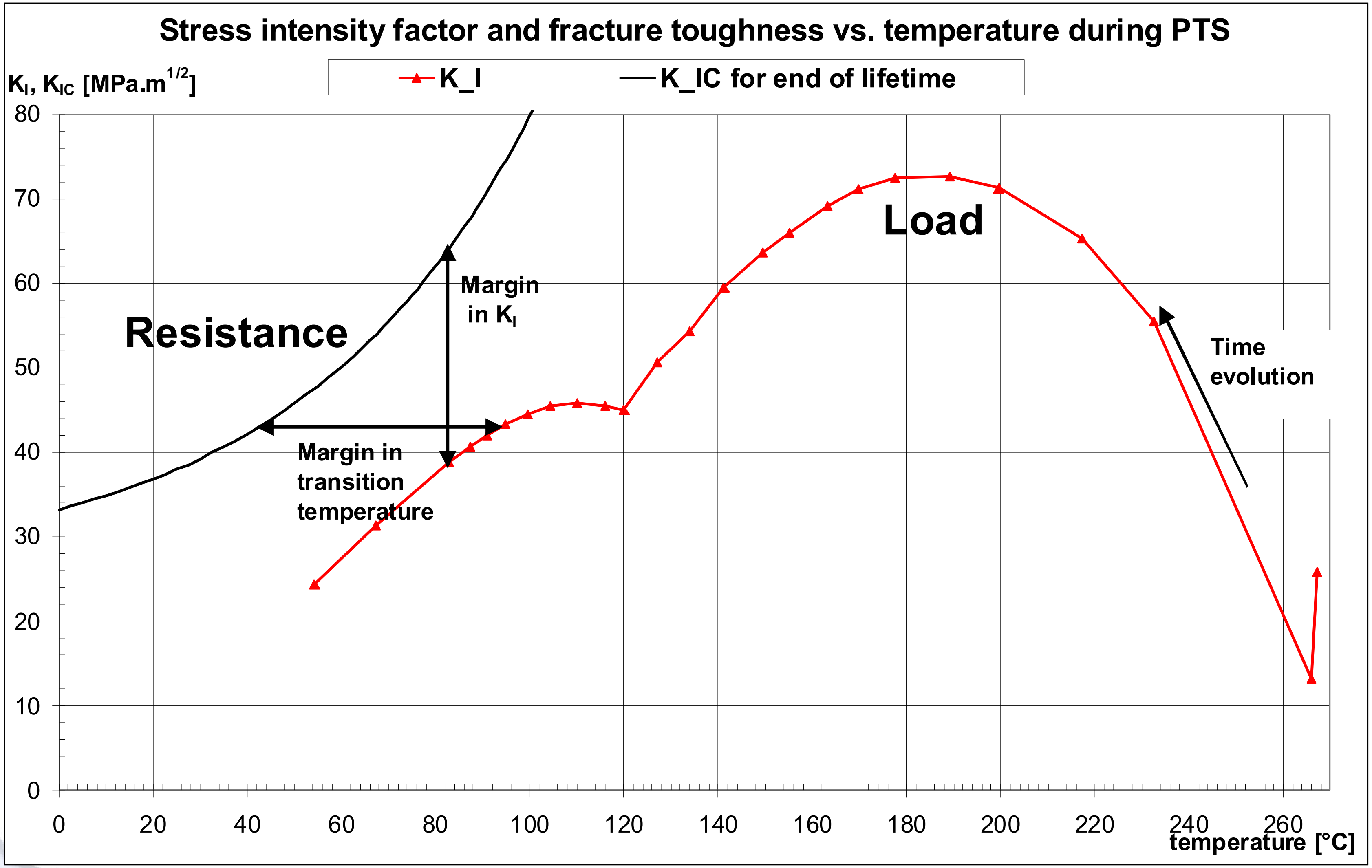
RPV INTEGRITY - PTS

- DETERMINATION OF MAXIMUM ALLOWABLE TRANSITION TEMPERATURE IS PERFORMED BY COMPARISON OF ALL EMERGENCY COOLING REGIMES FOR POSTULATED/CALCULATED DEFECT WITH DESIGN CURVE OF FRACTURE TOUGHNESS
- MAIN GOAL OF AN EMERGENCY CORE COOLING IS TO PREVENT ACTIVE CORE MELTING (WITH THE ASSURANCE OF RPV INTEGRITY)
  - EMERGENCY CORE COOLING IS PERFORMED BY APPROPRIATE SYSTEMS (SAOZ FOR VVER, ECCS FOR PWR), THAT CONTAIN HIGH-PRESSURE AND LOW-PRESSURE WATER VESSELS AND TANKS
- THE MOST IMPORTANT EMERGENCY COOLING REGIMES ARE REGIMES OF PTS TYPE (PRESSURIZED THERMAL SHOCK), e.g.:
  - FRACTURE OF PIPING IN PRIMARY SIDE (LOCA – LOST OF COOLANT ACCIDENT)
  - STEAM LINE FRACTURE
  - STEM GENERATOR TUBE FRACTURE
  - CLOSURE OF A SAFETY VALVE IN PRESSURIZER etc.

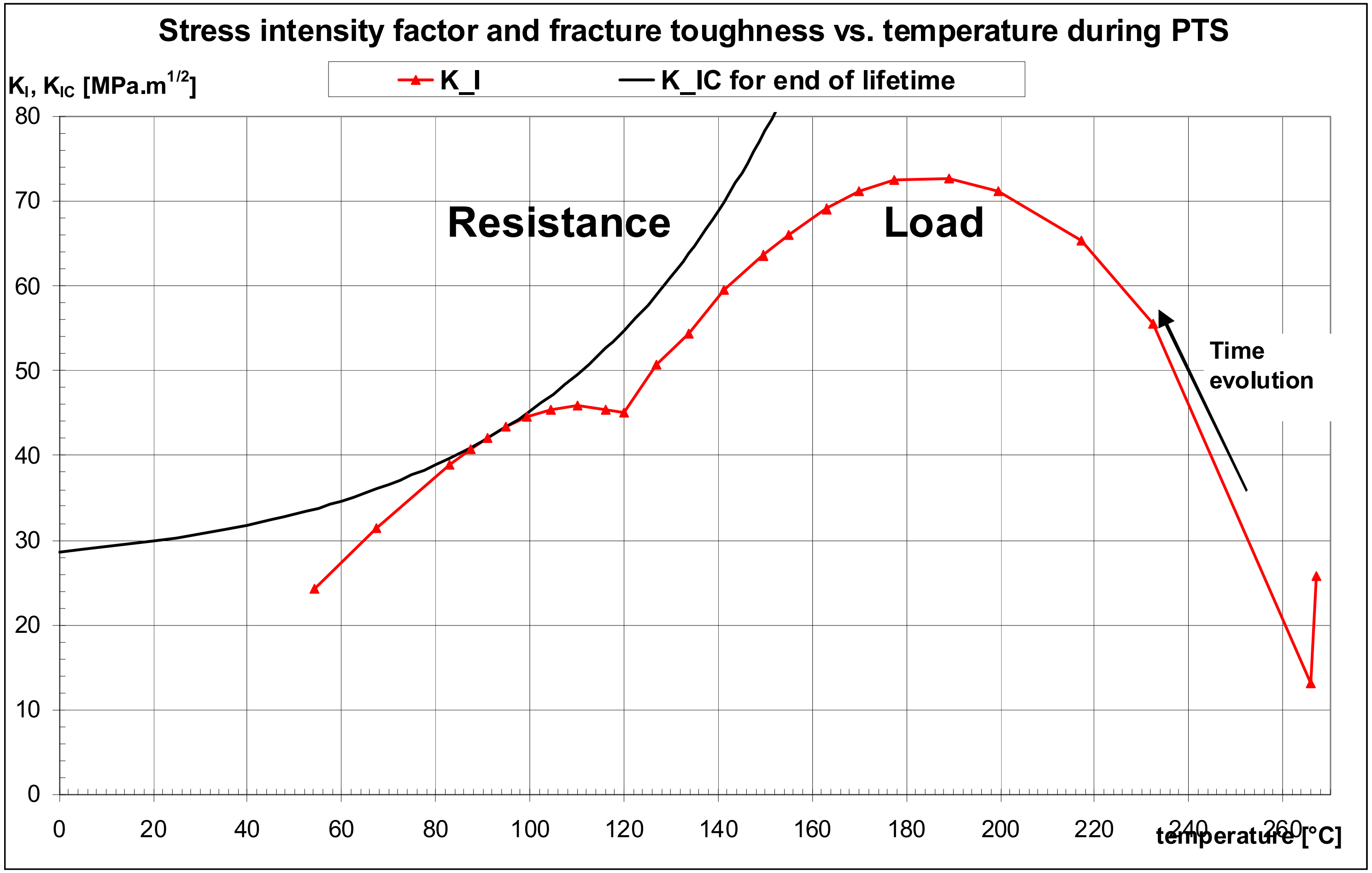
RPV INTEGRITY - PTS

- TIME DEPENDENCIES OF PRESSURE AND TEMPERATURE OF A COOLANT IN INLET TO RPV DEPENDS ON A REGIME TYPE
- IN SEVERAL CASES,CONSERVATIVE ASSUMTION IS MADFE THAT MAIN CIRCULATING PUMPS STOP DUE TO THE LOSS OF POWER – IN SUCH CASE, STAGNATION OF COOLANT FLOW IS OBSERVED AND „COLD PLUMES“ ARE CREATED IN RPVs“
- THIS APPROACH IS USED ONLY FOR DETERMINISTIC DETERMINATION OF MAXIMUM ALLOWABLE TRANSITION TEMPERATURE, IN PROBABILISTIC APPROACH (i.e. PWR RPVs IN ACCORDANCE WITH ASME) ONLY AXISYMMETRIC COOLING IS TAKEN INTO ACCOUNT, i.e. WITHOUT „PLUMES“
- INVOLVEMENT OF „COLD PLUMES“ INTO ASSESSMENT IF MORE CONSERVATIVE AND GIVES LOWER ALLOWABLE TRANSJITIONH TEMPERATURES

RPV INTEGRITY - PTS



RPV INTEGRITY - PTS



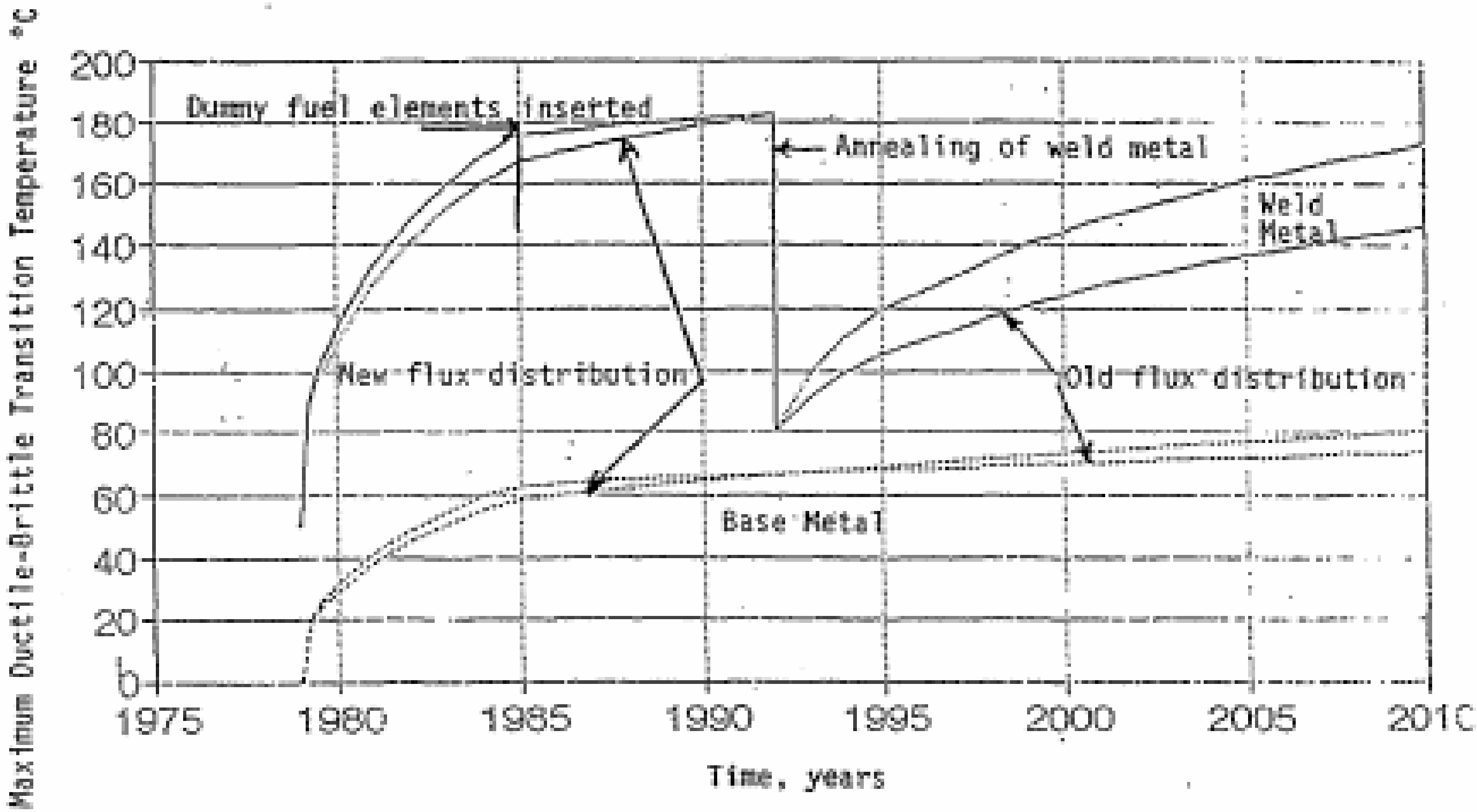
CONTENT

LIFETIME

- RPV LIFETIME (FROM POINT OF VIEW RESISTANCE AGAINST NON-DUCTILE FAILURE) IS EQUAL TO TIME INTERVAL WHEN (WITH SOME SAFETY FACTOR) RPV MATERIALS TRASNSITION TEMPERATURE WILL REACH ITS MAXIMUM ALLOWABLE VALUE, T_k^a

- THIS MAXIMUM ALLOWABLE MATERIAL TRANSITION TEMPERATURE T_k^a DOES NOT DEPEND ON MATERIAL EMBRITTLEMENT CONDITION BUT IT IS GIVEN ONLY BY REACTOR DESIGN, CORE EMERGENCY SYSTÉM COOLING AND BY USED MATERIALS (STRENGTH PROPERTIES, DESIGN FRACTURE TOUGHNESS CURVE), i.e. IT IS EQUAL FOR DIFFERENT RPVs OF THE SAME DESIGN

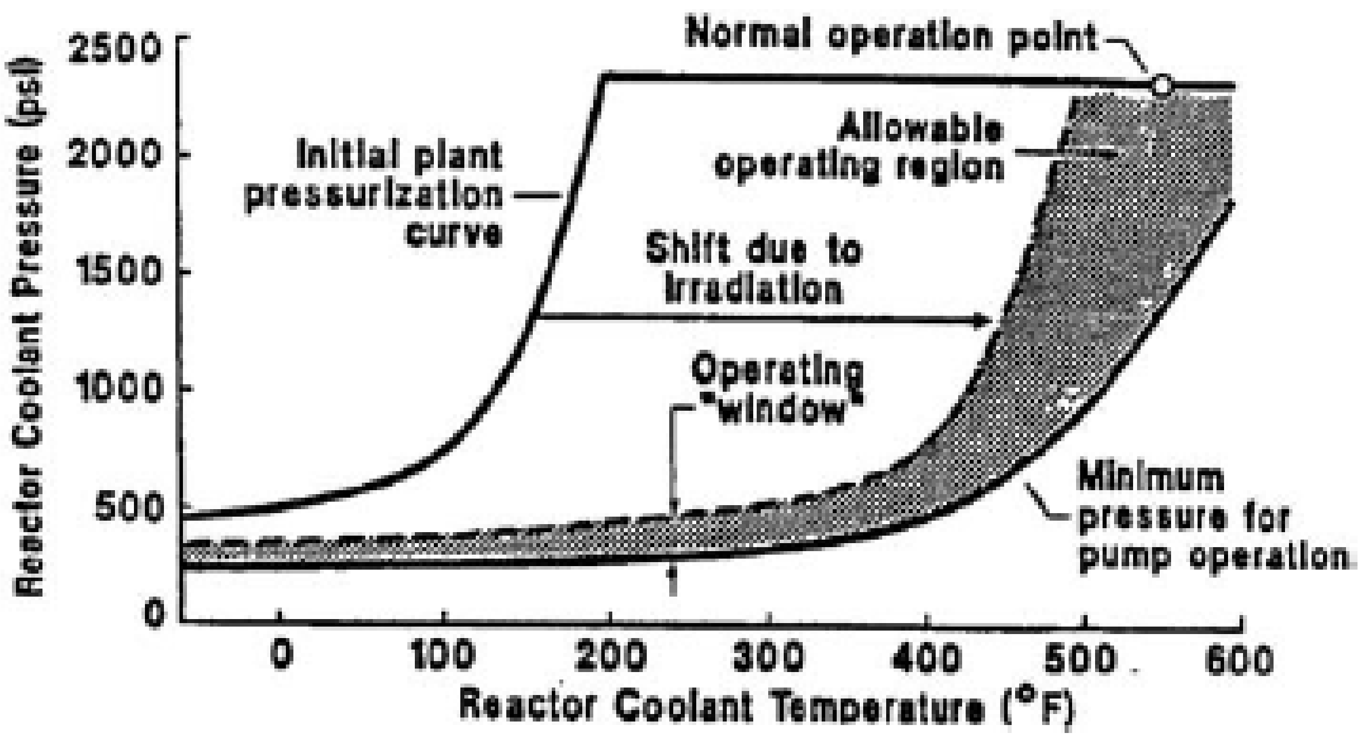
LIFETIME



Maximum Ductile-Brittle Transition Temperature °C
200
180
160
140
120
100
80
60
40
20
0
1975
1980
1985
1990
1995
2000
2005
2010
Time, years
Dummy fuel elements inserted
Annealing of weld metal
Weld Metal
New flux distribution
Old flux distribution
Base Metal

LIFETIME

- FURTHER RESULT OF CALCULATIONS IS DETERMINATION OF ALLOWABLE PRESSURE-TEMPERATURE CURVES FOR NORMAL OPERATION CONDITIONS AND FOR HYDROTESTS



CONCLUSION

- THIS PRESENTATION WOULD LIKE TO SHOW SOME IMPORTANT ASPECTS OF DESIGN, MANUFACTURING AND OPERATION OF LWR RPVs, THAT ARE SIMILAR FOR PWR AND VVER TYPE REACTORS
- INDIVIDUAL DESIGNS ARE DIFFERENT IN THEIR REALISATION BUT PRINCIPAL ASPECTS ARE THE SAME
- INDIVIDUAL RPVs CAN BE DIFFERENT (AND THEY ARE) EVEN WITHIN ONE DESIGN DEPENDING ON THEIR MANUFACTUREING/USED MATERIALS AND TECHNOLOGIES AND OPERATION

- ATTEMPS FOR NPP LIFE EXTENSION (AND ALSO THEIR RPVs) FROM DESIGN 30 (40) YEARS TO 60 AND MORE YEARS (EVEN 80 – 100?) BRING FURTHER PROBLEMS IN MATERIAL AND ALSO ORGANISATION SIDES

IAEA-TECDOC-1120

Assessment and management of ageing of major nuclear power plant components important to safety:

PWR pressure vessels

INTERNATIONAL ATOMIC ENERGY AGENCY IAEA

October 1999

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