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IGORR-II

2nd Meeting of the International Group on Research Reactors,

May 18-19, 1992 - Saclay, France

IRRADIATION EFFECTS ON ALUMINIUM AND BERYLLIUM

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The High Flux Reactor (HFR) in Petten (The Netherlands) is a 45 MW light water cooled and moderated research reactor. The vessel was replaced in 1984 after more than 20 years of operation because doubts had arisen over the condition of the aluminium alloy construction material.

Data on the mechanical properties of the aluminium alloy Al 5154 with and without neutron irradiation are necessary for the safety analysis of the new HFR vessel which is constructed from the same material as the old vessel.

Fatigue, fracture mechanics (crack growth and fracture toughness) and tensile properties have been obtained from several experimental testing programmes with materials of the new and the old HFR vessel.

- Low-cycle fatigue testing has been carried out on non-irradiated specimens from stock material of the new HFR vessel.

  The number of cycles to failure ranges from 90 to more than 50,000 for applied strain from 3.0% to 0.4%.

- Fatigue crack growth rate testing has been conducted :
  - with unirradiated specimens from stock material of the new vessel
  - with irradiated specimens from the remnants of the old core box.

Irradiation has a minor effect on the sub-critical fatigue crack growth rate. The ultimate increase of the mean crack growth rate amounts to a factor of 2. However crack extension is strongly reduced due to the smaller crack length for crack growth instability (reduction of K_{IC}).

- Irradiated material from the core box walls of the old vessel has been used for fracture toughness testing.

  The conditional fracture toughness values K_{IQ} ranges from 30.3 down to 16.5 MPa$\sqrt{m}$.

  The lowermost meaningful "K_{IC}" is 17.7 MPa$\sqrt{m}$ corresponding to the thermal fluence of 7.5 10^{26} n/m^2 for the End of Life (EOL) of the old vessel.

- Testing carried out on irradiated material from the remnants of the old HFR core box shows an ultimate neutron irradiation hardening of 35 points increase of HSR_{15N} and an ultimate tensile yield stress of 589 MPa corresponding to the ductility of 1.6%.

Besides, due to the effects of embrittlement and swelling induced by irradiation, the HFR beryllium reflector elements had to be replaced after more than 25 years of operation.

Operational and practical experiences with these reflector elements are commented, as well as main engineering features of the new reflector elements : upper-end fittings of both filler element and insert in stainless steel, no radially drilled holes and no roll pins.

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INTRODUCTION

° THE HIGH FLUX REACTOR (HFR) IN PETTEN (THE NETHERLANDS) IS A 45 MW LIGHT WATER COOLED AND MODERATED RESEARCH REACTOR

° IN OPERATION DURING MORE THAN 30 YEARS

° INSTALLATION KEPT UP-TO-DATE BY REPLACING AGEING COMPONENTS

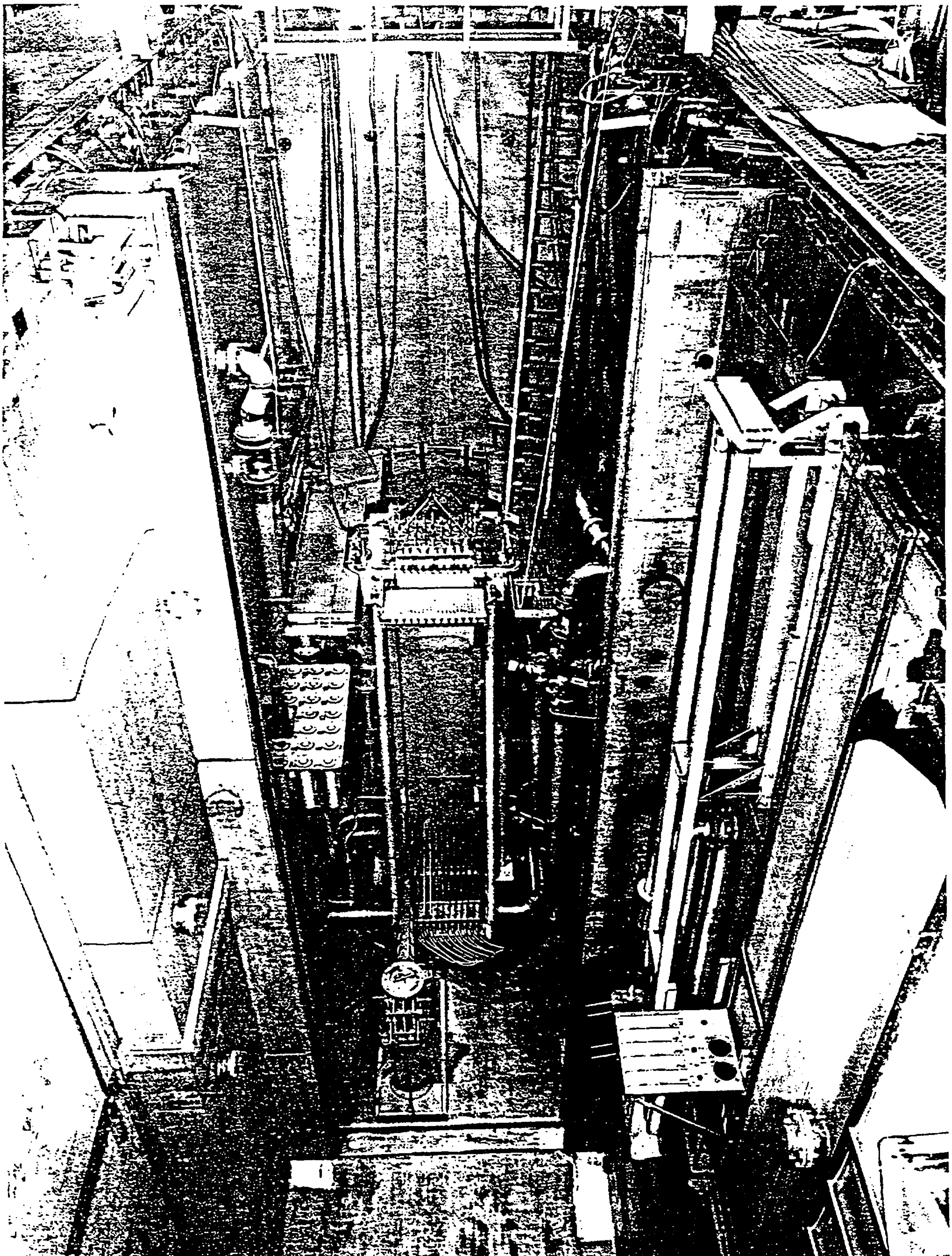
° REPLACEMENT IN 1984 OF THE ALUMINIUM REACTOR VESSEL AFTER MORE THAN 20 YEARS OF SERVICE

° DESIGN OF THE NEW ALUMINIUM 5154 ALLOY REACTOR VESSEL IS BASED ON THE DEMONSTRATION OF EVIDENCE THAT THE VESSEL CONTAINS NO CRITICAL DEFECTS

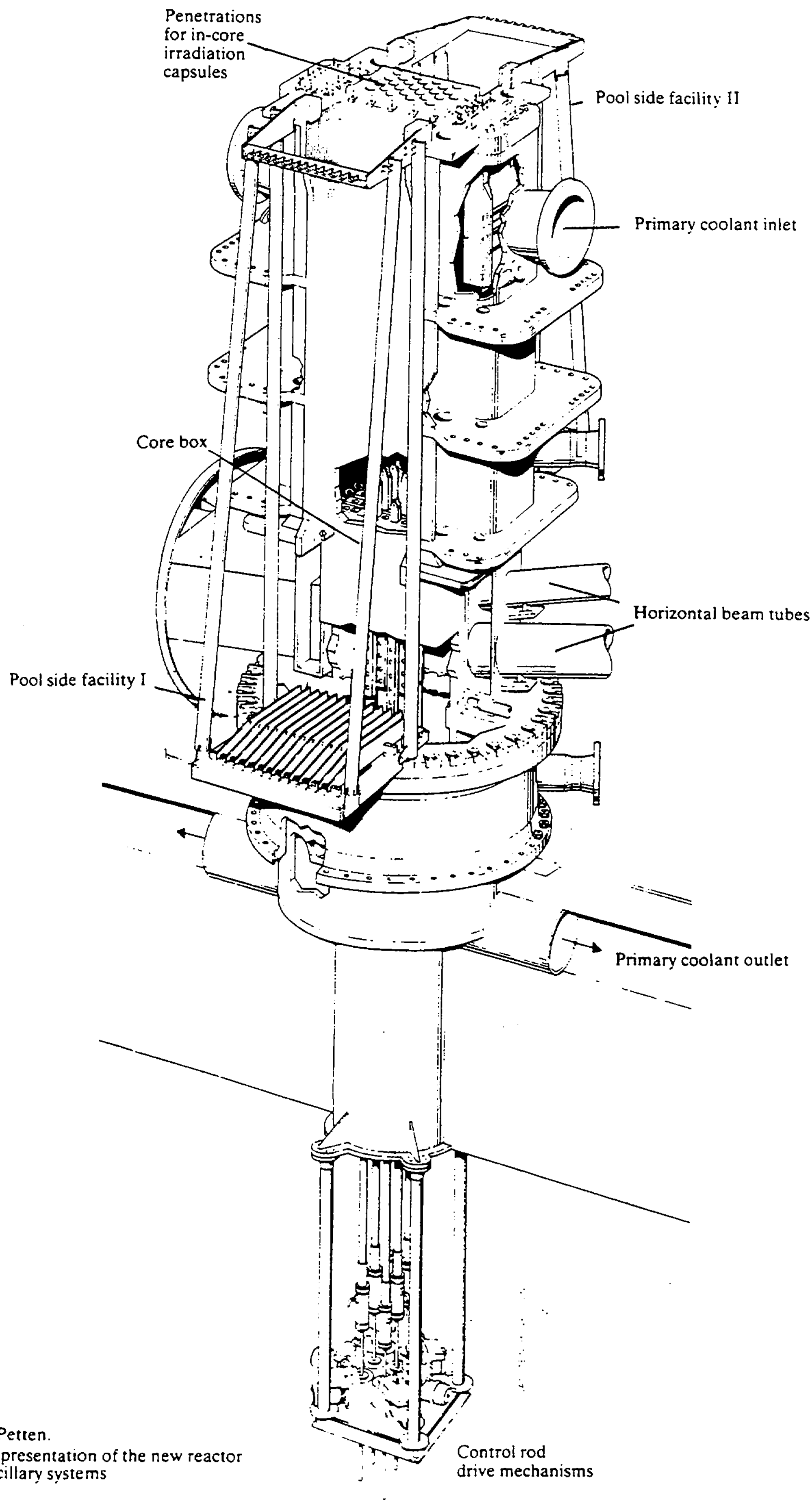
° KNOWLEDGE OF MATERIAL PROPERTIES AND LIKELY DEFECT PRESENCE AND SIZE IS REQUESTED FOR THE ASSESSMENT OF THE HFR VESSEL INTEGRITY

° REPLACEMENT OF THE BERYLLIUM REFLECTOR ELEMENTS AFTER MORE THAN 25 YEARS OF OPERATION, DUE TO EMBRITTLEMENT AND SWELLING INDUCED BY IRRADIATION

VIEW INTO THE REACTOR POOL OF HFR PETTEN



HFR REACTOR VESSEL



HFR Petten.
Perspective representation of the new reactor vessel with ancillary systems

CHEMICAL COMPOSITION OF THE MATERIALS OF THE OLD AND THE NEW HFR VESSELS

	Mg	Si	Cu	Mn	Fe	Zn	Cr	Ti	Al
Old core box	3.78	0.14	0.04	0.33	0.28	0.01			bal.
New vessel	3.21	<0.25	<0.05	<0.10	<0.40	<0.20	0.24	0.11	bal.

CALCULATED NEUTRON FLUENCE VALUES FOR THE MID-CENTRE POSITIONS OF THE OLD CORE BOX WALLS

Fluence, 10^{26} n/m^2	West wall	East wall
thermal ($E < 0.414$ eV)	7.5	3.2
fast ($E > 0.1$ MeV)	6.9	0.8
ratio thermal/fast	1.1	4.0

OLD CORE BOX TIME EXPOSURE TO NEUTRON IRRADIATION = 4,24 10^8 SEC.
FROM NOVEMBER 1961 UNTIL NOVEMBER 1983

MATERIAL PROPERTY TESTING PROGRAMMES

- DATA ON THE MECHANICAL PROPERTIES OF ALUMINIUM ALLOY AL 5154 WITH AND WITHOUT NEUTRON IRRADIATION ARE NECESSARY FOR THE SAFETY ANALYSIS OF THE HFR VESSEL AT BOL AND EOL

- FATIGUE, FRACTURE MECHANICS (CRACK GROWTH AND FRACTURE TOUGHNESS) AND TENSILE PROPERTIES OBTAINED FROM SEVERAL EXPERIMENTAL TESTING PROGRAMMES WITH MATERIALS OF THE NEW AND THE OLD HFR VESSEL

- TESTING CARRIED OUT BY ECN

FATIGUE EXPERIMENTS WITH ALUMINIUM ALLOY 5154 SPECIMENS

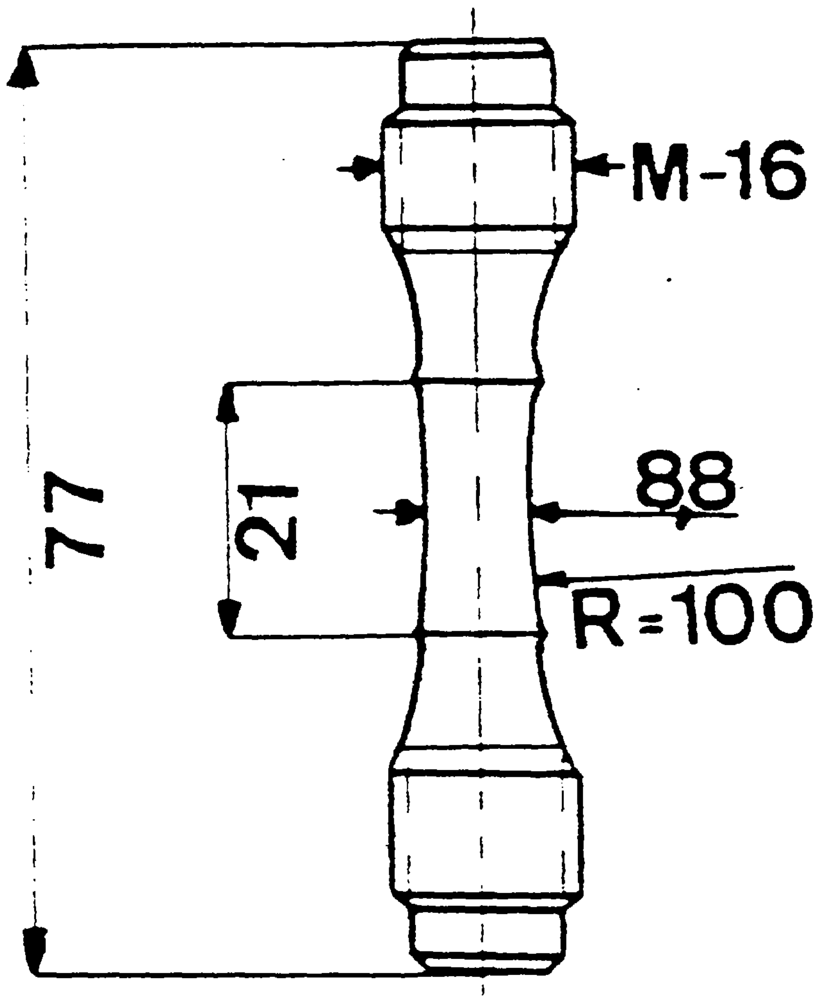
° INFORMATION ON THE FATIGUE PROPERTIES OF THE CONSTRUCTION MATERIAL OF THE NEW VESSEL (ALUMINIUM ALLOY TYPE AL 5154) REQUESTED BY THE NETHERLANDS LICENSING AUTHORITIES

° TESTING PROGRAMME OBJECTIVES:

- TO PERFORM SPOT-CHECKS ON THE FATIGUE DESIGN CURVE
- TO MEASURE FATIGUE CRACK GROWTH RATES IN IRRADIATED AND NON-IRRADIATED SPECIMENS

° TESTING CARRIED OUT BY ECN:

- LOW CYCLE FATIGUE TESTS AND FATIGUE CRACK GROWTH MEASUREMENTS WITH UN-IRRADIATED SPECIMENS FROM STOCK MATERIAL OF THE NEW HFR VESSEL
- FATIGUE CRACK GROWTH TESTS WITH IRRADIATED SPECIMENS FROM MATERIAL OF THE OLD HFR CORE BOX



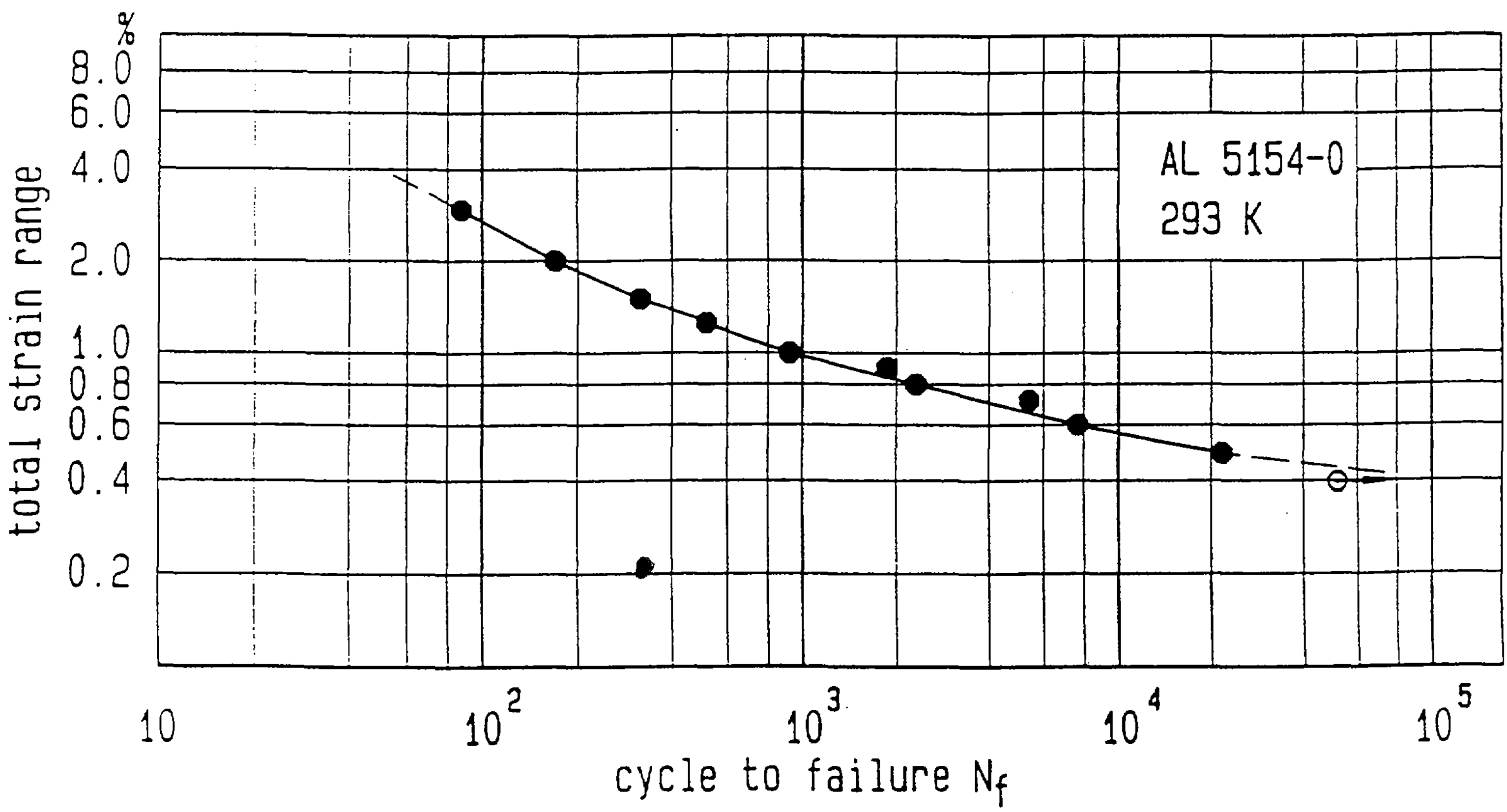
Dimensions of the Low Cycle Fatigue Specimen

LOW CYCLE FATIGUE TEST RESULTS

- ° THE NUMBER OF CYCLE OF FAILURE RANGES FROM 88 TO 50.000 FOR APPLIED STRAIN FROM 3,0% TO 0,4%. THE CORRESPONDING ULTIMATE CYCLIC STRESS VARIES FROM 580 MPa TO 305 MPa.

- ° THE STRESS AMPLITUDE INCREASES WITH THE NUMBER OF FATIGUE CYCLES FROM 106 MPa FOR THE FIRST LOOP AT 0,4% STRAIN RANGE TO 289 MPa FOR THE SATURATION LOOP AT 3,0% STRAIN RANGE.

FATIGUE LIFE CURVE OF NON-IRRADIATED Al ALLOY 5154



FATIGUE CRACK GROWTH MEASUREMENT

° FATIGUE CRACK GROWTH TESTS HAVE BEEN PERFORMED ACCORDING TO ASTM E 647-83

° TWO SERIES OF EXPERIMENTS:
  - WITH UN-IRRADIATED SPECIMENS FROM STOCK MATERIAL OF THE NEW HFR VESSEL
  - WITH IRRADIATED SPECIMENS FROM THE OLD CORE BOX REPRESENTING DIFFERENT NEUTRON RATIO RANGING FROM 1 TO 5

° CONTINUOUS CRACK MONITORING BY DIRECT CURRENT POTENTIAL DROP TECHNIQUE

° CRACK EXTENSION CHECKED BY OPTICAL MEANS

° FATIGUE CRACK GROWTH TEST CONDITIONS:

Loading type:	cyclic tensile-force loading
Specimen type:	CT-specimen, W = 50 mm
Specimen thickness:	B = 10.0 mm (East wall) or 12.5 mm (others)
Mechanical notch:	a_n = 12.5 mm
Control parameter:	constant load amplitude (ΔP)
Wave form:	triangular
Environment/humidity:	air/51% - (88% * For the 2 tests in water)
Temperature:	room temperature (about 300 K)
Pre-crack-extension (Δa_i):	1 - 3 mm
Crack growth loading:	constant ΔP
Crack growth (Δa):	10 - 15*mm
Pmax:	4.0 kN - 2.4 kN
Number of tested specimens:	8* un-irradiated (including 2 in water)
	12 irradiated (8 west wall and 4 East wall)

FATIGUE CRACK GROWTH

- FC GROWTH EXPERIMENTS TO PROVIDE INFORMATION ON THE LINEAR ELASTIC CRACK GROWTH BEHAVIOUR OF AL 5154 ALLOY

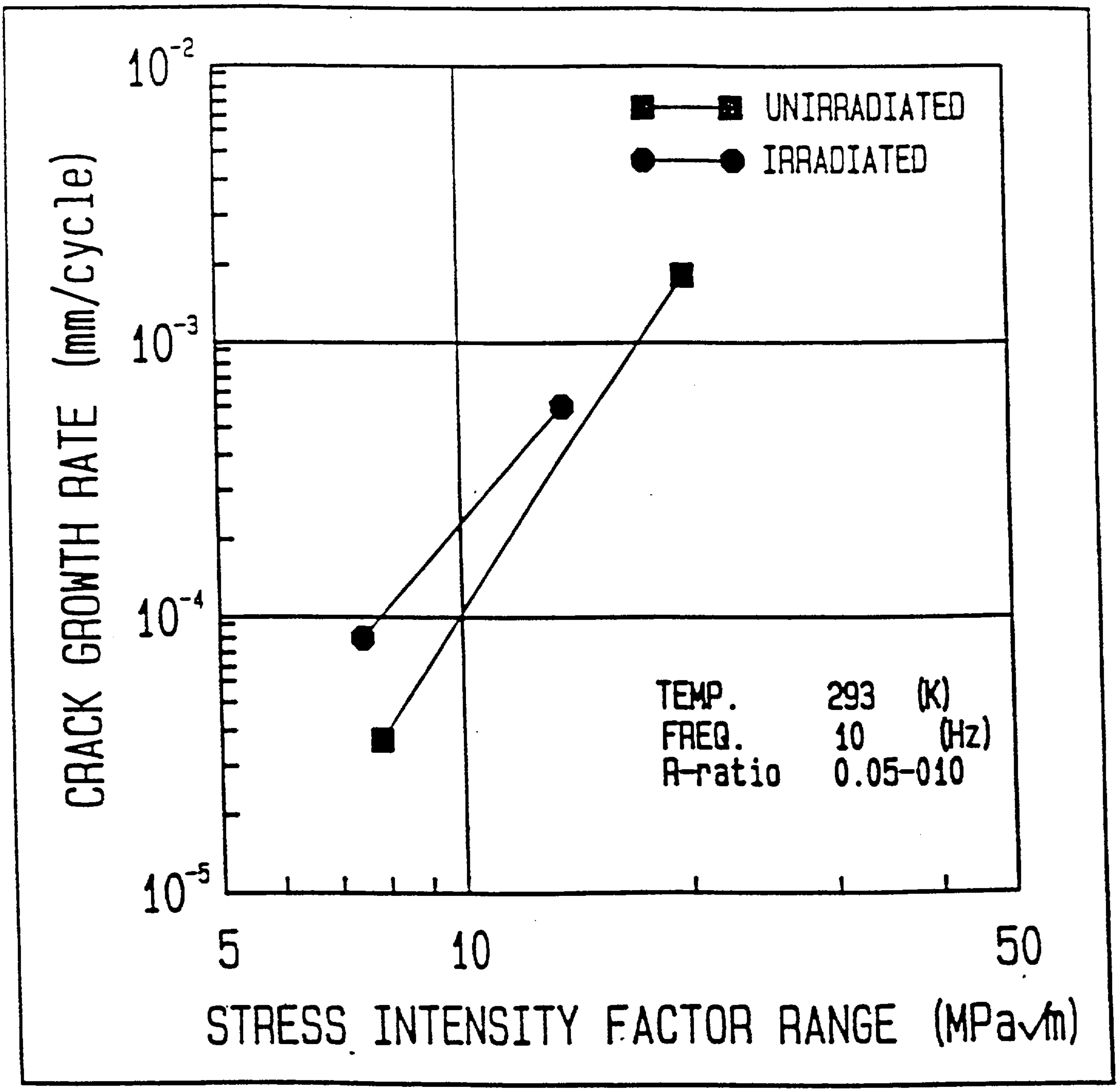
- EMPIRICAL "PARIS RELATIONSHIP" BETWEEN CRACK GROWTH RATE da/dn AND THE CRACK TIP STRESS INTENSITY FACTOR RANGE ΔK

  $$da/dn = C\,(\Delta K)^n$$

- IRRADIATION HAS A MINOR EFFECT ON THE SUB CRITICAL FATIGUE CRACK GROWTH RATE. THE ULTIMATE INCREASE OF THE MEAN CRACK GROWTH RATE AMOUNTS TO A FACTOR OF 2

- CRACK EXTENSION IS STRONGLY REDUCED DUE TO SMALLER CRACK LENGTH FOR CRACK GROWTH INSTABILITY (REDUCTION OF K_{IC})

SUBCRITICAL FATIGUE CRACK GROWTH "PARIS CURVE" OF IRRADIATED AND NON-IRRADIATED AL 5154



FRACTURE TOUGHNESS

- IRRADIATED MATERIAL FROM THE CORE BOX WALLS OF THE OLD VESSEL HAS BEEN USED FOR FRACTURE TOUGHNESS TESTING

- THE CONDITIONAL FRACTURE TOUGHNESS VALUES K_{IQ} RANGES FROM 30.3 TO 16.5 MPa√m

- THE LOWERMOST MEANINGFUL "K_{IC}" IS 17,7 MPa√m CORRESPONDING TO THE THERMAL FLUENCE OF 7.5 10^{26} n/m^2 FOR THE END OF LIFE OF THE OLD VESSEL

CONDITIONAL FRACTURE TOUGHNESS (K_{IQ}) OF IRRADIATED A

K_{IQ} MPa√m	thermal neutron fluence 10^{26} n/m^2 (E<0.414eV)
25.3	5.4
22.0	5.8
24.9	6.1
25.3	5.8
23.9	6.1
24.0	5.0
27.0	3.2
28.9	2.6
27.8	2.6
30.3	1.7
23.0	6.2
24.2	5.3
24.3	5.0
26.6	3.7
26.5	4.4
24.4	5.0
22.3	6.9
* 17.7	7.5
16.5	7.5
25.7	5.0

HARDNESS, STRENGTH AND DUCTILITY

- TESTING CARRIED OUT ON IRRADIATED MATERIAL FROM THE OLD REACTOR VESSEL

- HARDNESS IS STRONGLY INCREASED BY NEUTRON IRRADIATION. TESTING SHOWS AN ULTIMATE HARDENING OF 35 POINTS INCREASE OF HSR_{N15} AND AN ULTIMATE TENSILE YIELD STRESS OF 589 MPa AND WITH A DUCTILITY OF 1.6%

SURVEILLANCE PROGRAM (SURP)

- AN IRRADIATION DAMAGE SURVEILLANCE PROGRAMME HAS BEEN SET UP IN 1985 FOR THE NEW VESSEL MATERIAL TO PROVIDE INFORMATION IN FRACTURE MECHANICS PROPERTIES.

- COMPACT TENSION AND TENSILE HAVE BEEN PLACED IN AN IN-CORE AND A POOL SIDE FACILITY (PSF) POSITION FOR THE PROPER SIMULATION OF THE NEUTRON FLUX CONDITIONS OF THE DIFFERENT WALLS OF THE CORE BOX.

- NEUTRON MONITOR SETS ARE REMOVED EVERY 3 YEARS.
THE SPECIMENS ARE SCHEDULED TO BE REMOVED FROM IRRADIATION AND TO BE TESTED AT DIFFERENT INTERVALS OF THE REACTOR VESSEL LIFE.

- THE THERMAL NEUTRON EXPOSURE REACHES ABOUT $2.5 * 10^{26}$ n/m^2 IN 1992.

CONCLUSION

- ROUTINE IN-SERVICE INSPECTION HAS BEEN PERFORMED IN 1991 IN ACCORDANCE WITH THE OPERATING LICENCE REQUIREMENTS AND LEADS TO THE CONCLUSION THAT THERE HAS BEEN NO CHANGE IN THE VESSEL SINCE ITS INSTALLATION IN 1984.

- INFORMATION ON LIKELY DEFECT SIZES TOGETHER WITH KNOWLEDGE OF THE MATERIAL PROPERTIES INCLUDING THE EFFECTS OF IRRADIATION ALLOWS THE DEMONSTRATION THAT THERE IS NO CRITICAL DEFECT AND THEN TO ASSESS THE INTEGRITY OF THE REACTOR VESSEL.

IRRADIATION EFFECTS ON BERYLLIUM ELEMENTS

- INDUCED BY NEUTRON IRRADIATION, NUCLEAR REACTIONS IN BERYLLIUM LEAD TO GAS FORMATION CONSISTING OF MAINLY 4 He

- THE BERYLLIUM ELEMENTS WERE DELIVERED BY ALLIS CHALMERS MANUFACTURING IN THE LATE FIFTIES TO THE HFR

- A BERYLLIUM ELEMENT CONSISTED OF A BERYLLIUM FILLER ELEMENT WITH A CYLINDRICAL BORE (ø 52,37 mm) IN WHICH A BERYLLIUM INSERT IS POSITIONED

- SEVERE PROBLEMS DURING CORE LOADING BACK IN 1975 OCCURRED WITH BERYLLIUM ELEMENTS DUE TO RADIATION INDUCED EFFECTS (SWELLING AND EMBRITTLEMENT) AND TO OPERATIONAL HANDLING DAMAGE ON ALUMINIUM PARTS.

- SINCE VESSEL REPLACEMENT, THERE ARE THREE CATEGORIES OF Be ELEMENTS

- REPLACEMENT OF Be ELEMENTS OCCURRED AFTER MORE THAN 25 YEARS OF OPERATION

- DESIGN IMPROVEMENT OF THE NEW Be ELEMENTS BASED ON EXPERIENCE WITH THE OLD Be ELEMENTS

- THE CORE OF THE HFR PETTEN CONSISTS OF 9 X 9 ARRAY CONTAINING 33 FUEL ASSEMBLIES, 6 CONTROL RODS, 19 EXPERIMENT POSITIONS AND 23 BERYLLIUM REFLECTOR ELEMENTS

- 3 CATEGORIES OF BERYLLIUM ELEMENTS SINCE REACTOR VESSEL REPLACEMENT
  - IN-CORE REFLECTOR ELEMENTS
  - I ROW REFLECTOR ELEMENTS
  - CORNER ELEMENTS

DESIGN IMPROVEMENT OF Be ELEMENTS

- NO RADIALLY DRILLED HOLE AND NO ROLL PIN

- INCREASING OF THE CENTRAL BORE DIAMETER

- UPPER-END FITTINGS IN STAINLESS STEEL

REFLECTOR ELEMENTS

IN-CORE REFLECTOR ELEMENT:

A. BERYLLIUM FILLER ELEMENT
   * BERYLLIUM BODY WITH Ø 52.37 BORE
   * ALUMINIUM UPPER- AND LOWER END PIECES

B. BERYLLIUM INSERT
   * SOLID BERYLLIUM BODY (Ø 47.55)
   * ALUMINIUM UPPER AND LOWER END PIECES

I-ROW REFLECTOR ELEMENT:

A. BERYLLIUM FILLER ELEMENT
   * IDENTICAL TO IN-CORE ELEMENT

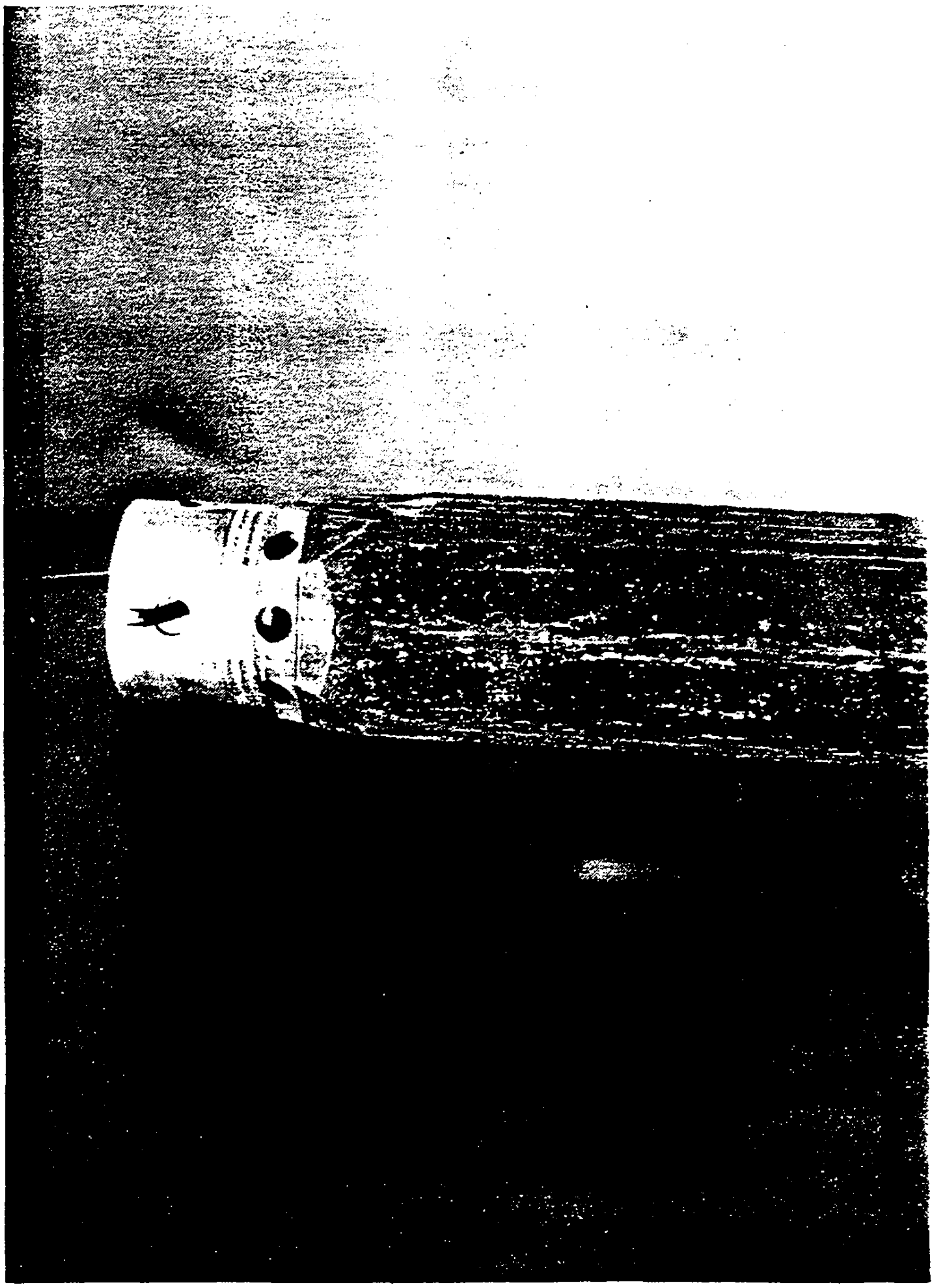
B. BERYLLIUM INSERT
   * MODIFIED IN-CORE INSERT (RESTRICTOR)

CORNER ELEMENT:

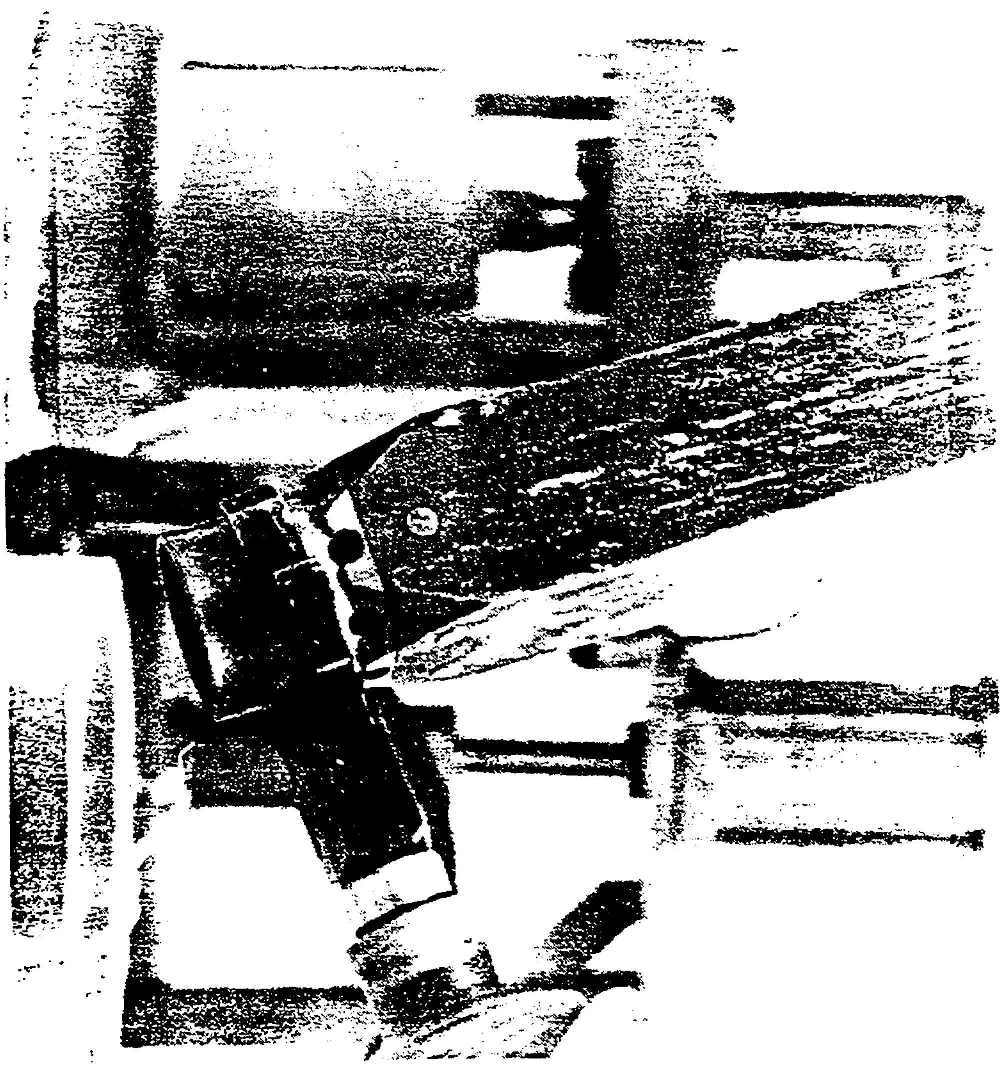
A. ALUMINIUM FILLER ELEMENT
   * ALUMINIUM BODY WITH Ø 75.0 BORE
   * ALUMINIUM LOWER END PIECE
   * STAINLESS STEEL UPPER END PIECE

B. BERYLLIUM INSERT
   * SOLID BERYLLIUM BODY (Ø 70.2)
   * ALUMINIUM UPPER AND LOWER END PIECES

Beryllium Reflector Element
after 25 years of utilization



Beryllium Reflector Element
after 25 years of utilization



CONCLUSIONS

- AT THE HFR, REFLECTOR MATERIAL HAS BEEN USED MORE THAN 25 YEARS OF REACTOR OPERATION CORRESPONDING TO A MAXIMUM NEUTRON FLUENCE OF 2.56 10^{26} m^{-2} (E > 1.0 MeV) WITH REGULAR INSPECTIONS AND RE-MACHINING

- RADIALLY DRILLED HOLES AND MOUNTED ROLL PINS ARE THE WEAKEST POINTS ON FILLER ELEMENTS AND INSERTS. SEVERE CRACKING WAS OBSERVED IN THESE LOCATIONS

- PRESENCE OF BLISTER FORMATIONS DUE TO RADIATION INDUCED HELIUM

- HANDLING DAMAGE CAN BE REDUCED BY A PROPER CHOICE OF END FITTING MATERIAL

- THE AVERAGE SWELLING OF THE REFLECTOR ELEMENTS AFTER 21 YEARS OF HFR OPERATION (1962-1983) WAS 0.9% WITH 1.39% AS MAXIMUM AND 0.61% AS MINIMUM