ANALYSIS OF FUEL OPERATIONAL RELIABILITY AND FUEL FAILURES

Ivan Smieško
SLOVAK ELECTRIC
NPP JASLOVSKÉ BOHUNICE

Prepared for IAEA Regional Training Course
„WWER Fuel Design, Fabrication, Performance and Back End"
Bratislava , June 1999

Fuel failure

Loss of fuel rod (cladding) integrity
Corruption of second barier
for fission product release from fuel

Consequences

- Increase of primary coolant activity (operation limit)
- Increase of fission product releases to environment
- Increase of radwaste activities (Inventory for disposal)
- Potential increase of personnel exposure

Fuel failure rate

defined as

$$R = r.D/N$$

r - number of failed rods per FA (for WWER 1,3)

WWER Fuel

~ 0.55 % for Bohunice (Martin calculated acc. to this eqn.)

Failure rate 0,005 - 0,008 %

Comparable to PWR and BWR results

...very good results with regard to limited number of failed fuel PIE´s

Main causes of fuel failure

- poor fuel design
- inadequate quality controll during manufacturing
- poor operational/handling practice

Only few easily identified leak categories

⇒ **Fuel failure analysis is very similar to „criminology“**

Leaks - through wall cracks

- cladding
- end caps
- welds

Mechanisms of Fuel Failure

- grid/rod fretting
- spacers deformation/rod bowing
- primary hydriding
- fuel densification
- manufacturing (assembliing) defects
- debris fretting
- PCMI
- cladding corrosion and deposits
- secondary hydriding

Spacers Deformation/Rod Bowing

- design deficiency
- rod bowing - very rare cases
- no failures atributed directly to this effect
- WWER 1000 - control rod drop time delays
  - assembly distortion by axial loads beyond design limits

Fuel Densification/Cladding Collapse

- 1970's - forming of axial gaps in fuel stack
  - modification of pellet manufacturing and pre-pressurization of fuel rods

Grid/Rod Fretting

- <u>second largest contribution to fuel failures</u>
- potential design deficiency
- loss of metal by mechanical wear
  - sliding, impingement
- thermohydraulics (fluid instability) related fuel assembly or rod vibration
- WWER fuel - different relaxation of SS steel grid and ZrNb cladding - insuficient support of fuel rod in spacer - potential cause of WWER 440 V-230 failures ?
- improved design - Zircaloy spacer grids

Pellet to Clad Interaction

- closure of gap between pellet and cladding
- iodine induced IGA SCC (axial cracking)
  - slow growth to 60 um depth then acceleration
  - whole process may take only minutes
  - next power ramp may lead to leak
- WWER fuel - excellent resistance
- very low failure occurence at high burnups
- occured only at
  - violation of operating rules (power ramps)
  - loop reconnection
- WWER - 1000 - improvement after reduction of permissible cladding defects from 60 to 35 um

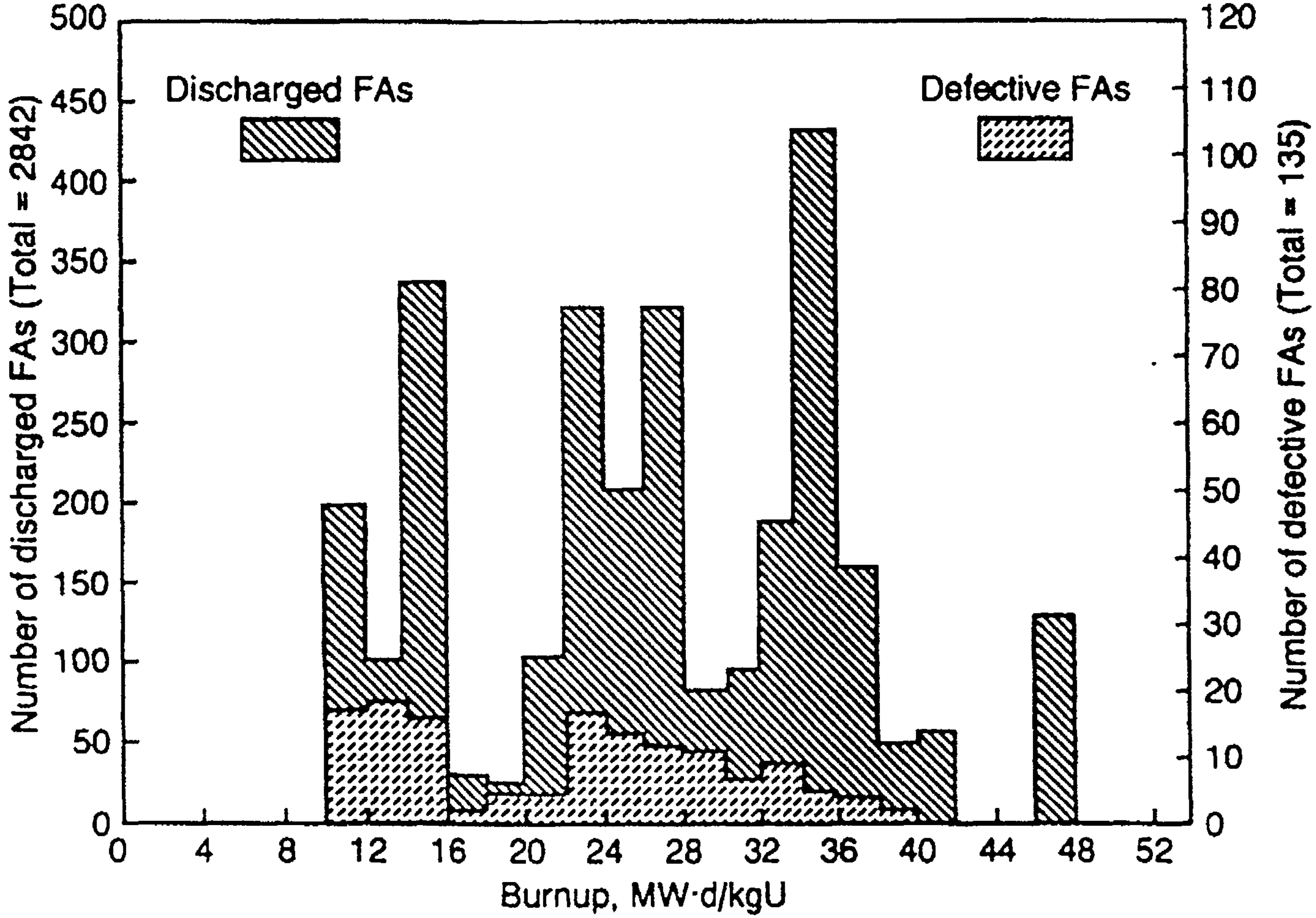


FIG. 21. Burnup distribution of discharged (including defective) WWER-1000 FAs [10].

Debris Fretting

- largest contribution to fuel failures
- common failure mechanism for all reactor types
- circulation of various types of debris - machining chips, others (repair and maintenance operations)
- traps for particles - lower end plate, spacer grids
- rapid fretting leading to wall penetration
- instalation of debris filter - big particles trapped
- particle size reduction - debris failures prevailingly in early stage of fuel operation life
  - positive influence of increased burnup - hard protective oxide layer (harder than base alloy)
- WWER - optimised design - no springs, short spacers, higher coolant velocity, bottom grid as debris filter

Internal Corrosion

- internal oxidation very low (O_2 liberated by fission)
- hydriding (H_2 pick-up)
  - migration of H_2 from free surface to Zr/ZrO_2 interface - (throgh microcracks, subgrain boudaries)
  - residual moisture critical (open porosity)
- large variation
  - uniform - no signifacnt consquences arised.
  - „Sunburst“ local patches - (local contamination or depassivation - massive hydriding - stress forming) - hydride precipitation perpendicular to stress
- Hydrogen - solubility limit 200 ppm
  - WWER fuel 50-60 ppm real values
  - no evidence of ammonia / hydrazine chemistry influence to increased hydriding

External Corrosion

- uniform cladding corrosion - very low
  - external corrosion - dark layer 6-8 microns thickn.
  - standard water chemistry - anual corrosion rate 0,3-2,9 microns
- ZrNb alloy - high sensitivity to free oxygen
  - (ZrNbSnFe improved resistance)
- nodular corrosion (BWR) - observed occasionally
  - causes not clear (repartition and size of second phase particles, impurities Cu, Si,Ca,Mg, galvanic and radiolytic effects)
- local boiling (operation limits violation)

⇒ not significant problem of WWER fuel

Deposit Formation

- corrosion products
  - mobilised by chemistry/temperature (solubility) change or „brushing“ by foreign particles
  - decontamination residuals - insufficient flushing
- impurities (foreign materials - ion-exch. resins, graphite particles e.g)
- local deposition enhancement by overheating
- preferably at lower parts of fuel assembly
- heavy deposit regions - potential pitting initiation

Secondary Failures

- appearance in different forms
  - difficulties to identify primary cause
- primary defect - ingress of coolant into fuel rod
  - steam oxidizing cladding and fuel + radiolytic decomposition of steam to hydrogen and peroxide - formation of hydrogen
  - masive hydriding remote (upwards) from primary defect - nucleation centers for cladding cracks - secondary defects

Secondary Failures - continued

- more damages in upper part of fuel rod (high temperature region)
- very dependent on the primary defect size and less to its position
- small leaks or cracks do not necessarily lead to excessive hydriding - „resealing“ with corrosion products observed
- fabricated (intentionally made) fuel leaks too big - different (unrepresentive) behaviour for operational defects

Failure cause characteristics

Possible cause	Time of leak appearance	$^{131}I/^{133}I$ act. ratio
End caps	Any time	> 1
Primary hydriding	0-60 days	0.5-0.7
Grid-rod fretting	Any time	0.3-0.6
Debris fretting	0-60 days typ.	1.549
PCMI	After power ramp	not exp.
Handling damage	0-60 days	0.3-0.6
Secondary damage	After power ramp	0.741

Fuel Failure Monitoring

- during operation
- stedy state primary coolant activities - global core evaluation
  - noble gases - simple chemical behaviour - transport driven by diffusion high volatility - early identification of leak appearance (^{133}Xe)
  - iodines - more complicated transport mechanisms but by operational experience still applicable
  - non-volatile species - ^{239}Np - large defects indication
  - difficulties to distinguish large leaks from tramp uranium

Fuel Failure Monitoring - continued

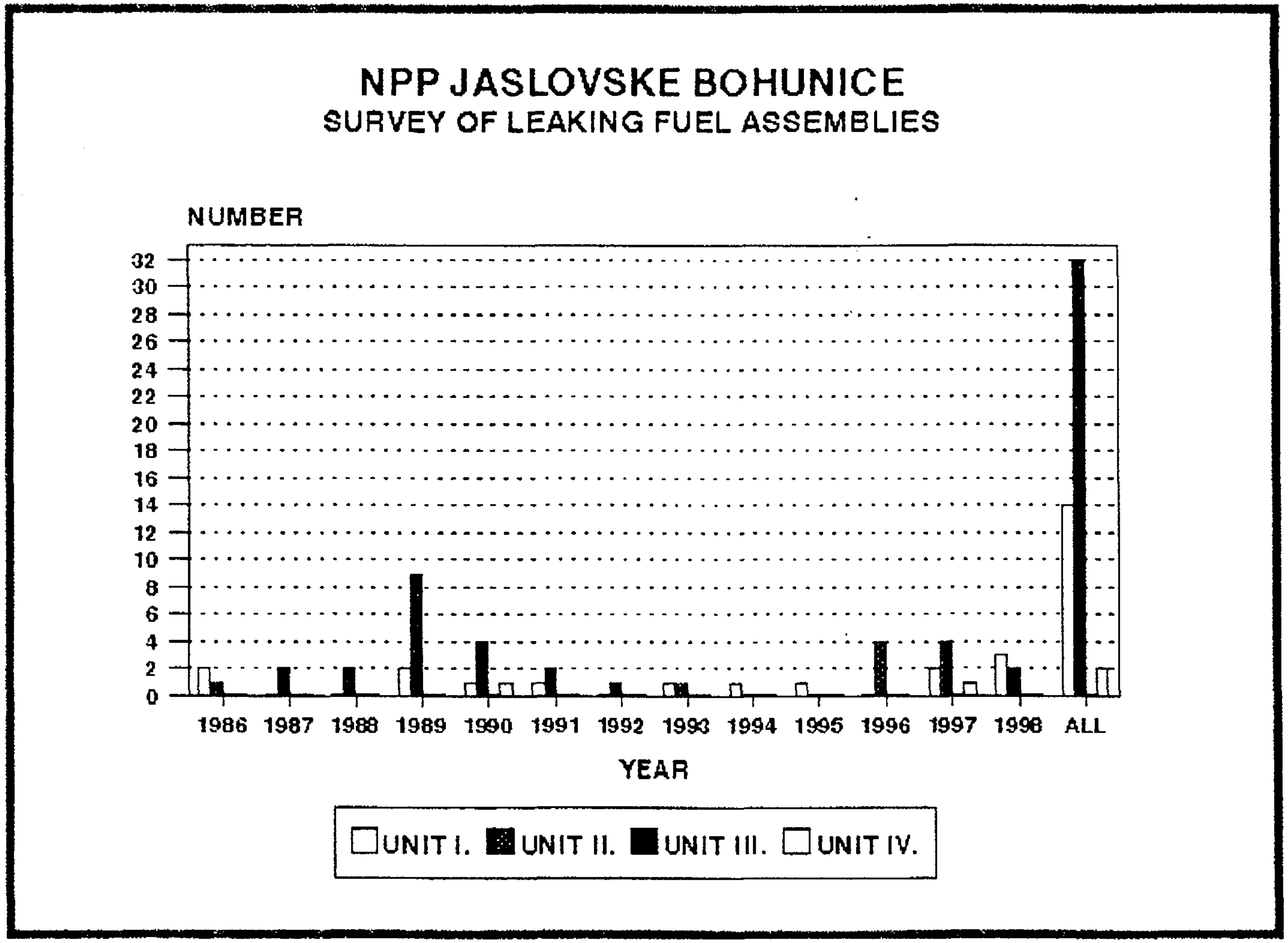
- power transients - iodine spiking - release of fission products from pellet-cladding gap in the defect vicinity
  - defect size and location dependent

Leaking Fuel Reloading

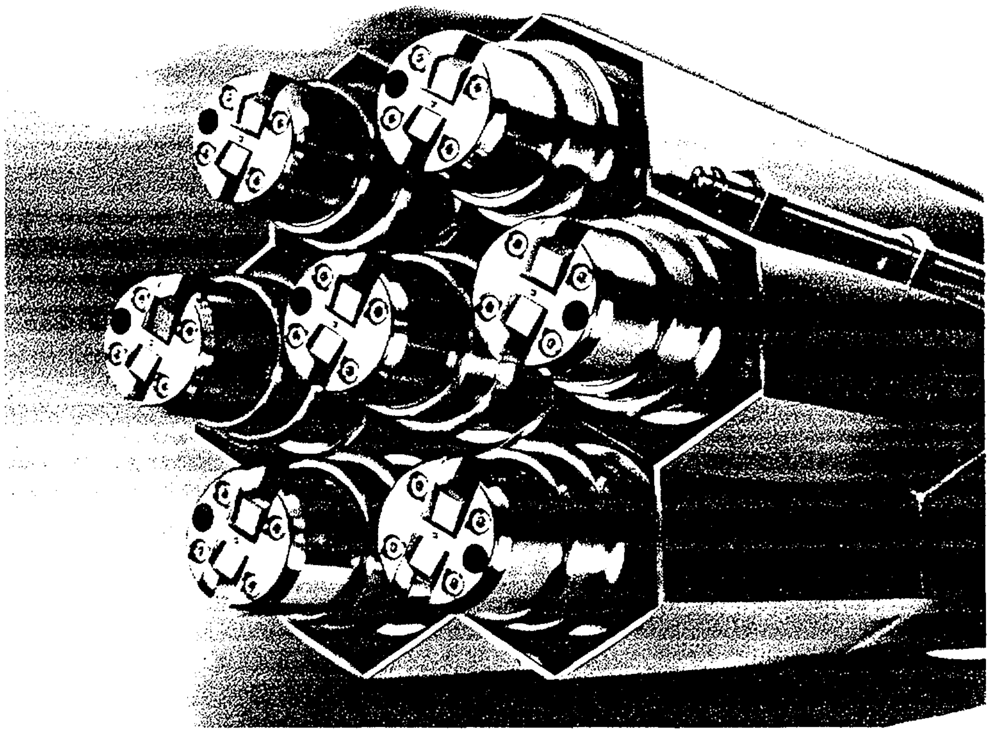
- currently discouraged -"zero defect strategy"
- possible in controlled way (EdF)
  - avoid fdurher fuel release into primary circuit
  - limitation in defect size (quantitative sipping) and number of reloaded assemblies
- experience also in Russia and Ukraine

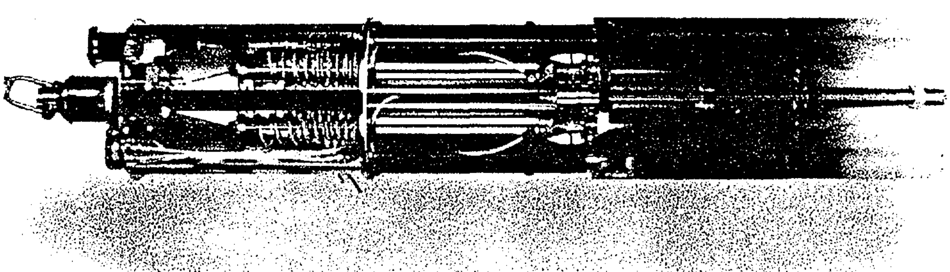
Identification of Failed Fuel Assemblies

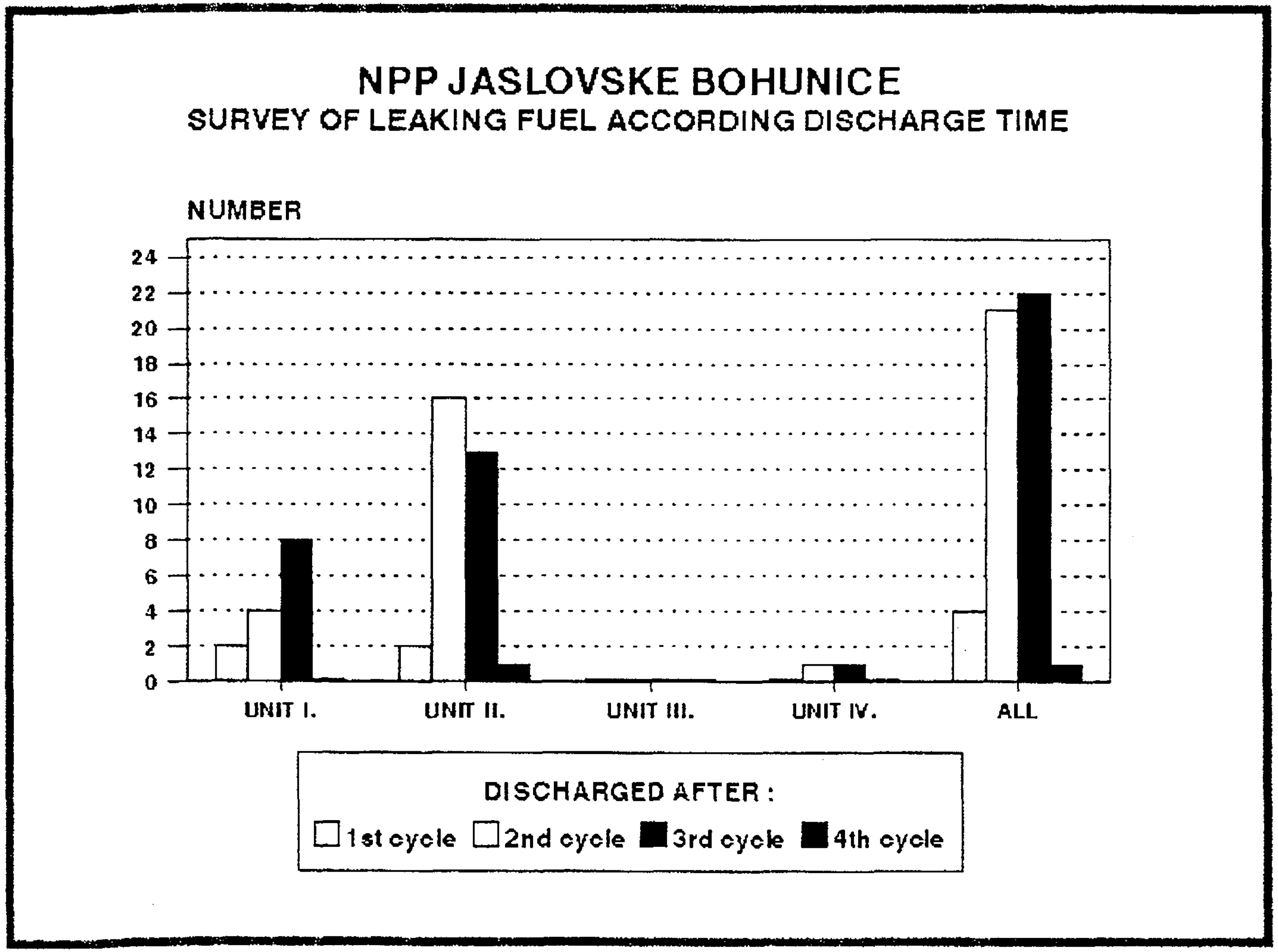
- **during operation - limited capabilities to core region or fuel burnup**
  - flux tilting - not recommended
  - $^{137}Cs/^{134}Cs$ activity ratio related to fuel burnup
- **during refuelling - identification of particular leaking assembly**
  - in-core sipping - suction hood (temperture change) or in-mast (pressure change) - fast
  - in-cell (cannister) sipping - temperature and pressure change - more time dependant - more reliable



NPP JASLOVSKE BOHUNICE
SURVEY OF LEAKING FUEL ASSEMBLIES
NUMBER
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 ALL
YEAR
UNIT I. UNIT II. UNIT III. UNIT IV.






NPP JASLOVSKE BOHUNICE
SURVEY OF LEAKING FUEL ACCORDING DISCHARGE TIME
NUMBER
24
22
20
18
16
14
12
10
8
6
4
2
0
UNIT I.
UNIT II.
UNIT III.
UNIT IV.
ALL
DISCHARGED AFTER :
1st cycle
2nd cycle
3rd cycle
4th cycle

NPP Bohunice Experience

- on-line gammaspectrometry of primary coolant activity
- different modells used for operational data evaluation
- since 1986 in-core sipping combined with cannister sipping
- Totally 48 leaking fuel assemblies identified
  - 46 FA's at V-1 (two WWER 440 V-230 units)
  - 2 FA's at V-2 (two WWER 440 V-213 units)
- <u>Difference V-1/V-2 still not understood</u>
- NPP Dukovany and Paks records similar to V-2
- NPP Loviisa data similar to V-1
- except of one case no reloading of leaking fuel assembly

NPP Bohunice
Possible causes of fuel failures

- Manufacturing - low number of leaks in 1st cycle
- Grid/Rod fretting
  - possible explanation of V-1 / V-2 difference (different flow conditions)
  - improvement after spacer grids material change?

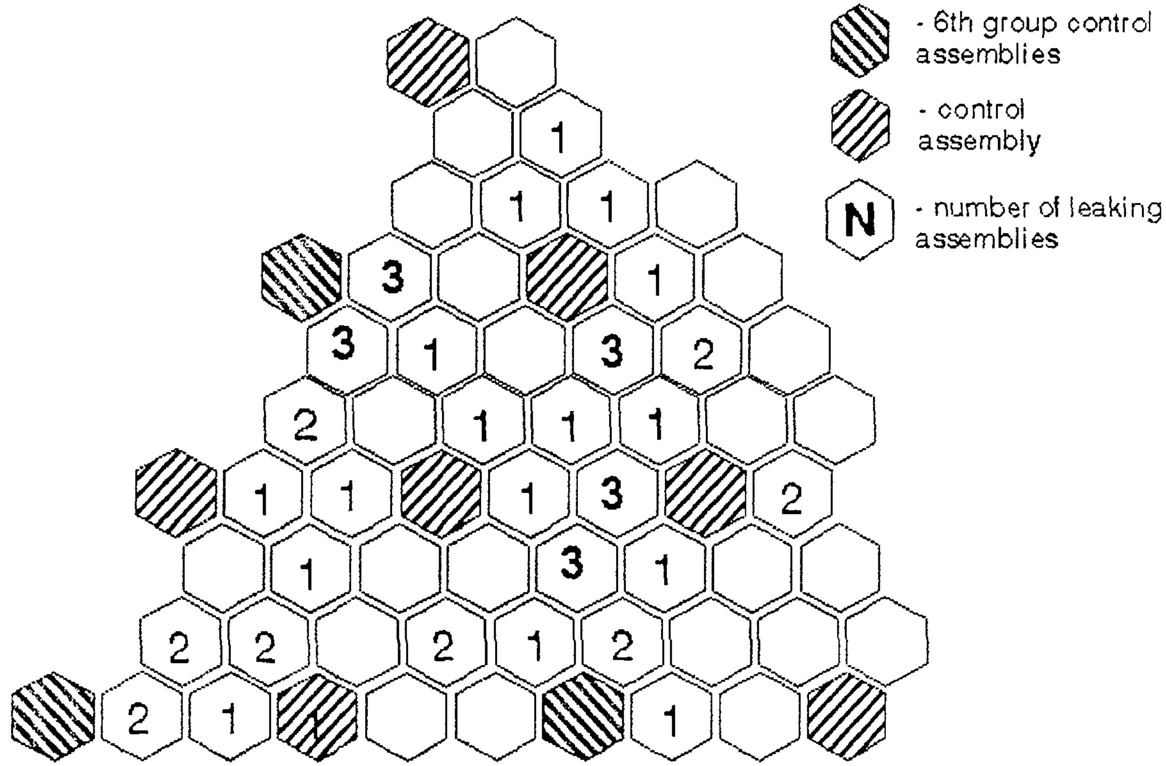
  Current status of fuel loading (Zr-SS spacer grids) :

  EBO 1 - 283/30 EBO 2 - 236/77

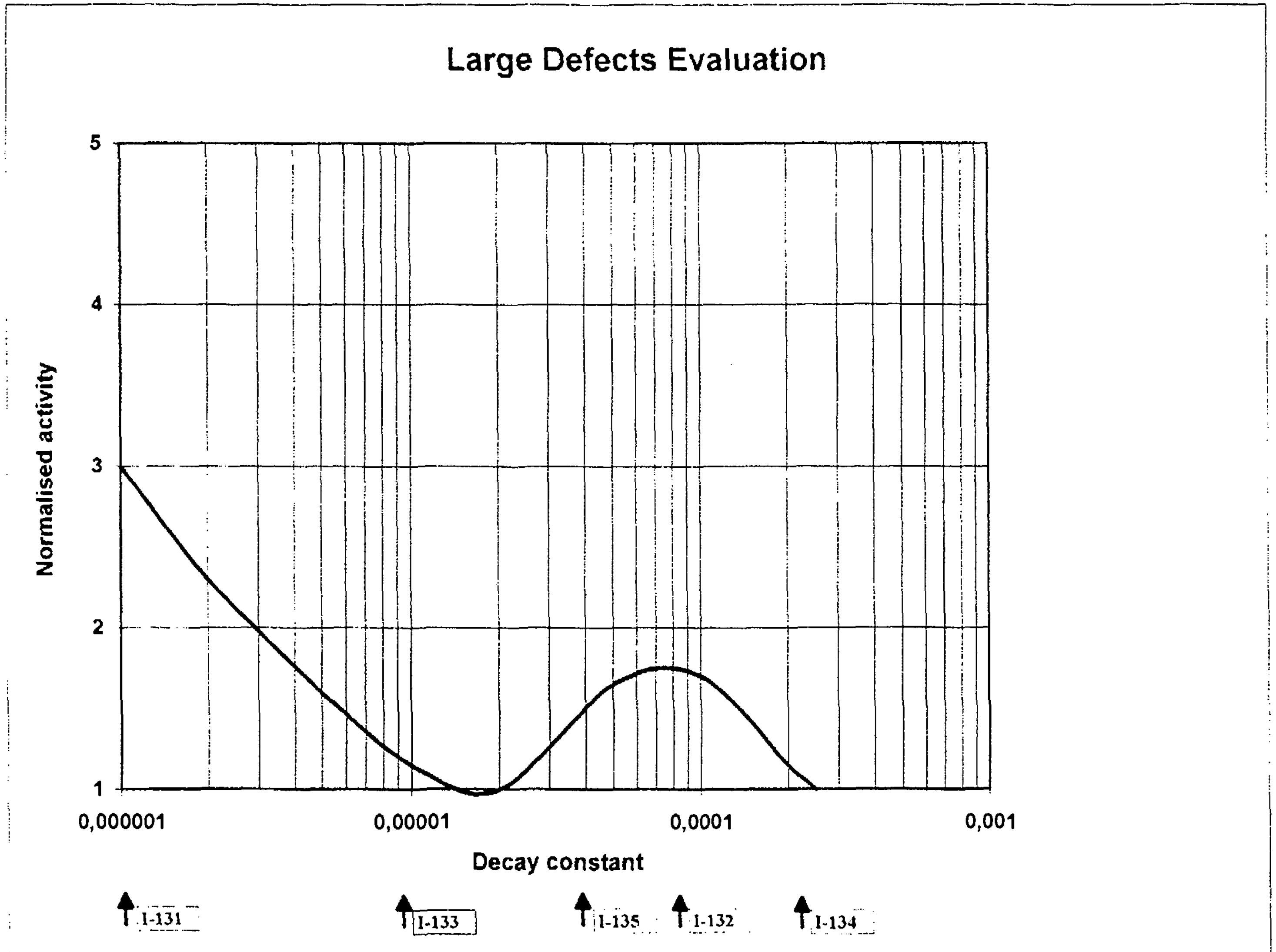
  EBO 3 - 342/7 EBO 4 - 277/72
- Debris fretting - no posiibilities to identify, no supporting arguments from operation, maintenance

NPP Bohunice
Possible causes of fuel failures - continued

- PCI - not probable
  - low failure rate at high burnups
  - only one control assembly found as leaking so far
  - no influence of increased load after refueling
  - no indications from PCI model calulations
  - do not explain V-230/V-213 difference
  - **BUT** - statistically increased leak occurence at neighbourhood of 6th group of control assemblies - **similar results from NPP Bohunice and Loviisa**

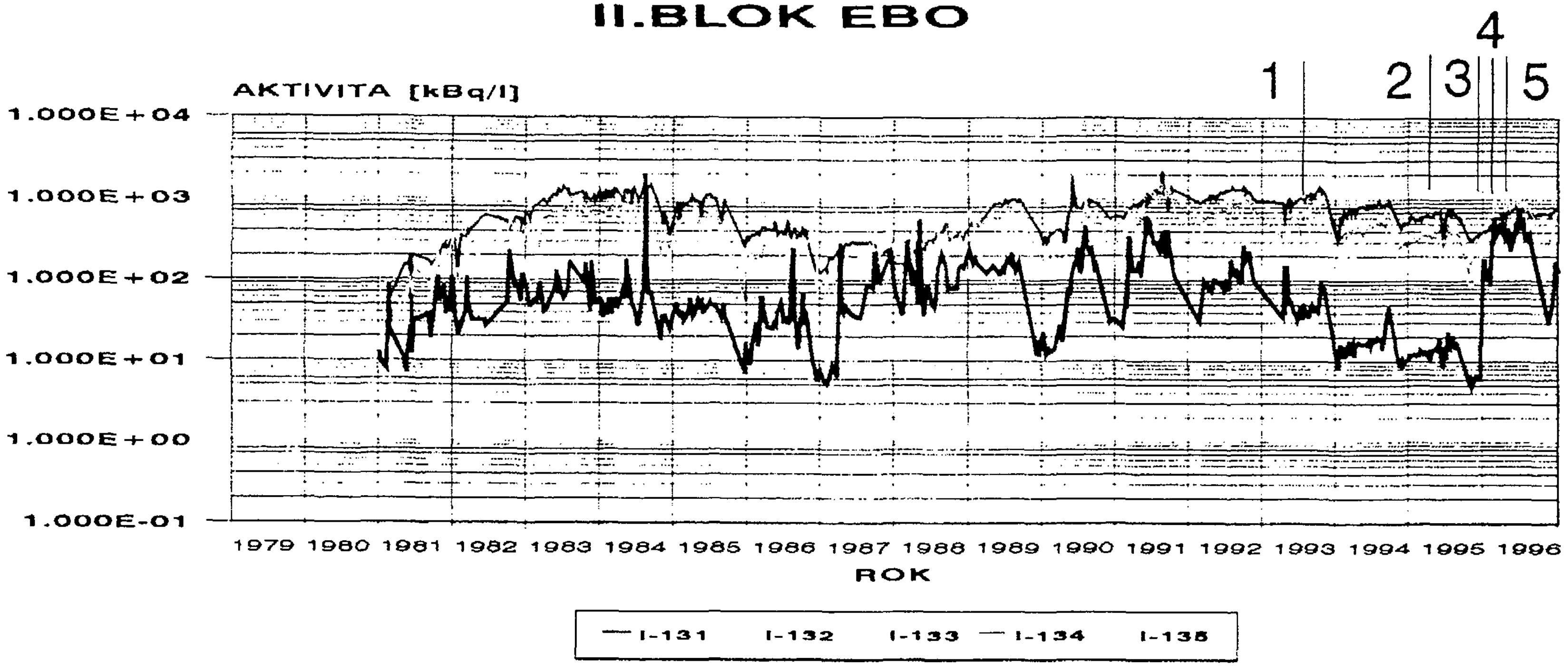


Leaking fuel assemblies - last cycle position

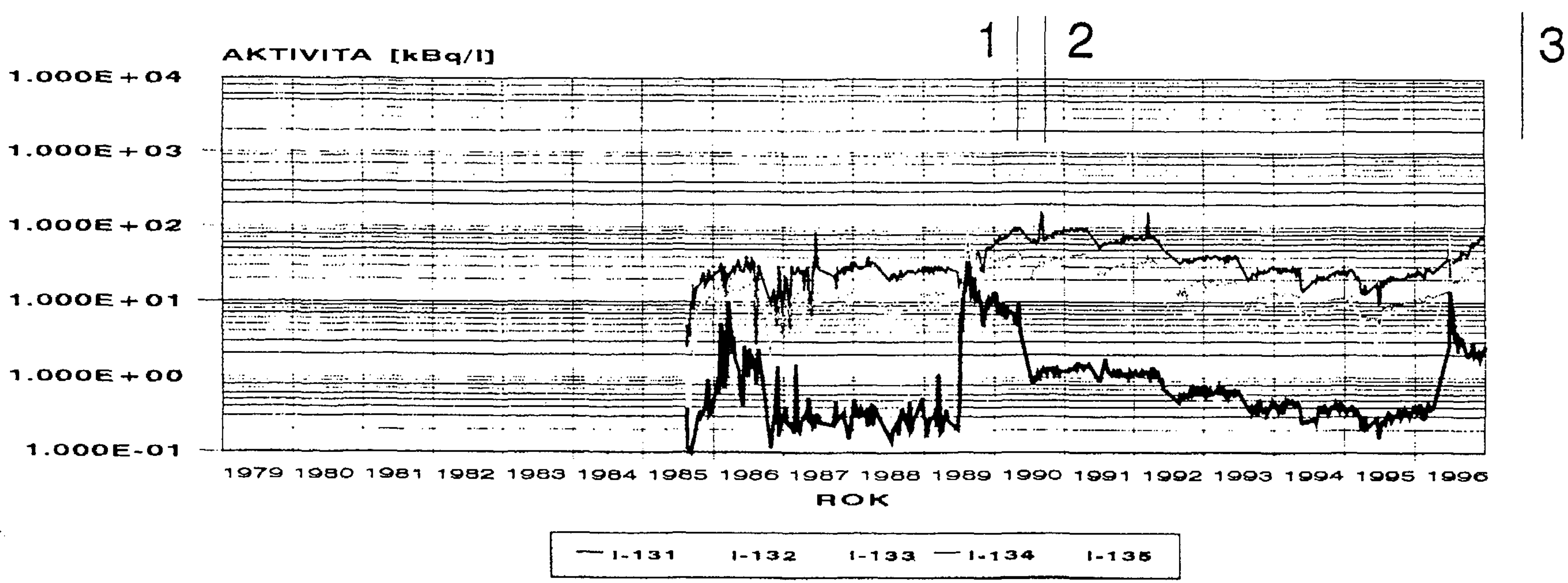


Large Defects Evaluation
5
4
3
2
1
Normalised activity
0,000001
0,00001
0,0001
0,001
Decay constant
I-131
I-133
I-135
I-132
I-134

II.BLOK EBO



IV.BLOK EBO



NPP Bohunice
Fuel Failures Impact to Plant Operation

- Personnel exposure - still too low coolant activities to observe any effects
- Releases to atmosphere - affected only in short-term periods - resolved by technical measures
- Radwaste activities - activity ratios of long-lived fission products and transuranium radionuclides in V-1 and V-2 evaporator botooms are well corresponding to ratio of leaking fuel assemblies