Approach for the Fuel Element Failure Section of NEEP-423

- **Very Comprehensive Treatment of pre-1977 period given in:**

"The Main Causes of Fuel Failure in Water-Cooled Power Reactors"

by

F. Garzaolli, R. von Jan, H. Stehle
Atomic Energy Review, Vol. 17, No. 1, p. 31 (1979)

- **Two Very Comprehensive reviews of the period in the 1980's and up to mid 1990's:**

"Review of Fuel Failures in Water Cooled Reactors", Technical Report Series No. 388, International Atomic Energy Agency, Vienna, 1998

"Proceedings of the 1997 International Topical Meeting on Light Water Reactor Fuel Performance"

Portland, Oregon, March 2-6, 1997

TABLE I. OPERATIONAL REQUIREMENTS FOR LWR FUEL (TYPICAL VALUES)

	PWR	BWR
Average linear heat generation rate (W/cm)	155 – 225	155 – 230
Residence time (a)	3	4
Hot channel factor		
steady state	1.5 – 2.1	1.8 – 2.2
transient	2.3 – 2.5	2.3 – 2.5
Neutron flux, thermal ($cm^{-2} \cdot s^{-1}$)	$4 - 6 \times 10^{13}$	$3 - 5 \times 10^{13}$
fast ($cm^{-2} \cdot s^{-1}$)	$6 - 9 \times 10^{13}$	$4 - 6 \times 10^{13}$
Burnup target		
(assembly average) (GW·d/t(U))	28 – 34	22 – 28
Coolant pressure (bar)	145 – 158	72
Coolant temperature (°C)	303 – 316	287

TABLE III. MAIN FUEL TYPES FOR WATER REACTORS (WESTERN COUNTRIES)

Reactor Type	Reactor Manufacturer	Former fuel design: Number of rods	Former fuel design: Rod o.d. (mm)	Former fuel design: Ave. LHGR (W/cm)	Former fuel design: Number of plants[a]	Present fuel design: Number of rods	Present fuel design: Rod o.d. (mm)	Present fuel design: Ave. LHGR (W/cm)	Present fuel design: Numbe of plan
PWR	Babcock & Wilcox and BBR	15 X 15–17	10.92	177–200	8	17 X 17–25	9.63	170–180	0
	Combustion Engineering	14 X 14–4 X 5	11.18	184–194	6	16 X 16–4 X 5	9.70	170–180	0
	Kraftwerk Union	14 X 14–16 15 X 15–20	10.75	177–226	1 3	16 X 16–20	10.75	207	2
	Westinghouse[b] and Framatome	14 X 14–17 15 X 15–21	10.72	150–220	17 16	17 X 17–25	9.50	170–180	6
BWR	ASEA Atom	8 X 8	12.25	126–155	3	8 X 8–1	12.25	158–175	2
	Gen. Electric[c] and Kraftwerk Union	6 X 6 7 X 7[d]	14.3	150–234	7 30	8 X 8–2	12.5	170–200	4
HWR	AECL[e] (D_2O-CANDU)	19/28	15.2	80–260	8	37	13.08	210	2
	Kraftwerk Union (PHWR)	37/36	11.9	116/232	2	–	–	–	–
	UKAEA/BNFL (SGHWR)	36	16.0	210	1	60	12.2	–	0

[a] Number of plants (>20 MW(e)) in operation since January 1978.
[b] Including Mitsubishi.
[c] Including Hitachi and Toshiba.
[d] 8 X 8 reload since 1973/74.
[e] 50 cm length of bundle.

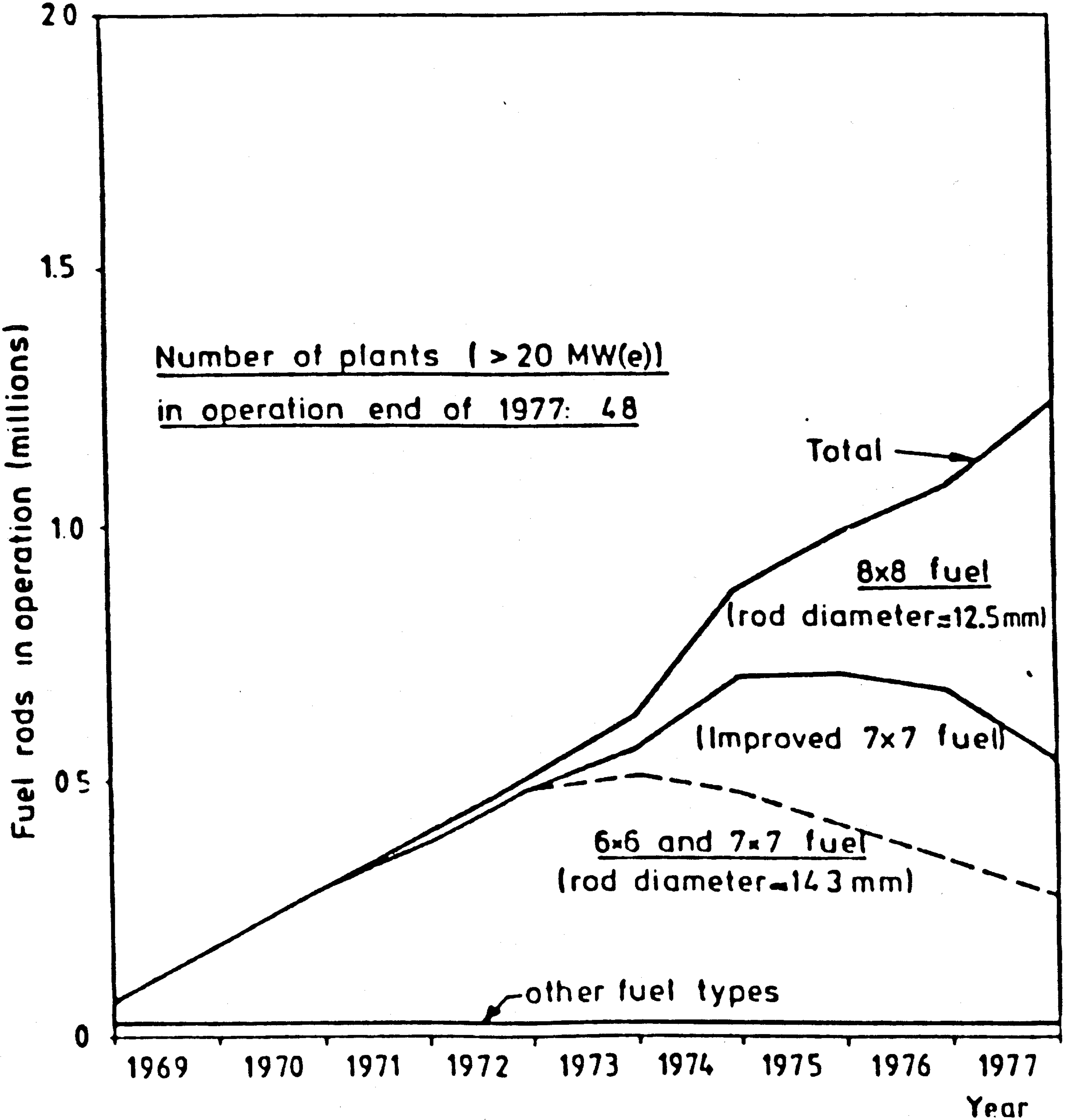

FIG.4. Number of BWR fuel rods in operation.

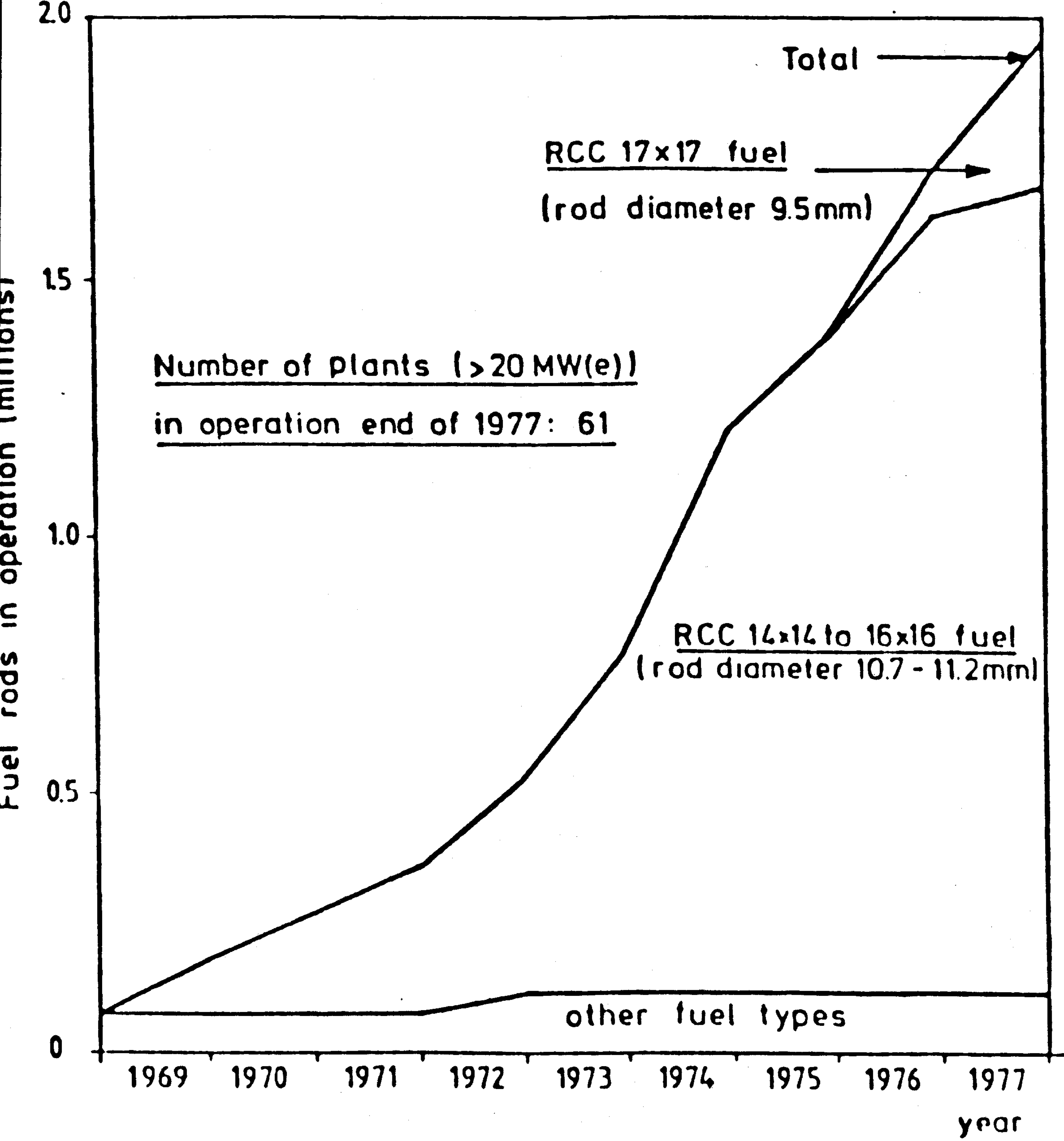

FIG.3. Number of PWR fuel rods in operation.

TABLE 2.1. OBSERVED PRIMARY FAILURE MECHANISMS

Fuel rod failures	
Manufacturing defects	in clad, end plug or weld
Hydriding	by moisture or other contamination in pellets/rods
PCI/SCC	by high power ramps, or assisted by clad/pellet imperfections
Corrosion	with large variety of different root causes and contributing factors
Dryout[a]	only one case of overheating by excessive channel bow (BWR)
Clad collapse[b]	by axial gaps in the fuel column due to fuel densification (PWR)
Grid–rod fretting	with large variety of different root causes and contributing factors
Debris fretting	from metallic debris circulating in the coolant
Rod bow[b]	from several root causes, can lead to exceeding design limits, but has not caused fuel rod failures except in one early event of excessive bow
Baffle jetting	by cross-flow from defective core baffle joints (PWR)
Damage to the assembly structure[c]	
Assembly bow	from several root causes, can lead to handling damage or other problems
Other deformation[b]	by Zry growth/differential growth leading to structural misfit
Fretting wear	from a large variety of phenomena with different root causes
Zry hydriding[a]	only one case of excessive hydrogen takeup in guide tubes (PWR)

[a] Isolated event.

[b] Earlier occurrences, no noticeable problems during the last ten years.

[c] With few exceptions no leaking rods.

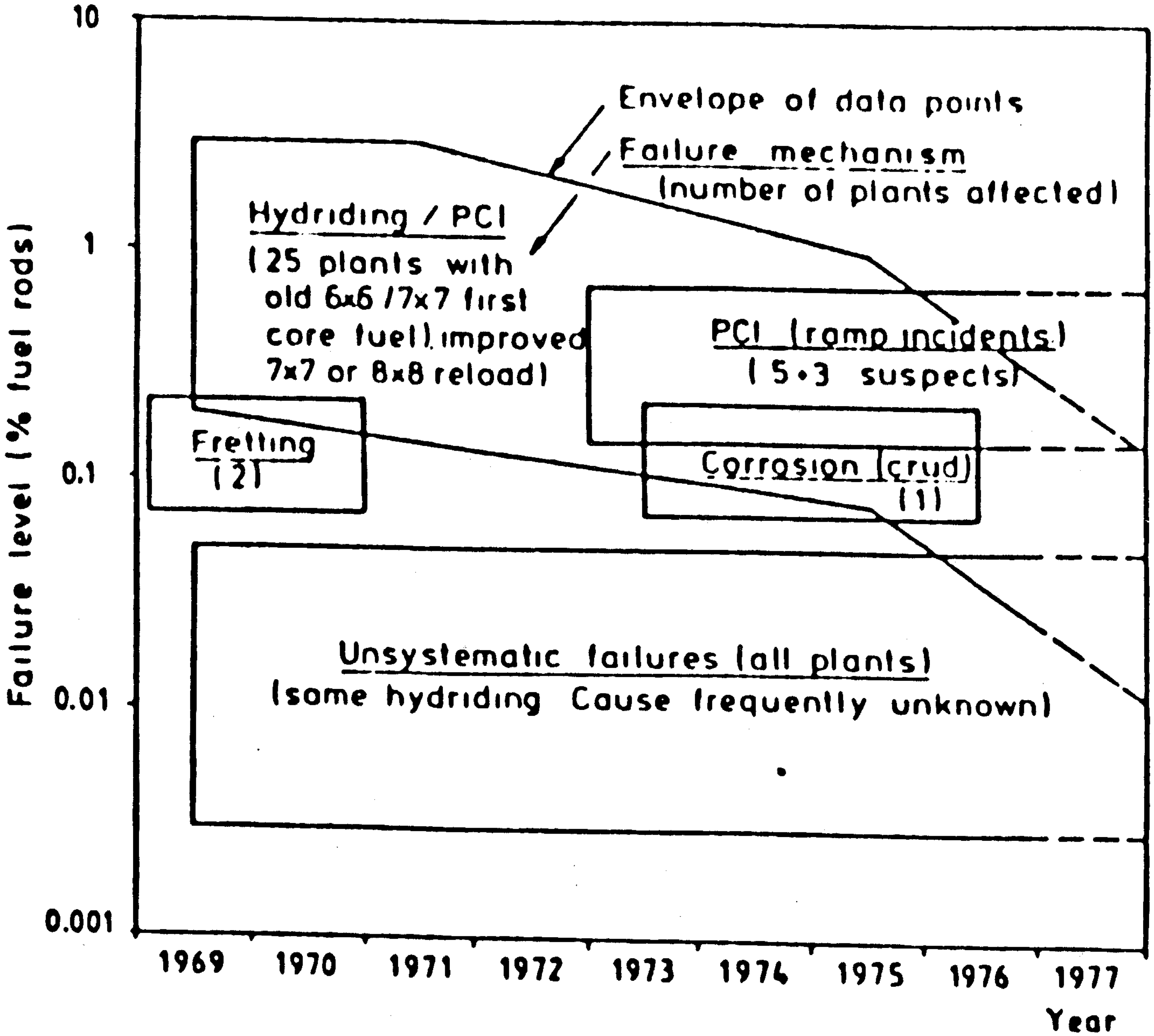

FIG.9. Fuel failure levels in individual BWR plants.

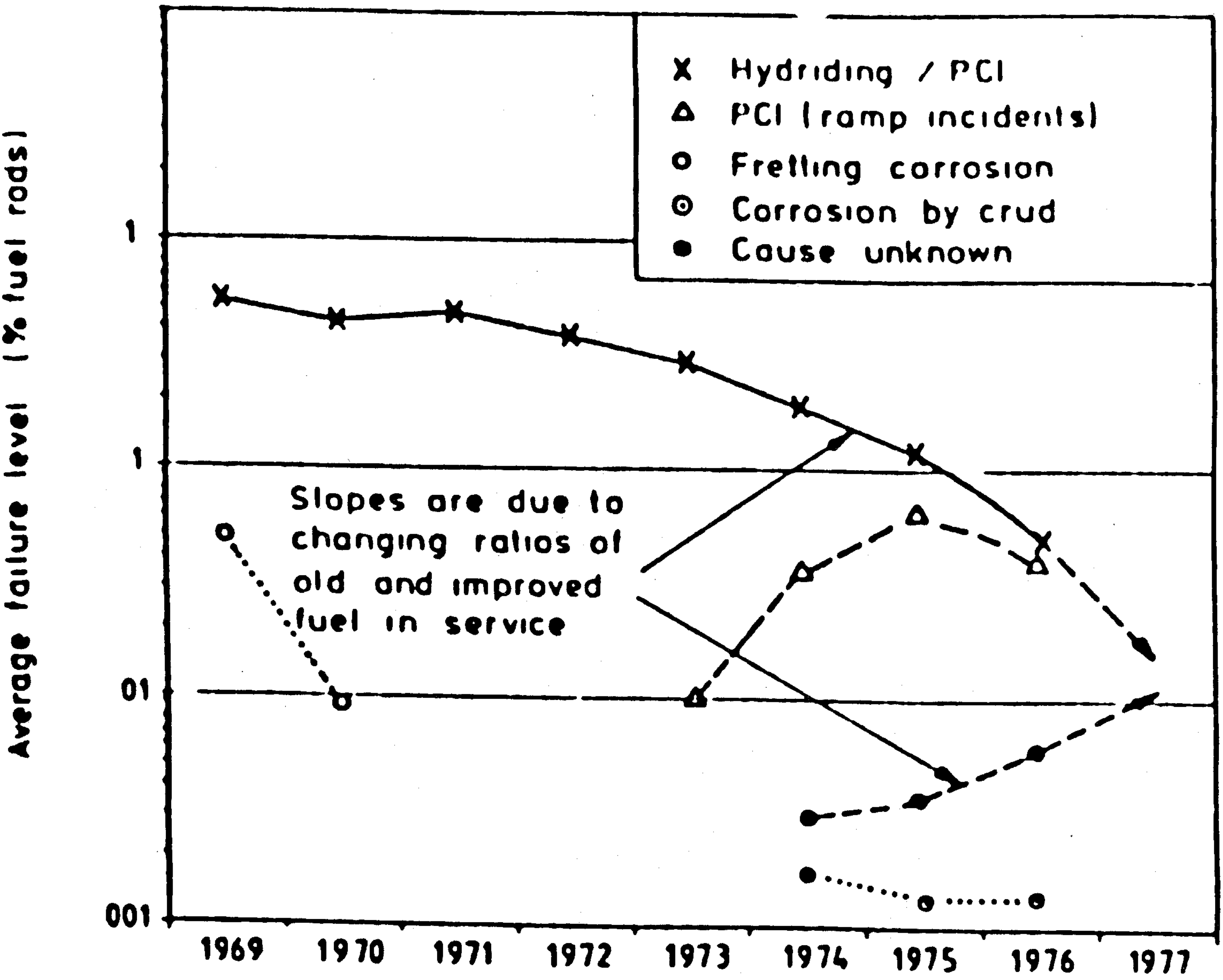

FIG.11. Overall significance of fuel failures in BWR plants.

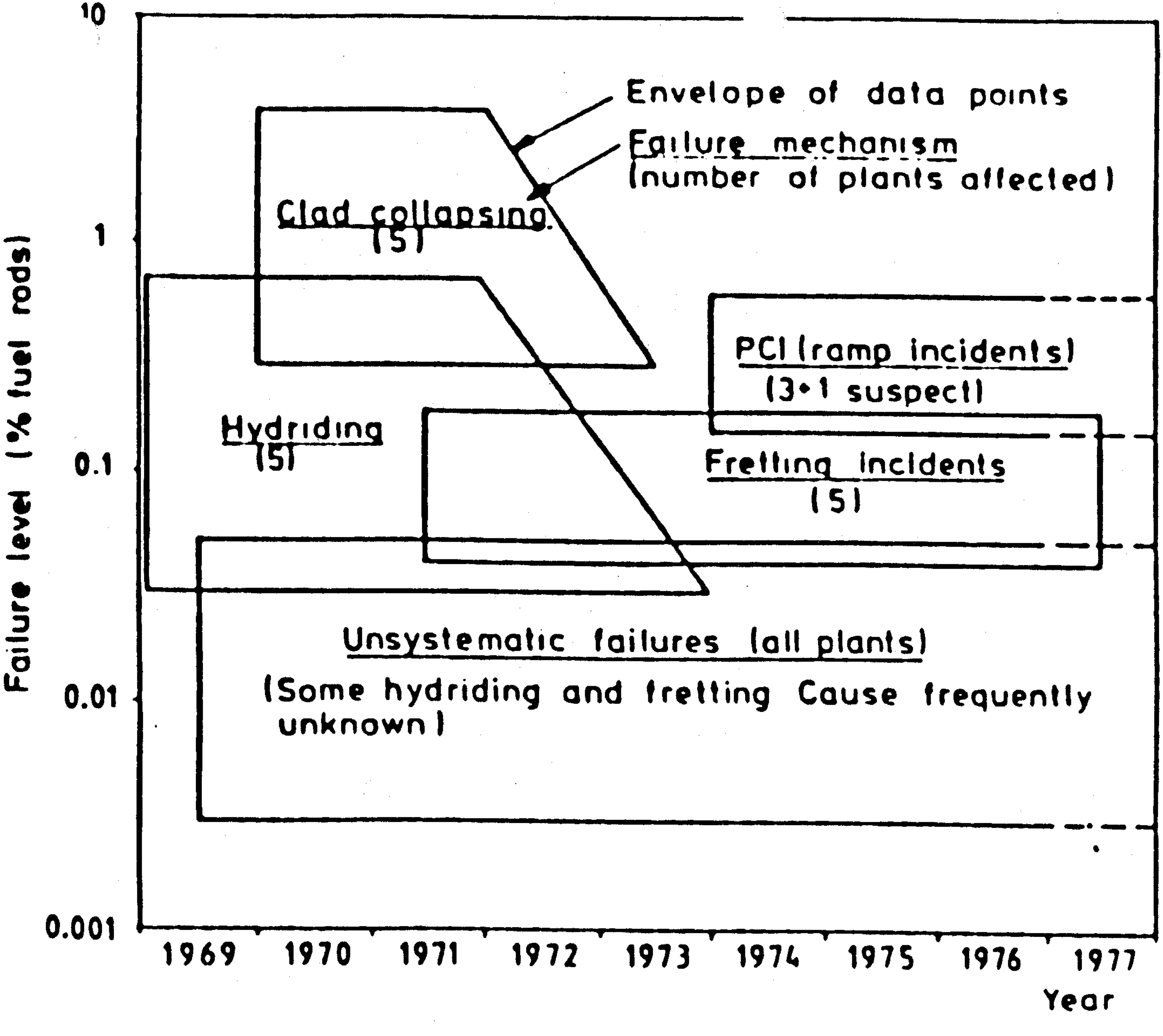

FIG.8. Fuel failure levels in individual PWR plants.

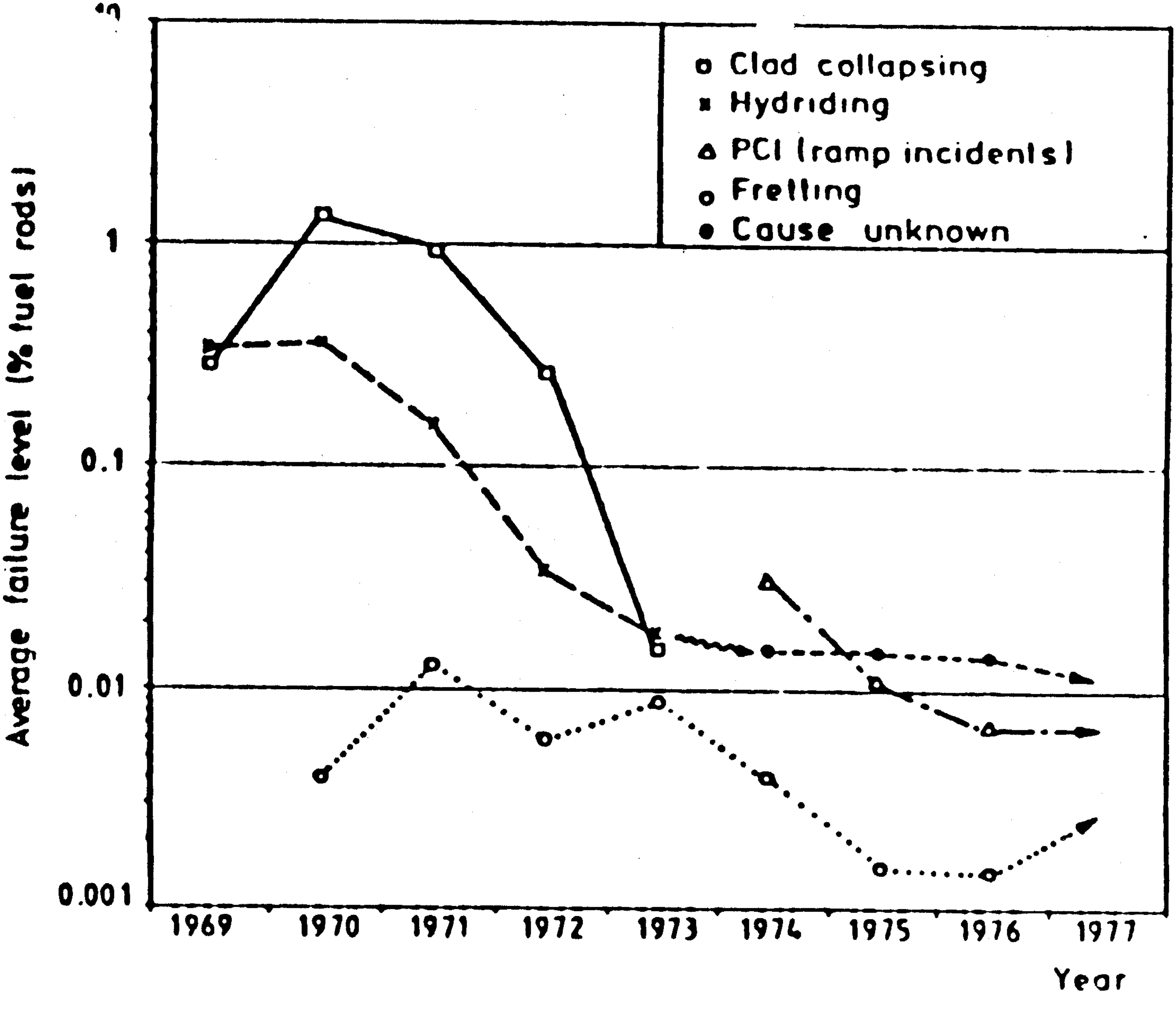

FIG.10. Overall significance of fuel failures in PWR plants.

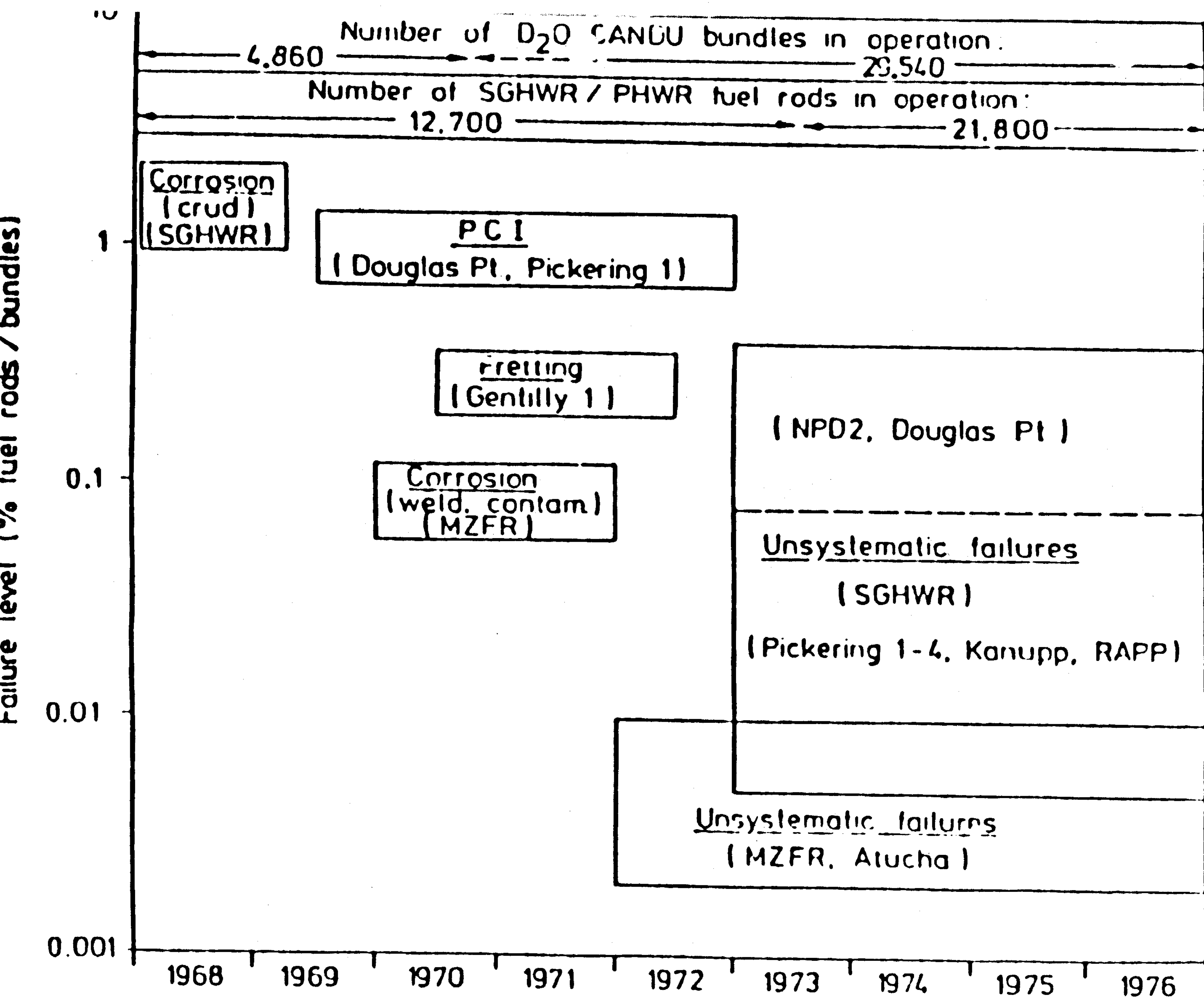

FIG. 7. Fuel performance summary of HWR plants.

TABLE 2.2. FUEL TYPES IN OPERATION (Dec. 1993)

Type of plant	Fuel matrix	No. of plants in operation	Comments
BWR	6 × 6	1	Dodewaard
	7 × 7	2	Tarapur 1+2, derived from 6 × 6 fuel
	8 × 8	69	May have loaded some 9 × 9 or 10 × 10 fuel
	9 × 9	15	Estimated >50% 9 × 9 fuel in core
	10 × 10	3	Estimated >50% 10 × 10 fuel in core
	Others	1	Big Rock Point
total BWR		91	
PWR	14 × 14	26	Plants of several vendors
	15 × 15	29	Plants of several vendors
	16 × 16	8	Siemens plants
	16 × 16[a]	10	Westinghouse and CE plants
	17 × 17[a]	122	Plants of several vendors
	18 × 18[a]	3	Siemens plants
total PWR		197	
WWER	126 hex	26	WWER-440
	312 hex	19	WWER-1000
total WWER		45	
CANDU	19 circ	8	7 in India, 1 in Pakistan
	28 circ	8	Pickering plants in Canada
	37 circ	16	14 in Canada, 1 each in Argentina and the Republic of Korea
total CANDU		32	
Overall total		365	

[a] PWR fuel with 'small' rod diameter.

TABLE 3.1. WORLD AVERAGES OF INSERTED FUEL PER GW(e) INSTALLED CAPACITY (December 1993)

	BWR	PWR	WWER	CANDU
Number of plants in operation	91	197	45	32
Installed capacity, GW(e)	78	192	30	20
Fuel assemblies (bundles)				
Number of assemblies in operation (10^3)	55	33	12	158
Average GW(e)/10^3 assemblies	1.4	5.8	2.5	0.13
Fuel rods (elements)				
Number of rods in operation (10^6)	3.6	8.1	2.1	5.0
Average GW(e)/10^5 rods	2.2[a]	2.4	1.4	0.4

[a] Approximate value for 1993; will decrease in future owing to larger portions of 9 × 9 and 10 × 10 fuel.

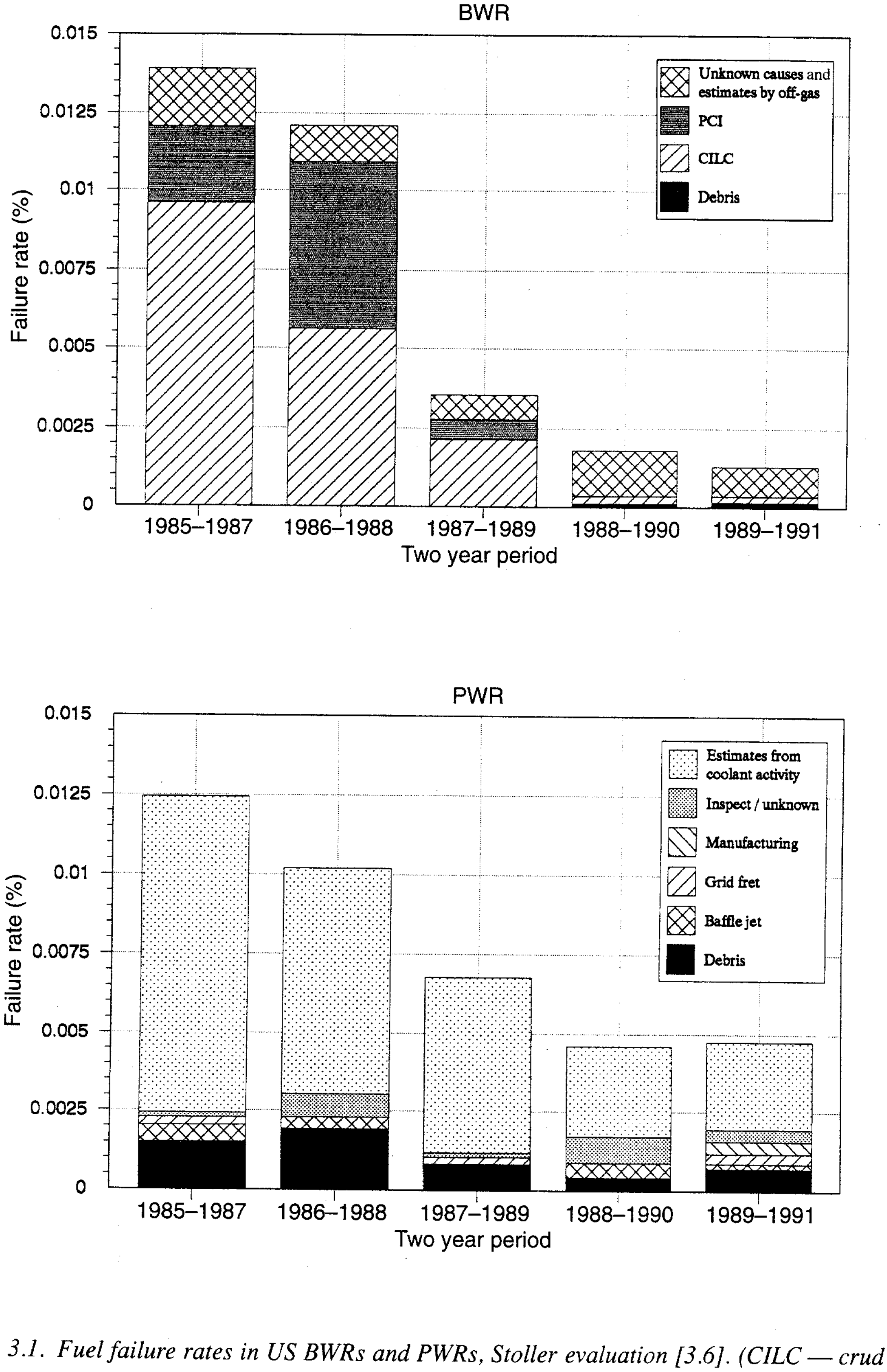

FIG. 3.1. Fuel failure rates in US BWRs and PWRs, Stoller evaluation [3.6]. (CILC — crud induced localized corrosion.)

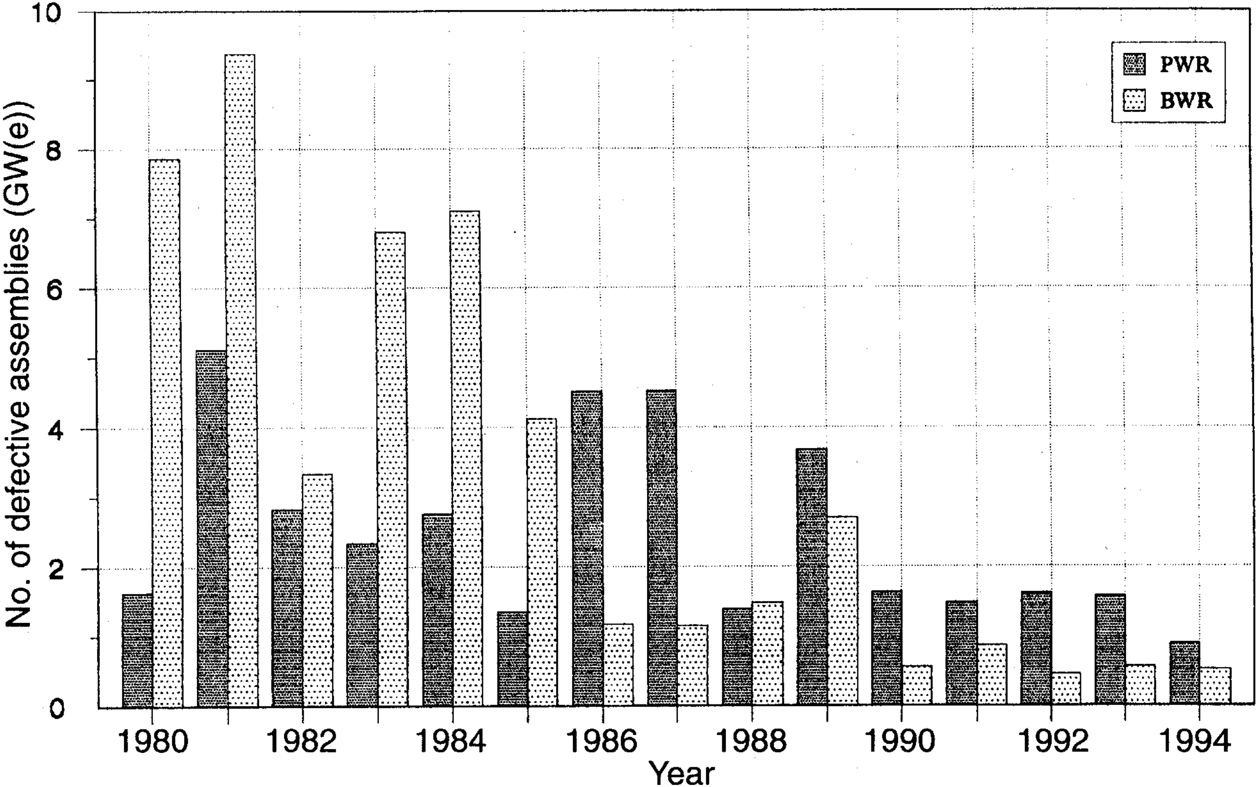

FIG. 3.2. Normalized assembly failure rates in US LWRs, EPRI evaluation.

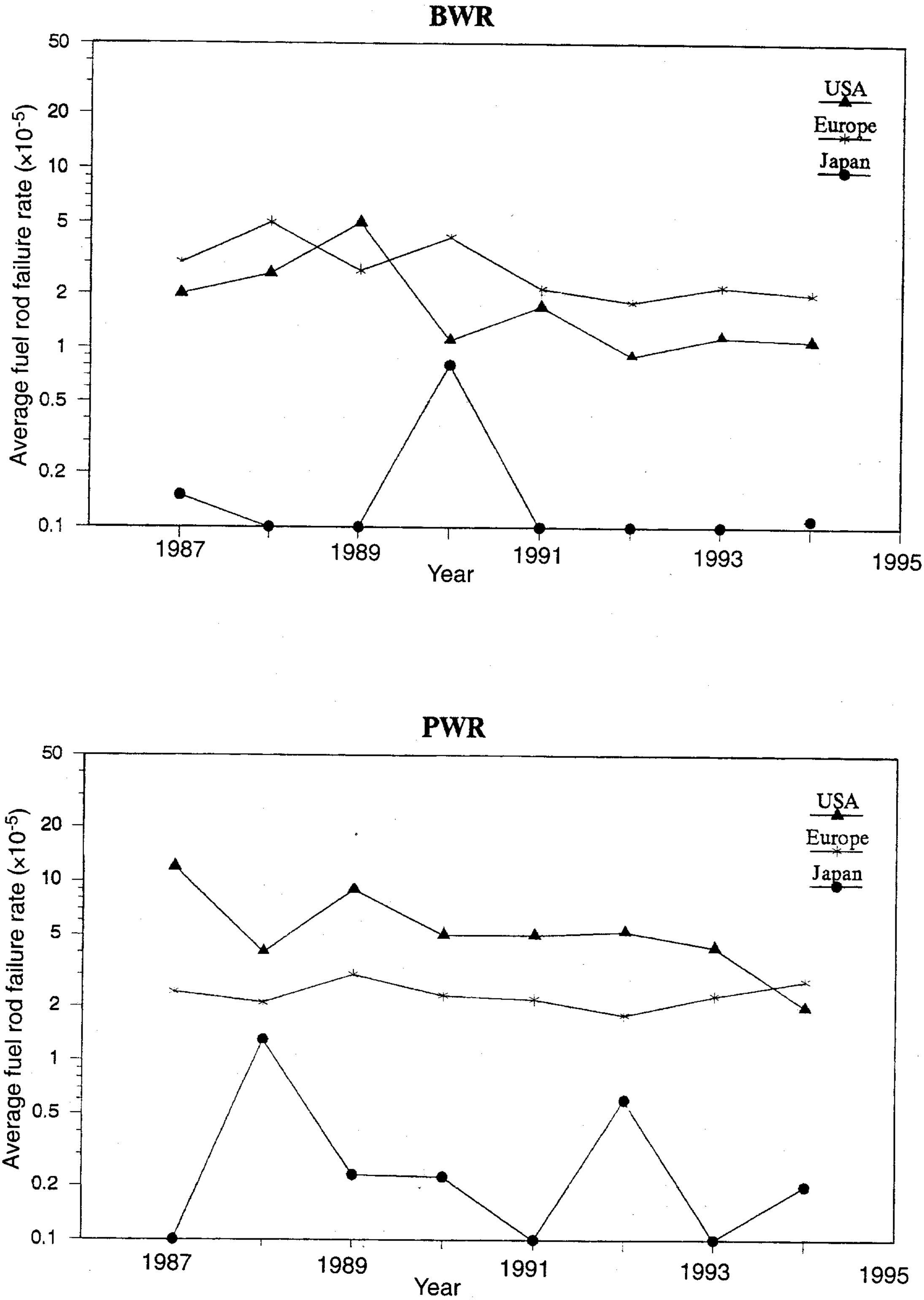

FIG. 3.6. Estimated time evolution of regional average fuel failure rates (BWRs, PWRs, 1987–1994).

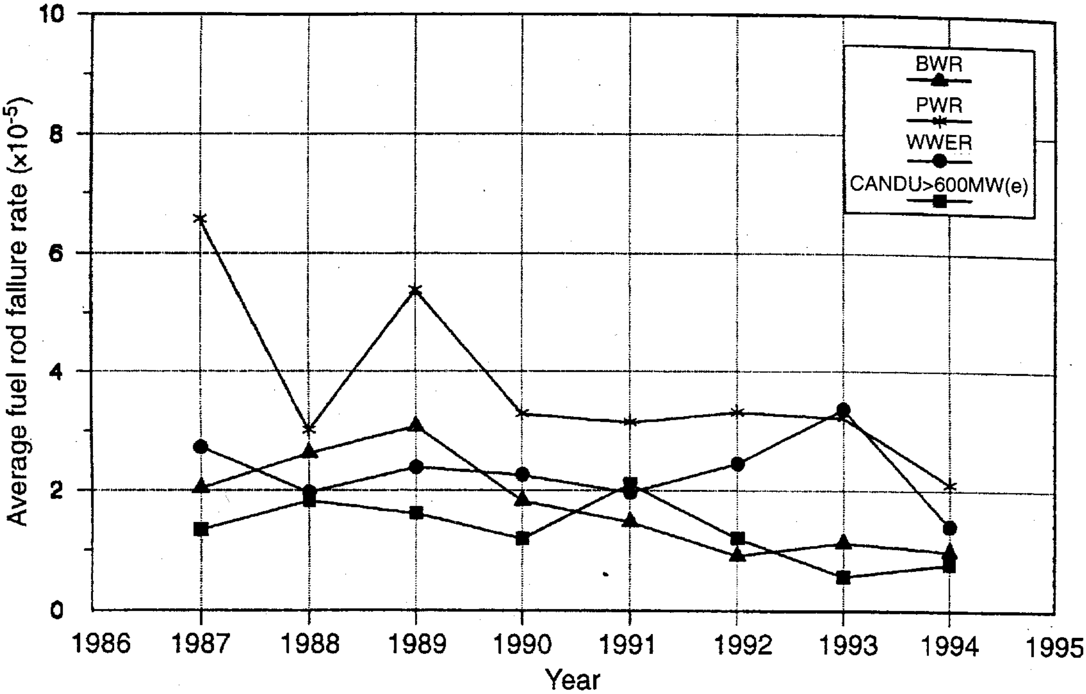

FIG. 3.7. Estimated time evolution of world average fuel failure rates 1987–1994.

TABLE 3.5. ESTIMATED WORLD AVERAGE ANNUAL FUEL ROD FAILURE RATES 1991–1994

	BWR	PWR	WWER	CANDU
Average annual failure rates[a]:				
— failed rods (elements) per 10^5 rods	1.1	2.9	2.3	≈2
— failed rods (elements) per GW(e)	0.5	1.2	1.6	5
— exposed fuel in kgUO_2 per GW(e)[b]	1.5	2.0	2.4	2.5

[a] Calculated from failed assemblies (bundles) assuming:
1.1 leaking rods per failed assembly for BWR, WWER-440 and CANDU;
1.3 leaking rods per failed assembly for PWR, WWER-1000.

[b] Based on typical weight of fuel in one rod (element)
BWR: 3.0 kg (8 × 8 fuel)
PWR: 1.7 kg (17 × 17 fuel)
WWER: 1.5 kg (WWER-1000)
CANDU: 0.5 kg (37 element bundle).