FUEL FAILURES IN COMMERCIAL NUCLEAR POWER REACTORS

for the

Quality Assurance Branch
Directorate of Licensing
U.S. Atomic Energy Commission

by

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June 1974

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I. INTRODUCTION

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Fuel failure data for commercial light water reactors were presented by M. D. Freshley in the FY-1972 report[a] prepared by Battelle Pacific Northwest Laboratories for the Quality Assurance Branch, Directorate of Licensing, USAEC. During FY-1974, the literature (especially that published after mid-1972) was reviewed and over 150 entries of possible interest were located and many of these were examined for relevancy. The previously submitted tables summarizing fuel failure data from commercial boiling water and pressurized water power reactors (plus some heavy water reactors) have been updated. The updated tables (Tables 1 and 2) are shown in Section II and now include entries for 50 reactors.

(a) M. D. Freshley, "VI. Task 5 - Types and Causes of Fuel Failure," Nuclear Fuel Reliability-A Preliminary Study, July 1972.

II. SUMMARY

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Fuel failure data are summarized in Tables 1 and 2.

Through 1973, a total of about two million Zircaloy-clad UO_2 fuel rods have been irradiated in commercial water-cooled nuclear power reactors as described below. Through 1973, General Electric Company has acquired experience with over 10,000 Zircaloy-clad UO_2 fuel assemblies (over 500,000 fuel rods) and less than 1% of the fuel rods have been affected by failure mechanisms.[(a)] GE reported earlier (i.e., for over 440,000 fuel rods), only about 0.2% had been detected as having perforations of the cladding and before the problem of internal hydriding arose, the cumulative percentage of fuel rod failures was 0.1%.[(b)] A total of 450,000 Zircaloy-clad fuel rods, designed and fabricated by Westinghouse Electric Corporation, have been operated in 17 commercial PWRs through the end of 1973 and the number of defected fuel rods (based on coolant chemistry) is on the order of 1/2 to 2 per 10,000.[(c)] As of May 1973, the Canadians have irradiated over 45,000 Zircaloy-clad UO_2 fuel assemblies (50,000 fuel assemblies represents over 10^6 fuel rods) in nine CANDU power reactors and have experienced a failure rate of less than 0.5%.[(d)] Kraftwerk Union AG (KWU) experience includes operation of about 112,000 Zircaloy-clad fuel rods in three reactors (MZFR, KWO, KKS).[(e)]

(a) H. E. Williamson, "Operating Experience with Boiling Water Reactor Fuel," Trans. Am. Nucl. Soc., Vol. 18, pp. 248-249, June 1974.

(b) "Nuclex '72-Report on Technical Meeting, Part 1," Nuclear Engineering International, pp. 1027-1030, December 1972.

(c) T. B. Burley, J. DeStefano, and J. B. Melehan, "PWR Fuel: Experience and Current Development Problems," Trans. Am. Nucl. Soc., Vol. 18, p. 249, June 1974.

(d) J. A. L. Robertson, R. D. Page, and L. L. Bodie, Canadian Fuel Performance, AECL-4520, May 1973.

(e) D. Knödler and H. Stehle, "PWR Fuel Reliability and Quality Assurance," BNES Conference, October 15-19, 1973.

In November 1973, Gulf United Nuclear Fuels Corporation reported that since 1968 they have had more than 20,000 Zircaloy-clad UO_2 fuel rods irradiated in both BWRs and PWRs.[a] Another 20,000 Zircaloy-clad fuel rods were fabricated under Westinghouse license and were installed in an overseas PWR.[b]

Stainless steel-clad fuel rods were used in most early Westinghouse fuel assemblies. With the ~200,000 stainless steel-clad fuel rods irradiated in six PWRs (Yankee, Indian Point-1, Haddam Neck, San Onofre, Chooz, and Trino), the overall defect rate is estimated to be only about 1/10,000 fuel rods.[c]

As of June 18, 1974, there were 46 nuclear plants (represents approximately 6.3% of total U.S. electric generating capacity) with operating licenses, 54 with construction permits, 110 on order, and 12 with letters of intent/options.[d] As of January 1973, the average burnup of all U.S. discharged fuel was 15,000 MWd/MTU, the average burnup of all U.S. fuel curently in core was 4,593 MWd/MTU, and the average burnup of all world-wide discharged Zircaloy-clad fuel was 10,336 MWd/MTU.[e] For Zircaloy-clad fuel and on a world-wide basis as of January 1973, the highest discharge burnup for quantities of fuel of ≥5 MTU was ~23,000 MWd/MTU for BWRs and ~27,000 MWd/MTU for PWRs.[f]

(a) R. B. Holden, N. Fuhrman, and L. Raven, "In-Reactor Densification Experience with Gulf United Fuel," Trans. Am. Nucl. Soc., Vol. 17, pp. 169-170, November 1973.

(b) W. J. Dollard and F. W. Kramer, "Westinghouse Nuclear Fuel Operating Experience," American Power Conference, April 1972.

(c) H. M. Ferrari, "Nuclear Fuel Experience in Westinghouse Pressurized Water Reactors," Trans. Am. Nucl. Soc., Vol. 16, p. 101, June 1973.

(d) Atomic Industrial Forum, INFO Bulletin, June 19, 1974.

(e) Nuclear Assurance Corporation, Nuclear Industry Status, p. 29, January 1973.

(f) Nuclear Assurance Corporation, Nuclear Power Plant Performance, pp. 24-25, January 1973.

TABLE 1. Fuel Failure Summary Categorization

Category	See Item No. in Table 2:
Cladding strain as a result of fuel-cladding mechanical interaction	1c, 1d, 5b, 5g, 16a, 40b, 41d, 42b.
Crud-related fuel failure from accelerated high-temperature corrosion	5c, 6b, 6c, 6e, 44a, 44b.
Internal hydrogenous contaminants	1c, 2a, 2b, 2c, 2d, 2e, 2f, 3c, 5b, 5c, 5f, 5g, 5h(?), 6c, 6e, 7b, 9a, 10b, 11a, 12a, 14a(?), 15a(?), 16a, 16c(?), 18a, 18b, 18c, 26a, 26b, 27a, 27d, 30b, 44a, 44b, 45a, 48a, 49a, 50a.
Manufacturing defects	1a, 1b, 2a, 4d, 5b, 5f, 5h, 5i, 8a(?), 13a(?), 16a, 16c, 16d, 22a(?), 24c, 31a, 32a, 43a, 45a, 47a, 50a.
Fretting and wear	3a, 5a, 5b, 5c, 5d, 5f, 5g, 8a(?), 10b, 18c.
Mechanical damage	20a, 20b, 20c, 20d, 21a(?), 21c, 21e, 21f, 24a, 25a, 31c, 32a, 38a, 40a, 41a, 47a.
Accelerated corrosion from rod bowing	1a.
Stress corrosion cracking	40b, 41c, 41d, 42b, 50a.
Power increase or cycling	40b, 41b, 41c, 41e, 42a, 42c, 46a, 50a.
Design deficiencies	1a, 6g, 13a(?), 21a(?), 21b, 25b, 26a, 26b, 26c, 27d, 27e, 27f, 27g, 27h, 28b, 29b, 30b, 31b, 44b, 45a.
Unknown or type unreported	2a, 2f, 3b, 4a, 5e, 6a, 6d, 6f, 7a, 8a, 10a, 14a, 14b, 15a, 16b, 17a, 19a, 20e, 20f, 21d, 22b, 23a, 24b, 27h, 28a, 29a, 29c, 29d, 29e, 30a, 30c, 30d, 32b, 32c, 33a, 34a, 34b, 35a, 36a, 37a, 39a, 49b.
Other (commercial fuel)	6h, 9b, 27b, 27c, 29c, 44b.
Other (experimental fuel)	4b, 4c, 6f, 44b, 50a.

TABLE 2. Fuel Failure Data for Commercial Boiling Water and Pressurized Water Reactors

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
1a	Dresden-1	BWR	Type 1	Zircaloy-2	33,800	1960	Sept. 1969	Of 77,184 fuel segments, 22 failed (<0.1%). Ten of these failed during fourth operating cycle (May 1965-February 1967).	Five fuel segments failed because of accelerated corrosion due to bowing, five failed because of internal corrosion due to end plug stringers, and 12 failed because of design deficiencies (inadequate space for expansion and fission gas release).	1	Spring, 1971
1b	Dresden-1	BWR	Type III B, III F, V	Zircaloy-2	15,500 (V)	Prior to Sept. 1969	Sept. 1969	Of 400 fuel assemblies, 5 failed. The 5 leakers in 400 assemblies could result from imperfections in 5 out of 13,000 fuel rods (<0.1% defects).	Underwater inspection of 4 of these 5 assemblies revealed no fuel rod failures. The fifth assembly had one fuel rod with a cracked bottom end-plug weld.	1	1971
1c	Dresden-1	BWR	Type III B, III F, V	Zircaloy-2			Sept. 1969 outage	29 fuel assemblies failed (3 Type III B, 19 Type III F, 7 Type V).	Of the fuel rod failures, approximately half due to brittle longitudinal cladding cracks caused by strain localization and half due to internal hydriding.	1-3	Spring 1971, May 1972 and April 1972, resp.
1d	Dresden-1	BWR	Type III B, III F, V	Zircaloy-2			Sept. 1971	Sipping results at end of Cycle 6 (Sept. 1969) indicated 29 leaking fuel assemblies and at end of Cycle 7 (Sept. 1971) another 20 leaking fuel assemblies. In the 49 assemblies, 58 failed fuel rods noted (<0.4% of the 14,472 fuel rods of Type III B, III F, and V reload fuel).	The 58 failed fuel rods had brittle longitudinal cracks characteristic of pellet-to-cladding interaction mechanism (longitudinal crack-strain localization failures)	2,3	May 1972 and April 1972, resp.
2a	Dresden-2	BWR		Zircaloy-2			June 1970	Significant offgas release observed as early as first week of May 1970 during operation and testing at 50% of rated power. A total of 131 fuel assemblies were sipped out of the core and 27 assemblies identified as failed on basis of sip signals. Two other fuel assemblies remained out of core on basis of visual inspection results.	Four fuel assemblies disassembled and fuel rods examined. Defects observed were minor and were primarily small blisters on individual rods. The blisters indicate highly localized chemical reaction in the cladding; the localized points of reaction are brittle. Some failed fuel was located in areas of the core considerably removed from the high probability suspect areas defined by flux tilting. Cause of the fuel failures has not been determined at this time, but it is most likely due to an abnormal condition introduced during fuel manufacturing. The 29 defective fuel assemblies were replaced with identical new assemblies that had been fabricated for Dresden-3.	31	July 1970

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
2b	Dresden-2	BWR		Zircaloy-2			March 1971	Off-gas began increasing in May 1970. In March 1971, 215 fuel assemblies removed.	Investigative work in June 1970 indicated that leaky fuel rods were caused by zirconium hydriding from inside of the fuel rod due to an unidentified hydrogenous material from an unidentified source. The 215 fuel assemblies were removed based on their confirmed leakage, other suspicious data, or statistical evaluation performed to determine potential leakers.	57	June 1971
2c*	Dresden-2	BWR		Zircaloy-2	~4,800	Oct. 1969	Sept 1971	Of 724 fuel assemblies, 69 identified as leaker assemblies and the prospect exists of considerable additional failures or incipient failures still remaining in core.	Early-life failures caused by internal hydriding caused by an initial hydrogen impurity inadvertently introduced during fabrication. The specific impurity or exact means of introduction could not be determined. Initial fuel load was not vacuum outgassed.	2,3	May and April 1972, resp.
2d	Dresden-2 (Cycle I)	BWR		Zircaloy-2		Dec. 1969	June 1970	28 leaker assemblies; of the 28 assemblies, 19 each had at least 1 perforated fuel rod, 4 each had at least 1 defective fuel rod, and 5 each had at least 1 questionable fuel rod. It was estimated early in 1971 that 60-70 fuel assemblies were causing the off-gas problem.	Internally initiated, localized hydriding of cladding caused by some unspecified hydrogenous impurity or impurities (trace amounts of alcohol and other hydrocarbons found) most likely introduced in the manufacture.	7	Nov. 1973
2e	Dresden-2 (Cycle IA)	BWR	Dresden-2; Dresden-3 replacements	Zircaloy-2		Aug. 1970	Feb. 1971	41 of 668 sipped fuel assemblies identified as leakers. 35 of the 37 Dresden-1 type and 4 of 4 Dresden-2 type fuel assemblies each had at least 1 perforated fuel rod.	Fuel rod failures caused by hydrogenous impurities introduced during manufacture.	7	Nov. 1973
2f	Dresden-2 (Cycle II)	BWR	CY, DN	Zircaloy-2		May 1971	Feb. 1972	Of 239 fuel assemblies sipped, 2 of the 215 CY type and 1 of 7 DN type fuel assemblies were identified as leakers. Questionable fuel rods (7 no.) and 5 defective fuel rods were replaced with other sound discharged fuel rods.	2 of 5 defective rods revealed blisters of type attributed to internal hydriding; other 3 showed nothing unusual.	7	Nov. 1973
2g	Dresden-2 (Cycle III)	BWR		Zircaloy-2	7,945 (Aug. 1973)	May 1972	(after Sept 1973)			7	Nov. 1973

* In entries 2c, 5a, 5b, 9a, 10b, 11a, 12a, 14a, and 15a combined, 10% of the fuel assemblies leaked which was 0.7% of the total(1) number of rods irradiated.

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
3a	Garigliano	BWR	Type A	Zircaloy-2	24,700	1963	Dec. 1969	Of 11,502 fuel segments, one failed.	One fuel assembly with a failed fuel rod was detected and removed during summer 1968 shutdown. Failure due to cladding fretting caused by a broken in-core chamber and was thus unrelated to the fuel performance.	1	Spring 1971
3b	Garigliano	BWR	Type A	Zircaloy-2	>18,000		June 1970	3 leaky fuel assemblies identified by sipping.	The 3 Type A fuel assemblies had exceeded their design exposure by several thousand MWd/Te. Failure type unknown.	2	May 1972
3c	Garigliano	BWR	Type 5A		>10,000	1968	June 1970	4 leaky fuel assemblies identified by sipping.	The 4 Type 5A fuel assemblies exhibited characteristics of early-life hydride failures.	2	May 1972

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
4a	KAHL	BWR		Zircaloy-2	~1,400	1960	Aug. 1968	Core contained 1368 fuel segments; 2 leaky fuel assemblies reported.	Visual examination did not reveal any cladding perforations. Failure type unknown.	1	Spring 1971
4b	KAHL	BWR	Twisted tape	Zircaloy-2		June 1961		1 fuel rod in 1 experimental assembly failed at 9100 MWd/MTM.	Rod defect not typical for twisted tape assembly as such (hydriding defect). Zry-2 tapes are subject to hydrogen embrittlement due to small thickness.	9	May 1971
4c	KAHL	BWR	Boiling superheater bundles	Austentic steel, Inconel, etc.	8,300		1970	1 of 4 bundles failed at burnup (max.) of 3100 MWd/MTM.	Burnout defect on one fuel rod was encountered during a start-up operation and was caused by axial bowing. Vibration also a factor.	9	May 1971
4d	KAHL	BWR		Zircaloy				Very few fuel failures reported by ASEA-Atom.	A batch of fuel developed leaks in top end-plug welds due to faulty TIG welding procedure and "is only known case of failures in commercially delivered fuel fabricated by ASEA-Atom."	10	Dec. 1972
5a*	Gundremmingen-1 (KRB)	BWR	Type A	Zircaloy-2		1966	July 1967	10% of the fuel assemblies gave some indication of leaking. One failed rod found in each of three fuel assemblies inspected.	The 3 fuel rod failures were caused by fretting wear of cladding due to presence of foreign material (demister wires) in fuel assemblies.	1	Spring 1971
5b*	Gundremmingen-1 (KRB)	BWR	Type A	Zircaloy-2	~17,100	1967	1969	Approximately 20% of the fuel assemblies gave some indication of leaking. The detailed examination revealed 127 failed rods out of the 13,140 in the reactor. These 127 rods plus the 3 defective rods detected in 1967 make a total of 130 in-service failures out of original core loading of 13,248 rods (i.e., <1%).	Approximately one-half of the failures were due to fretting wear (by demister wires), one-fourth were due to tube flaws introduced during fabrication (led to strain localization), and one-fourth were due to attack by internal impurities (i.e., internal hydriding).	1	Spring 1971
5c	Gundremmingen-1 (KRB)	BWR	Initial Core	Zircaloy-2	8,500 (average)	Nov. 1966	mid-1969	140 bundles repaired; actual defective rods amounted to ~1% of whole charge.	Five types of defects revealed: fretting corrosion caused by small wires, crater shaped holes; bulges, partly with cracks; longitudinal cracks; and end-plug failures. Crater-shaped holes typical evidence of local hydriding, originating from the inside; bulges and bulges with cracks considered to be early stage of this type of defect. End-plug defects (secondary defects) predominantly found on fuel rods with other defects. Accelerated corrosion observed in some cases at KRB, especially close to spacer contact points, and due to copper content of primary water.	9, 49	May 1971 and Nov. 1972, resp.

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
5d	Gundremmingen-1 (KRB)	BWR	Initial core and second core.	Zircaloy-2	12,000	mid-1969	June 1971	3defective bundles identified.	Investigation of one bundle showed failures still being caused by little wires and moving within the circuit.	9	May 1971
5e	Gundremmingen-1 (KRB)	BWR	Type A	Zircaloy-2	~22,400	1960	June 1971	100% of core sipped and 26 leaky fuel assemblies identified.	Failure type unknown; fuel assemblies had not been examined in detail yet.	2, 3	May 1972 and April 1972, resp.
5f	Gundremmingen-1 (KRB)	BWR	Type A	Zircaloy-2		1960		Operated with leaking fuel for about 2 years.	Hydride-caused fuel failures in production pellet fuel were first encountered by GE in the initial core fuel of the KRB reactor. Examination of fuel after a few months of operation had disclosed only cladding penetration due to fretting wear by extraneous material trapped in the spacer. Examinations of fuel subsequently produced and irradiated showed evidence in the failed fuel of an undetected variability in production (outgassing).	3	April 1972
5g	Gundremmingen-1 (KRB)	BWR						Number of leaker bundles has decreased from 18% to 8% which amounts to approximately 0.1% of fuel rods experiencing cladding failure. History of leaking fuel elements:	Fuel performance has followed typical BWR problems which include three failure mechanisms: mechanical failure caused by cladding abrasion caused by extraneous wires from the steam separator, cladding hydriding failures, and UO_2-Zircaloy interaction.	10	Dec. 1972
							Cycle 1	67 leaking fuel elements, 29 repaired and returned to service			
							Cycle 2	33 leaking fuel elements, of which 6 were repaired fuel elements			
							Cycle 3	38 leaking fuel elements, of which 4 were repaired fuel elements			
							Cycle 4	31 leaking fuel elements.			
5h	Gundremmingen-1 (KRB)	BWR	Initial core	Zircaloy-2				Wet sipping tests used to detect defected fuel bundles after each cycle.	Hot cell examinations carried out with established methods always showed localized hydride attack in vicinity of the questionable area of cladding. Thus, question of whether primary or secondary hydriding caused the cladding defect remains still unanswered. Main area of interest on the question was the original moisture content of first core fuel. "Historical" approach failed because the moisture had not been measured during manufacturing of first core fuels for KRB and KWL.	37	Oct. 1973

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
5i	Gundremmingen-1 (KRB)	BWR	First Core	Zircaloy-2				Fuel bundle failure rates of first core fuel have been nearly constant through 4 operating cycles.	Data indicate no systematic influence of burnup on fuel failure rate. Failure rate of KRB/KWL first core fuel increases with increasing linear rod power. Overall statistical behavior and fact that absolute failure rate is much lower with later fuel batches, rather indicate that these failures were due to substandard fuel quality. Power changes due to fuel shuffling were found to have no influence on the fuel reliability.	39	Oct. 1973
6a	Big Rock Point	BWR	Type B	Zircaloy-2	~29,500	1967	1969	Prior to April 1969, there were no known failures and there were two suspected leakers in Type B fuel assemblies.	Failure (?) type unknown.	1	Spring 1971
6b	Big Rock Point	BWR	Type B and Type E	Zircaloy-2	~29,500	1967	1969	During April 1969 refueling outage, dry sipping revealed 7 leaky fuel assemblies (4 Type B and 3 Type E). Inspection of 2 Type B and 2 Type E leaker fuel assemblies revealed 5 and 9 failed fuel rods, respectively. (Also noted were 8 failed fuel rods in centermelt development fuel assembly D-50.)	The observed fuel rod failures were of the same character in all fuel types inspected and were limited to ≤20 in. of active fuel length in any given rod. The fuel rod failures resulted from heavy buildup of crud scale that caused the cladding surfaces to overheat to abnormally high temperatures (i.e., accelerated corrosion due to crud).	1	Spring 1971
6c	Big Rock Point	BWR	Type B Type E Type EG	Zircaloy-2 Zircaloy-2 Zircaloy-2	~35,400 ~15,500 ~15,600	1967 1968 April, 1969	Feb. 1970 Feb. 1970 Feb. 1970	100% of the core sipped and 19 leaky fuel assemblies identified (5 Type B, 11 Type E, 3 Type EG).	Examination of the Type B and E leaker assemblies indicated failures are predominantly crud-related (i.e., accelerated corrosion due to crud). The Type EG fuel failures gave indication of early-life hydriding.	2	May 1972
6d	Big Rock Point	BWR		Zircaloy-2		Jan. 1971	June 1971	Several fuel assemblies failed.	Premature failure of several E fuel assemblies.	22	Aug. 1971
6e	Big Rock Point	BWR	Type B Type E Type EG	Zircaloy-2 Zircaloy-2 Zircaloy-2		1967 1968 April, 1969	Feb. 1971 Feb. 1971 Feb. 1971	100% of the core sipped and 17 leaky fuel assemblies identified (5 Type B, 11 Type E, and 1 Type EG).	Examination indicated that the Type B and E leaker assemblies are predominantly of the character of the crud-related failures previously described (i.e., accelerated corrosion due to crud). The Type EG failures appeared to be divided roughly between crud-related and early-life hydride failures.	2	May 1972
6f	Big Rock Point	BWR				Jan. 1972	June 1972	31 of 84 fuel assemblies were found to have failed.	The failed fuel assemblies consisted of 4 types of experimental fuel bundles.	20	Aug. 1972

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
6g	Big Rock Point	BWR					March 1973	Cobalt target rods in 4 fuel assemblies became unlocked.	Fuel inspection determined that several of the cobalt target rods had become unlocked in four fuel assemblies. The loose cobalt rods were removed and the fuel assemblies recharged into outer rows in the core. Analysis shows power peaking will not occur; also change in flow distribution will not have a large effect. Unlocking resulted from insufficient force in the spring that locked the rods in position. Modification made that increases force required to unlock target rods (i.e., installed auxiliary spring which has locking force of 18 lb).	26, 27	March and April 1973, resp.
6h	Big Rock Point	BWR	E	Zircaloy-2				1 failed fuel rod.	Tie rod from "E" type fuel bundle unexpectedly found on spent fuel pool.	8	Nov. 1973
7a	Humboldt Bay-3	BWR	Type II	Zircaloy-2	~21,400	1965	1969	3 leaky fuel assemblies detected by sipping.	Failure type unknown. The 3 leaker fuel assemblies had exceeded their design exposure.	2	May 1972
7b	Humboldt Bay-3	BWR	Type III	Zircaloy-2	~14,300	1969	1969	11 leaker fuel assemblies identified.	The failed fuel rods in the leaker fuel assemblies exhibit the characteristics of early-life hydride failures.	2	May 1972
8a	Tarapur-1	BWR		Zircaloy-2	~13,700	May 1969	Oct. 1971	100% of core (568 fuel assemblies) sipped and 25 leaky fuel assemblies identified.	Failure type unknown; no detailed examination performed yet. Two possible causes mentioned: (1) fretting wear by steam separator wires, or (2) fuel fabricated prior to introduction of vacuum outgas process step during fabrication.	2	May 1972
9a*	Oyster Creek-1	BWR		Zircaloy-2	~12,000	June 1969	Sept. 1971	100% of core (560 fuel assemblies) sipped and 44 leaky fuel assemblies identified.	Fuel rod failures identified predominantly had characteristics of early-life hydride attack. Of the 44 leaker fuel assemblies, 20 were repaired (i.e., failed rods replaced) and recharged into reactor.	2	May 1972
9b	Oyster Creek-1	BWR		Zircaloy-2		Dec. 1969	June 1973	100% of core (560 fuel assemblies) sipped during each outage. Bundle failure (activity release to coolant) is due to only a few perforated rods among the 49 in an assembly. Fuel rod failure rate was <0.5%, even for earliest cycles.	Relationship between fuel assembly and fuel rod failure frequency indicates some positive correlation in fuel rod behavior within an assembly. Observed clustering of failures is felt due to similarity in operating environment within an assembly rather than casual failure interaction mechanisms between rods.	46	June 1973
10a	Nine Mile Point	BWR		Zircaloy-2		Jan. 1971	June 1971	Above-normal off-gas activity indicated increasing fuel-rod leakage.	Maximum reactor power will be limited until fuel is replaced.	25	June 1971

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
10b*	Nine Mile Point	BWR		Zircaloy-2	~8,400	Sept. 1969	Sept. 1971	100% of core (532 fuel assemblies) sipped and 38 leaky fuel assemblies identified.	The leaker fuel assemblies showed predominant failure characteristics of early-life cladding hydride attack; however, 10 of the leaker assemblies had fuel rod failures attributed to fretting wear from debris trapped in spacers. Of the 38 leaker fuel assemblies, 22 were repaired (failed rods replaced) and 14 of the 22 recharged into reactor.	2	May 1972
11a*	Tsuruga	BWR		Zircaloy-2	~12,000	Dec. 1969	Sept. 1971	Sipping has identified leaker [illegible] assemblies.	The failed fuel rods have the characteristics of the early-life hydride failures observed in other reactors with nonoutgassed fuel. The initial core fuel in Tsuruga was not vacuum outgassed.	2	May 1972
12a*	Fukushima-1	BWR		Zircaloy-2	~4,400	Nov. 1970	Sept. 1971	Sipping identified 8 leaky fuel assemblies in the core (has 400 fuel assemblies).	The fuel rod failures experienced were early-life hydride type (i.e., internal hydriding).	2	May 1972
13a	Fukushima-2	BWR		Zircaloy-2					Mechanical interference between fuel-bundle channels and control blades was found.	69	Jan. 1973
14a*	Millstone Point-1	BWR		Zircaloy-2	~5,300	Nov. 1970	Sept. 1971	Offgas trend suggests some fuel rod failures exist in the core (has 508 fuel assemblies).	Failure type unknown; no fuel inspection to date. The fuel rod failures are suspected to be early-life hydride failures. Only a portion of the initial core fuel assemblies contain fuel rods which have been vacuum outgassed.	2	May 1972
14b	Millstone Point-1	BWR		Zircaloy-2	7,300 (average)		Sept. 1972 (Cycle 1)	Of 112 fuel assemblies discharged, 105-110 leakers determined by sipping out of core.	No visual inspection results available yet.	16	Jan. 1973
15a*	Monticello	BWR		Zircaloy-2	~3,900	Feb. 1971	Sept. 1971	Offgas trend suggests that some fuel rod failures have occurred in the core (has 484 fuel assemblies).	No fuel inspection performed yet. Fuel rod failures probably due to early-life hydriding. Initial core fuel loaded in Monticello was not vacuum outgassed during fabrication.	2	May 1972
16a	[illegible]ngen (KWL)	BWR		Zircaloy-2		May 1968	August 1970	46 rods (defective or at least suspect) withdrawn from 26 bundles. 139 fuel rods (some sound) from an addition 51 bundles also withdrawn. KWL assumed to have 1% defect rate.	Defects classified in following manner: 38% crater-shaped holes; 56% bulges, partly with cracks; 2% longitudinal cracks; and 4% end-plug failures. KWL fuel rods did not collect any crud (primary circuit contains only stainless steel). Definite relationship between magnitude of sipping signal, the burnup, and number of defective fuel rods in a bundle (see Table 5 in report).	9	May 1971
16b	Lingen (KWL)	BWR	Initial Core	Zircaloy-2		1968	1970	About 1% of the fuel rods of the initial core failed.	Predicted burnups were obtained in a satisfactory manner but the mechanical performance of the fuel was not satisfactory.	49	Nov. 1972

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
16c	Lingen (KWL)	BWR	Initial Core	Zircaloy-2		1968		Wet sipping tests used to detect defected fuel bundles after each cycle.	See entry (5h) under Gundremmingen-1 (KRB).	37	Oct. 1973
16d	Lingen (KWL)	BWR	Initial Core	Zircaloy-2		1968		Fuel bundle failure rates of first core fuel have been nearly constant through 3 operating cycles.	See entry (5i) under Gundremmingen-1 (KRB).	38	Oct. 1973
17e	Gentilly-1	BLWR				May 1972	May 1973	Of 3,214 bundles, few (about 14) are known to have developed leaks.		13	May 1973
18a	Vermont Yankee	BWR		Zircaloy-2		March 1972		Because of excessive gaseous release activity levels, power level was reduced until mid-January 1973 shutdown. Vendor indicated possibility that 183 fuel rods out of 18,392 could fail.	Cause of activity release is believed to be fuel cladding perforations due to internal hydriding of the zirconium. Cause of hydriding is excessive moisture in fuel rod as a result of inadequate vacuum outgassing during fuel rod fabrication.	53	Dec. 1972
18b	Vermont Yankee	BWR		Zircaloy-2			Feb. 1973	54 of 368 fuel assemblies identified as leakers by sipping. Of the 54, 51 had perforated and/or defective fuel rods (an average of 7 rods per assembly). 370 defective fuel rods in 51 leaking assemblies have been replaced.	Cause of failure is thought to be internal hydride attack of the Zircaloy cladding. In 8 fuel assemblies which showed no indication of failure by sipping, examination revealed that an average of 4 fuel rods per assembly were defective.	60, 68	April and Feb. 1973, resp.
18c	Vermont Yankee	BWR		Zircaloy-2			1973	Of 368 fuel assemblies, 14 fuel assemblies were hydrided. Of 53 fuel channels, 19 had cracks, holes, and worn spots.	Hydriding noted on 14 fuel assemblies. Temporary neutron-poison curtains believed to have vibrated and rubbed against channels because of rapid water flow. 100 fuel channels were replaced because of wear holes and cracks; flow holes in channels were plugged.	43	Jan. 1974
19a	Quad Cities-1, -2	BWR		Zircaloy-2		Oct. 1971 and April 1972, resp.	July 1973	Release rate for ^{131}I, exceeded several times during a 5-day period.	Defective fuel elements will be replaced during upcoming refueling outage.	64	July 1973
20a	LaCrosse (Genoa)	BWR					June 1969		Fuel rods of 2 assemblies found to be bowed in bottom quarter. Bowing of one may be enough to affect future behavior. Cause of bowing not known—unless locked-in tube-drawing stresses were released by tubes standing in 540°F water.	19	June 1969
20b	LaCrosse (Genoa)	BWR					Nov. 1969		Bowed fuel rods in 13 fuel assemblies. Bowed fuel rods on side of assembly adjacent to fully withdrawn control rods.	19	Nov. 1969
20c	LaCrosse (Genoa)	BWR					1970		Several fuel elements removed from reactor had fuel rods that were significantly bowed.	55	April 1970

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
20d	LaCrosse (Genoa)	BWR				May 1969	Nov. 1970		Bowing of fuel pins first observed in May 1969. 1969. It was determined that shroud locking rings had been unlocked during previous operation. This condition caused the fuel elements to be improperly seated and produced twisting and stressing of the fuel elements.	56	Jan. 1971
20e	LaCrosse (Genoa)	BWR					August 1972	Fission product leakage occurred in several fuel elements. One fuel rod was severed.	The fission product leakage resulted in a stack release of ^{131}I in excess of technical specification limits. Inspection of one fuel element (No. 64) revealed a severed fuel rod.	58	August 1972
20f	LaCrosse (Genoa)	BWR					Dec. 1972	5 fuel elements may have cladding failures.	When failed-fuel-element-detection system placed in service, results indicated that cladding failures may have occurred on 5 fuel elements.	57	Dec. 1972
21a	Yankee Rowe	PWR		Zircaloy			1966	2 assemblies removed	Two Zircaloy-clad test assemblies removed in 1965 because of grid and clip failures. Corrections were made to later test assemblies.	17	March 1969
21b	Yankee Rowe	PWR		Zircaloy			Aug 1969		Removal of 4 Zircaloy-clad test fuel assemblies proposed because inspection indicates length change of fuel rods greater than expected.	21	Aug. 1969
21c	Yankee Rowe	PWR					August 1969	1 fuel assembly damaged.	Crane operator mispositioned spent fuel assembly and damaged fuel assembly and refueling equipment.	28	Sept. 1969
21d	Yankee Rowe	PWR		Stainless Steel	~46,000	1960	1971	Possibility of only one pinhole sized leak.	Failure (?) type unknown. Reactor coolant activity seems to indicate that the pinhole had either sealed itself or that no defect has existed and activity increase represented some uranium contamination on the fuel rod surface.	4	April 1972
21e	Yankee Rowe	PWR					Oct. 1972	1 damaged fuel assembly will not be reused; the fuel assembly was not ruptured.	When upper core barrel was lifted, a fuel assembly stuck to it and was lifted 6 ft above core. While trying to reinsert fuel assembly, it was dislodged and fell several inches to top of core adjacent to its original position. Upper nozzle and upper fuel assembly wrapper sheet were damaged. The fuel assembly will not be reused. The hang-up was caused by a small foreign object locking the assembly in place; marks were found on the upper core-support plate.	62, 73	Dec. and Nov. 1972, resp.
21f	Yankee Rowe	PWR	Core X				March 1973	1 fuel assembly slightly damaged.	The fuel assembly was slightly damaged while the upper core barrel was being removed. A new pressurized fuel assembly was used as the replacement.	54	March 1973

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
22a	Haddam Neck (Connecticut Yankee)	PWR					May 1970	2 fuel assemblies.	Fuel assembly difficult to latch; examination showed radial vane of spider assembly, which holds absorber rods, broken from spider. A second fuel assembly was also found to have another severed vane.	[illegible]	[illegible]
22b	Haddam Neck (Connecticut Yankee)	PWR		Stainless Steel	~40,000	Prior to March 1970	April 1971	Coolant activity indicates existence of a few leaking fuel rods since the first reactor cycle.	Fuel failure type unknown.	4	April 1972
23a	San Onofre	PWR		Stainless Steel	~34,000			Coolant activity implies existence of one or two leaking fuel rods during second operating cycle.	Visual examination of fuel discharged during second refueling outage disclosed two damaged fuel rods, which corroborated radiochemistry results. No other anomalies were found.	4	April 1972
24a	Indian Point-1	PWR					Aug. 1970	1 fuel assembly with broken top nozzle.	After loading a spent fuel assembly into shipping cask and while trying to disengage the loading tool which would not release, the top nozzle was broken from the fuel assembly. Fuel rods were not damaged. Cause of nozzle and grapple failures is being investigated.	23	Aug. 1970
24b	Indian Point-1	PWR		Stainless steel	~30,000	Jan. 1965	April 1972	Coolant activity has indicated the existence of one or two leaking fuel rods.	Failure type unknown.	4	April 1972
24c	Indian Point-1	PWR	Core B	Stainless Steel	23,150 (core region average)	April 1966		Top nozzles on two fuel assemblies became separated from the perforated stainless steel cans.	In both cases, tack welds holding the can to the nozzle failed during refueling and spent-fuel cask loading operations.	48	June 1973
25a	Jose de Cabrera	PWR		Zircaloy-4	~30,000	1968	1971	One peripheral fuel assembly had 2 broken fuel rods and one severely damaged rod.	Damage was confined to one corner of the fuel assembly. No evidence of fuel leakage or loss of integrity was found in remainder of core. Detailed examination indicated cause was most probably the result of mechanical damage sustained by one or two grids in the affected fuel assembly prior to plant operation, which allowed excessive vibration leading to subsequent failure of fuel rods.	4	April 1972
25b	Jose de Cabrera	PWR		Zircaloy-4			Cycle 1 (June 1971)		During Cycle 1 refuelling, a large number of fuel rods were observed to be in interference with the top nozzles and a few of these rods were bowed. Rod interference and bowing were due to larger-than-expected Zircaloy growth during irradiation.	45	June 1973

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
26a	Beznau-1	PWR		Zircaloy-4	~19,000	June 1969	June 1971	Chemical analysis indicated coolant activity in Sept. 1969 due to fuel leaks (0.8%).	Direct and TV visual examinations plus individual fuel assembly leak tests disclosed that leaks came from one core region (Region 3) and tended to confirm previous postulate that localized cladding hydriding resulting from excessive moisture in fuel pellets was cause of fuel rod defects. Observations also disclosed a number of rods in various Region 2 fuel assemblies with collapsed sections (1/2- to 2 1/2-in. long) but no indication of leaks in any of the fuel assemblies containing collapsed fuel rods.	4	April 1972
26b	Beznau-1	PWR		Zircaloy-4		1971		0.8%, based on primary coolant activity early in first cycle, completed cycle (additional 600 days) with no further defect indications.	Study, without visual examination, indicated most probable cause to be internal hydriding due to moisture which was later confirmed. Prior to this, modifications in fuel production had been introduced to eliminate this since it had been expected. In addition, observations of spent fuel assemblies showed small number of rods with short sections collapsed (but no leak indications); majority of these assemblies left in for second cycle operation.	10	Dec. 1972
26c	Beznau-1	PWR		Zircaloy-4			1971		Prior to 1971, Westinghouse reactors had not experienced fuel rod flattening. Flattened fuel rods were first detected in Region II of Beznau-1 during the Cycle I refueling in 1971. A single flattened length of 0.6-3.0 in. in the upper 40% of the fuel column length was observed in approximately 2% of the rods in Region II. Fuel rods in Regions I and III exhibited no flattening at that time; however, a small fraction of the Region I fuel rods were found to be flattened during the recent Cycle II refueling. All cladding flattening observed to date has occurred in unpressurized fuel rods. Fuel densification and axial settlement were identified as cause of gap formation in fuel columns which led to flattening of cladding because of thermal- and irradiation-enhanced creep of the cladding under the coolant pressure. Cladding flattening is expected at higher exposures in some of the earlier designs of prepressurized fuel rods since the pressure levels are predicted to be too low to prevent cladding flattening.	33	Oct. 1973

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
27a	Ginna	PWR		Zircaloy-4	~25,000	Nov. 1969	March 1971	Coolant activity increases observed in March 1970. Leaks were confined to 12 fuel assemblies in Region 3. Replacing the 12 leaker assemblies with fresh ones reduced activity to about half the level prior to outage.	Leaky fuel assemblies identified by visual examinations and leak testing. Evaluation of observations suggested local hydriding resulting from fuel-contained moisture as the likely cause of the leaks;[4] it was later confirmed that source of leaks was moisture contained in the fuel.	4, 24	April 1972 and Sept. 1971, resp.
27b	Ginna	PWR		Zircaloy-4			Oct. 1972	End plug separated from fuel rod	During refueling operations, one fuel element would not bottom properly, protruding 1/2 in. above other core assemblies. Four days later an end plug from a Region 3 fuel assembly was retrieved from the bottom core plate. Plug to be examined to see why it separated from the fuel rod.	59	Oct. 1972
27c	Ginna	PWR		Zircaloy-4		June 1972	Dec. 1972	Fuel rod end-plug recovered. No indicators of fuel deterioration observed after 48 fuel assemblies were replaced with other assemblies.	About 13 days required for replacement of 48 unpressurized fuel assemblies and recovery of a fuel rod end-plug from the lower core-support plate.	29	Feb. 1973
27d	Ginna	PWR		Zircaloy-4				0.4%, based on primary coolant activity early in first cycle; went additional 400 days before further defects indicated.	Study, without visual examination, indicated most probable cause to be internal hydriding due to moisture which was later confirmed. Prior to this, modifications in fuel production had been introduced to eliminate this since it had been expected. During spring refuelling, collapsed rods observed with collapsed sections ranging from 4-8 cm in length and are the result of gradual creepdown of cladding over an unsupported length due to high differential pressure.	10	Dec. 1972
27e	Ginna	PWR		Zircaloy-4			Cycle 1		During Cycle 1 refuelling, a large number of fuel rods were observed to be in interference with the top nozzles and a few of these rods were bowed. Rod interference and bowing were due to larger-than-expected Zircaloy growth during irradiation.	45	June 1973
27f	Ginna	PWR		Zircaloy-4			1972		Flattened fuel rods observed in Regions I, II, and III (all unpressurized fuel) during the Cycle 1 refueling in 1972. See last three sentences under Beznau-1 (entry 26c).	33	Oct. 1973
27g	Ginna	PWR		Zircaloy-4			July 1972		Some fuel rods collapsed because of in-reactor densification of fuel. Densification phenomenon reported by AEC to occur at linear heat rates as low as 1 to 2 kW/ft (33 to 65 W/cm).	35	Oct. 1973

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
27h	Ginna	PWR		Zircaloy-4	22,000 (Average)		Oct. 1972 (Cycle 3)		Fuel failures and collapsed cladding noted. Final 48 nonpressurized fuel rods discharged from core.	16	Jan. 1973
28a	Mihama-1	PWR		Zircaloy-4	~16,000	July 1970	Nov. 1971	Coolant activity indicated presence of a few leaking fuel rods in core at start-up (0.035%).	Failure type unknown. Coolant activity never exhibited a sharp increase similar to that observed at Beznau and Ginna. Mihama-1 has pressurized fuel rods. Also, more stringent controls on fuel moisture specifications and quality control procedures applied in manufacture of Mihama-1 fuel (and all other fuel delivered since Beznau and Ginna).	4	April 1972
28b	Mihama-1	PWR		Zircaloy			1973		During the past few months, fuel rod flattening has been observed in Region I fuel (unpressurized). See last three sentences under Beznau-1 (entry 26c). No collapsed cladding observed in other regions which contain pressurized fuel.	33	Oct. 1973
29a	Point Beach-1	PWR		Zircaloy-4	~19,000	Jan. 1971		Low-level coolant activity observed from beginning indicating one or two leaking fuel rods.	Failure type unknown.	4	April 1972
29b	Point Beach-1	PWR		Zircaloy-4		Fall 1970	Sept. 1972	70 fuel rods in 26 unpressurized fuel assemblies showed indications of collapse, representing a collapse ratio of 3.5%.	Examination performed by binocular observation. At time of shutdown, core had 13,000 effective full power hours. Prepressurized rods exhibited no evidence of collapse.	63	Oct. 1972
29c	Point Beach-1	PWR		Zircaloy-4			Nov. 1972	Of 105 fuel assemblies sipped, 23 were leakers and 1 was suspect.	Weak relationship found between leaky fuel assemblies and those with collapsed fuel rods. No correlation was found between collapses and core location, burnup, or fuel-assembly inserts.	71	Nov. 1972
29d	Point Beach-1	PWR		Zircaloy-4			1973		During the past few months, flattened fuel rods have been observed in Region I fuel (unpressurized). See last three sentences under Beznau-1 (entry 26c). No collapsed cladding observed in other regions which contain pressurized fuel.	33	Oct. 1973
29e	Point Beach-1	PWR		Zircaloy-4	18,847 (average)		Sept. 1972 (Cycle 1)	25 fuel assemblies with failed rods (collapses and leaks), 6 fuel assemblies with collapsed sections have no leaks.		16	Jan. 1973

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period		Approximate Failure Frequency	Failure Type	Reference	
						Start	End			No.	Date
30a	Obrigheim (KWO)	PWR		Zircaloy		1969		In first core, first refuelling revealed signs of damage in about 10% of fuel assemblies, but the number of defective fuel rods did not exceed 1%. During first refuelling, 11 fuel assemblies with defective rods were clearly found by wet sipping. During second refuelling, 3 fuel assemblies with defective rods were removed.		10, 11	Dec. 1972 and 1972, resp.
30b	Obrigheim (KWO)	PWR		Zircaloy-4	~38,000	March 1969		Defective fuel rods were only a problem during the first KWO operational cycle. The overall failure rate is smaller than 0.1%, with most of the fuel defects occurring in one batch of the initial core loading.	All defective fuel rods found after the first cycle were from the same fabrication series. Preferential alignment and craterlike appearance of the defects strongly pointed to internal contamination of fuel rods as cause of failure (pickling and autoclaving of empty tubes or fuel rods was eliminated on or after the first KWO reload). Visual inspection of KWO fuel assemblies during first refuelling confirmed the problem of irradiation growth of Zircaloy; 38 fuel assemblies from zone of highest enrichment were repaired by replacing lower end fixture of assembly with a new one which provided more axial clearance for fuel rod expansion. Crud deposition was unusually high during first cycle but caused no defects. First core fuel rods were not prepressurized; no evidence of cladding collapse was found.	32, 40	Jan./Feb. 1971 and Oct. 1973, resp.
30c	Obrigheim (KWO)	PWR	First core	Zircaloy-4	>36,000	March 1969	March 1974	On a fuel rod basis, the failure rate is 0.21%.		44	June 1974
30d	Obrigheim (KWO)	PWR	Reloads	Zircaloy-4	>33,000	Fifth Cycle	March 1974	On a fuel rod basis, the failure rate is 0.017%.		44	June 1974
31a	H. B. Robinson-2	PWR		Zircaloy-4			May 1973	Rod-control cluster failure in one fuel assembly.	[illegible] for rod-control cluster in a fuel assembly separated from the spider nut during operation. Failure occurred in braze joint; no cause found and no other failure was found.	65	May 1973
31b	H. B. Robinson-2	PWR		Zircaloy			1973		During the past few months, flattened fuel rods have been observed in Region I fuel (unpressurized). See last three sentences under Beznau 1 (entry 26c). No collapsed cladding observed in other regions which contain pressurized fuel.	33	Oct. 1973

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
31c	H. B. Robinson-2	PWR				March 1971	Nov. 1973	One grid trap on one bundle failed.	Two small sections of a fuel assembly spring clip grid strap made of Inconel were discovered in steam generator. Normal reactor coolant flow would readily carry the grid strap sections into the steam generator channel head. The spring clip grid pieces came from a single corner area of one grid; hence, six fuel rods are partially unsupported at the one grid location. Most likely explanation is that the grid edge caught on some portion of an adjacent assembly as the affected assembly was being inserted into its core position during refueling operations. Results suggest that the grid pieces are from previously irradiated fuel. During forthcoming refueling outage, comprehensive fuel inspection to be conducted to determine location of damaged fuel assembly and effect, if any, on surrounding fuel assemblies.	14	Dec. 1973
32a	Maine Yankee	PWR		Zircaloy-4			Sept. 1972	One fuel assembly replaced because of damaged grids. One fuel assembly had to be modified.	Basket containing in-core loading detector was being removed and caught under hold-down plate of an adjacent fuel assembly, lifting it off its 4 alignment pins and damaging 2 spacer grids. The fuel assembly was replaced with a spare. Two diagonally located support-plate alignment pins were found to be out of alignment (fabrication error); a fuel element had to be modified by enlarging the pinholes before it would fit properly.	72	Nov. 1972
32b	Maine Yankee	PWR	First core	Zircaloy-4			1974	Higher than average coolant activity indicates that some fuel rods have failed.	Failure type not indicated yet. Reactor may be shut down in June 1974 (originally scheduled for refueling next year) to correct condition.	15	May 1974
32c	Maine Yankee	PWR	First core	Zircaloy-4	~13,400	Dec. 1972 (First Cycle)	March 1974	On a fuel rod basis, the failure rate is <0.1%.		44	June 1974
33a	Oconee-1	PWR	Mark B	Zircaloy-4	>4,000	May 1973	June 1974	Coolant activity levels observed correspond to fission gas escape through small pinholes.	There has been very little change in activity level as a function of time since startup, so these leakers may be classed as "infinite mortalities" and are normal for a first-of-a-kind unit. In January 1973, one-half of fuel was replaced with prepressurized fuel rods.	42, 43	June 1974 and Jan. 1974, resp.

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
34a	Stade-1 (KKS)	PWR		Zircaloy-4	~18,000	March 1972		Coolant activity was already detected during low power period of reactor operation. It increased immediately when full power was achieved and has stayed there since then.	Failure type unknown. Response to power changes by activity peaks was rather rapid. Unlike KWO experience, the ^{239}Np activity was very low and just at the detection limit. Fuel is to be inspected during scheduled refuelling in July/August 1973.	32, 40	Jan./Feb. 1971 and Oct. 1973, resp.
34b	Stade-1 (KKS)	PWR	First core	Zircaloy-4	>25,0??	March 1972 (Second Cycle)	March 1974	The failure rate on a fuel rod basis is ~0.05%.		44	June 1974
35a	Palisades	PWR	First core	Zircaloy-4	~13,100	Aug. 1972 (First Cycle)	March 1974	On a fuel rod basis, the failure is <0.1%.		44	June 1974
36a	Fort Calhoun-1	PWR	First core	Zircaloy-4	~5,000	Sept. 1973 (First Cycle)	March 1974	On a fuel rod basis, the failure rate is <0.01%.		44	June 1974
37a	Turkey Point-3	PWR					July 1973	Coolant activity increases caused by fuel-cladding defects (much less than 1%).		66	July 1973
38a	Turkey Point-4	PWR			Zero			1 fuel assembly dropped during initial fuel loading.	Fuel assembly dropped 4 or 5 inches (cable clamps did not grip cable) while being raised to the vertical position. Skeleton of fuel assembly replaced before assembly was loaded.	61	April 1973
39a	Borssele (KCB)	PWR	First corr	Zircaloy-4	>4,000	Sept. 1973 (First Cycle)	March 1974	On a fuel rod basis, the failure rate is <0.1%.		44	June 1974
40a	NPD-2 (Rolphton)	BHWR				1962	May 1973	Of 3,328 bundles, 11 have failed. The mean failure rate is one bundle/year or <0.4%.	Some failures were the result of mechanical damage by fuelling machines during unusual maneuvers (e.g., reverse fuelling of a channel) and a few may have been damaged by the handling equipment only after discharge. No evidence of sheath collapse into interpellet gaps has been observed in NPD or other CANDU reactors.	13, 47	May and June 1973, resp.
40b	NPD-2 (Rolphton)	BHWR		Zircaloy-2		1962	1973	For NPD-2, Douglas Point, and Pickering reactors, the defect rate is well below 1% of all bundles fuelled.	Most probable defect mechanisms, acting separately or together, are stress corrosion cracking by fission products, or rupture of the neutron-embrittled cladding in regions of high stress and strain concentrations. See entry (41c) under Douglas Point.	34	Oct. 1973

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
41a	Douglas Point	PHWR (1150 psi)		Zircaloy-2, -4	19,800		Prior to May 1968	5 fuel failures detected out of ~5,282 fuel rods (335 fuel assemblies.	All fuel failures attributed to maloperation of fuel-loading equipment.	1	Spring 1971
41b	Douglas Point	PHWR		Zircaloy-2, -4			May 1973	Of 8,387 bundles, 69 have failed. The cumulative failure rate is <1%. Up to mid-1971, less than 1% of all bundles failed, including those suspected of having failed but in which a defect could not be positively identified. At mid-1972, the figure was still under 1% and, indeed, had decreased significantly. The current failure rate is about one fuel bundle per year.	Program to monitor fuel performance at Douglas Point and Pickering revealed a small but significant increase in fuel failure rate. Many of the failed bundles had undergone power increases shortly before giving evidence of failure. Tests confirmed that increasing the power (rapid increase is not required) of fuel that has already been appreciably irradiated does indeed cause failures. The delay between increasing the fuel's power and any evidence of a sheath failure can range from a few minutes to several days. Examination of failed bundles showed much hydriding damage; however, analysis revealed that hydrogen in the sheath consisted largely of the deuterium isotope, so much of the observed damage was the consequence of the original failure rather than its cause.	12, 13, 43	Jan., May, and June, 1973, resp.
41c	Douglas Point	PHWR		Zircaloy-2, -4			1973	For Douglas Point, NPD-2, and Pickering reactors, the defect rate is well below 1% of all bundles fuelled.	Ten potential mechanisms identified: (1) thermal neutron fluxes higher than fuel design value; (2) mechanical damage during fuel handling; (3) faulty components, poor design, or manufacturing error; (4) strain reversal at longitudinal ridges in cladding; (5) external corrosion of cladding; (6) migration of vacancies to form voids in the Zircaloy; (7) low cycle fatigue failure of cladding; (8) internal contamination by hydrogenous material to cause cladding hydriding; (9) stress corrosion cracking of cladding; and (10) tensile failure of cladding embrittled by fast neutron irradiation, possibly aggravated by stress concentrations. Many of the defects in experimental fuel were ascribed to one or more of the first eight defect mechanisms; however, some defects, including the majority of those in power reactor fuel, did not fit these mechanisms but did have a common characteristic (i.e., they were associated with sudden increases in the power output of the fuel). Defects occur in Zircaloy-clad UO_2 fuel rods if their power output is increased significantly after a burnup of 50 kWhr/kg U. The investigators state that the two most probable defect mechanisms, acting separately or together, are stress corrosion cracking by fission products, or rupture of the neutron-embrittled cladding in regions of high stress and strain concentrations.	34	Oct. 1973

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
41d	Douglas Point	PHWR		Zircaloy		1968		Fuel bundles in low-power region shifted on-power and went through peak in power (remained at peak for 15 minutes), one fuel bundle defected but over 1000 other bundles did not fail. However, defects occurred if bundles were left in peak power position.	Investigators unable to distinguish between local strain concentrations and fission product attack as the main failure mechanism, it is probable that both mechanisms play a role.	34	Oct. 1973
41e	Douglas Point	PHWR		Zircaloy-2		1968	Dec. 1973	Of 43,800 fuel bundles irradiated in Douglas Point and Pickering reactors, 170 fuel bundles (0.3%) have been defective.	Essentially all fuel defects have been caused by increases in fuel power after appreciable irradiation at lower power.	41	June 1974
42a	Pickering-1, -2, -3, -4	PHWR		Zircaloy-4		1971, 1971, June 1972, 1973, resp.	May 1973	Of 27,222 bundles, about 84 have failed (almost all in Unit 1).	Power increases following low power operation caused failures. One source of power increases was improper sequencing for introduction of absorber rods used to provide xenon over-ride during a reactor start-up. Early detection of the fault allowed it to be eliminated before it caused fuel failures in the other 3 units.	13	May 1973
42b	Pickering-1, -2, -3, -4	PHWR		Zircaloy-4		1971, 1971, June 1972, 1973, resp.	1973	For Pickering, Douglas Point, and NPD-2 reactors, the defect rate is well below 1% of all bundles fuelled.	Most probable defect mechanisms, acting separately or together, are stress corrosion cracking by fission products, or rupture of the neutron-embrittled cladding in regions of high stress and strain concentrations. See entry (41c) under Douglas Point.	34	Oct. 1973
42c	Pickering-1, -2, -3, -4	PHWR		Zircaloy-4		1971, 1971, June 1972, 1973, resp.		Of 43,800 fuel bundles irradiated in Pickering and Douglas Point reactors, 170 fuel bundles (0.3%) have been defective.	Essentially all fuel defects have been caused by increases in fuel power after appreciable irradiation at lower power.	41	June 1974
43a	Rajasthan (RAPP-1)	PHWR	Initial core	Zircaloy-2		Aug. 1972		About 640 defective fuel bundles detected.	During preoperational testing, fuel bundle inspection revealed defects such as gouging of cladding under wire wrap spot welds and missing welds between the end plates and the caps of the fuel. Replacements for about 540 defective fuel bundles were obtained.	50	Sept. 1973
44a	SGHWR	BWR (pressure tube)		Zircaloy	~9,000	Dec. 1967	June 1969	30 leaker fuel assemblies.	Of the 30 leaker fuel assemblies, 3 due to internal hydriding and 27 due to crud-related accelerated corrosion.	6	Oct. 1969

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
44b	SGHWR	BWR (pressure tube)		Zircaloy-2	18,500 (earlier cores <10,000)	Jan. 1968	April 1973	More than 48 defective fuel elements removed from reactor.	The defects which have occurred in SGHWR fuel elements, apart from those attributed to crud and special experiments, have not been related to design or operating conditions, but are all believed to be due to defects in components. Some fuel elements had to be discharged prematurely because fuel pin axial growth exceeded design allowance. Harmful crud (thick, copper-rich) deposition caused 33 defects. Of 15 other defects, 8 were in "high risk" experiments; the remaining 7 were of particular interest since in 2 cases the cladding rapidly developed multiple micron-size holes and the other 5 elements involved internally autoclaved cladding (residual hydrogen led to observed multiple hydride "sunbursts" and sometimes transverse cracks). Fretting noted on 2 first core elements at bottom end. Found 3 fuel elements in reactor which had become detached from hangar bars and were lodged at bottom of pressure tube; damage to elements was very slight.	30	Oct. 1973
45a	Karlsruhe (MZFR)	PHWR		Zircaloy-2	~5,000	Dec. 1966		MZFR fuel performed with a failure rate of <0.02%. The first defective fuel rod was recorded at a burnup as low as 588 MWd/MTU.	The few fuel rod failures observed shortly after startup gave valuable information for fabrication improvements. The first defective rod revealed a "hydride sunburst;" the source of hydrogen was easily traced back to moisture trapped in the fuel rod during fabrication. Some other fuel rods failed at their final end plug welds; the standard steam autoclave test routinely used did not reveal these poor quality welds. Residual air inside fuel rod was cause of heavy weld contamination. Dimensional check of almost 20% of MZFR first core fuel elements revealed problem of irradiation growth of Zircaloy cladding.	32, 40	Jan./Feb. 1971 and Oct. 1973, resp.
46a	Vulcain	PWR	UO_2-PuO_2	Stainless steel	45,000			The one UO_2-PuO_2 fuel element (37 fuel pins) was intact; however, failures were induced in UO_2 fuel elements.	Cause of the failures of the UO_2 fuel elements (37 fuel pins/element, both stainless steel and Zircaloy-4 cladding have been used) was operation in a regime where first half was at steady power and second half involved a period of power cycling.	31, 32	Oct. 1973 and Jan./Feb. 1971

TABLE 2. (contd)

Item No.	Reactor	Reactor Type	Fuel Type	Fuel Rod Cladding	Approximate Peak Rod Burnup (MWd/MTM)	Operating Period Start	Operating Period End	Approximate Failure Frequency	Failure Type	Reference No.	Reference Date
47a	Agesta	PHWR	UO_2-PuO_2	Zircaloy-2	~11,600			Of 4 fuel elements (60 fuel pins), 2 fuel elements failed.	One fuel element failed because of mechanical damage caused by a handling incident. The other failure was due to a crack which developed in a weld.	31	Oct. 1973
48a	CVTR	PWR		Zircaloy-4	~19,800		Prior to Aug. 1968	5 fuel rod failures were detected in the total of 1390 fuel rods (<0.5% failures).	Evidence suggests that the failures were caused by internal sources of hydrogen which led to local hydriding of the Zircaloy cladding (i.e., gas-phase hydriding). Peak exposures (MWd/MTM) of the 5 failed rods were: 10,600; 6,800; 12,800; 18,900; and 19,100.	1	Spring 1971
49a	Saxton	PWR	UO_2-PuO_2	Zircaloy-4	~45,000	1966	1969	No leaking fuel rods.	Blisters formed as a result of internal hydriding.	5	May 1970
49b	Saxton	PWR	Core 3				May 1972	7 leaking fuel assemblies.	3 leaking fuel assemblies sent to BMI and 4 sent to Waltz Mill site. Core 3 had 5,819 MWd of operation.	67	Oct. 1972
50a	Cirene (Latina)	LWCHWR-1		Zircaloy-2	~9,800	1966	1973	Of 350 fuel rods which have completed irradiation (in other reactors such as Halden HBWR, Agesta, ESSOR, etc.), 31 fuel rods failed and 10 fuel rods had nonpenetrating defects.	About 240 of the 350 irradiated fuel rods were examined in hot cells: 23 fuel rod failures (and nonpenetrating defects on 10 other fuel rods) were caused by localized attacks by internal hydrogen and, to a lesser extent, defects at the end plug welds; 7 other fuel rods failed as a consequence of a stress corrosion mechanism during power ramps; and 1 fuel rod failed because of an extra (and long) overpower transient. The 7 fuel rods all failed either with small axial cracks at ridges on the cladding or with circumferential cracks in the end plug welds. The single rod failed because of a penetrating crack in the cladding.	32, 36, and 38	Jan./Feb. 1971, Oct. 1973, and Oct. 1973, resp.

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