, 8l. Es 7800238

CONF-780622--4466 PNL-SA-6917

IMPACTS OF REACTOR-INDUCED CLADDING DEFECTS ON SPENT FUEL STORAGE

A. B. Johnson, Jr.
Staff Scientist
Battelle, Pacific Northwest Laboratories

For Presentation
NEA Seminar on the Storage of Spent Fuel Elements
Madrid, Spain June 20-23, 1978

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A. B. Johnson, Jr.
Battelle, Pacific Northwest Laboratories
Richland, Washington USA

ABSTRACT

Defects arise in the fuel cladding on a small fraction of fuel rods during irradiation in water-cooled power reactors. Defects from mechanical damage in fuel handling and shipping have been almost negligible. No commercial water reactor fuel has yet been observed to develop defects while stored in spent fuel pools. In some pools, defective fuel is placed in closed canisters as it is removed from the reactor. However, hundreds of defective fuel bundles are stored in numerous pools on the same basis as intact fuel. Radioactive species carried into the pool from the reactor coolant must be dealt with by the pool purification system. However, additional radiation releases from the defective fuel during storage-appear to be minimal, with the possible exception of fuel discharged while the reactor is operating (CANDU fuel). Over approximately two decades, defective commerical fuel has been handled, stored, shipped and reprocessed.

LES DEFAUTS DANS LES GAINES DES BARRES DE COMBUSTIBLE PRODUITS PAR LES REACTEURS ET LEUR INFLUENCE SUR LE STOCKAGE DES COMBUSTIBLES EPUISES

RÉSUMÉ

Pendant l'irradiation de barres de combustible dans les réacteurs de puissance a' l'eau un tres pétit nombre des défauts se produit dans les gaines. Défauts due au endammage mécanique pendant le "handling" et transport avaient été presque négliables. On n'a pas encore pue observé de défauts dans le combustible pour un réacteur a eau qui se soient produits pendant son stockage dans une piscine. Dans certaines piscines, le combustible défectueux est placé dans des boites métalliques fermées lorsqu'on l'enlève due réacteur. Cependant, des centaines de barres de combustible défectueux sont stockés dans des piscines dans les memes conditions que le combustible intact. Des espèces radioactives emportées du fluide de refroidissement et introduites dans la piscine doivent etre traitées par le système de purification de la piscine. Des dégagements supplémentaires de rayonnements provenant des combustibles defectueux pendant leur stockage semblent pourtant avoir été minimale, a l'exception éventuelle d'un combustible déchargé pendant que le réacteur est en cours de fonctionnement (combustible CANDU). Il y a maintenant depuis plus d'environ vingt ans que l'on manié, stocké, transporté et retraité les combustibles industriels defectueux.

INTRODUCTION

All spent nuclear fuel is discharged to a water storage pool at the reactor site. Eventually, the fuel will be shipped to an interim storage facility, to a reprocessing center or to a final disposal facility. In fuel storage and handling operations, it is important to define what, if any, special procedures will be required, for defective fuel.

The great majority (>99%) of nuclear fuel rods discharged from nuclear reactors to water pools has cladding which did not develop defects during the reactor exposure. Published assessments from Canada [1], Germany [2], Sweden [3], the United Kindgom [4,5], and the United States [6,7] indicate that the storage behavior of water reactor fuel is excellent in water pools during exposures up to 19 years for Zircaloy-clad fuel and 12 years for stainless-clad fuel.

This paper will focus on storage characteristics of spent fuel with defective cladding, including a description of typical defects, how they arise and a summary of defective fuel storage experience.

NUCLEAR FUEL CHARACTERISTICS AND EXPOSURE CONDITIONS

Commercial water reactor fuel consists of metal tubes (Zircaloy or stainless steel) containing uranium dioxide fuel pellets (Fig. 1). Characteristics of commercial boiling water reactor (BWR), pressurized water reactor (PWR), and pressurized heavy water reactor (PHWR) fuel are summarized in Table I. Table II compares fuel conditions in the reactor and in the fuel pool, emphasizing the much more benign conditions in the pool.

DEFECTIVE NUCLEAR FUEL

During reactor residence, a small fraction of the fuel rods typically develop defects in the fuel cladding. When a hole develops in the cladding, gaseous fission products (e.g., iodine, krypton, and xenon isotopes) escape to the reactor coolant. If the hole is sufficiently large, water may enter the fuel rod, resulting in leaching of non-volatile radioactive species.

The fission product activity released by defective fuel in-reactor circulates in the primary coolant. Some of the fission products absorb on the corrosion products (crud layer) and on other fuel bundle surfaces. When the fuel is discharged to the pool, water from the primary circuit mixes with pool water, carrying along radioactive fission products and corrosion products. The radioactive species also desorb from fuel bundle surfaces during pool storage. The principal fission products which occur in fuel pools appear in Table III. However, additional leaching of activity from irradiated fuel exposed at fuel defects appears to occur slowly at fuel pool conditions.

The short-lived isotopes such as I-131 generally decay to insignificant levels before the fuel leaves the reactor pool. Due to these short-lived activities and to the radioactive species carried into the reactor pool from the primary coolant, reactor pools generally have higher radiation levels, at least periodically, than radiation levels at away-from-reactor (AFR) pools.

How Fuel Defects Occur

In-Reactor Defects - Defects which occur in commercial water reactor fuel during reactor residence are the source of defective fuel stored in pools. As indicated below, defects from other sources are almost negligible. As reactor technology developed, several fuel failure mechanisms appeared, were identified and largely eliminated. Consequently, current fuel failure rates (estimated to be 4 or 5 rods per year for a 1000 MWe reactor [8]) are substantially lower than those encountered in the 1960s and early 1970s.

Failure rates for Canadian fuel are reported to be 0.03% [9]. In U.S. reactors the failure rate has been somewhat higher, but several fuel failure mechanisms have been eliminated, and the failure rates are decreasing.

The major fuel failure mechanisms which have occurred and methods to suppress them are briefly summarized in Table IV.

Defects from Fuel Handling and Shipment - Mechanical damage during fuel handling operations has contributed very few defective bundles to the stored fuel inventory. During the period 1974-76 nine fuel handling accidents were reported to the U.S. NRC, but only one resulted in a detectable radiation release.[6]

There has not been a systematic assessment of damage during fuel shipments, but current perceptions suggest that the damage is minor, and does not contribute significantly to defective pool-stored fuel.

Defects from Storage in Fuel Pools - The published assessments of commercial (oxide) water reactor spent fuel indicate that cladding failure rates during pool storage have so far been zero for both Zircaloy-clad and stainless-clad fuel.[1-7] Progressive cladding failures during pool storage have occurred on defective Zircaloy-clad metallic uranium fuel [6], and on stainless-clad gas reactor fuel [4,5,10]. Magnox (Mg-0.8Al-0.0038e) gas reactor fuel has been subject to in-pool corrosion failures [11] which appear to be controllable by proper water chemistry [12].

Fuel Defect Types

Only a small fraction of the defects on nuclear fuel are readily visible. The defects generally are either too small for easy detection or they occur on interior rods. The following discussion will briefly summarize the types of defects which have been identified.

Pinhole Defects - The large majority of defects appear to be pinholes or small cracks (Fig. 2). The small holes permit evolution of gases, but probably rarely permit substantial water entry. The relatively low pool temperatures would tend to promote closure of small defects, compared to reactor operating conditions.

Cracks and Holes - Some defects are sufficiently large that closure does not occur on cooling. For example, Figure 3 shows a hole caused by hydriding of Zircaloy cladding at a weld. Figure 4 shows a severe longitudinal crack caused by a pellet-clad interaction failure.

Broken Fuel Rods - A few cases involving broken fuel rods have been observed following reactor exposures. In these cases, fuel pellets often are visible and are directly accessible to the reactor or pool water. However, the soluble species have already largely dissolved in the reactor coolant in most cases.

Methods of Defective Fuel Storage in Pools

Methods of defective fuel storage are summarized below.

- In most U.S. spent fuel pools, defective fuel is stored on the same basis as intact fuel, without use of closed canisters. Severely-failed fuel sometimes is placed in closed canisters, particularly when the fuel is shipped.
- Canadian pool operators generally place known defective fuel in closed canisters, due to fission product releases from defective bundles discharged to the pool while the reactor is on-line.
- Some European pool operators store defective fuel in closed canisters. In some cases the environment inside the canister is wet (e.g., Windscale Pool), in some cases it is dry (e.g., Mol Pool).[3]

- At the WAK pool in Germany, defective fuel is stored in canisters, but with a loose-fitting lid.[2]

Water Chemistry and Radiation Control

Pool purification technology has been developed to control water purity and levels of radioactivity in pool water. The following procedures are available, though all are not required at all pools:

- Ion exchange columns to remove ionic species
- Filters to remove particle species
- Skimmers to remove floating species
- Vacuum cleaners to remove particles which settle to the bottom of the pool.

Dose rates above spent fuel pools typically are a few mrem/hr. A case cited later indicates average radiation levels of 0.5 mrem/hr at a spent fuel pool where substantial numbers of failed fuel rods are stored and handled.[3] The radiation doses for the pool staff were in the range of 90 to 110 mrem over a 5-week period when extensive rebuilding of fuel bundles was on-going. Radiation doses up to ~100 mrem/hr have been reported at fuel pools [6], but this is generally only over a very brief period during fuel discharges at reactors. At AFR pools, radiation doses are typically a few mrem/hr. Doses for the pool technicians and shift supervisors typically average 1000 to 2000 mrem/year. At pools where relatively high radiation levels have occurred in the pool water, some radiation dose occurs during filter changes, but the values are typically ~20 mrem and occur only a few times per year.

Case Histories - Defective Fuel Storage and Handling

The experience of two decades of fuel handling has included numerous cases involving discharge, handling, storage, shipment, and reprocessing of defective fuel. The experience will be illustrated with several case histories.

Case History No. 1 - Handling of Defective Stainless-Clad Fuel at the Humboldt Bay Reactor, Eureka, CA (US)[6]

Stainless steel was the first cladding used for BWRs. Failures occurred in the stainless steel cladding due to stress corrosion cracking under the BWR primary system conditions. Over a period of about five years, 270 stainless-clad bundles were discharged, from the Humboldt Bay reactor, stored, shipped, and reprocessed at the Nuclear Fuel Services plant at West Valley, New York. Most of the bundles had one or more defective rods. The bundles were stored in the reactor pool without any special procedures, such as canning. However, ~190 of the bundles with failed fuel rods were canned prior to shipment to the reprocessing plant. Radioactivity concentrations in the reactor basin water were $\sim 10^{-5}$ μCi/ml prior to discharging the failed fuel, but rose to $\sim 10^{-2}$ μCi/ml after the fuel discharges; they have since decreased to $\sim 10^{-3}$ μCi/ml, by a combination of ion exchange and filtration.

The principal impact was time and expense involved in canning the fuel at the pool and decanning it prior to reprocessing. For some experimental stainless-clad fuel from the Vallecitos Boiling Water Reactor, the steel cans were dissolved along with the fuel, precluding a need for decanning.

Case History No. 2 - Swedish Experience With Defective Spent Fuel[3]

Reactors which discharge and store substantial amounts of defective fuel have higher activity levels in the pool water than pools where defective fuel is minimal or absent.

At the Oskarshamn 1 spent fuel pool, 56 defective fuel bundles are stored (discharged over the period 1971 to 1977). The activity in the water is predominantly Cs-134 and Cs-137, and the steady state activity level is ~$2x10^{-4}$ μCi/ml. At other Swedish pools, where defective fuel is not a factor, the activity levels are ~10^{-5} μCi/ml, and the predominant isotopes are Co-60, Zn-65, Co-58, Zr-Nb-95, Cr-51, and Sb-124. At Oskarshamn 1, 110 defective rods were detected in 46 leaking assemblies. Approximately ten rods had cracks 20 to 40 mm long and some broken rods were observed.

A major campaign was conducted in the Oskarshamn 1 pool to rebuild several hundred fuel bundles. With no irradiated fuel in the pool (1972) the beta/gamma activity was <$5x10^{-6}$ μCi/ml. Steady-state values after mixing reactor and fuel pool waters were ~$1x10^{-4}$ μCi/ml in 1976 and $2.3x10^{-4}$ μCi/ml in 1977. When the bundle rebuilding campaign began in 1976, fission products accounted for ~96% of the active species. The fuel pool personnel involved in the rebuilding program worked in a radiation field which averaged only 0.5 mrem/hr. Therefore the defective fuel and associated fission products had a minor impact on the extensive fuel handling operations.

One broken rod with ~100 mm missing from the bottom end was subjected to several measuring and handling operations. During the operations, no fuel pellets fell from the rod. This agrees with other Swedish experience indicating that it is difficult to remove pellets from rods after reactor operation. This was attributed to UO_2 pellet cracking which caused wedging of the pellets. (Note: bonding of pellets to the cladding also has been observed, particularly with high-burnup PWR fuel.[13])

<u>Case History No. 3</u> - Experience with Defective Fuel at An Away-from-Reactor Spent Fuel Pool[6]

Several hundred fuel bundles with one or more leaking rods are stored at the General Electric Company, Morris Operation in Illinois. The defects developed due to hydriding from the fuel side. Gaseous radiation releases from the defective bundles are not detectable. The pool purification system maintains the radioactivity levels at ~1 to $4x10^{-4}$ μCi/ml.

<u>Case History No. 4</u> - Swedish Observations and Experiments Regarding Fission Gas Evolution[3]

Swedish modeling indicates 2% fission gas release at 40,000 MWD/MTU for BWR fuel (measured values are 0.1 to 1.0%); for PWR fuel at a similar burnup, the fission gas release is expected to be higher (~15%). Below ~1000°C, fission product evolution rates are negligible. Therefore, at fuel temperatures during pool storage (~100°C) fission gas evolution is expected to be almost imperceptible. This was verified in a test with three rods with burnups from 7,000 to 20,000 MWD/MTU which had operated at heat loads of 125 to 172 W/cm. The rods were punctured in the Oskarshamn 1 pool, releasing between $1.3x10^{-3}$ and $1.7x10^{-3}$% of the Xe-133 and between $0.25x10^{-7}$ and $0.5x10^{-7}$% of the I-133. The low releases reflected the relatively low heat loads during the reactor exposure, and confirmed the model developed in other Swedish experiments indicating that ~1% of the fission gas inventory in the fuel pellets will be released at an in-reactor heat load of 385 W/cm and a burnup of 20,000 MWD/MTU.

<u>Case History No. 5</u> - Periodic Visual Observations on a Fuel Bundle With a Defective Rod--WAK Pool, Karlsruhe, Germany[2]

In cases where fuel pellets are exposed to pool water, leaching of radioactivity occurs very slowly. There is no visually detectable dissolving of the UO_2 pellets. At the WAK pool, a fuel rod having a visible defect with exposed UO_2 is removed from the pool and photographed annually. Over a period of ~6 years there has been no visible leaching of the exposed UO_2 in the pool water. This agrees with the work of Katayama which indicates low steady-state leach rates of activity from irradiated UO_2 pellets.[14]

Case History No. 6 - Detailed Exam of Defective SGHWR Fuel Rod After Pool Storage, Windscale, U.K.[5]

A Steam Generating Heavy Water Reactor fuel bundle having a burnup of ~1900 MWD/MTU developed a defective fuel rod during the reactor exposure. It was removed from the reactor and placed in water inside a closed canister, which was stored for nine years in the Windscale spent fuel pool. In 1977 a detailed investigation of the bundle was made. The water in the closed container had ~1 mCi of Cs-137 and <10 ppb of iodine. There was no evidence of metallurgical changes in the defective fuel cladding during the 9-year storage period. There was a small increase in the fuel rod diameter near the defect, but no evidence that substantial oxidation of the fuel was taking place (e.g., $UO_2 \rightarrow U_3O_8$). A Swedish calculation[3] based on an extrapolation of Canadian UO_2 oxidation data[15] suggested that at pool temperatures (~50°C), fuel oxidation rates would not be expected to exceed $\sim 5 \cdot 10^{-6}$ mm/100y. Below 250°C there is evidence that U_3O_8 may not form.[3]

Case History No. 7 - Summary of Fuel Which Developed Failures In-Pool

Water reactor fuel has been stored up to 19y without failure in spent fuel pools. However, other types of fuel have failed during water pool storage. Three such cases are briefly summarized here.

Case 7-A - In-Pool Failure of Damaged Zircaloy-Clad Metallic Uranium Fuel[6]

Zircaloy-clad metallic uranium fuel which developed cladding defects in-reactor or during fuel discharge at the Hanford N-Reactor underwent a progressive attack on the uranium metal core during pool storage. Over 150 N-Reactor fuel elements developed advanced stages of degradation during shipping and storage at the Nuclear Fuel Services pool. Radioactive species in the pool water rose from near 10^{-3} to near 10^{-2} μCi/ml. In November 1971 the last fuel in the pool was reprocessed, the pool was drained, vacuumed and scrubbed with brushes. After the pool was re-filled, radiation levels decreased to values between 10^{-3} and 10^{-4} μCi/ml.

Case 7-B - Corrosion Attack on Sensitized Stainless-Clad Gas Reactor Fuel[4,5,11/p.29]

At temperatures in gas-cooled reactor (450-750°C), stainless steel has extended reactor residence at temperatures which cause sensitization or chromium depletion of the surface layers. Substantial corrosion has been observed on stainless-clad fuel from the British gas reactors, but the extent of in-pool failure has to this point been minor.

Case 7-C Magnox Fuel Failures[11]

The magnesium alloy cladding on Magnox reactor fuel has developed failures during pool storage, resulting in some fission product releases to the pool and then to an adjacent water body. Proper control of pool water chemistry appears to preclude the in-pool failures.[12]

Case History No. 8 - Handling and Storage of Failed Stainless-Clad Fuel, LaCrosse BWR, LaCrosse, WI (USA)

The LaCrosse BWR is fuelled with 72 bundles, each having 100 stainless-clad fuel rods. In May 1977, all fuel bundles were discharged from the reactor, including six bundles which had one or more defective rods. Three bundles had sections missing from several rods. The bundles were withdrawn from the reactor over a special catch screen to intercept any loose fuel pellets or cladding sections. Prior to the refuelling outage, the gross β-γ activity in the pool was $\sim 2 \times 10^{-3}$ μCi/ml. During the refuelling outage, the β-γ activity rose to 5×10^{-2} μCi/ml. Between May 1977 and February 1978 the pool purification system (25 gpm to the ion exchange/filter system) returned the β-γ activity to 2×10^{-3} μCi/ml. The alpha activity peaked at 6.5×10^{-6} μCi/ml and decreased to 2.2×10^{-7} μCi/ml. The average radiation dose on the refuelling machine bridge was ~20 mrem/hr. The fuel pool operation results in relatively low radiation doses. No significant increase in air-borne activity occurred during the refuelling outage. The principal isotopes in the fuel pool during the outage appear below:

Isotope	Concentration μCi/ml	Isotope	Concentration μCi/ml
^{133}Xe	4.93×10^{-3}	^{137}Cs	3.91×10^{-3}
^{99m}Tc	8.77×10^{-4}	^{58}Co	9.30×10^{-4}
^{131}I	2.76×10^{-3}	^{60}Co	1.66×10^{-4}
^{134}Cs	2.51×10^{-3}		

None of the failed fuel has been isolated in closed cans, but future canning of selected bundles is being considered.

Case History No. 9 - Fission Gas Release from Defective CANDU Fuel

The CANDU reactors are refuelled during reactor operation. Therefore, defective fuel is discharged immediately into the pool. Experience has shown that the freshly discharged defective CANDU fuel continues to eject fission gases in the pool. Therefore, it is standard practice in Canada to can the defective fuel soon after discharge. Can designs vary at the various CANDU reactors. The most recent design utilizes a two-bundle sealable container, which traps the fission gases and provides for heat transfer. Transfer of the fuel bundles into the container occurs in a matter of about one or two minutes. However, the container is relatively expensive (~$3000 in 1978). After about six months the defective fuel is transferred to cheaper (~$300) containers, freeing the more expensive type for additional freshly-discharged defective fuel.

Summary of Case Histories

The case histories cited above indicate that satisfactory techniques have been developed to discharge, store, ship, and reprocess defective spent fuel. Light water reactor (LWR) fuel generally is discharged several days after reactor shutdown, providing time for thermal cooling and decay of short-lived isotopes. Radioactivity carried into the pools from defective fuel can be controlled by water purification systems. Further evolution of radioactivity from LWR fuel defects appears to be minimal due to two aspects:

- The volatile radioactive species (e.g., Kr, I, Xe) are released to the reactor coolant when a clad defect develops in-reactor; further gas releases at pool temperatures are negligible.
- UO_2 pellets are relatively inert to pool water.

The situation with CANDU fuel differs somewhat because the fuel is discharged while the reactor is on-line, arriving in the pool thermally hot and without time for radioactive decay. Therefore, canning is common practice for Canadian fuel with known defects.

Casual and systematic observations of defective commercial water reactor fuel stored in pools has not indicated evidence that progressive degradation occurs at the defects. Defective fuel is canned as a matter of operating policy in some pools. However, hundreds of light water reactor bundles with defective rods are stored at numerous pools on the same basis as intact fuel, with acceptable impacts.

The principal impacts of the failed fuel are:

- Fission product activities carried into the pool from the reactor primary system.
- Special procedures sometimes required during fuel discharge to collect fuel and cladding debris.
- Ion exchange resin disposal sometimes required as transuranic waste.
- Canning generally required for off-site shipment and storage of bundles with broken fuel rods.

WHAT REMAINS TO BE DONE?

The foregoing discussion reflects the minimal impacts which have developed to date in handling, storing, shipping, and reprocessing defective nuclear fuel. However, there continue to be broad differences in philosophy regarding the need for storage of defective fuel in closed canisters. Local regulations and incentives may determine to some extent whether defective fuel is canned or not. However, there appears to be a need for a more systematic set of criteria for defective fuel handling. When canning is required, storage, shipping, and receiving facilities must be prepared to handle the can geometries.

At current levels of perception, further degradation of commercial water reactor fuel at defects appears to be minor. However, as storage times increase, further surveillance is justified to develop sustained assurance that the defects are passive.

Further definition of uranium and fission product leaching rates from exposed fuel pellets may have some value for long-term storage assessments.

The behavior of defective fuel (for example, effects of water logging) may have significance in some long-term storage scenarios, particularly where subsequent extended dry storage at elevated temperatures is being evaluated.

ACKNOWLEDGMENTS

The author is grateful to many organizations and individuals who provided data and insights to the technology of spent fuel storage in water pools. The author is particularly grateful to Dr. John W. Bartlett and Dr. R. L. Dillon of Battelle's Pacific Northwest Laboratories for frequent discussions. The support of the U.S. Department of Energy Waste Management Program made the study possible, under Contract EY-76-C-06-1830.

REFERENCES

1. Mayman, S.A. "Canadian Experience with Wet and Dry Storage Concepts," presented at the American Nuclear Society Conference on Spent Fuel Policy and Its Implications, Buford, GA (USA) April 1978.

2. Huppert, K.L. and Zimmerman, G., "Experience with Regard to Long-Term Storage of LWR Fuel Elements," (In German) Reactor Congress, Mannheim, March 29-April 1, 1977, AEC-CONF-77-013-112 pp. 447-450.

3. Vesterlund, G. and Olsson, T. Degraderingmeckanismer Vid Bassanglagering och Hantering av Utbrant Kraftreaktorbransle, RB 78-29, ASEA-ATOM Report, Västerås, Sweden, (to be published in in Swedish); English translation, Degradation Mechanisms During Pool Storage and Handling of Spent Power Reactor Fuel, BNWL-TR-320, May 19, 1978.

4. Warner, B.F. "The Storage in Water of Irradiated Oxide Fuel Elements," Testimony presented at Windscale Inquiry on Spent Fuel Reprocessing, Windscale, United Kingdom, 1977.

5. Flowers, R.H., "Results of an Examination of Irradiated Oxide Fuel Following Storage in Water," Testimony presented at Windscale Inquiry on Spent Fuel Reprocessing, Windscale, United Kingdom, 1977.

6. Johnson, Jr., A.B., Behavior of Spent Nuclear Fuel in Water Pool Storage, Battelle, Pacific Northwest Laboratories, Richland, WA, (USA), BNWL-2256, September 1977.

7. Johnson, Jr., A.B. "Spent Fuel Storage Experience," to be published in Nuclear Technology.

8. Locke, D.H., "Review of Experience with Water Reactor Fuels 1968-1973," Nucl. Eng. and Design, Vol. 33, pp. 94-124, 1975.

9. Page, R.D. Canadian Power Reactor Fuel, Atomic Energy of Canada, Ltd., Toronto, Canada, AECL-5609, March 1976.

10. Long, Jr., E.L. and Michelson, C., Some Observations of the Intergranular Corrosion of Irradiated Type 304 Stainless Steel, Oak Ridge National Laboratory, Oak Ridge, TN (USA), ORNL-3684, 1964.

11. Hon. Mr. Justice Parker, The Windscale Inquiry, Vol. I, Report and Annexes 3-5, London, Her Majesty's Stationary Office, January 26, 1978, p 6.

12. Case, B., and Hilton, D.A., "Water Chemistry Control and Corrosion Inhibition in Magnox Fuel Storage Ponds," Proceedings of the British Nuclear Energy Conference on Water Chemistry of Nuclear Reactor Systems, Bournemouth, England, October 1977.

13. Fuhrman, N, "Evaluation of Fuel Rod Perforamnce in Maine Yankee Core I," EPRI NP-218, Research Project 586-1, Final Report, November 1976, pp. 21-25.

14. Katayama, Y.B., Leaching of Irradiated LWR Fuel Pellets in Deionized and Typical Ground Water, Battelle, Pacific Northwest Laboratories, Richland, WA (USA) BNWL-2057, July 1976.

15. Boase, D.G., and Vandergraaf, T.T., "The Canadian Spent Fuel Storage Canister: Some Materials Aspects," Nucl. Tech. Vol. 32, pp. 60-71, January 1977.

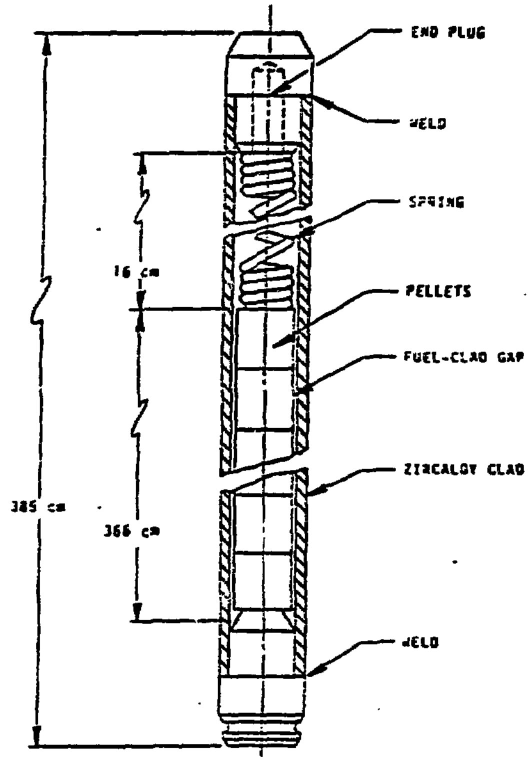
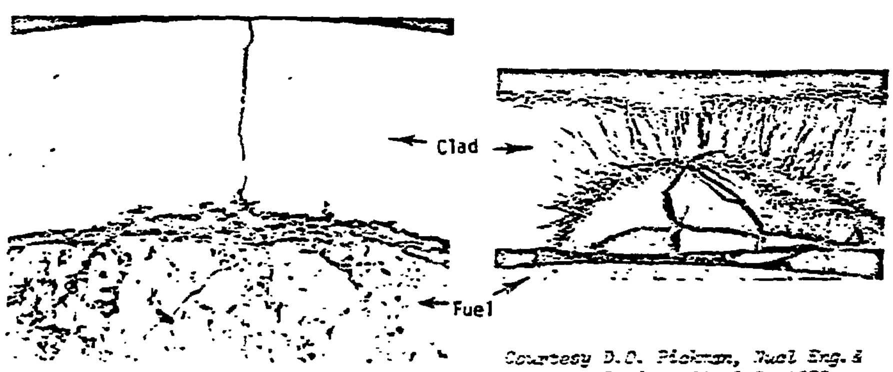


Figure 1. Typical Fuel Rod



Courtesy M.D. Freshley, Battelle Northwest

Courtesy D.D. Pickman, Nucl Eng. & Design, 33, 142, 1975

Figure 2. Two Examples of Narrow Defects

Figure 3. End Closure Failure Due to Hydriding
Courtesy of M.D. Freshley, Battelle Northwest

Figure 4. Severe Longitudinal Cracking
Courtesy S.Aas, Nucl. Eng. & Des. 21 p 238, 1972

Table I. Nuclear Fuel Bundle Characteristics

Reactor Type	Fuel Rod Length m	Fuel Rod Diameter cm	Fuel Rods Per Bundle
BWR	up to 4.0	1.25	49 to 100
PWR	up to 3.8	0.95	225 to 289
PHWR	~0.5	1.5 to 2.5	7 to 35

Table II. Comparison of Conditions for Water Reactor Fuel

	In-Reactor	In-Pool
Fuel Temperature, °C (peak centerline)	1200-1350	~100
Water Temperatures:		
BWR, °C	270- 300	20-50
PWR, °C	320- 340	20-50
Clad (Inside) Surface Temp, °C	340- 400	~30-60[a)]
Gas Pressure:[b)]		
BWR, psi	70- 700	30- 300
PWR, psi	565-2200	250-1200
Calculated Fission Gas Evolution:		
BWR	~2%[c)]	Negligible
PWR	15%	"
Surface Heat Fluxes, w/cm^2	up to 80	0.03[d)]
Radiation Fluxes (max)		
Neutron, n/cm^2 sec, >1Mev	3-6x10^{13}	~10^5
Gamma, R/hr	~10^9	~10^5

a) After cooling for several weeks; the exterior surface temperature is ~10°C above the bulk water temperature; the interior and exterior clad surface temperatures are essentially the same at pool storage conditions.

b) For intact fuel rods.

c) Based on modelling calculations; measured values generally are lower (see Case History No. 4).

d) After cooling for ~one year.

Table III. Principal Fission Products Released To Fuel Pool Waters

Isotope	Half-Life
^{131}I	8.05 d
^{134}Cs	2.1 y
^{137}Cs	30 y
^{3}H	12.3 y
^{90}Sr	28.8 y
^{144}Ce	285 d
^{106}Ru-^{106}Rh	1.0 y - 2.2 hr
^{95}Zr-^{95}Nb	65 d - 35 d
^{133}Xe	5.3 d
^{85}Kr	10.7 y

Table IV. Fuel Failure Mechanisms

Failure Type	Method to Improve Fuel Performance
Manufacturing Defects	Improved Quality Control
Crud-Induced Failures	Replaced Cu Alloy Reactor Components
Fretting Corrosion	Improved Fuel Bundle Design
Hydriding (Fuel Side)[a)]	Low Fuel Moisture Specifications
Fuel Densification	Modified Fuel Pellet Specifications
Pellet-Clad Interaction	Not Fully Resolved

a) Cause of the largest number of fuel failures