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SUBJECT: **GE Experience with BWR Fuel Through December 1992**

The attached report provides an update of the in-reactor surveillance programs as well as overall GE BWR fuel experience through December 1992.

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GE EXPERIENCE WITH BWR FUEL
THROUGH DECEMBER 1992

I. Introduction

This information report provides an updated review of GE experience with production and developmental BWR Zircaloy–clad UO_2 fuel rods through December 1992. This experience includes successful commercial reactor operation of fuel bundles to 68,000 MWd/MTU peak pellet exposure.

The performance of GE fuel continues to be highly successful as demonstrated by a fuel rod reliability greater than 99.99% for fuel manufactured since January 1988.

II. GE BWR Fuel Experience Base

As of December 31, 1992, over 4.5 million GE 8X8 and later fuel type production Zircaloy–clad UO_2 fuel rods were in, or had completed, operation in commercial BWRs. Figure 1 shows cumulative 8X8 and later fuel rods loaded as a function of calendar year. As of December 31, 1992, nearly 1.5 million GE fuel rods were in operation. Figure 2 illustrates GE's core loadings at the end of 1992 by fuel type. As of December 31, 1992, GE had loaded approximately 1.77 million pellet–clad interaction (PCI) resistant barrier fuel rods in commercial BWR's.

III. In–Reactor Surveillance Programs and Summary of Surveillance Results

One of the most important aspects of the GE fuel design process is the in–reactor performance monitoring of a design before and after its introduction. In keeping with the GE philosophy of test–before–use, lead use assemblies (LUA's) containing selected key design features are used to demonstrate the satisfactory performance of these features and to provide lead experience for future production fuel. The fuel surveillance program adopted by GE and accepted by the NRC is described in References 1 through 4.

A summary of GE's lead use assembly surveillance program is contained in Table 1. Examination results are provided below:

A. Barrier Fuel Program

The goal of this program was the demonstration of a Pellet–Cladding Interaction (PCI) resistant fuel under conditions which would provide statistically significant results. The PCI–resistant fuel features the barrier concept to protect the fuel cladding from failure caused by PCI. The barrier fuel program consisted of four lead use assemblies, loaded into Quad Cities–1 in 1979 at the beginning of cycle 5, and a demonstration reload of 144 bundles with Zr–lined cladding placed into the core of Quad Cities–2 in 1981 at the beginning of cycle 6. This program was part of a USDOE–sponsored program which included severe power ramp testing. The USDOE severe power ramp testing revealed that PCI failure could occur with barrier fuel, although this testing, in conjunction with separate GE severe power ramp testing and subsequent extensive commercial irradiation experience has demonstrated that the probability of PCI failure in barrier fuel, while finite, is very low.

The barrier LUA's at Quad Cities–1 operated for up to 5 cycles and underwent five poolside examinations consisting of visual inspections and non–destructive testing of selected fuel rods. These examinations revealed that the bundles and individual fuel rods exhibited characteristics typical of normal operation.

Six fuel rods were removed from one of the discharged LUA's (at 43,000 MWd/MTU) and were then exchanged with 6 rods from a bundle that had completed two cycles of operation. The reload bundle containing the 6 barrier LUA rods was reinserted in Quad Cities 1 for Cycle 11. In November 1990, at the end of Cycle 11, examination of these six rods showed that they continued to exhibit normal performance. This bundle was reinserted for operation during Quad Cities 1, Cycle 12. This bundle was discharged at the end of Cycle 12 resulting in an estimated peak pellet exposure of 68,000 MWd/MTU in the 6 barrier LUA fuel rods.

The Quad Cities–2 barrier fuel program was designed to subject the barrier cladding fuel to significant power increases in order to demonstrate the PCI resistance of barrier fuel. Two power increase demonstrations were performed; the first in 1983 at the end of cycle 6 and the second in 1985 at the end of cycle 7. Sixteen barrier bundles were involved in each demonstration. During the following plant outage, all demonstration barrier bundles were evaluated by vacuum offgas sipping and determined to be sound. Subsequent to the power increase demonstrations, all PCIOMR operating restrictions were removed from the barrier fuel bundles in the core. Plant offgas surveillance indicated that all fuel bundles in the core operated reliably. Of the 144 bundles in the reload, 32 operated for 3 cycles, 80 operated for 4 cycles, 16 for 5 cycles and 16 bundles operated for 6 cycles and were finally discharged in 1992.

B. Improved Design Feature Lead Use Assemblies

Several Lead Use Assemblies have been designed and placed in operation for the purpose of obtaining experience and performance data on new product design features. These LUAs have undergone extensive preirradiation characterization, with plans for interim poolside examinations. These Improved Design Feature LUAs include:

1. 1983 Lead Use Assemblies

   Four LUAs were loaded into a BWR 4 in 1983. The first poolside examination of these bundles was completed in August 1985, after one cycle of operation, and showed characteristics typical of normal operation. The second poolside examination was completed in November 1987, after two cycles of operation, and showed characteristics typical of two cycles of normal operation. The third poolside examination was completed in October 1991, after three cycles of operation, and showed characteristics typical of three cycles of normal operation. The LUAs were discharged after achieving bundle average exposures of about 32,000 MWd/MTU

2. 1984 Lead Use Assemblies

Five LUAs were loaded into a BWR 4 in 1985. Four of the LUAs were loaded in central core locations and one LUA was loaded at the edge of the core. The first poolside examination of these bundles was completed in April 1987, after one cycle of operation, and showed characteristics typical of normal operation. The second poolside examination was completed in October 1988, after two cycles of operation, and showed characteristics typical of two cycles of normal operation. The third cycle of operation ended in June 1990. The edge LUA was inspected and showed characteristics typical of three cycles of normal operation. The four central LUAs achieved bundle average exposures of about 40,000 MWd/MTU and were discharged. The edge LUA continued operation for one additional cycle to about 33,000 MWd/MTU and was discharged in early 1992.

3. 1987 Lead Use Assemblies

Four LUAs were loaded into a BWR 4 in 1987. These fuel assemblies represent lead use GE8X8NB fuel. The first poolside examination of these bundles was completed in October 1988, after one cycle of operation, and showed characteristics typical of normal operation. The second poolside examination of these bundles was completed in March 1990, after two cycles of operation, and again showed characteristics typical of normal operation. The third poolside examination of these bundles was completed in October 1991, after three cycles of operation at bundle average exposures of about 32,000 MWd/MTU, and also showed characteristics typical of normal operation. These bundles were reinserted for continued operation in November 1991.

A second group of four LUAs were loaded into another BWR 4 in 1989 at the beginning of cycle 8. The first poolside examination of these bundles was completed in February 1991 after the first cycle of operation, and showed characteristics typical of normal operation. These bundles completed a second cycle of operation in September 1992 achieving average exposures of about 23,000 MWd/MTU. The inspection showed characteristics typical of normal operation. These bundles were reinserted for continued operation in December 1992.

4. Cladding Corrosion Performance LUAs

Six LUAs were loaded into a BWR 4 in early 1988 and six LUAs were loaded into another BWR 4 in late 1988. Features tested include cladding material, heat treatment, and surface conditioning and the most recent corrosion improvement processes. Three LUAs were examined in the first BWR 4 reactor in late 1989, after one cycle of operation. Another three LUAs were examined in the second BWR 4 reactor in early 1990, also after one cycle of operation. These LUAs reflected bundle average exposures up to 13,000 MWd/MTU. Visual inspection revealed excellent corrosion resistance along the full length of the fuel rods. The second poolside examinations of the LUAs were completed in March 1991 and in October 1991. Visual inspection after bundle average exposures up to 23,000 MWd/MTU again revealed excellent corrosion resistance along the full length of the fuel rods.

In the first BWR the LUAs were reinserted for continued operation in June 1991 and completed a third cycle of operation in September 1992 achieving average exposures of about 33,000 MWd/MTU. Inspection of these LUAs again revealed excellent corrosion performance. Four of these LUAs were reinserted in November 1992 for a fourth cycle of irradiation. In the second BWR the 6 LUAs were reinserted for a third cycle of operation in November 1991.

5. GE8X8NB-1 Channel Lead Use Assemblies

Four LUAs were loaded into a BWR 4 in 1988. These LUAs represent lead use of GE8X8NB-1 design features. The first poolside examination of these bundles was completed in April 1989, after one cycle of operation, and showed characteristics typical of normal operation. The second poolside examination of these bundles was completed in March 1991, after two cycles of operation at bundle average exposures of about 14,000 MWd/MTU, and showed characteristics typical of normal operation. The third cycle of irradiation was completed in October 1992. After three cycles the bundle average exposures were about 25,000 MWd/MTU. The bundles were reinserted for a fourth cycle of continued operation.

6. GE11 Lead Use Assemblies

In 1990 four GE11 LUAs were loaded in each of three reactors (Two BWR 4s and one BWR 5). In 1992 bundle average exposures for these LUAs ranged from 9,000-13,000 MWd/MTU. Poolside examinations were performed in one of these reactors in April 1991; the GE11 fuel assemblies showed characteristics typical of normal operation. The bundles were reinserted for continued operation.

In 1991 four more GE11 LUAs were loaded in each of three BWR 4s. In 1992 bundle average exposures for these LUAs ranged from 12,000-13,000 MWd/MTU. Poolside examinations were performed in two of these reactors in October 1992 and the GE11 bundles showed characteristics of normal operation. The bundles were reinserted for continued operation.

IV. Generic Fuel Performance Mechanisms

Pellet-cladding interaction (PCI), crud-induced localized corrosion (CILC), undetected manufacturing defects and debris fretting are the primary cladding perforation mechanisms that have affected fuel performance in recent periods. As described below, product and process improvements have been developed to eliminate these failure mechanisms.

A. Pellet-Cladding Interaction

Light Water Reactor (LWR) nuclear fuel is susceptible to fuel rod cladding perforation, commonly called pellet-cladding interaction (PCI) failure, when subjected to fast power increases at moderate to high exposures. Operational procedures (PCIOMRs), which involve slow approaches to power, have essentially, but not completely, eliminated PCI failures in LWRs, but at the cost of reactor capacity factor losses. Zirconium barrier fuel was invented by GE as a material solution to the PCI failure problem. Extensive test reactor and laboratory tests along with successful in–core power ramp demonstrations in the Quad Cities Unit 2 power reactor have shown that Zr–barrier fuel is convincingly failure resistant. Barrier fuel was commercially introduced by GE in 1983. With the successful completion of the Quad Cities–2 barrier demonstration program, GE recommended the removal of all PCIOMR operating restrictions on GE barrier fuel. Over 50 reactor cycles of operation have been successfully completed by GE barrier fuel without restrictive PCIOMR controls. The effectiveness of the GE barrier cladding design feature has been confirmed by the extensive commercial reactor experience where not a single barrier fuel rod failure due to PCI has been observed in over 1,400,000 GE barrier fuel rods completing at least one cycle of operation.

B. Crud–Induced Localized Corrosion

In 1979, an unexpected failure mechanism of localized fuel rod cladding corrosion was revealed in some BWRs. Poolside examination of the failed fuel rods revealed plant corrosion product (crud) scale deposits with high copper concentrations. The nature of the failures led to identification of special conditions of environment, operational history, and material–susceptibility that must occur simultaneously to cause failure. These crud–induced localized corrosion (CILC) failures have been limited to plants with copper alloy condenser tubes and filter demineralizer condensate cleanup systems.

Mitigating actions have been taken both by the BWR owners and GE. Mitigating actions taken by the BWR owners include replacement of copper bearing condensers with either titanium or stainless steel units, installation of deep bed condensate cleanup systems, and improved water chemistry controls. Mitigating actions taken by GE include the development and implementation of improved tubing fabrication processes and quality assurance testing methods to ensure fuel rod cladding with improved nodular corrosion resistance.

A reproducible out–of–reactor test for measuring the susceptibility of Zircaloy to in–reactor nodular corrosion was developed by GE and correlated to in–reactor performance (Reference 5). This test confirmed a previously undetected variability in the susceptibility of Zircaloy to in–reactor nodular corrosion. This test has been patented and made available to the industry on a non–profit basis through the ASTM.

The effectiveness of these mitigating actions is demonstrated by operating experience. As of December 1992, more than 1.37 million improved corrosion–resistant fuel rods (fabricated after December 1985) have completed at least one cycle of operation without a single fuel rod failure due to CILC, with the exception of a single, severe chemical intrusion event at one US reactor in 1989.

C. Debris Fretting

Debris fretting is the vibratory wear of the cladding caused by foreign material (small pieces of wire, machining turnings, etc.) entrapped adjacent to the fuel rod. The failure location is usually observed as a perforation in a smoothed abraded area with secondary hydriding away from the debris perforation. Historically, debris fretting has been an infrequent cause of failures but an increasing trend has been observed in recent years. In addition to providing inspection and debris removal services, GE has recently introduced changes in the bundle design to limit debris access to the fuel bundle and thereby reduce the incidence of debris fretting failures.

With the GE11 fuel design, the lower tie plate pressure drop has been increased to maximize channel hydrodynamic stability. This pressure drop increase was achieved primarily through the adoption of smaller flow holes. These smaller flow holes significantly reduce the size of passable debris.

D. Undetected Manufacturing Defects

Undetected manufacturing defects resulting in fuel rod failures have historically been tubing reduction flaws or end plug weld defects. Historically, failures due to undetected manufacturing defects have been rare, although an increased frequency has been observed starting in 1988. The cause of the defect frequency increase has been identified as the inability of the standard tubing flaw inspection to reliably detect certain reduction flaw configurations. GE initiated corrective action in 1988 resulting in an improved ultrasonic tubing flaw inspection system. This improved tubing flaw inspection system is expected to eliminate tube reducer generated flaws as a cause of in–reactor fuel failures.

GE has similarly developed and implemented significant improvements to maximize end plug weld integrity. With the introduction of the GE8X8NB design in 1989, the higher stressed lower end plug weld joint was redesigned to produce an ultrasonically–inspectable flush weld. A high resolution ultrasonic microscope inspection system was developed by GE to provide 100% inspection of these flush lower end plug welds. With the introduction of the GE11 design in 1991, the flush weld configuration and 100% ultrasonic microscope examination were extended to the upper end plug in addition to the lower end plug weld.

V. Conclusions

GE has developed a substantial fuel experience base that, coupled with an aggressive fuel surveillance program, has provided significant feedback on statistically significant numbers of fuel rods with regard to the performance effectiveness of design, operational and manufacturing changes. The success of the GE Fuel Reliability Program is illustrated by comparing Figure 3 (from Reference 6 showing the number of failed bundles per GW(e) for the US BWRs) to Figure 4. Figure 3 presents the results of an EPRI study showing the number of defective assemblies per GW(e) installed capacity for all US BWR fuel. The bulk of the experience shown in Figure 3 is GE BWR fuel experience. Figure 3 indicates a dramatic progressive improvement in fuel reliability over time. Figure 4 presents these same EPRI results for 1986–1990 as well as the average failure rates determined by EPRI for PWR and BWR fuel in addition to EPRI's proposed reliability target (1 defective assembly per GW(e) installed capacity). Included in Figure 4 are the GE fuel performance results for 1991 and 1992 for comparison. It is concluded that the experience gained with GE production and developmental fuel continues to demonstrate the high reliability of the GE designed BWR fuel.

VI. References

1. J. S. Charnley (GE) to C. H. Berlinger (NRC), "Post Irradiation Fuel Surveillance Program", November 23, 1983.

2. J. S. Charnley (GE) to L. S. Rubenstein (NRC), "Fuel Surveillance Program", February 29, 1985.

3. J. S. Charnley (GE) to L. S. Rubenstein (NRC), "Additional Details Regarding Fuel Surveillance Program", May 25, 1984.

4. L. S. Rubenstein (NRC) to R. L. Gridley (GE), "Acceptance of GE Proposed Fuel Surveillance Program", June 27, 1984.

5. B. Cheng, H. A. Levin, R. B. Adamson, M. O. Marlowe, V. L. Monroe, "Development of a Sensitive and Reproducible Steam Test for Zircaloy Nodular Corrosion", ASTM 7th International Conference on Zirconium in the Nuclear Industry, Strasbourg, France, June 24–27, 1985.

6 W. F. Naughton, "Excellence in Nuclear Fuel Performance", USCEA, Nuclear Fuel Cycle 91 Conference, March 27, 1991, Phoenix, Arizona.

Table 1
Summary of Ongoing Lead Use Assembly Surveillance Programs as of December 1992

Program	Reactor Class	Number of Bundles	Number of Completed Cycles of Operation	Bundle Average Exposure At Last Outage (GWd/MTU)	Objectives
Barrier LUA's	BWR 3	2	5*	43	Barrier Cladding
1983 LUA's	BWR 4	4	3	32	improved design features
1984 LUA's	BWR 4	1	4	33	Improved design features
1987 LUA's	BWR 4	4	3	32	Lead Use GE8X8NB
	BWR 4	4	2	23	
Corrosion Performance	BWR 4	6	2	23	Clad Mat'l Process Variables
	BWR 4	6	3	33	

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* Six rods have been irradiated for 7 cycles to rod average exposures of 50 to 58 GWd/MTU

Table 1. Continued
Summary of Ongoing Lead Use Assembly Surveillance Programs

Program	Reactor Class	Number of Bundles	Number of Completed Cycles of Operation	Bundle Average Exposure At Last Outage (GWd/MTU)	Objectives
GE8X8NB–1 Channel LUA's	BWR 4	4	3	25	Lead Use GE8X8NB–1 Features
GE11 LUA's	BWR 4	4	1	13	Lead Use GE11
	BWR 4	4	1	9	
	BWR 5	4	2	11	
	BWR 4	4	1	13	
	BWR 4	4	1	12	
	BWR 4	4	–	–	

Figure 1. BWR GE Fuel Rod* Experience

* 8X8 and Later GE Fuel Designs

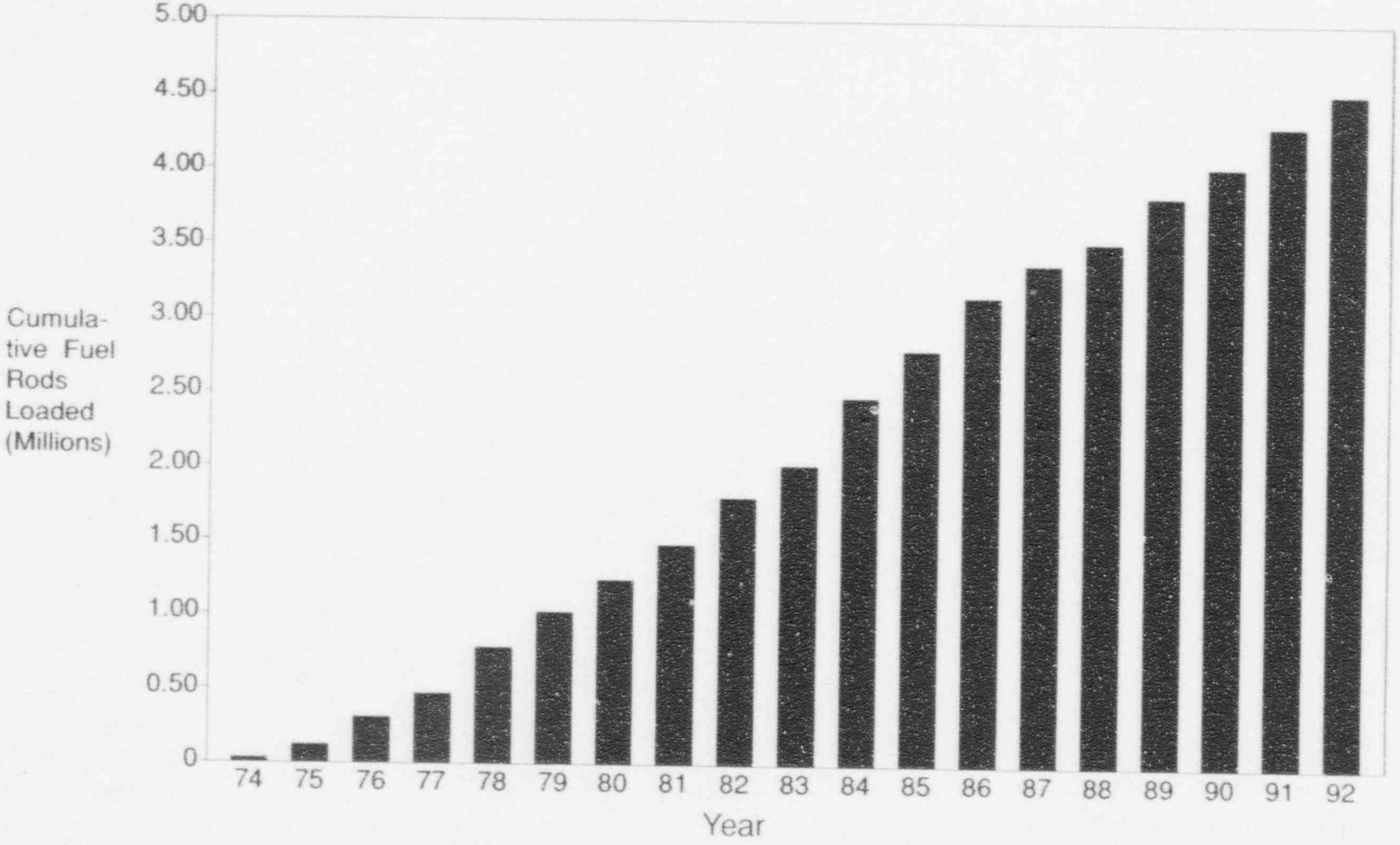


Figure 2. GE BWR Fuel Rods in Operation on 12/31/92

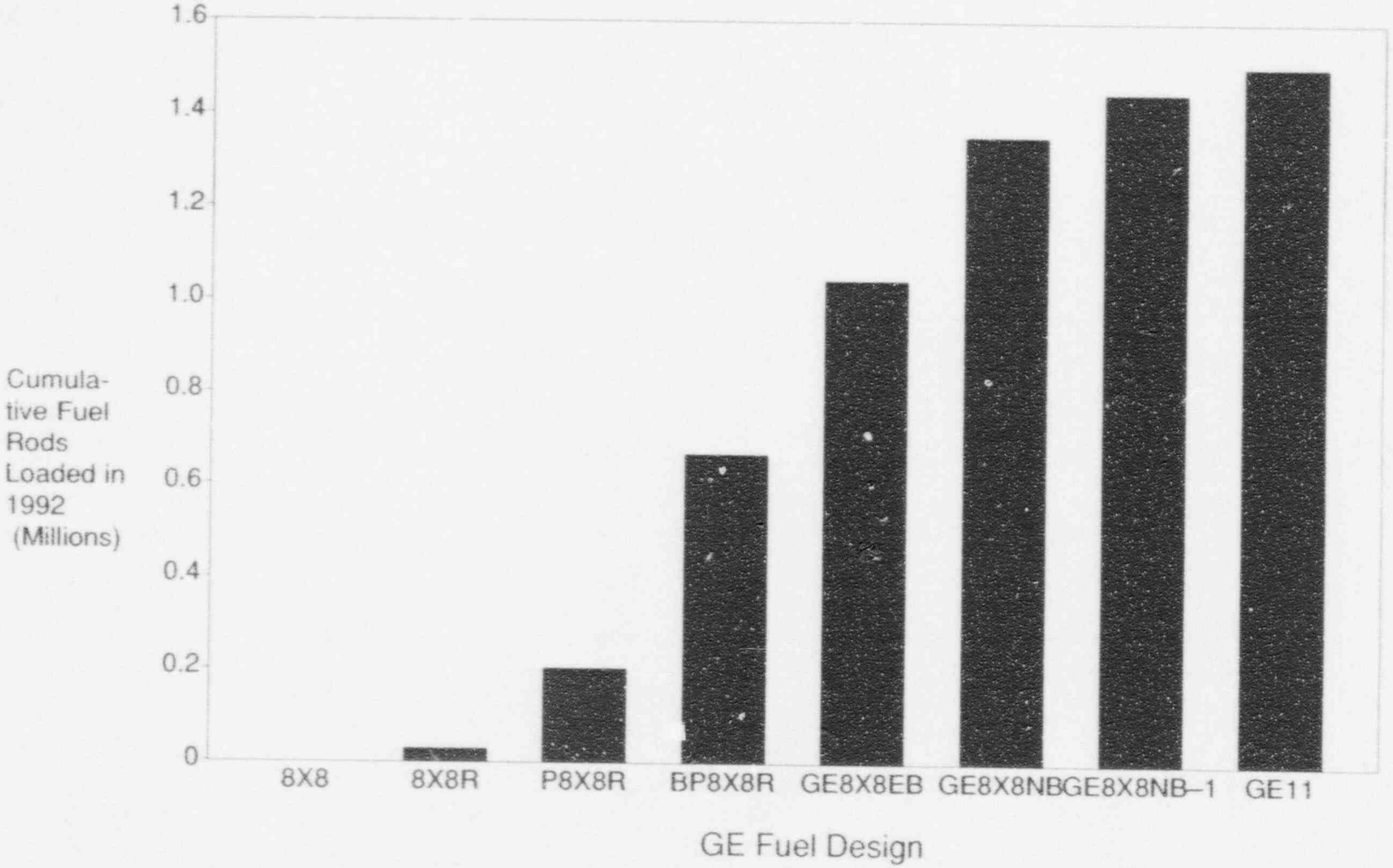
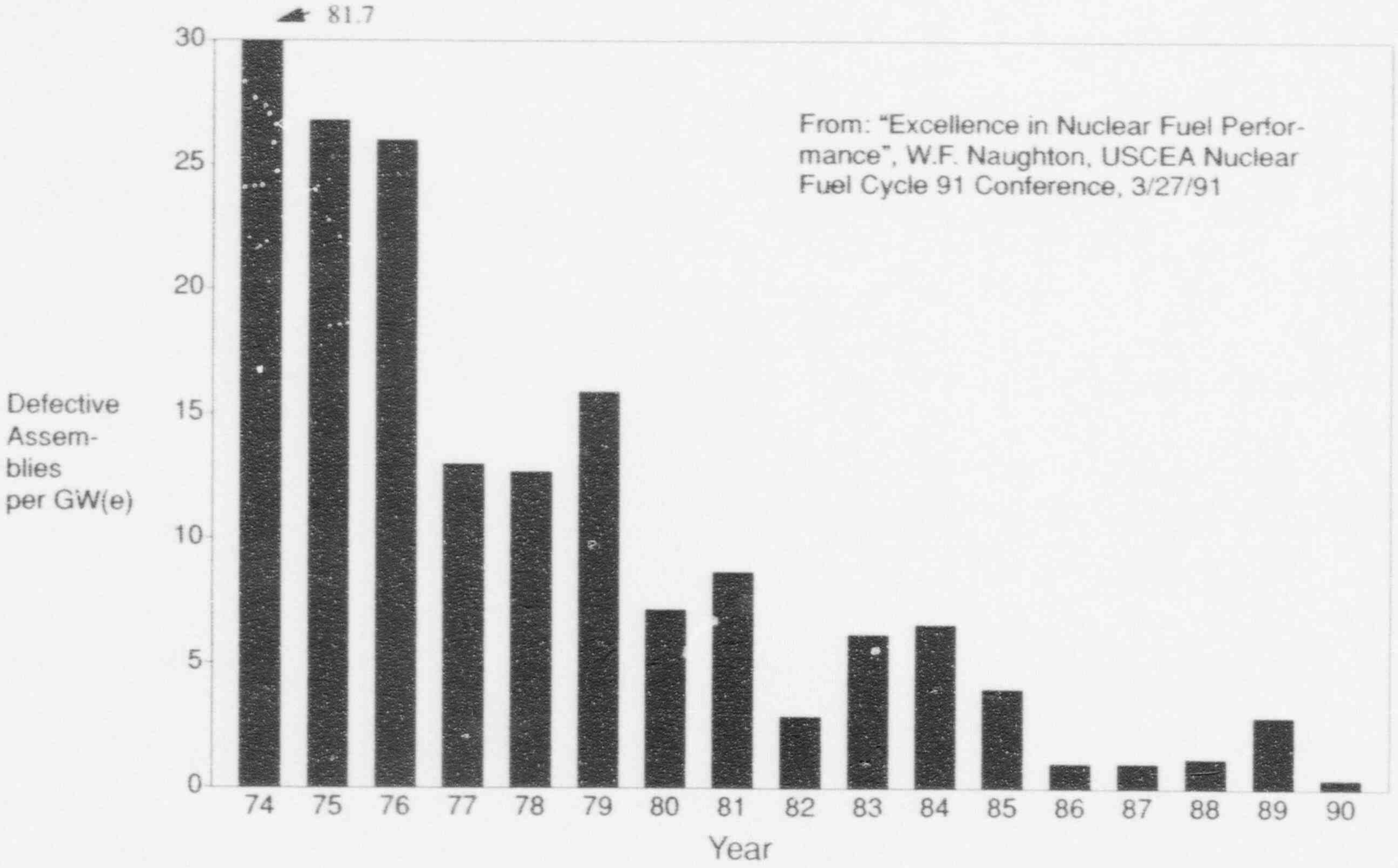


Figure 3. BWR Failed Assemblies per GW(e) Installed Capacity

17–Year Trend Based on EPRI Data



From: "Excellence in Nuclear Fuel Performance", W.F. Naughton, USCEA Nuclear Fuel Cycle 91 Conference, 3/27/91

Figure 4. BWR Failed Assemblies per GW(e) Installed Capacity vs GE failures (post 1990)