Refueling Outage Trends in Light Water Reactors

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Prepared by
Science Applications, Inc.
Palo Alto, California

ELECTRIC POWER RESEARCH INSTITUTE

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LEGAL NOTICE

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This interim report is a product of an ongoing program at EPRI to analyze existing power plant data and to provide feedback on the analysis to the power industry. This particular report is an analysis of nuclear power unit refuelings. The information compiled herein comes entirely from data collected by the Nuclear Regulatory Commission (NRC) from nuclear plants. Other studies are underway both at EPRI and the Department of Energy to study refueling outages in detail and to implement solutions to problems identified. These latter studies are not limited to data analysis but also involve in-plant investigation of refueling procedures and problems.

PROJECT OBJECTIVE

Refueling outages are the major contributor to nuclear plant unavailability and, as such, deserve special attention in efforts to improve nuclear plant performance. The objective of this study was to quantify the impact of refueling outages on nuclear unit availability and characterize the major critical path work which comprises the refueling outage. Other studies conducted under this project have also had the objective of showing the effects of particular problem areas on nuclear unit performance. Reports have been published on piping failures and on instrumentation and control failures in nuclear units.

CONCLUSIONS AND RECOMMENDATIONS

Since the results of this report are based entirely upon data submitted to standard format data bases (e.g., the NRC Gray Books), much of the detail necessary to completely characterize refueling outages is lost. Such detail can only be gained through extensive surveys of plant historical records or through in-plant surveys of actual refueling outages and perhaps in the future from improved power plant data systems. Nevertheless, the report has successfully summarized what the average nuclear plant can expect from a refueling outage.

This report supports the concept of extending the normal twelve month refueling cycle to eighteen months. This is justified in the report principally from a predicted plant availability improvement standpoint. There has not been enough documented experience to date with the eighteen month refueling cycle to show that increased plant availability will actually be realized.

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ABSTRACT

Operating experience in U.S. light water reactors (LWRs) has shown that the impact of refueling outages on plant unavailability is much higher than has been previously anticipated. The purpose of this report is to identify the principal causes of the extensions of refueling outages, the effect of these outages on plant productivity, and an alternative refueling cycle to reduce their impact. Both the refueling outages and other major outages are displayed as a function of plant age; this method allows identification of trends in these outages as a plant matures. In addition, 27 refuelings are investigated in depth to determine the contributors to refueling outage extensions. Based upon this summary of refueling outages, an evaluation is made of the decision to refuel on an annual basis versus a longer cycle (i.e., 18 months). The result of the evaluation indicates that utilities can improve plant availability by up to 6% per year by increasing the time between refuelings from an annual to an 18 month refueling cycle.

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Section 1.0

INTRODUCTION AND SUMMARY

The annual refueling cycle which is approximated in most commercial nuclear power plants in the U.S. has evolved based upon the belief that refuelings can be performed in one to three weeks and that other plant maintenance can also be conveniently handled on an annual basis. Refueling outages have proven to be highly complex operations requiring large efforts in planning, organization, and coordination, including supplementation of the normal contingent of plant personnel with outside contractor personnel. Acting as a "magnet", the refueling outage has attracted an increasing amount of diverse, non-refueling oriented work efforts which can be performed in parallel with the refueling operations. The refueling outage may include 2000-3000 work orders, including such tasks as:

- Tests of operating and safety-related equipment
- Inspections of key equipment
- Repairs
- Equipment replacement
- Maintenance (preventive & required)
- Refueling operations

All of these tasks have combined to make refueling outages significantly longer than originally anticipated. Based upon the unexpected length of refueling outages, it may be time to reevaluate the philosophy behind the refueling outage to determine whether the impact of refueling on plant availability can be decreased.

In order to deal with the complexity of a refueling outage, planning must include the allocation of time, personnel, and spare parts. The operating experience accumulated in U.S. LWRs can be used to guide key decisions in outage planning, outage scheduling, and contingency planning. Therefore, this report presents a review of the operating experience of nuclear power plant refueling outages to determine if the assumption of rapid refuelings is valid, or if acceptable alternatives are available to reduce the impact of refuelings on plant availability.

1.1 Background

Operating experience indicates that plant availability is highly sensitive to refueling outage durations[1,2,3]. Because of its potential for high impact on plant availability, the length of a refueling outage also affects reliability goals, fuel management schemes, alternate fuel cycle decisions, and a wide variety of other utility planning decisions. Heretofore, the LWR operating experience with refueling outages has not supported past claims by nuclear steam supply system (NSSS) vendors that refueling can be consistently performed in 1 to 3 weeks[4,5,6]. This conflict in projected refueling outage duration and practical reality has led to some confusion as to what can be expected of future performance during refueling outages. Because of this confusion, it appears desirable to consolidate the large accumulation of operating experience over the past few years and to identify those areas of refueling outages which appear most fruitful for improvements to reduce the impact of refueling outages on plant availability. The following examples are given in order to stress the importance of the refueling outage length in decisions affecting power plant planning:

- Utilities and architect engineering firms have targeted overall LWR plant availabilities in the range of 86 to 90% for new plants[1,2,3]. In order to achieve this goal, refueling outages have been targeted for approximately 30 days per year[3]. The ability to complete a refueling outage in 30 days is based upon projected improvements in plant and equipment design and arrangement.

- Current annual refueling cycles and the initial fuel enrichments have been set more by tradition than a detailed optimization of the economic parameters involved. Some utilities have taken the initiative to increase the interval between refuelings because of potential improvements in the plant availability.

- Economic and regulatory decisions within the government can sometimes be based upon incomplete information. In 1975, the Federal Power Commission[7] projected that since refueling outages were accomplished more quickly during each subsequent refueling that eventually the refueling outage could be reduced to approximately 3 to 4 weeks.

- Changes in national policy concerning LWR fuel reprocessing have caused a great deal of current interest in alternative fuel cycles which would lead to better utilization of existing uranium resources. A program sponsored by the Department of Energy (DOE) is evaluating nonproliferation alternative systems including schemes which would increase the frequency of refuelings[8].

- Fuel cycle costs are one contributor to the overall cost of nuclear power production. One element of the fuel cycle is the enrichment of the uranium required and its cost in LWRs. If enrichment facilities are overtaxed, or if fuel costs become a dominating factor in the economic equation, reduced enrichments can be used in LWRs if more frequent refuelings are allowed. Past studies have indicated there may be a potential economic advantage to semi-annual refuelings coupled with a rapid refueling[4].

- Fuel management schemes and optimization have incorporated a number of assumptions which are not borne out in the real world. These assumptions include: equal intervals between refuelings of ~11 months, capacity factors of 75 to 85%, and negligible impact of the variability of refueling outage time on the cycle length. These lead to a certain band of initial enrichments, end-of-life (EOL) elemental distribution, batch sizes, and residence times in-core[9] which are not supported by operating experience to date.

Each of the above items describes an important decision in the planning of nuclear power plant operation, maintenance or fuel cycle which is being made without full utilization of the existing operating experience on refueling outage lengths. This report can supply some of the input information for these decision making programs.

Some aspects of refueling outages have received a great deal of attention in efforts to reduce the current refueling outage length. The methods which have been suggested in the past to reduce the impact of refueling outages on plant availability can be categorized as follows: 1) plan and prepare personnel organization, work schedules, etc. (see References 10 through 22); 2) improve refueling equipment, procedures, and plant arrangement[1,23]; and 3) increase the interval between refuelings[4].

The first of these areas has been discussed extensively in the literature (see References 10 through 22) and is summarized here in capsule form:

- Design plants to facilitate maintenance[1,16,17]
- Schedule maintenance at appropriate times[17]
- Make use of operating experience data to improve preparation for maintenance and repair[13,15,16,20,21]
- Consider the use of highly specialized contracting services to perform special tasks[15]
- Ensure that personnel are well trained[11,15,16]
- Provide a detailed schedule and assign tasks within a refueling organizational chart[10,11,14,16]
- Establish a priority list of items required to be maintained and efforts required during the next outage [18]
- Begin planning for a refueling outage approximately nine[10] months in advance[10,15,16,21]
- Establish communication chains, such as daily meetings, plans-of-the-day[10,16], etc.
- Develop detailed procedures[16]
- Make use of full scale models to practice the refueling operation or other key events (e.g., steam generator inspection)[22]

The second area of potential for decreasing the refueling outage duration is the improvement in refueling equipment and procedures. This effort has taken the form of a DOE sponsored program[23] which is designed to reduce refueling outages by concentrating on the modification of refueling equipment and procedures. DOE is co-sponsoring programs with each of the major NSSS vendors and cooperating utilities to evaluate equipment and procedures during a selected refueling at each of four plants:

NSSS Vendor	Plant
Babcock & Wilcox	Oconee 3
Westinghouse	Zion 1
Combustion Engineering	Fort Calhoun
General Electric	Brown's Ferry

The results of this program will be improved equipment design for refueling operations and inspection plus changes in outage management and scheduling. Section 4.0 gives an estimate of the magnitude of the benefit which can be expected from this program.

The third area of potential improvement is increasing the intervals between refuelings[4], thereby, in principal, eliminating a portion of the plant unavailability (see Section 5 for a detailed discussion).

1.2 Objectives

The purpose of this report is to utilize operating experience data to identify trends in LWR refueling outages and to recommend possible changes to improve plant availability.

Many people in the utilities who are directly involved in nuclear power plant operation know the reasons for their particular plant outages and outage extensions. However, the industry in general has not been provided with a composite picture of the primary causes of refueling outage extensions based upon overall industry experience. The purpose of the current study is to present a summary of refueling outages and, based upon a selected sample of refueling outages, to estimate what the principal causes of refueling extensions are and in which areas further investigation would be most fruitful for the improvement of power plant productivity.

A statistical summary of LWR refueling experience is presented for the 128 U.S. refuelings. Emphasis is placed on defining the overall range of refueling outage durations, the intervals between refuelings, the effect of plant size on refueling outages, and the impact of refueling outages on availability. Twenty-seven refueling outages are dissected to determine the causes of refueling outage extensions.

Utility operation managers, component designers, and architect-engineers must make numerous key decisions on plant design, arrangement, and operation without the aid of adequate data. This summary report is aimed at providing a small piece of the data which can lead to better decisions for improving plant availability.

1.3 Scope and Limitations

The scope of this report is limited to the following areas:

- Outages: Refueling outages.
- Population: All U.S. LWRs larger than 150 MWe which are in commercial operation. The detailed breakdown of activities occurring during a refueling outage is based upon 27 selected refuelings for which adequate data is available in the public record.
- Time Frame: January 1960 through June 1977.

The classification of outages in nuclear power plants borders on being an art rather than an exact science. Because a nuclear power plant is a complex unit whose availability to produce power is dependent upon a wide variety of interrelated systems, many times it becomes difficult to pinpoint the exact cause of an outage. To determine the reasons for the extensions of an outage without access to the detailed plant records is even more difficult.

Refuelings would seem, at first, to be precise and well defined events. However, as we shall see in this report, outages which have been reported as refueling outages have included refueling operations, plant maintenance, testing, in-service inspections, and equipment repair. In this report we shall investigate the causes of extensions of the refueling outage, areas for potential increases in plant availability, and alternative refueling cycle lengths.

The majority of outages included in this report involve refueling operations as the principal event. However, some outages which were primarily due to other causes, such as turbine blade failure, are referred to in this report as refueling outages since a core refueling was accomplished in parallel: this is similar to the nomenclature used in the Nuclear Regulatory Commission (NRC) "Gray Books"[24]. In addition, unless a reactor is brought to criticality subsequent to refueling, the outage extension is considered an integral part of the "refueling".

The population considered has been limited to plants with design electrical ratings larger than 150 MWe in order to focus on those plants which are most representative of the current and future generation of nuclear plants: those plants which are eliminated from the current study are small prototype units which have generally had good records but are not considered indicative of future trends (e.g., Humboldt Bay - 65 MWe, LaCrosse - 50 MWe, Big Rock Point - 72 MWe). In addition, Indian Point 1 has not been included because it is presently shutdown with no immediate plans for continued operation.

The data which has not been included in the evaluation is summarized briefly in the table below:

Plant	Type	Design Electrical Rating	Years of Operation	No. of Refuelings	Avg. Refueling Duration (months)
Big Rock Point	BWR	72 MWe	14	13	2.0+
Humboldt Bay	BWR	65 MWe	14	12	1.3
Indian Point 1	PWR	265 MWe	12	4	2.3
LaCrosse	BWR	50 MWe	6	3++	2.7

\+ Based upon the last eight refuelings.

++ Only three refuelings have been identified from available data.

It should be noted that the refueling outages not included in this report have an average length similar to that obtained for the remainder of the population. This is the case for all plants except Humboldt Bay which has an exceptionally good record of rapid refuelings - approximately 1.3 months per refueling.

While the overview of refueling outages is based upon the total population of U.S. refuelings, the investigation into the detailed make-up of refueling outages and the causes of their extensions (Section 4) has a limitation on the population sample in that only 27 refuelings have been considered. The only reason for using this sample size is the lack of available information in the public record.* In addition, the emphasis in this report is on determining the general causes of refueling extensions for those refueling outages under 3 months in length. There is no attempt to classify the causes of refueling outage extensions by equipment type since the available data on 27 refueling outages is insufficient to support that degree of detail in the analysis.

*Primarily information available in documents which are located in the NRC Public Document Room

As in most nuclear data evaluations, one problem which must be accounted for in assessing the data is that the industry is constantly improving its equipment, designs, and methods. The operating experience from ten years ago may not be completely applicable to the designs of today. However, this report will attempt to show that perturbations in design, while important, can be treated as small changes in the overall refueling outage assessment. An example of changing design is the evaluation of the "integrated closure head lift" on PWRs. The concept is to lift the entire closure head package (including studs) at one time, therefore minimizing the assembly and disassembly times for this operation (see Section 4.4). The impact from this design change can be estimated based upon this report. The implication then is that vendors are acutely aware of problems in refuelings and are constantly improving their methods. However, other considerations such as the increasing burden of testing and inspection, the tighter security measures, and finally, the longer times to perform prescribed maintenance may lead utilities to incorporate other basic changes in the refueling philosophy.

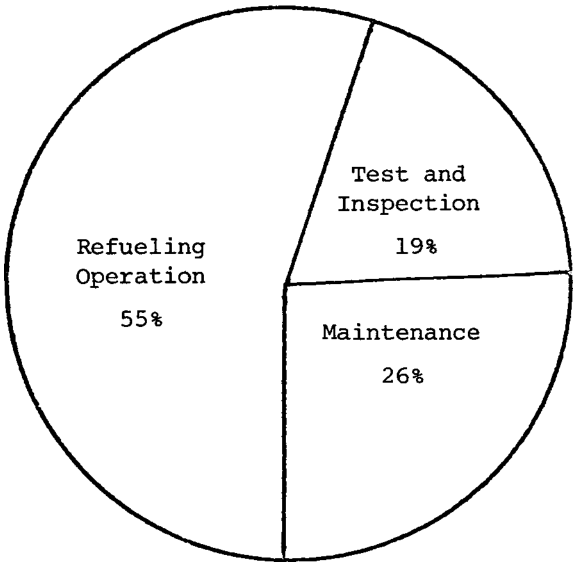
One area of refueling outage management which has not been treated in this study is the impact of using outside contracted services in lieu of plant maintenance personnel. Past experience[16] with outside services indicates that they rely heavily on craft people from local unions and that the quality of work and length of outages tends to be much more variable than would be the case if sufficient plant maintenance personnel could be brought to bear on the problem. However, information on the degree to which outside services are utilized is not readily available and is difficult to quantify; therefore, this area enters as an uncertainty in the analysis.

1.4 Summary of Conclusions

The major conclusions of this report are summarized briefly below:

1. Refueling outages accounted for approximately 40% of the plant unavailability during the period 1974-1977 when there was a high percentage of new plants. However, as plants mature, the trends indicate that the percentage effect of refueling outages is even larger, approaching 60% of the plant unavailability time for plants in commercial operation longer than 2 years.

2. Based upon operating experience, critical path refueling outage time is composed of the following broad categories:



The refueling operation can be further broken down in the following comparison between BWRs and PWRs (see Section 4):

	Length of Average Operation (Days)	
Refueling Operation (Days)	BWRs	PWRs
Closure Head Removal	3.4	8.5
Preparation to Move Fuel	2.3	2.4
Movement of Fuel	19.8	9.3
Closure Head Assembly	5.3	6.9
Closure Head Assembly Through Criticality	3.3	5.3
Criticality Through Power Operation	0.4	1.6
TOTAL	34.5	34.2

3. The average length of refueling outages per plant tends to decrease with plant age. Figure 1.1 emphasizes this decrease in refueling outage time as the refueling cycle number increases.

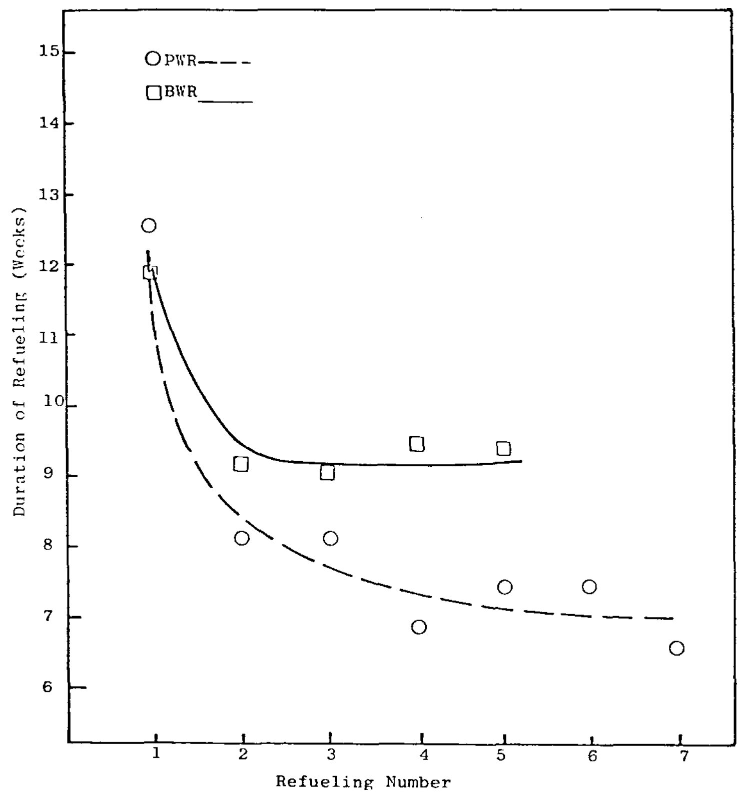


Figure 1.1. Refueling Duration as a Function of the Number of Refuelings

4. The impact of refueling outages on plant availability can be decreased by reducing the frequency of the refueling outages. Based upon the average refueling length determined in this report, the plant availability can be increased by up to 6% by reducing the frequency of refuelings from once per 12 months to once per 18 months.

5. There is a small positive correlation between plant size and the length of refueling outages. This means that larger plants will tend to have longer refueling outages.

6. European LWRs have refueling outages which are approximately 20% shorter than US LWR refueling outages.

7. The predictions on the length of refueling outages underestimate the actual length of refueling outages by one to three weeks. (The longer the estimated refueling, the greater the underestimate.)

8. The second year of commercial operation has the highest plant unavailability.

Section 2.0

IMPACT OF REFUELING OUTAGES

2.1 Nuclear Plant Population

The data for this report is taken from a population of fifty-six LWRs,* all of which differ appreciably in size, design, and age. Because of the wide diversity in the plants, it is important to apply the data carefully recognizing that it represents a limited sample of custom designed plants which have been treated as a homogeneous quantity. Therefore, while we have chosen to call our population "homogeneous" by neglecting the effects of size and detailed design features, we have attempted to categorize PWR and BWR plants separately in many cases. The reasons for this division are: a) the differences in PWR and BWR design can have a strong influence on the time required for various refueling operations; b) the populations contain sufficient data to allow separation; and c) the division is easily made and is not ambiguous. Two examples of the differences which are characteristic of the two designs and which are directly reflected in the time required for refueling operations are discussed in Section 4 and mentioned here:

1. Closure head assembly and disassembly times in PWRs are significantly longer than in BWRs possibly due to the fact that control rod drive mechanisms are located in the top closure head of PWRs while in BWRs they are located in the bottom closure head.

2. BWR fuel movement times are significantly longer than PWR fuel movement times, which is perhaps in part due to the larger number of fuel assemblies, the reuse of fuel assembly "channels", and fuel sipping requirements in BWRs.

Based upon these arguments and past efforts which have shown significant differences between PWR and BWR reactors, the profile of the nuclear plant population considered in this report is divided as shown in Figures 2.1 and 2.2 for BWR and PWR plants, respectively.

*Only plants greater than 150 MWe rated output are considered.

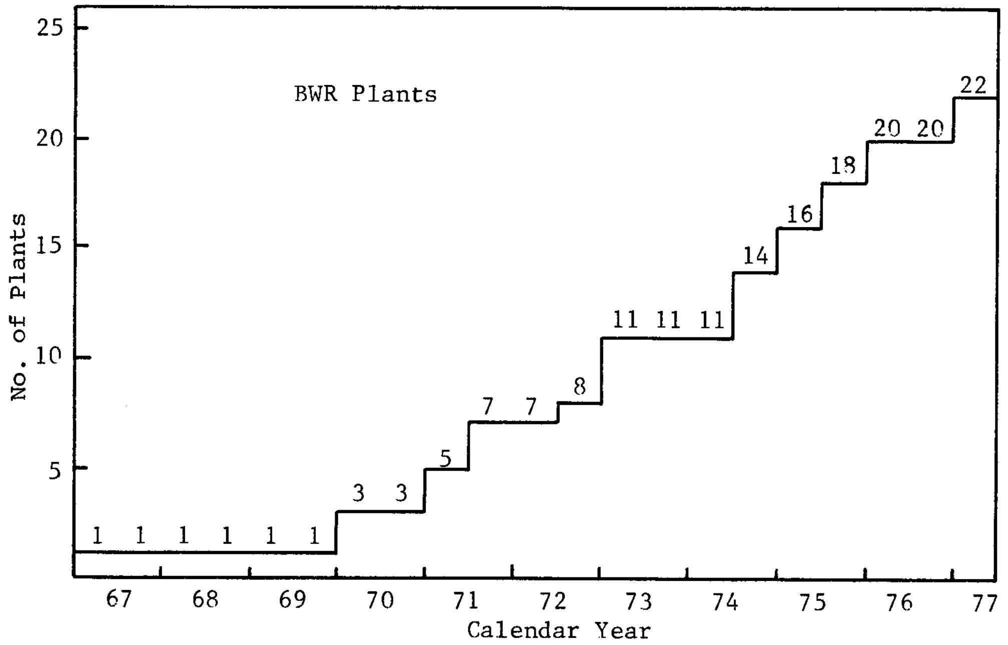


Figure 2.1. BWR Plants With Rated Capacity Greater Than 150 MWe in Commercial Operation versus Calendar Year

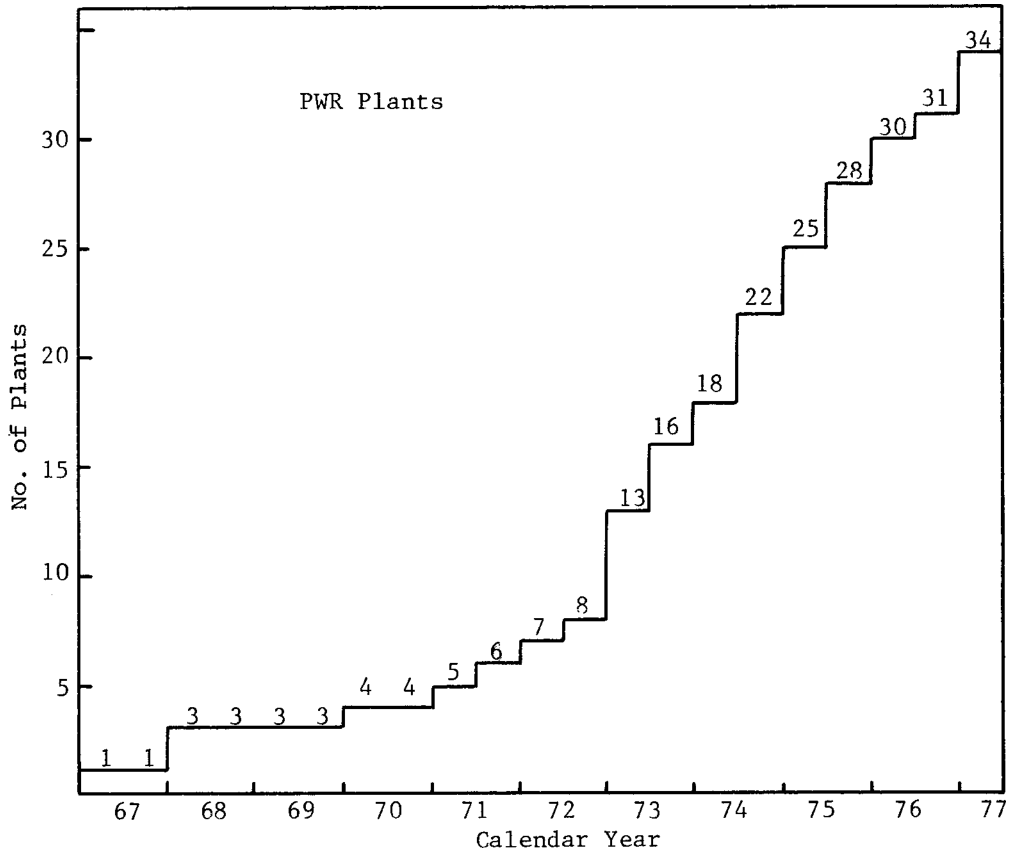


Figure 2.2. PWR Plants With Rated Capacity Greater Than 150 MWe in Commercial Operation versus Calendar Year

In addition to design differences, the plants also vary in age, from less than six months to more than 16 years. As can be seen, the largest concentration of plant experience is with plants which are relatively young - those which have come on line during the past 3 to 4 years (see Figure 2.3). Therefore, the population is heavily biased toward young plants, and necessarily, only their first few refuelings.

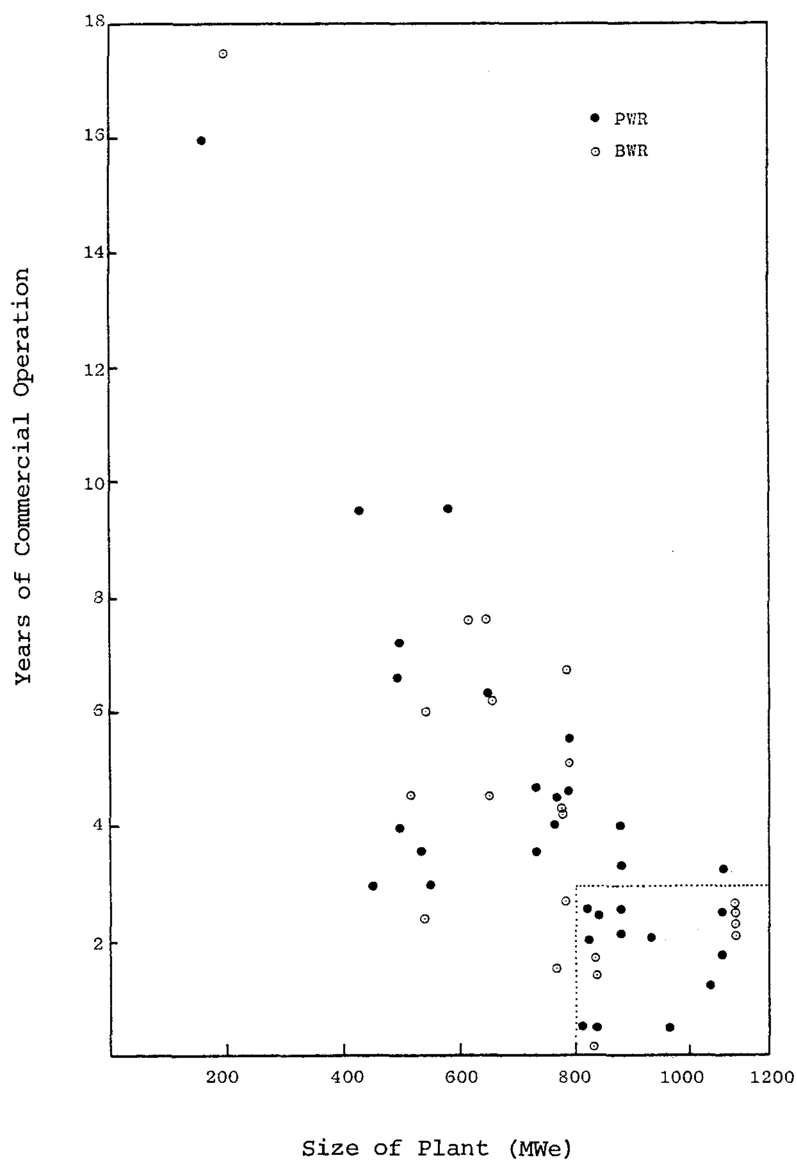


Figure 2.3. Variation in the Available Operating Experience as a Function of Plant Size

The bias in terms of relatively young plants is related to another bias which seems unavoidable in an expanding industry - the size of the plants. The size of nuclear power plants has grown from early, small, prototype units to the current, large 1000 MWe units. This is reflected in the fact that virtually all nuclear experience with plants greater than 5 years of age is with relatively small plants. The larger units, which are the rule for the future generation of plants, have a relatively small amount of operating experience, and, in general, this experience is for the first 3 years of operation (i.e., approximately one refueling). Figure 2.3 indicates the division of experience between small plants and large plants, and as suggested above, there is a very high negative correlation between age and size of plants. Virtually all plants >800 MWe design rating have less than three years commercial operating experience. The impact of this fact on subsequent conclusions results from the fact that there are only six refuelings other than first refuelings in plants >800 MWe.

The above review of the population which is contributing the data to the analysis indicates that a careful explanation of the conclusions is required in the light of the potential distortions which could be introduced by the evolution in plant size and design.

2.2 Profile of Nuclear Plant Performance

This section is a brief summary of the power plant performance of the U.S. LWR population to provide background information for the discussion on the causes of lost productivity. After establishing this background, we will show the relative impact of refueling outages on plant performance (Section 2.3)

There are several measures of nuclear plant productivity currently in use, such as: plant availability*, plant capacity factor**, and forced outage rate. The cost of nuclear generation of electricity is highly sensitive to plant availability and the capacity factor. However, statistically supportable data on anticipated capacity factors is lacking. A major problem is that there are virtually no data on large, mature units, i.e., those in the

*Availability is the time the plant is available to produce power divided by the total calendar time.

**The capacity factor is the total amount of electricity actually produced by a unit in a year divided by the amount of electricity the unit could produce running at full capacity for the entire year.

1,000 MWe range which have been operating for several years (see Figure 2.3). Estimates of nuclear plant performance must be made based largely on experience with units that are smaller than those now being built and have not operated more than a few years. The capacity factors used in this report are based on the plant design ratings. This does not account for seasonal variations caused by differences in cooling water temperature or deratings due to environmental or safety considerations.

Because of the diversity in plant design, size, and age, several methods of averaging plant performance parameters from the different units are possible. One approach is to weight each unit in proportion to its design rating. A less defensible method is to weight units according to the energy they actually generate; however, with this method a unit that is not operating (that has zero capacity factor) simply drops out of the calculation. An alternative is to weight all units equally regardless of size. The latter method is used in this section.

The plant performance parameters used in this section for plant productivity purposes are availability and maximum dependable capacity. For the purposes of this brief profile, we have considered only those plants which have completed at least one refueling cycle. Figures 2.4 and 2.5 compare the cumulative availability of PWR and BWR plants over their lifetimes. The observations are not weighted: equal weight is given to observations from young, old, large, and small plants. Note that this aggregate comparison indicates that PWR and BWR plants have approximately the same availability (~73%). Section 2.3 summarizes the principal causes of the reduction in plant availability.

The plant capacity factor, which includes reductions in productivity due to power restrictions, provides a slightly different measure of plant performance. Figures 2.6 and 2.7 compare the capacity factor for the same plants as above; however, the comparison of PWR versus BWR does not exhibit the same distribution characteristics as shown for availability. Instead, it is shown that the mean BWR capacity factor is 6.6% less than that calculated for the PWR plants (remembering that they both have the same availability factor).

Comparison of PWR and BWR Plant Availability* for Plants
Greater Than 150 MWe and Which Have Had
At Least One Refueling

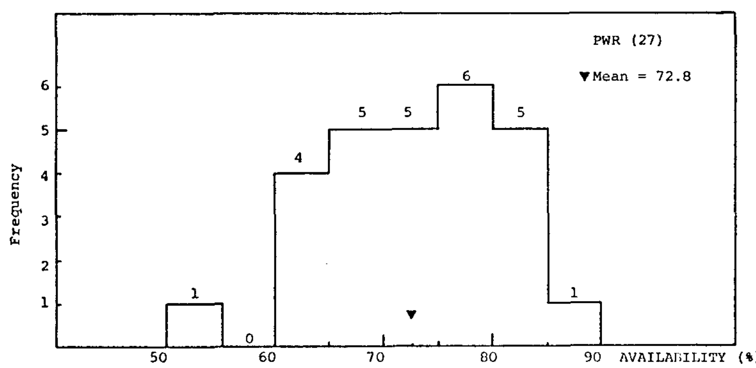


Figure 2.4. Frequency Histogram of PWR Plant Availability

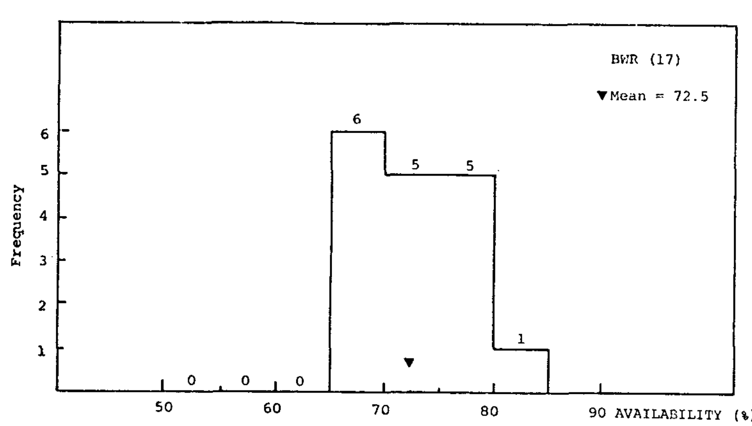


Figure 2.5. Frequency Histogram of BWR Plant Availability

*Availability of plants with more than one refueling.

Comparison of PWR and BWR Plant Capacity Factor for Those Plants Which Had at Least One Refueling Cycle (Plants < 150 MWe Not Included)

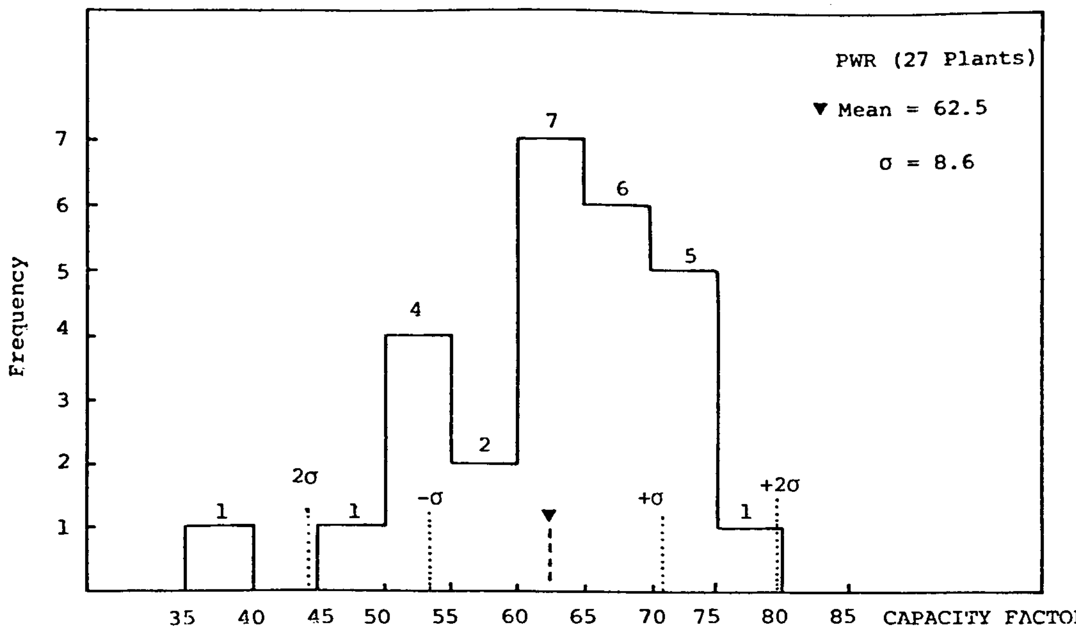


Figure 2.6. Frequency Histogram of PWR Plant Capacity Factors

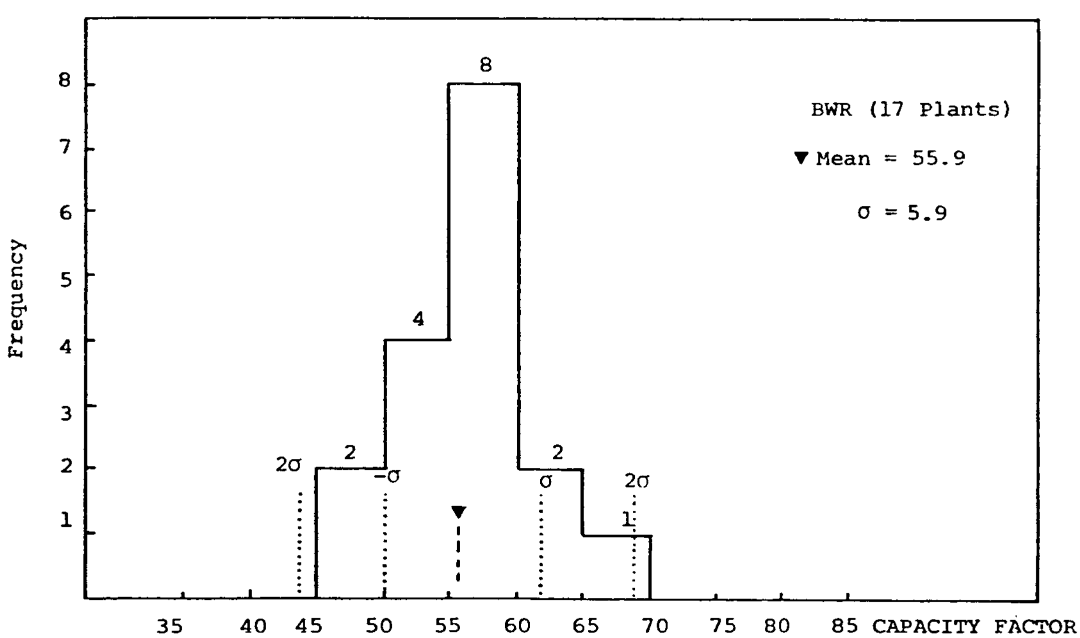


Figure 2.7. Frequency Histogram of BWR Plant Capacity Factors

2.3 Impact of Refueling Outages on Plant Availability

While refueling outages have been cited in the past as a major contributor to plant unavailability, the purpose of this section is to place the effects of refueling outages in more quantitative terms. A comparison is made of the contribution of refueling outages to plant unavailability relative to other outages.

First, consider an overall comparison of the causes of plant unavailability over the three year period from May 1974 to June 1977. Over this period of time, we find[24] that the fraction of unavailability time attributed to outages is as follows:

	PERCENT OF TOTAL OUTAGE TIME			
Time of Outage	1974 (May-Dec)	1975 (Jan-Dec)	1976 (Jan-Dec)	1977 (Jan-June)
Refueling	42%	32%	39%	51%
Outages >100 Hrs	39%	61%	32%	28%
Outages <100 Hrs	19%	7%	29%	21%

On the average, refueling contributed approximately 39.5% to unavailability over this period, and major outages* contributed 40%. The trends of refueling outages as a function of plant age are discussed in more detail in Sections 3 and 4. The trend of major outages as a function of plant age is discussed in detail in a separate EPRI report[25]. From Section 2.2, the plant unavailability time represents approximately a 27% reduction in capacity factor. Therefore, refueling outages contribute 40% of this, or a reduction of 11% in the capacity factor. In order to place the refueling outage impact in perspective, Figure 2.8 displays the 27% of plant unavailability in two different ways by: (a) cause (see also Table 2.1), and (b) outage duration. The reduction in plant productivity below the availability level is due to power limitations which have not been adequately addressed in the literature and may be an area where further investigation would provide valuable insight. While the operating data over the period May

*Major outages are defined here as outages greater than 100 hours in duration exclusive of refueling outages.

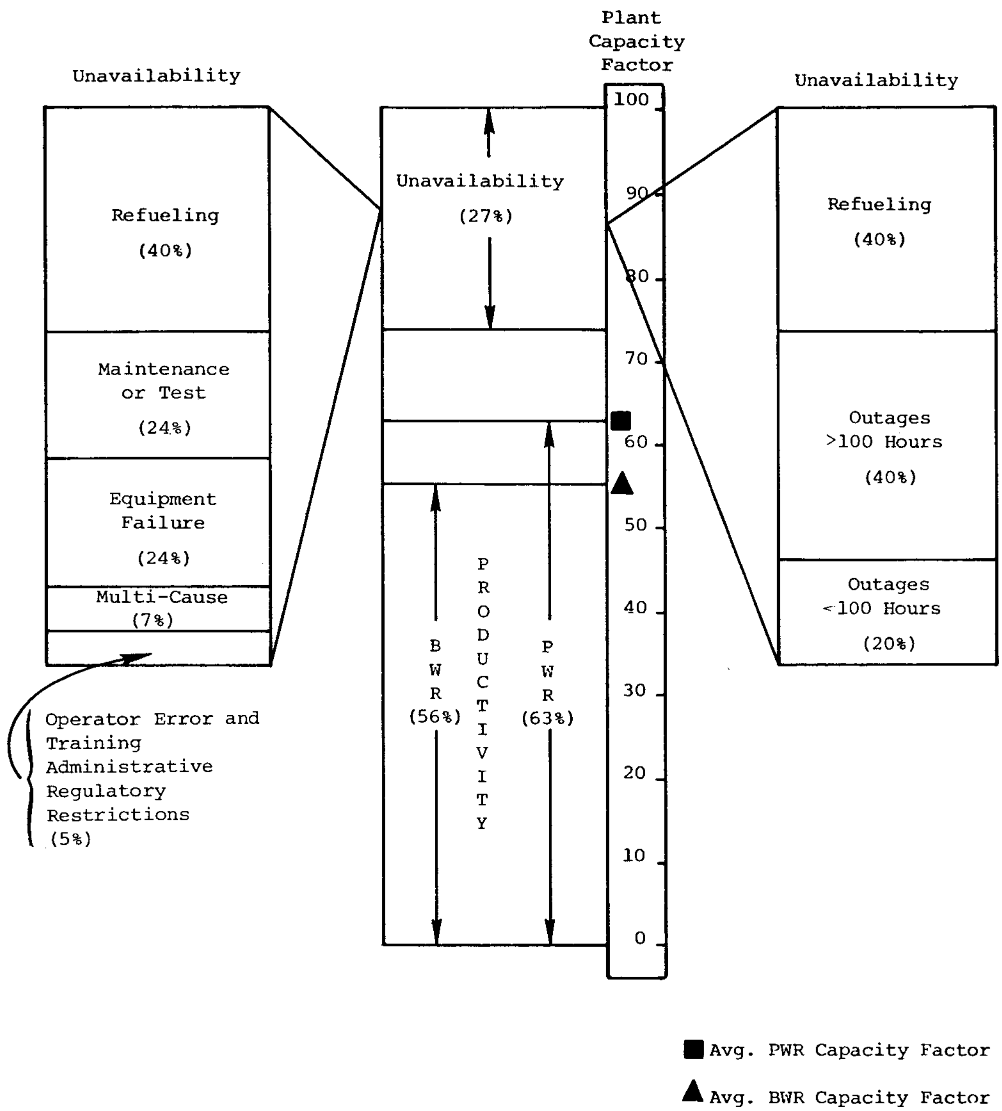


Figure 2.8 Summary of Plant Performance May 1974 Through June 1977

1974 through June 1977 has indicated that refueling outages account for approximately 40% of the plant unavailability, or an 11% loss in plant capacity factor, it must be remembered that the population sample is heavily biased to very young plants and, therefore, toward first refuelings. Section 3 discusses how the refueling outage trends can be interpreted and their potential effect on the plant productivity of a "mature" LWR.

Table 2.1. Summary of Outages Over the Period May 1974 - June 1977 by Contributory Cause

	Outages (Unit Hours)					
Outage Categories	1974 (8 months)	1975 (12 months)	1976 (12 months)	1977 (6 months)	Total (38 months)	% of Total
Refueling	27,738	35,776	56,671	32,775	152,980	39.5%
Maintenance/Tests	13,943	36.138	31,655	9,138	90,857	23.5%
Equipment Failure	14,710	28,282	35,226	13,752	91,970	23.8%
Other/Multi	2,839	8,530	12,368	5,879	29,607	7.7%
Operator Error	2,110	1,817	2,645	562	7,134	1.8%
Regulatory	3,628	1,703	5,340	1,658	12,329	3.2%
Administrative	525	282	1,136	122	2,065	.5%
Operator Training	231	47	233	132	633	.2%
Avg/Month	5,477/mo	9,379/mo	12,109/mo	10,668/mo	10,199/mo	

Section 3.0

CHARACTERISTICS OF REFUELING OUTAGES IN LWRs

Through June of 1977, U.S. light water reactor experience has accumulated approximately 250 reactor years of operating experience. The operating experience encompasses 128 refuelings in plants with ratings greater than 150 MWe. It is judged that this experience, although heavily biased toward relatively young plants, represents a sufficient sample to characterize general trends in LWR refuelings. In this section, the following aspects of refueling outages will be discussed:

a) Trends in LWR refueling outages (Section 3.1)

b) Comparison of PWR and BWR refuelings (Section 3.2)

c) Characteristics of the intervals between refuelings (Section 3.3)

d) Variation in the length of refueling outages as a function of plant size (Section 3.4)

e) Accuracy in predicting the length of refueling outages (Section 3.5)

f) Comparison of U.S. and European experience in LWR refuelings (Section 3.6)

An assessment of the trends in refueling outages including the uncertainties involved will assist utilities in management decisions for scheduling maintenance, inspections, and repair items, as well as for long range planning of fuel cycle requirements. In addition, by characterizing the causes of refueling outage extensions, it will provide designers, architect engineers, and regulatory personnel with a measure of the impact of their decisions on plant availability and performance. The refueling cycle is one area of plant operation in which the utility has some degree of latitude in the scheduling of time and energy expended between refuelings. Therefore, it is desirable to optimize the plant performance within the latitude of the length of refueling intervals.

3.1 Trends in LWR Refueling Outages

As discussed in Section 2, refueling outages have accounted for approximately 40% of the total nuclear plant outage time during the period May 1974 through June 1977. Thus far, however, the time variation of the refueling outage impact on plant availability has not been addressed. Figure 3.1 displays the time variation of refueling outages as a function of the plant age. The magnitude of the impact is measured in the average amount of unavailability time per plant per year which is caused by refueling outages. (Only the initial seven years are included.) The three principal facts which are displayed in Figure 3.1 for the hypothetical "average" plant are:

a) Very little outage time during the initial year of commercial operation is attributed to refueling.

b) The maximum outage contribution per plant from refuelings is during the second year of commercial operation when it is approximately 25% greater than in subsequent years.

c) Refueling outages contributed an approximately constant* level of unavailability each year on a per plant basis after the second year.

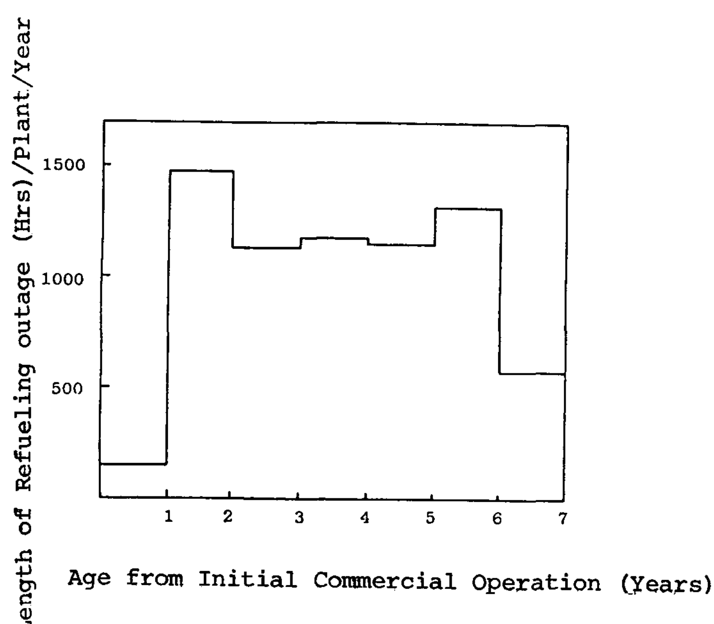


Figure 3.1. Average Variations of Refueling Outages as a Function of Plant Age on a Per Plant Year Basis, from All PWRs and BWRs with Rated Capacity Greater than 150 MWe.

*The sixth and seventh years of operation indicate some perturbation about this constant level; however, this is probably due to a lack of adequate statistics to produce an accurate estimate.

While Figure 3.1 shows that the impact of refueling outages stabilizes as plants increase in age, the overall trend in lost plant availability is a combination of refueling outages and all other outages. As discussed in Section 2, refueling outages and major outages [25] combine to account for nearly 80% of the total plant unavailability. Figure 3.2 displays the combined effects of refueling outages and major outages on a per plant year basis. The combined

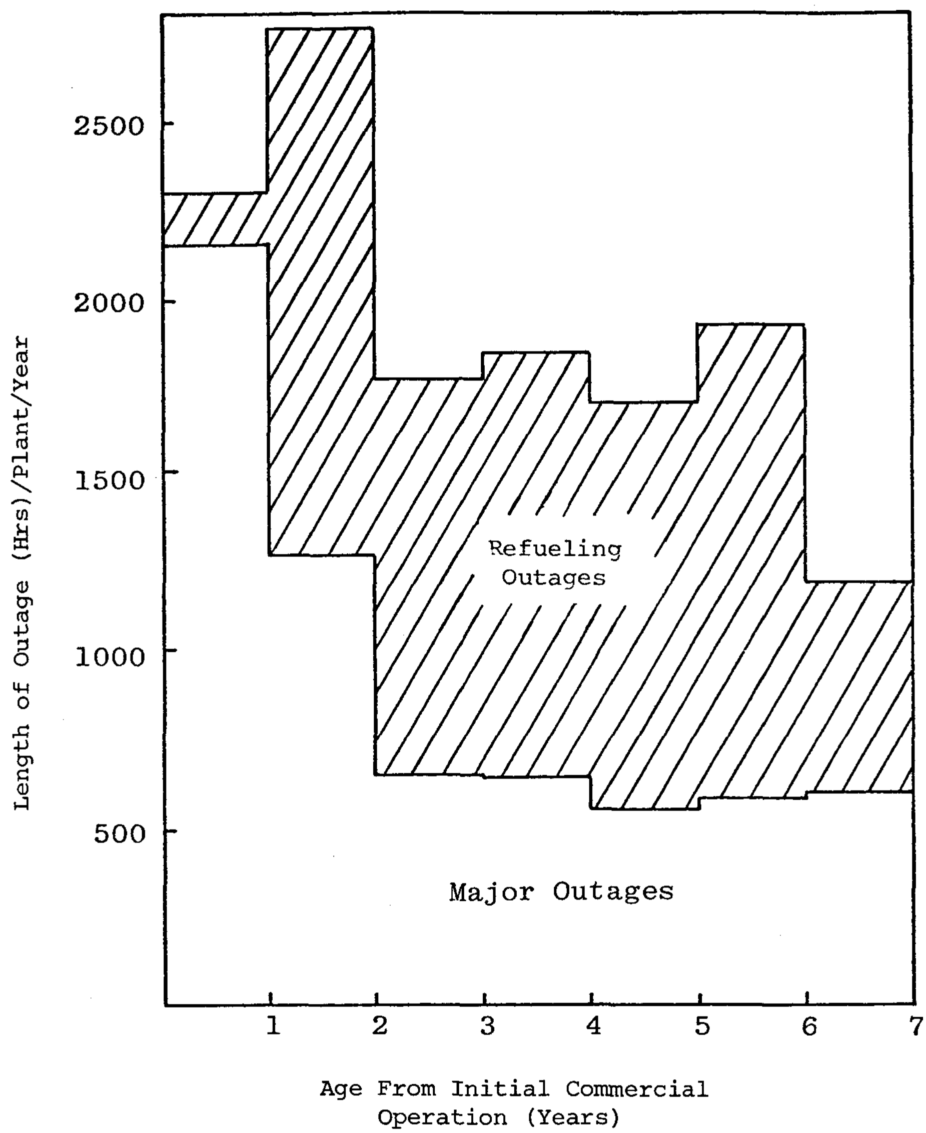


Figure 3.2 Distribution of LWR Outages as a Function of Plant Age

effects are quite important in that they indicate that the first two years of commercial plant operation incur 28% to 53% more outage time than subsequent years. In fact, the combination of high major outage contributions during the second year of operation plus lengthy first refuelings leads to the fact that the second year of commercial operation has the lowest availability* of any year. The trend towards increased plant availability in subsequent years is an encouraging indicator when assessing long term nuclear power plant performance.

An additional trend in Figure 3.2 which needs to be emphasized is that after a plant has reached maturity (i.e., after the second year of commercial operation) refueling outages tend to account for more than 40% of the plant unavailability time which was estimated based upon 1974 to 1977 data. The reason for this trend of an increasing importance of refueling outages is that the population of plants in the 1974-1977 data are predominantly young plants. Therefore, there is a heavy bias which emphasized the high major outage contribution during the initial two years of commercial operation. By unfolding the refueling outage information presented in Section 2 according to plant age, a pattern in the contributions of refuelings emerges. The trend from Figure 3.2 emphasizes the fact that, as plants mature, refueling outages will take on continually increasing importance in determining overall plant availability. This trend suggests that the total effect of refueling outages on plant unavailability during equilibrium fuel cycles approaches 60% of all the unavailability time in years after the second year of commercial operation.

If refuelings were indeed annual affairs, as is often suggested in the literature, Figures 3.1 and 3.2 would portray all the information needed to assess the trends of refueling outages. However, there is actually a wide distribution in both the refueling outage duration and the intervals between refuelings (see also Section 3.3). Therefore, we present here a comparison of the refueling outage length as a function of the refueling cycle number. Figure 3.3 gives a composite frequency histogram of the number of refueling outages as a function of outage length for all refuelings, summarized by fuel cycle number. This composite of refueling outages is a key to the understanding of typical nuclear power plant performance trends for mature plants. The important item to note from this comparison is that it graphically displays the pronounced difference

*Assumes that the contribution of short duration outages, (outages $<$100 hours in length) is constant or decreases with plant age.

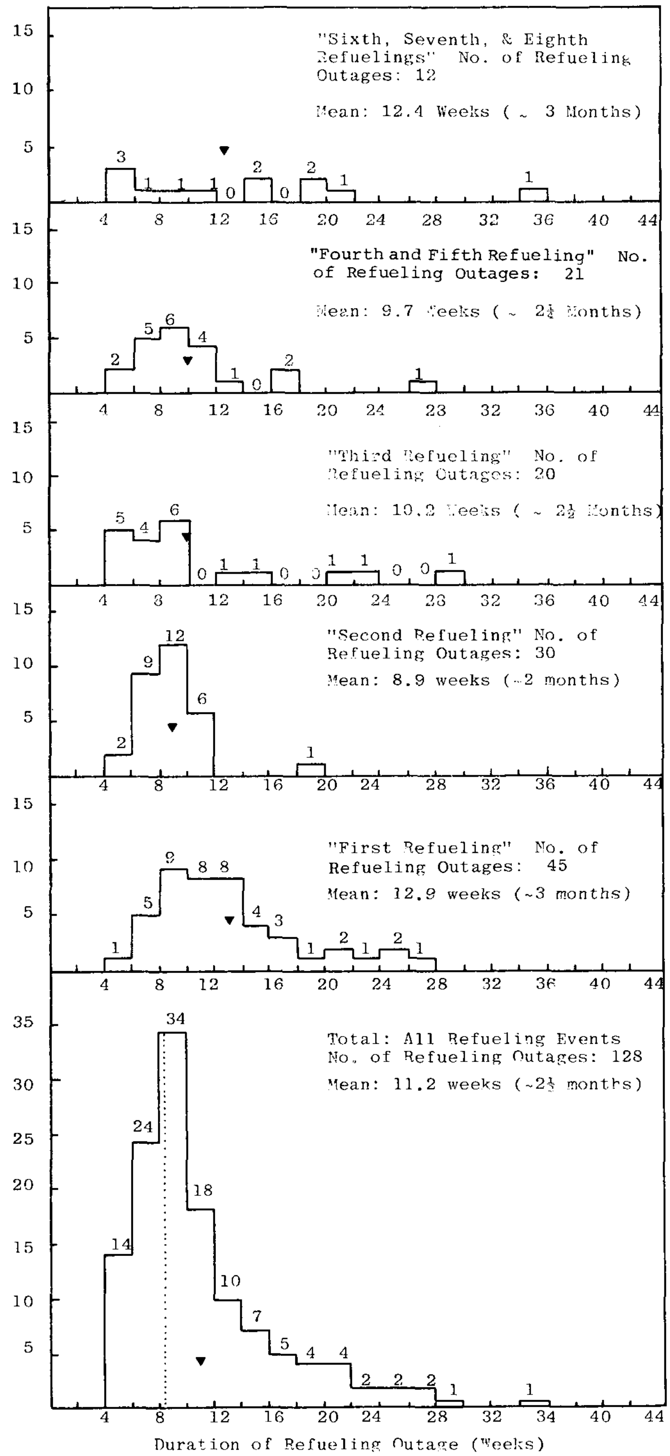


Figure 3.3. Frequency of Refueling Outages as a Function of Length of the Outage: Composite by Number of Refueling, First Through Eighth

between the first refueling outage (12.9 weeks or ~3 months) and subsequent refuelings (9.9 weeks or ~2.3 months). The one exception to this conclusion is the combined sixth through eighth refuelings which have a mean refueling length similar to that calculated for the first refueling. However, there is only a small population of plants in this category (sixth through eighth refuelings), and there is a large scatter in the outage times. In fact, the population of 6th through 8th refuelings has the highest percentage of refueling outages taking less than six weeks of any category. However, it also has a relatively large number of extended refueling outages. Because of the large uncertainty, it is judged that the combined data for the sixth through eighth refuelings do not represent the beginning of a trend, but only statistical scatter in the data. It is interesting to note that the group of refuelings which has historically taken the least time is the second refueling; its mean refueling outage time is two months, which is still much longer than previously expected by reactor suppliers.

In subsequent discussions, the focus of attention will be on mature plant performance and on the dominant trends affecting plant availability. As discussed previously, the "first-refueling" population represents a disproportionate fraction of the total population and could bias the results of any evaluation which did not account for this bias. Therefore, the mean refueling outage time considered in other sections of this report will be 9.9 weeks (~2.3 months). In particular, the mean refueling outage time of 9.9 weeks will be used in Section 5 to discuss the advantages and disadvantages of extending the refueling cycle to 18 months in order to improve plant availability. Section 4.0 discusses the reasons for the unexpected length of refueling outages and points out areas where improvements could potentially be incorporated into refueling operations to decrease the length of the outages.

Thus far, we have not discussed the scatter in the data. For each refueling, first through eighth, there is at least one case of a refueling being accomplished in a "short" time (i.e., 4 to 6 weeks). While 4 to 6 weeks has not been considered a short refueling in the past, the operating data indicates that this is the fastest time that can be expected under today's design and testing conditions. On the other end of the scale, there are a number of extremely long refueling outages whose length has been determined by plant problems which were corrected during the outage (e.g., feedwater sparger inspection/replacement, core vibration repair, turbine repair). However, it is apparent from the data that, while long refueling extensions are infrequent, they nevertheless continue to occur in the population and therefore must be considered in the evaluation of plant availability. For the moment, if we neglect all refueling outages greater than 12 weeks as not relevant to the discussion of typical refueling outages, then the average refueling outage is reduced from 2.3 months to slightly less than two months (which is still much higher than has been expected in the past).

An important facet of the scatter of the data is the variability from plant to plant. In terms of individual plants, there are some "good" plants with consistently short refuelings outages (e.g., Robinson 2, Point Beach, Vermont Yankee and Haddam Neck), and there are some plants which are on a longer learning curve and have not consistently refueled their units within the determined mean time.

To complete the overview of refueling outages, Figure 3.4 gives a composite graphical description of the duration of refueling outages for calendar years 1970 through 1977. The comparison does not indicate a clear trend as a function of calendar year. During any given year there are first, second, third, etc. refuelings, and remembering from Figure 3.3 that the variation between first refuelings and subsequent refuelings appears to be quite large, the combination of refuelings in a given calendar year tends to obscure any potential trends as a function of calendar year. The result, as determined for the composite, is that each calendar year has an average refueling outage of approximately 2.5 months. One trend which appears to surface from the comparison of refueling outages as a function of calendar year is that the number of refuelings in the range of 4-6 weeks may be decreasing. That is, it appears that short refuelings (i.e., less than 6 weeks duration) may slowly become harder and harder to achieve as the result of increased testing and inspection requirements (see Section 4) unless compensating time savings in refueling or maintenance operations can be achieved.

3.2 Comparison of PWR and BWR Refueling Outages Including Trends Versus Plant Age

In Section 3.1 all LWRs were considered together in one population. However,

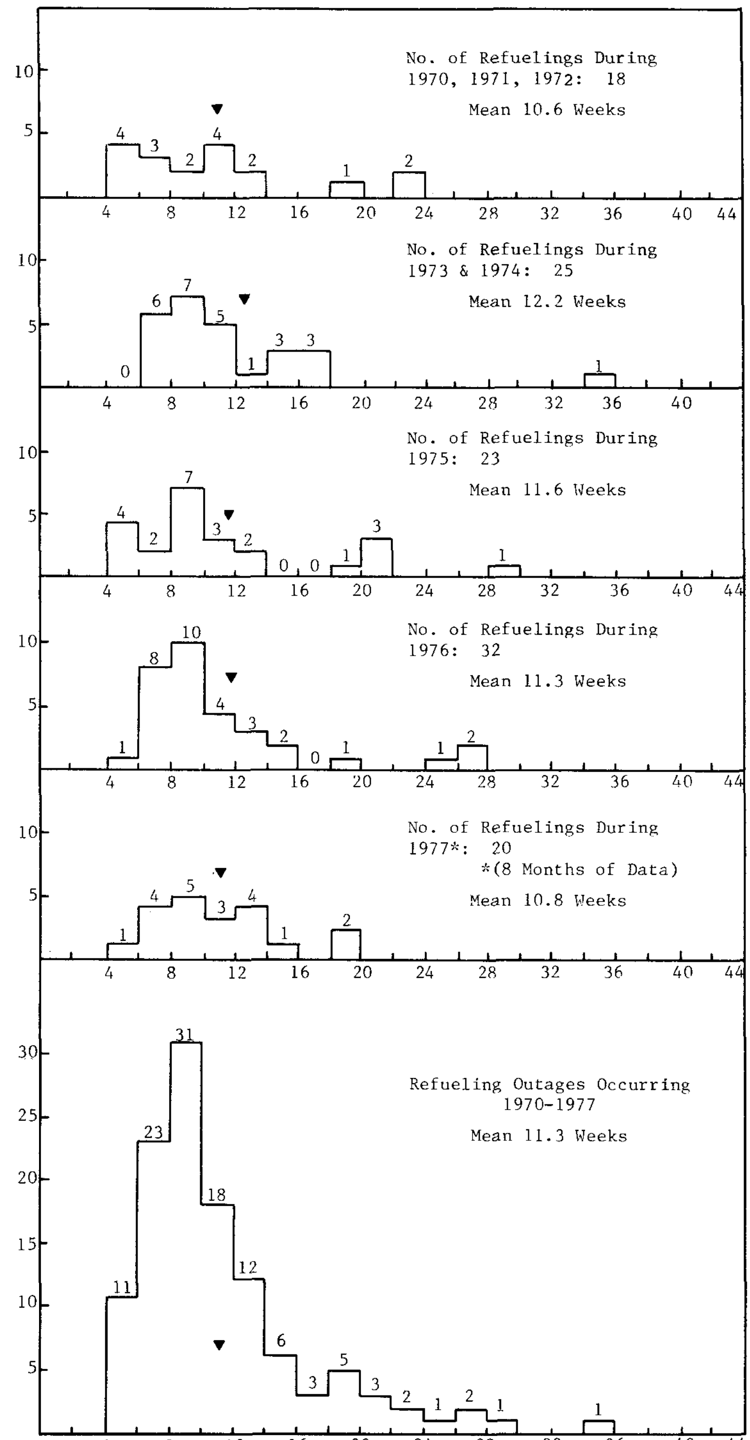


Figure 3.4 Frequency of Refueling Outages as a Function of Duration of the Outage Versus Calendar Year

as noted in Section 2, there is a wide variation in the details of plant design among the operating reactors. One general division which can easily be interpreted with little ambiguity is the distinction between PWRs and BWRs. As we shall see in Section 4.0, certain aspects of PWR and BWR design are reflected directly in the length of time it takes to perform similar operations in PWRs and BWRs (e.g., closure head removal). This subsection presents a comparison of the two reactor types in order to distinguish any fundamental differences in their respective operating histories.

A straightforward comparison of the refueling outage lengths for BWRs and PWRs in Figure 3.5 indicates an 18% difference in the average refueling outage length for the two distributions. The distributions of all BWR refueling outages has a higher mean value (12.3 weeks) than the PWR distribution and a broader variation, with a standard deviation of 6 versus 5 for PWRs. The remainder of this section is aimed at understanding the reason for this difference in refueling outages for the two types of LWRs.

In order to better understand the trend in PWRs and BWRs and in an attempt to explain the difference between PWRs and BWRs, consider a comparison of refueling outages as a function of refueling number. Since we are most interested in the trends of "typical" refueling outages and there have been some infrequent long duration outages, the method used in this comparison is to eliminate the highest duration outage in each refueling cycle (if it exceeds 4 months) as being non-representative of refueling outages. Figure 3.6 shows a plot of the distribution of average refueling outages as a function of refueling number. The length of the first refueling is similar for PWRs and BWRs (within 5%), and as discussed in Section 3.1, it is significantly longer than subsequent refuelings. For both PWRs and BWRs the lengths of the second through the fifth refuelings* are nearly constant, indicating that, after the first refueling, the plant can be considered as having reached refueling maturity and to have achieved an approximately constant outage time per refueling as is shown in Figure 3.6. The BWR plateau is 14 to 20% higher than an average PWR plateau, indicating that mature BWR plants may require more time to allow completion of all the necessary work items scheduled during refueling outages than in PWR plants. However, Section 4 shows that the actual time spent for required refueling operations is comparable for BWR and PWR plants; therefore, the differential

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*The sixth and seventh refuelings have a very small population, and consequently the statistics are inadequate to say anything meaningful about the trends.

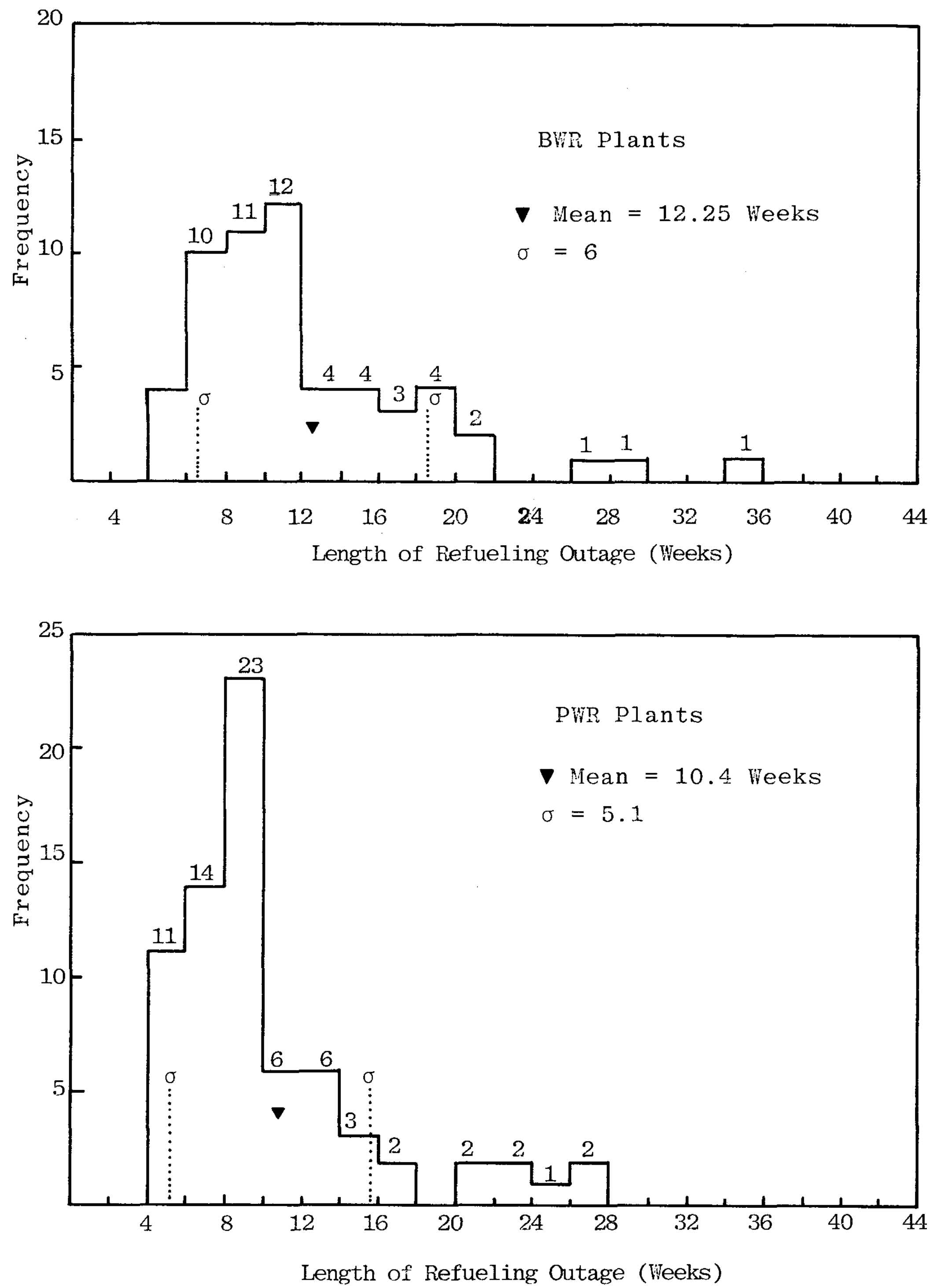


Figure 3.5 Comparison of the Length of Refueling Outages for BWRs and PWRs

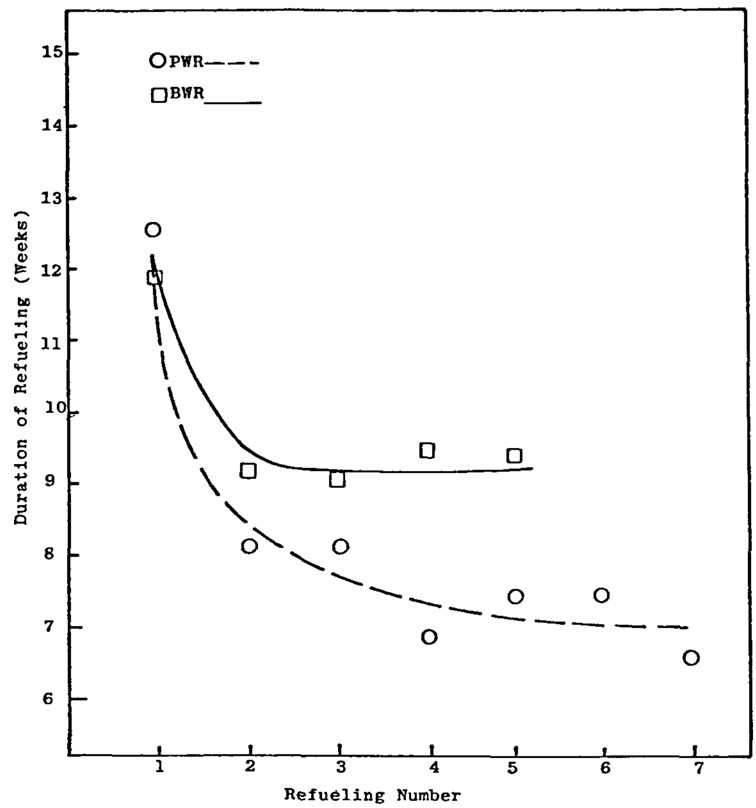


Figure 3.6 Refueling Duration as a Function of the Number of Refuelings

is in required plant maintenance. This can be explained in part by the larger number of generic problems that BWR plants have encountered thus far, which have forced extensions of the refueling outages (e.g., feedwater sparger and core spray problems, core internal modifications, replacement of marginal performance fuel which requires critical path time to identify).

A comparison of refueling outages for BWRs and PWRs from Figures 3.5 and 3.6 results in the following conclusions:

- The average BWR refueling outage is longer than the average PWR refueling outage.

- BWR and PWR first refuelings have approximately the same average length.

- It appears that the refueling length is approximately constant after the first refueling of a plant and that the average PWR refueling outage may be less than the average BWR refueling outage by approximately 15%.

- The average refueling length for a mature PWR plant is approximately 1½ weeks less than the comparable BWR outage length, as shown below:

	Average Refueling Length of Mature Plant (Weeks)
All Plants	8.8+
BWRs*	9.2*
PWRs*	7.8*

*The longest refueling outage, if greater than 4 months has been eliminated in the assessment of each refueling cycle average.

+All refuelings greater than 3 months have been eliminated.

3.3 Intervals† Between Refuelings

The preceeding two sections have dealt primarily with the length of refueling outages. In this section, the discussion is centered on the interval between refuelings as measured both in calendar time and in equivalent energy output. Refuelings have been referred to as annual occurrences. The purpose of this section is to identify the range of intervals between refuelings based upon actual operating experience. Are refuelings spaced equally in terms of calendar time or energy expended? The answer to this question is not straightforward due to the variation in plant operating philosophy among plants and the frequency of outages; however, there are a number of facts which can be

†The intervals between refuelings as used in this report are calculated from the completion of one refueling to the beginning of the subsequent refueling.

gleaned from the operating experience data concerning these intervals.

3.3.1 Variation of the Time Interval Between Refueling Outages

The interval between refuelings in months is presented as a frequency distribution for BWRs and PWRs in Figures 3.7 and 3.8, respectively. Since the primary interest of this report is in the characteristic trends of the mature plants, consider only the distribution in Figures 3.7 and 3.8 for the intervals between refuelings following the first. In this case, the distribution of intervals between refuelings for mature plants are nearly identical and have the following characteristics:

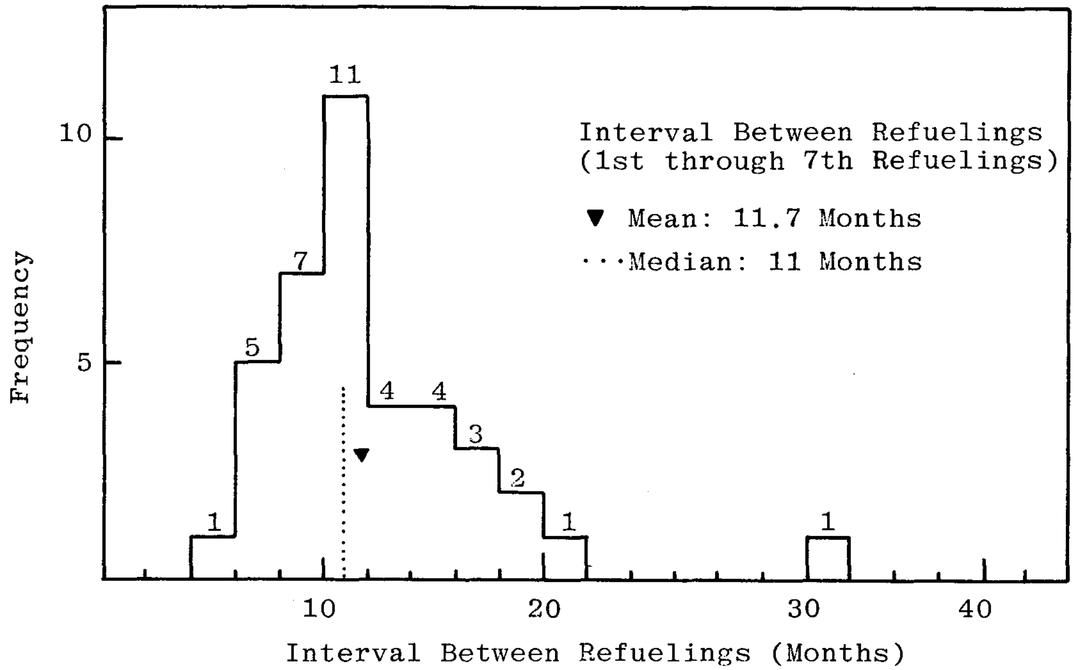
	BWR	PWR
Mean (months)	11.7	12.0
Mode (months)	10-12	10-12
Median (months)	11	10

If one literally interprets the operating experience using only these parameters of each distribution, he is led to say that the utilities are on a 10 to 12 month refueling cycle, i.e., there already exists a mean refueling time of approximately 2.3 months and an interval between refuelings of approximately 10 to 12 months. This is the fact: utilities are trying to maintain an annual refueling cycle by operating less than 10 months of the year. This can be seen by looking at the mode of the distribution of intervals.

The controlling item in determining the beginning of many refueling outages is not the fuel requirements but rather the time of the annual cycle. For instance, since most utilities have summer and winter energy loads far exceeding those of the spring and fall*, utilities prefer to keep the nuclear plants on-line during these peak load times and refuel them during the spring and fall, irregardless of whether the core has reached optimum predicted burnup. Section 3.3.2 summarizes the operating experience concerning the energy burn-up expended between refueling outages.

It should be carefully noted that in each of the figures the time between initial criticality and the beginning of the first refueling has been

*For example, the peak demand during the summer of 1977 was 35% higher than during the spring of 1977 [25].



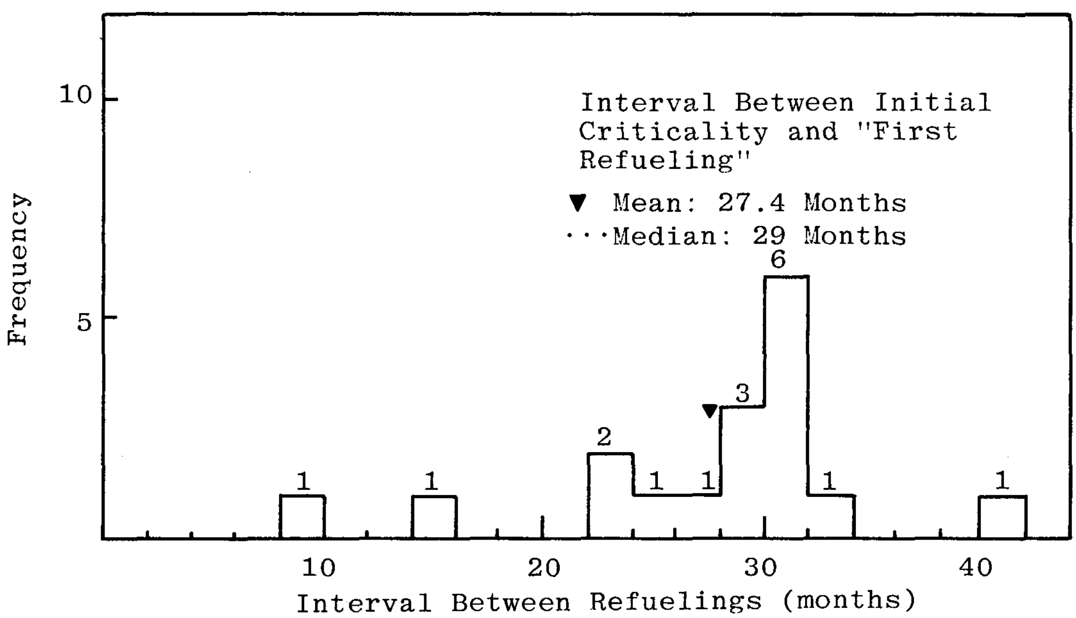
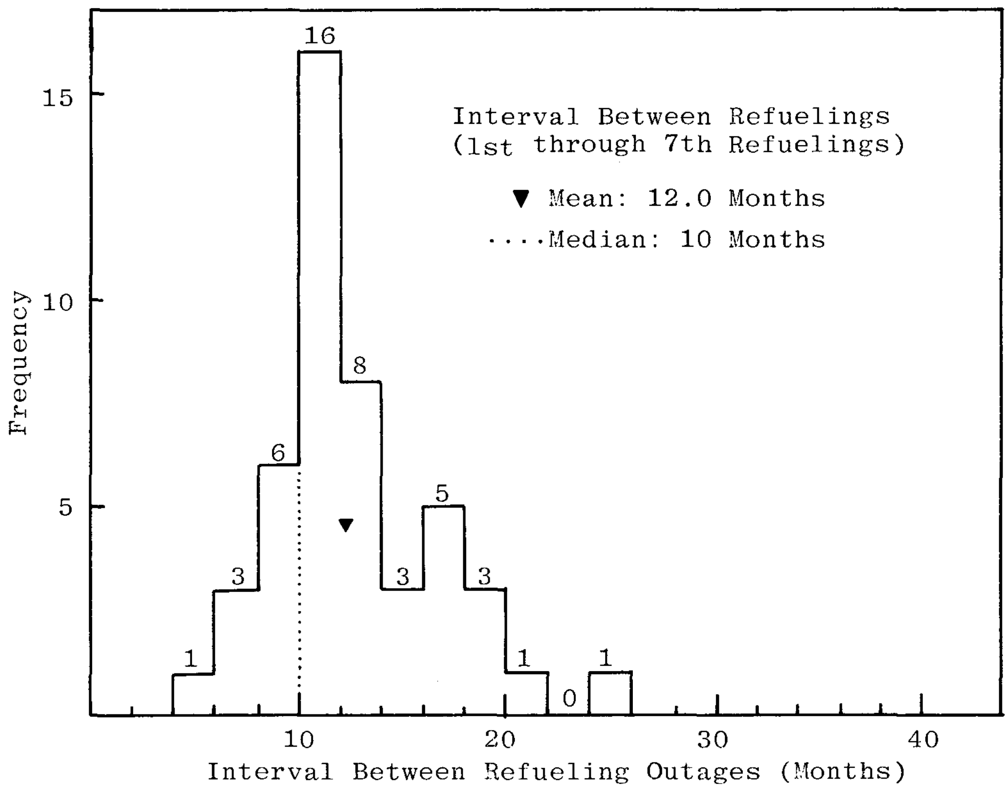


Figure 3.7 The Interval Between Refueling Outages in BWR Plants for: (a) The First Refueling; (b) Subsequent Refuelings



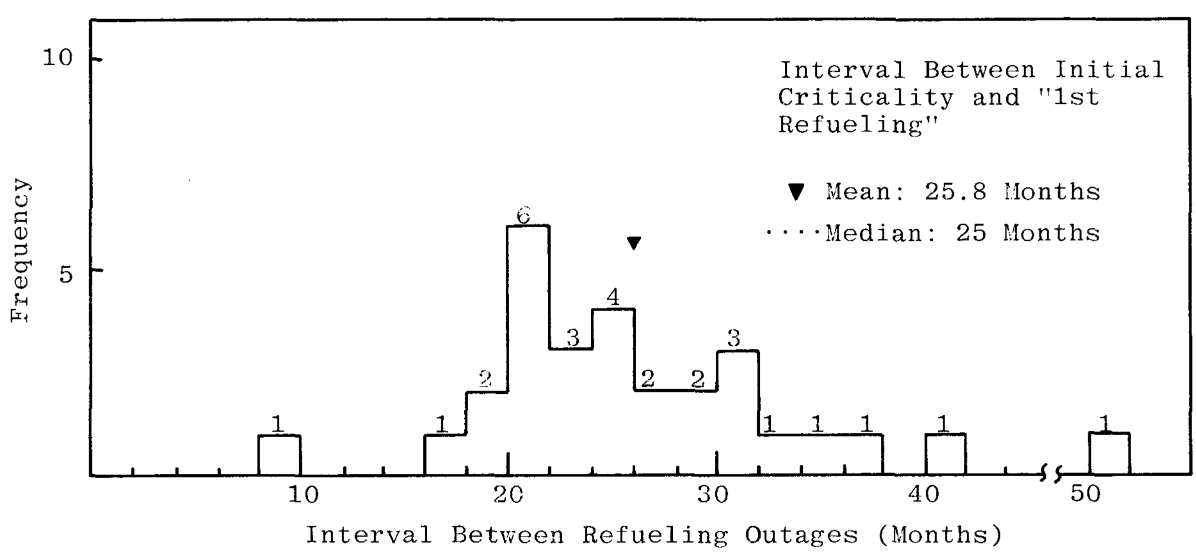


Figure 3.8 The Interval Between Refueling Outages in PWR Plants for: (a) The First Refueling; (b) Subsequent Refuelings

separated out since it represents a longer cycle in terms of energy production and calendar time than subsequent cycles due to the following reasons:

- Approximately 3-6 months of this time is taken up by startup testing in which less than full power operation is the rule.

- A significant amount of outage time occurs during this "break-in" period. Design related problems and manufacturing defects tend to surface at the beginning of a large complex station operation.

- The core is fully loaded with fresh fuel, while during subsequent fuel cycles there are batches of fresh fuel in addition to batches of partially depleted fuel. This leads to a larger amount of excess reactivity during the first cycle allowing longer power operation.

The average time from initial criticality until the first refueling is approximately 27 months for BWRs and 26 months for PWRs. However, the characterization of the distributions are significantly different between PWRs and BWRs. For instance, the mode and median times for the first refueling are as follows:

	Median	Highest Mode Frequency
BWR	29 mo.	31 mo.
PWR	24 mo.	21 mo.

3.3.2 Variation of the Energy Expended Between Refueling Outages

Another way to characterize the intervals between refueling outages is by the energy output of the plant. To normalize all plants to a common denominator, we shall use effective full power days (EFPD) as a measure of energy output.* EFPD as used here will be defined as

$$\text{EFPD} = \frac{\text{Gross Electrical Energy Generated (MWe Hr)}}{\text{Name Plate Rating (Gross MWe)} \times \frac{24 \text{ Hr}}{\text{Day}}}$$

or more simply, the number of equivalent days of full power operation to

*The comparison using EFPD is based upon the assumption that fuel systems are geared towards expending full power energy over an approximately annual cycle.

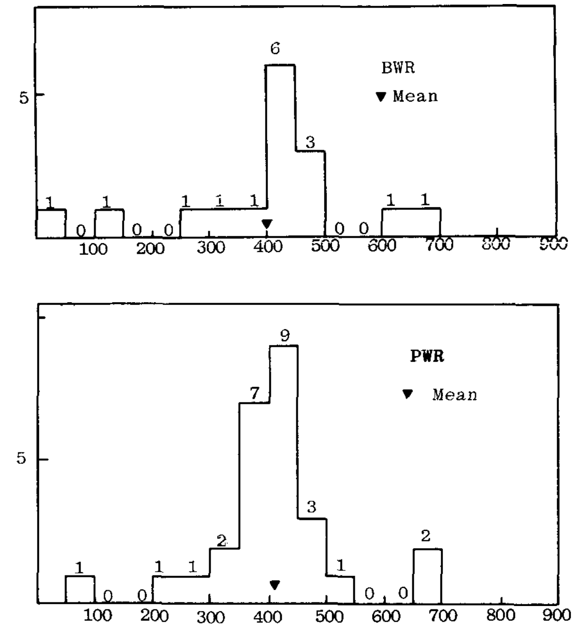
produce a given amount of energy.

The purpose of this approach is to eliminate the effect of other outages on the scheduling of refueling and to determine whether the timing of refuelings are based upon the energy consumed or if they are driven by other considerations such as time of year, or if utilities are attempting to refuel annually regardless of the energy actually consumed since the last refueling, as alluded to above.

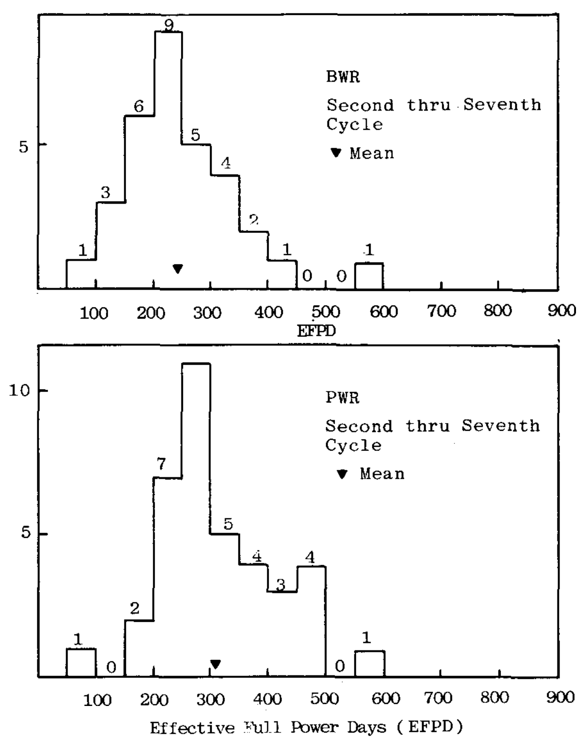
Figure 3.9 compares PWR and BWR refueling intervals using EFPD as the standard measure. As is indicated, the mean PWR EFPD usage during an average interval is 310 EFPD compared with 240 EFPD for BWRs. The average energy produced is therefore approximately 25 to 30% higher than the average energy per BWR fuel cycle. The key point to be noted from Figure 3.9 is that there is a wide variation for both BWRs and PWRs in the amount of energy expended during each cycle subsequent to the first: energy expended, as measured in EFPD,ranges from less than 100 to more than 500. This indicates that there is a wide variation in both calendar time intervals and expended energy intervals.

Great pains are taken to design cores and their fuel cycles so that energy is expended at approximately full power during the entire fuel cycle. However, this result has not been obtained; rather, there are shutdowns, power reductions, and load changes which may alter this intention and result in substantial variations in the plant cumulative energy output when the annual refueling is scheduled. Therefore, a distribution about a mean of the actual energy produced is to be expected in the real situation and that is the picture portrayed in Figure 3.9 which shows that while the mean refueling for PWRs and BWRs occurs approximately every 250-300 EFPD, there is a significant scatter in the distribution of individual plant intervals.

In order to estimate the difference between the planned energy expenditure and the actual expenditure reflected in the operating data consider the following calculation of EFPD for an idealized cycle:



(a) Comparison of the Energy Expended from Initial Criticality through the First Refueling



(b) Comparison of the Energy Expended between Subsequent Refuelings

Figure 3.9 Comparison of the Energy Expended Between Refuelings for BWR and PWR Plants (31, 33)

PWR: A typical PWR core has:

- 2200 MWt or 726 MWe rating
- 70 metric tons of uranium
- a scheduled replacement of 1/3 of the core at each cycle
- an average projected fuel assembly burn-up of 30,000 MWD/Mt

Therefore, the energy per cycle = 30,000 MWD/Mt x 70 tons/core x 1/3 core/cycle x 1/2200 MWt or 318 EFPD

BWR: A typical BWR core has:

- 2527 MWt or 829 MWe rating
- 142 metric tons of uranium
- a scheduled replacement of 1/4 of the core at each cycle
- an average projected fuel assembly burn-up of 24,000 MWD/Mt

Therefore, the energy per cycle = 24,000 MWD/Mt x 142 tons/core x ¼ core/cycle x 1/2527 MWt 351 EFPD

This indicates that PWRs are expending energy very close to the planned level on the average, while BWRs are expending energy at a rate approximately 30% below that planned. There are a number of reasons why the operating experience has differed from the projected ideal cycle. Some of these reasons are:

a) The initial fuel loading is atypical since it has only fresh fuel. Therefore the reactivity characteristics are quite different than the equilibrium fuel cycle cases. Following the initial refueling, the core makeup is still different than the equilibrium cycle, and cores tend to have higher excess reactivity. The greater excess reactivity leads to more energy available to produce power during the initial intervals.

b) Fuel rod problems have caused a number of perturbations in normal plant operating methods. For example, PWR fuel densification concerns have in the past forced PWR power restrictions, (24) and have led to some early refuelings. In addition, BWR concerns over fuel pellet/clad interaction (PCI) [27] have led to fuel failures and plant power restrictions [28] to maintain an acceptable off-gas activity level. BWRs have also implemented restrictions on the rate of power change allowable to reduce the concern over PCI.

c) Early shutdowns or an extended coastdown cycle may be required to keep the plant on-line during the peak seasonal periods.

d) Other plant problems may have forced an early shutdown during which the plant was refueled. This results in a less than ideal fuel utilization, the trade-off being in plant availability.

3.3.3 Summary of the Characteristics of Intervals Between Refuelings

In summary, then, the intervals between refuelings can be characterized by the following:

- The median interval between refuelings is 11 months for BWR and PWR plants, after the first refueling.

- The energy expended between refuelings is approximately 25% higher in PWR plants than in BWR plants.

- There is a wide scatter in the distribution of intervals between refuelings (whether characterized by calendar time or energy expended) indicating that some causes for refueling may be associa- with the time of the year (spring versus summer) or with required plant maintenance and are not based entirely upon the optimum energy production per cycle.

3.4 Variation of Refueling Outage Length as a Function of Plant Size

One aspect of utility planning for new plant capacity is the determination of the optimal plant size. The selection of plant size is based upon an assessment of many variables - including the amount of capital investment, the potential economy of scale, the projected energy needs, and the expected plant availability.

Past studies have attempted to evaluate the variation of plant availability as a function of plant size; however, the limited data and the large variability in the data have made the correlations statistically meaningless. This section takes a look at one contributor to plant availability - the refueling outage. Since refueling outages are a major contributor to plant unavailability, this section investigates if there is a correlation between refueling outage length and plant size. The determination of the variation in refueling outage duration versus plant size (rating) can be a useful input to improved planning. The analysis performed here is based upon data from the initial seven years of plant operations (less than one-fifth of the projected plant life). As mentioned previously this data is highly biased since 35% of the data points are first refuelings. Given these two strong limitations, a statistical analysis of the data was performed which indicates with 95% confidence that there is a small positive correlation between plant size and the length of the refueling outages. One test of the validity of this conclusion is a look at the lower bounds on the refueling outage length as a function of plant size. It is shown that this minimum time to refuel plants shows a trend similar to that for the best estimate slope. In other words, the minimum refueling outage time for both PWRs and BWRs exhibits a monotonically increasing function with increasing plant size.

A similar conclusion can also be gleaned from looking at the longest refueling outage lengths for a given size class. However, the longest refuelings show much more variability, indicative of the fact that the longer refueling outages are in general dominated by a major maintenance item such as turbine repair, plant modification, in-core repairs, etc. (see Section 4.3.6)

A linear regression analysis of the data for PWR and BWR plants indicates that the best fit approximation to the data has a positive slope. In order to show that this correlation holds with a high level of confidence (95%), consider the following sample regression calculation for BWR plants (see Figure 3.10).

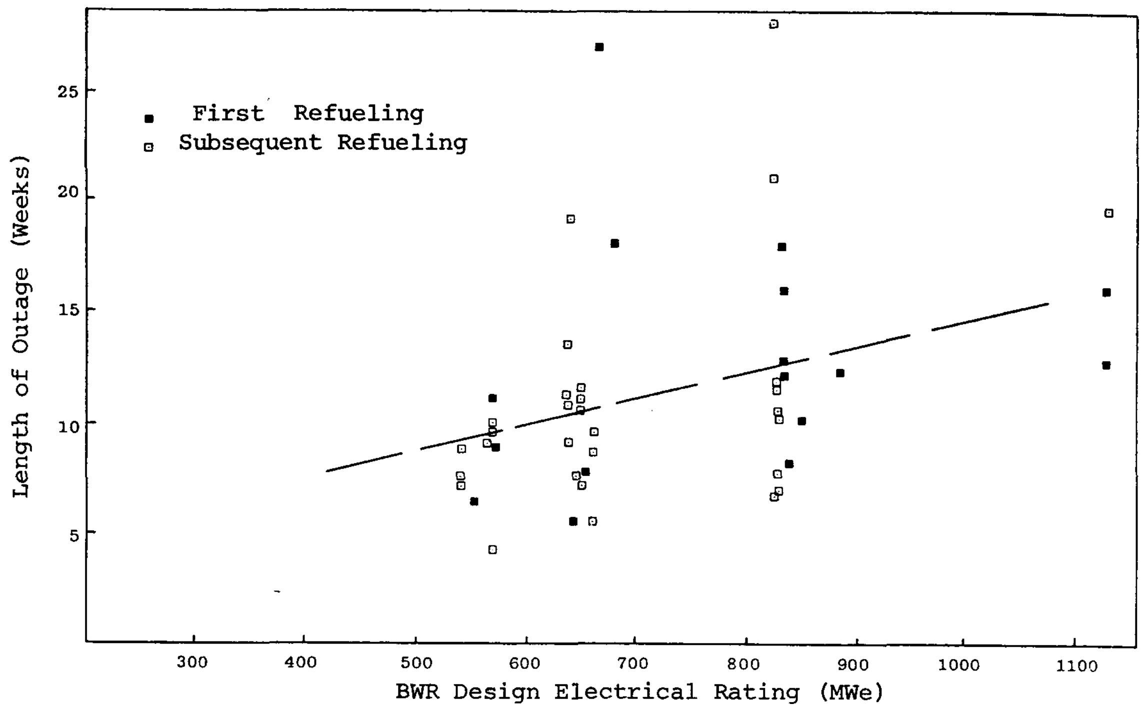


Figure 3.10. Variation of Refueling Outage Duration as a Function of Plant Rating for BWRs

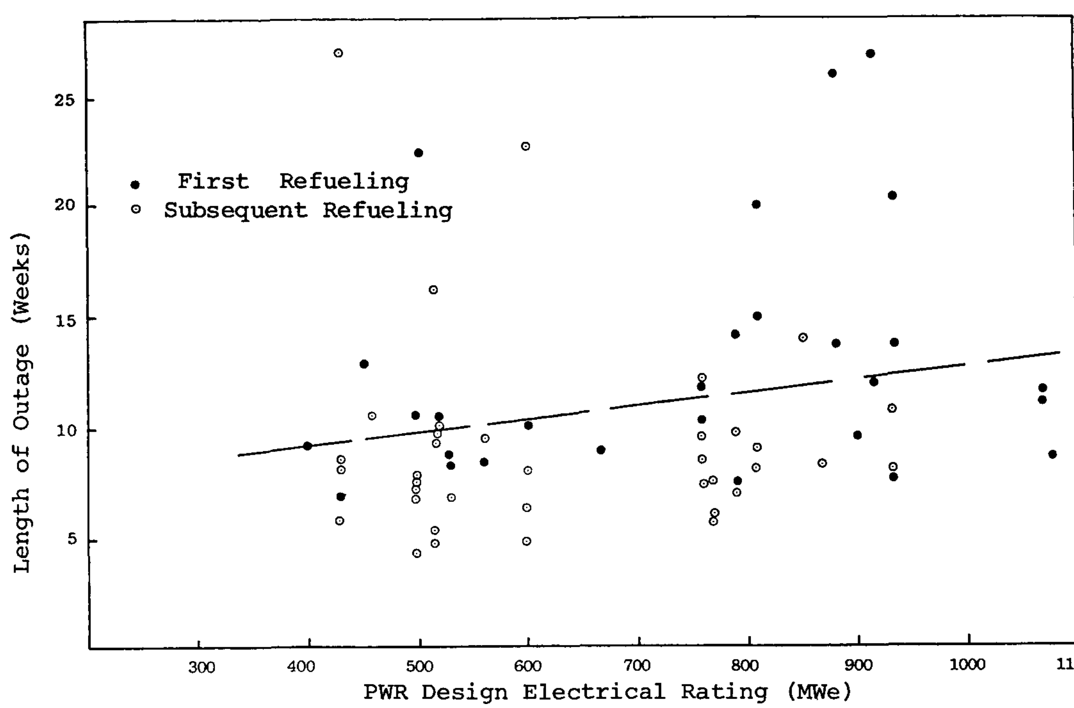


Figure 3.11. Variation of Refueling Outage Duration as a Function of Plant Rating for PWRs

BWR Regression Correlation Between Plant Size and Refueling Outage Length.

$\hat{\beta}$ = estimate of the slope of the best fit = 1.19×10^{-2} weeks/MWe

γ = the 95% confidence limit on the slope = $\hat{\beta} \pm 1.65\ \sigma_B$

σ_β = standard deviation on the estimate of the slope = $\sigma_y / \sqrt{N}\sigma_x$

σ_y = standard deviation of the refueling duration

σ_x = standard deviation of plant size

N = number of data points

$\sigma = \sigma_y / \sqrt{N}\sigma_x = 5.16 / \sqrt{46}\ 155 = 4.91 \times 10^{-3}$

$\gamma = \hat{\beta} \pm 1.65\sigma_B$

$= 1.19 \times 10^{-2} \pm 1.65\ (4.91 \times 10^{-3})$

$= (3.8 \times 10^{-3},\ 1.99 \times 10^{-2})$ weeks/MWe

These calculations show that the slope of the trend line for variation in refueling outage length versus plant size is positive with greater than 95% confidence. As an example, one can calculate the outage length differential between a refueling occurring in a 500 MWe plant versus that in a 1000 MWe plant. The following table compares the refueling outage length differential for the best estimate case and the ± 95% confidence intervals on the slope of the regression line:

BWR Plants	Confidence Level	Refueling Outage 500 MWe Plant	Refueling Outage 1000 MWe Plant
High Estimate	+ 95%	Base	Base + 10 weeks
Best Estimate		Base	Base + 6 weeks
Low Estimate	- 95%	Base	Base + 2 weeks

The best estimate regression indicates that a 1000 MWe BWR plant may take 6 weeks longer to refuel than a 500 MWe BWR. There is a great deal of scatter in the data which results in a large uncertainty for this regression model to predict precise numbers; however, as shown in the table, the operating experience data indicates a trend that large BWR plants take longer to refuel than smaller units.

The same calculation can be carried out for PWR plants as follows (see Figure 3.11):

$$\hat{\beta} = \sigma_Y/\sqrt{N}\ _X = 5.29/\sqrt{65}\ 175.86 = 3.73 \times 10^{-3}$$

$$\gamma = \hat{\beta} \pm 1.65\sigma_B$$

$$= 6.25 \times 10^{-3} \pm 1.65(3.73 \times 10^{-3})$$

$$= (9.4 \times 10^{-5}, 1.24 \times 10^{-2}) \text{ weeks/MWe}$$

Again the slope of the correlation is positive within 95% confidence limits however, the absolute value of the slope is less than determined for BWR plants. The PWR outage differential between 500 and 1000 MWe plants predicted by this correlation is summarized in the following quantitative comparisons:

PWR Plants	Confidence Level	Refueling Outage Duration 500 MWe Plant	Refueling Outage Duration 1000 MWe Plant
High Estimate	+95%	Base	Base + 6.2 weeks
Best Estimate		Base	Base + 3.1 weeks
Low Estimate	-95%	Base	Base + .1 weeks

It must be noted that the above regression analysis for PWR plants yields a minimum slope which is zero for all intents and purposes. This minimum slope would indicate that there is no correlation between PWR size and refueling outage strength. However, the above comparisons, as illustrated in Figures 3.10 and 3.11, indicate that there is a high probability that the calculated linear regression of the trend of refueling outage duration as a function of plant size has a positive slope for both BWR and PWR plants.

3.5 Accuracy in Predicting the Length of a Refueling Outage

The purpose of this subsection is to provide an approximate measure of the degree of uncertainty in the prediction of refueling outage lengths. The data used for this calculation is from the utility's estimate for the projected length of the refueling which was given to the NRC [24] versus the actual length. Only data on approximately 60% of the total refuelings considered in this report are available for use in this section; therefore, the statistics are drawn from a smaller overall population. In addition, the reader is cautioned to note that the estimate of outage duration can vary during the planning stages as new maintenance items, inspections, or tests are identified. For consistency, the projected refueling length used in this section is that provided by the utility to the NRC just before the outage began.

Figures 3.12 and 3.13 provide a simple comparison of the estimated refueling outage duration versus the actual length of PWR and BWR refueling outages. The conclusions from this comparison are the following:

- Predictions of the longest refueling outages (i.e. those which contain a significant amount of critical path maintenance) tend to have a much larger uncertainty than "pure" refuelings. In virtually all cases the uncertainty is in the direction of underestimating the length of the outage.

- First refuelings are the longest and have the highest deviation from the estimated length.

In order to further characterize the accuracy of the predicted refueling outage length, Figures 3.14 and 3.15 give a frequency histogram distribution of the differential between the actual refueling time and that estimated by the utility. The differential between the actual and estimated refueling outage time can be: (a) positive if the length of the refueling outage has been underestimated; (b) negative if the length of the refueling outage has been overestimated.

For BWR plants, data are available for 28 refuelings[24] which compare the utility estimate of the refueling outage with the actual time required. In general, there is a wide variability in the utility estimates versus the actual outage length (see Figure 3.14). The following are additional

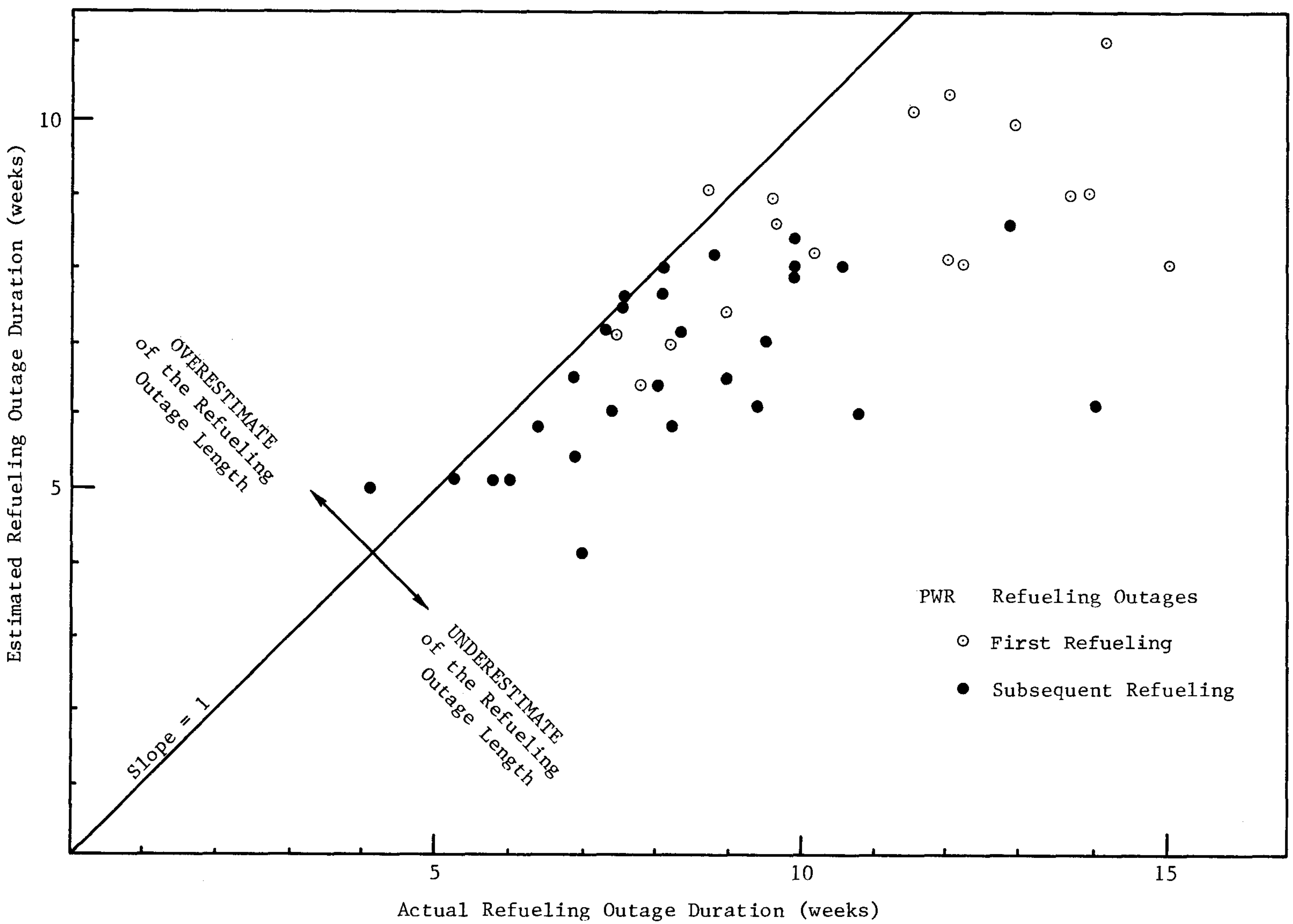


Figure 3.12. Comparison of the Estimated Versus Actual Refueling Outage Duration for PWR Refueling Outages.

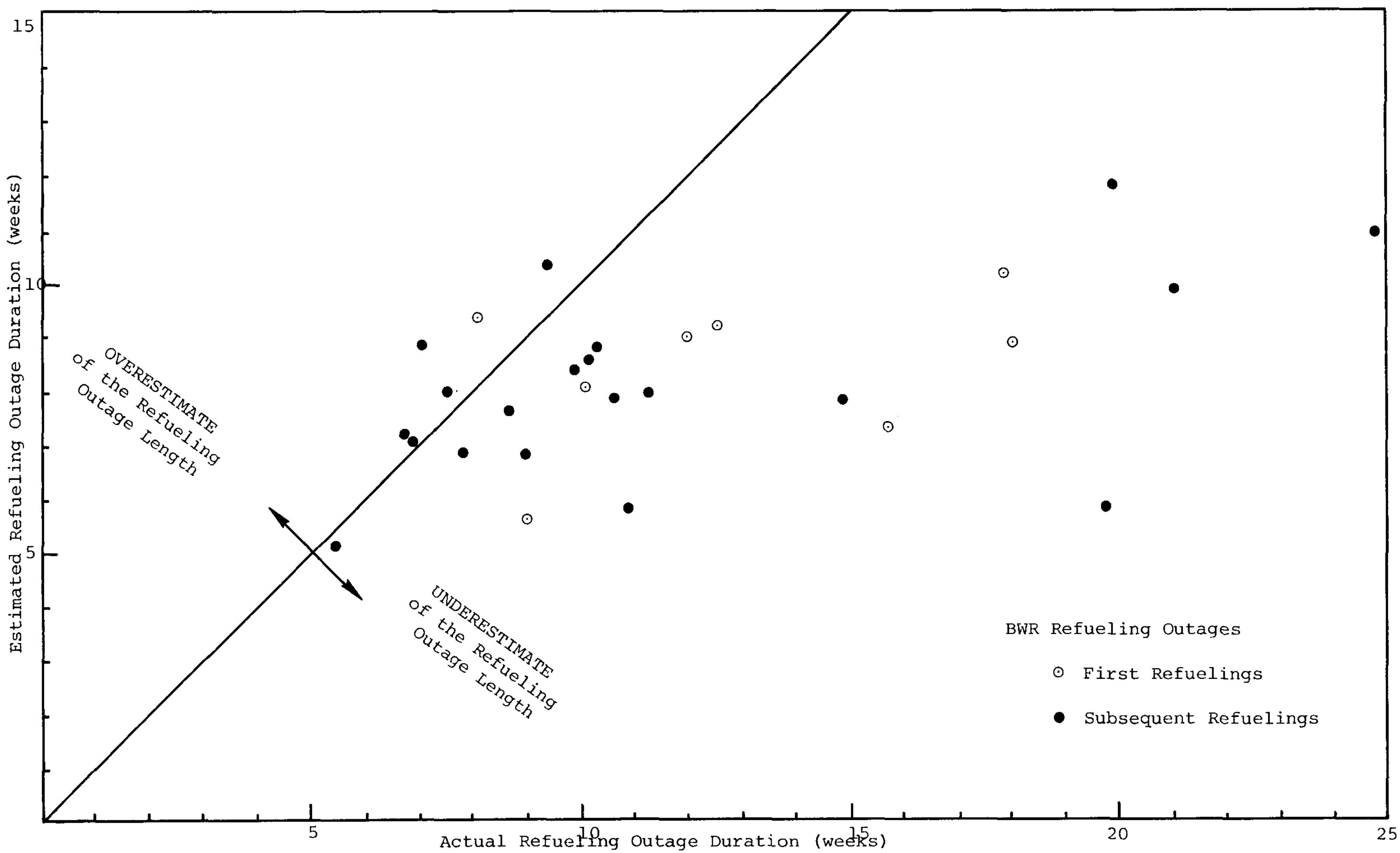


Figure 3.13. Comparison of the Estimated Versus Actual Refueling Outage Duration for BWR Refueling Outages

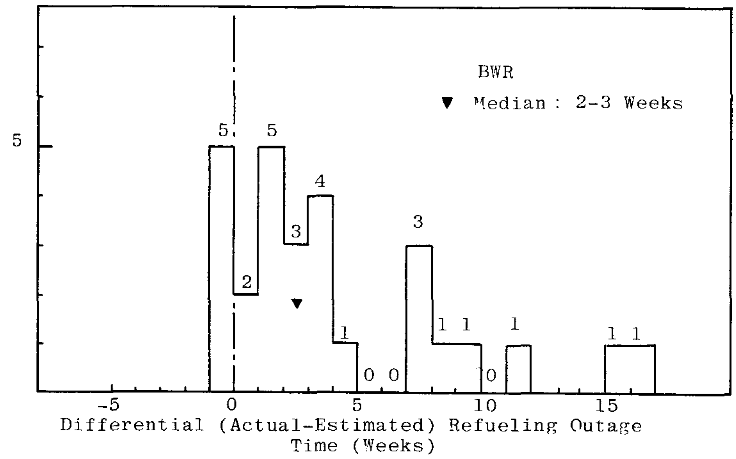


Figure 3.14 Accuracy of BWR Refueling Outage Predictions: A Frequency Histogram of the Difference Between the Actual and Estimated Outage Time.

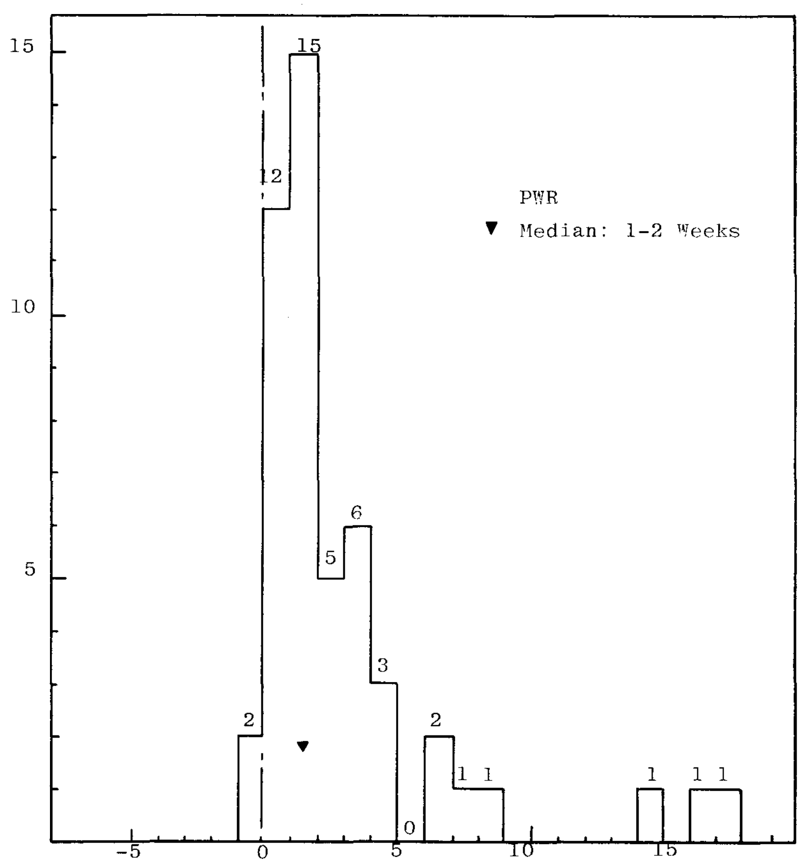


Figure 3.15. Accuracy of PWR Refueling Outage Predictions: A Frequency Histogram of the Difference Between the Actual and Estimated Outage Time.

conclusions for BWRs:

a) Major maintenance/repair discovered during refueling can significantly extend the outage far beyond that anticipated (e.g., feedwater sparger repairs, recirculation by-pass line repair).

b) Even when major maintenance is anticipated the complexity of the required tasks tends to be underestimated.

c) In general, the outages are consistently underestimated by approximately 2-3 weeks.

For PWRs, data are available for 50 refuelings[24] which compare the projected versus the actual refueling outage durations (see Figure 3.15). The conclusions from this comparison for PWRs is similar to those cited above for BWRs, with the following exceptions:

a) The median refueling underestimate for the PWRs is between 1 and 2 weeks.

b) The PWR distribution has approximately the same number of large underestimates of refueling outage length as in the BWR distribution, however the percentage effect is much smaller because of the larger number of PWR refueling outage data points.

c) The PWR distribution has a smaller standard deviation than the BWR distribution, indicating a slightly greater consistency in the estimated versus actual refueling outage length.

All of the above effects are subject to wide variability which can be caused by unexpected equipment failures, differences in planning and procedures, the quality of the maintenance personnel, and many other items. Therefore, conclusions based upon the accuracy of refueling outage predictions are of use in terms of informing utilities, vendors, and AEs of the necessity of: (a) planning outages carefully; (b) anticipating major maintenance efforts based upon operating experience at other plants; and, (c) allowing for adjustments to meet load requirements in the event of extended outages.

3.6 Comparison of U.S. and European Experience in LWR Refuelings

Thus far we have focused our attention on the U.S. light water reactor population. It is useful to measure how this population compares with other similar units in the world. The population chosen for comparison is that of the European light water reactors (see Appendix B). Drastically different concepts in reactor designs (e.g., gas cooled reactors and heavy water reactors)are eliminated. Hopefully, this simple comparison will provide a degree of insight into the state of technology, planning, maintenance, and approach to the refueling outage. The principal aim of this section is to obtain an appreciation of the comparative lengths of refuelings when different philosophies in maintenance and regulatory requirements are applied.

There are some qualifiers on the European LWR data [33] which is used here for comparison purposes: the European plants are, in general, smaller than the plants in the U.S. population; and data concerning the European plants is only available through 1975. Therefore, the data has at least two bias factors built into it which may distort the results.

Since there is approximately the same percentage of first refuelings in the European population (26%) as in the U.S. population (35.1%), it is appropriate to consider the distribution of outages based upon the entire population of refuelings. The comparison of the distribution of refueling outages by length for U.S. LWRs versus that for European LWRs (Figure 3.16) shows an interesting fact: while European units suffer from a small number of long duration refueling outages, as U.S. plants do, they have achieved a significantly lower median refueling duration (i.e., 7 weeks versus 9 for U.S. reactors). From Figure 3.16, it is clear that a large percentage of the European refuelings are accomplished in a very short time (in the 4 to 6 week time frame). Based upon the comparison in Figure 3.16, it appears that, in general, the LWRs operating in Europe experience shorter refueling outages than those in the U.S.

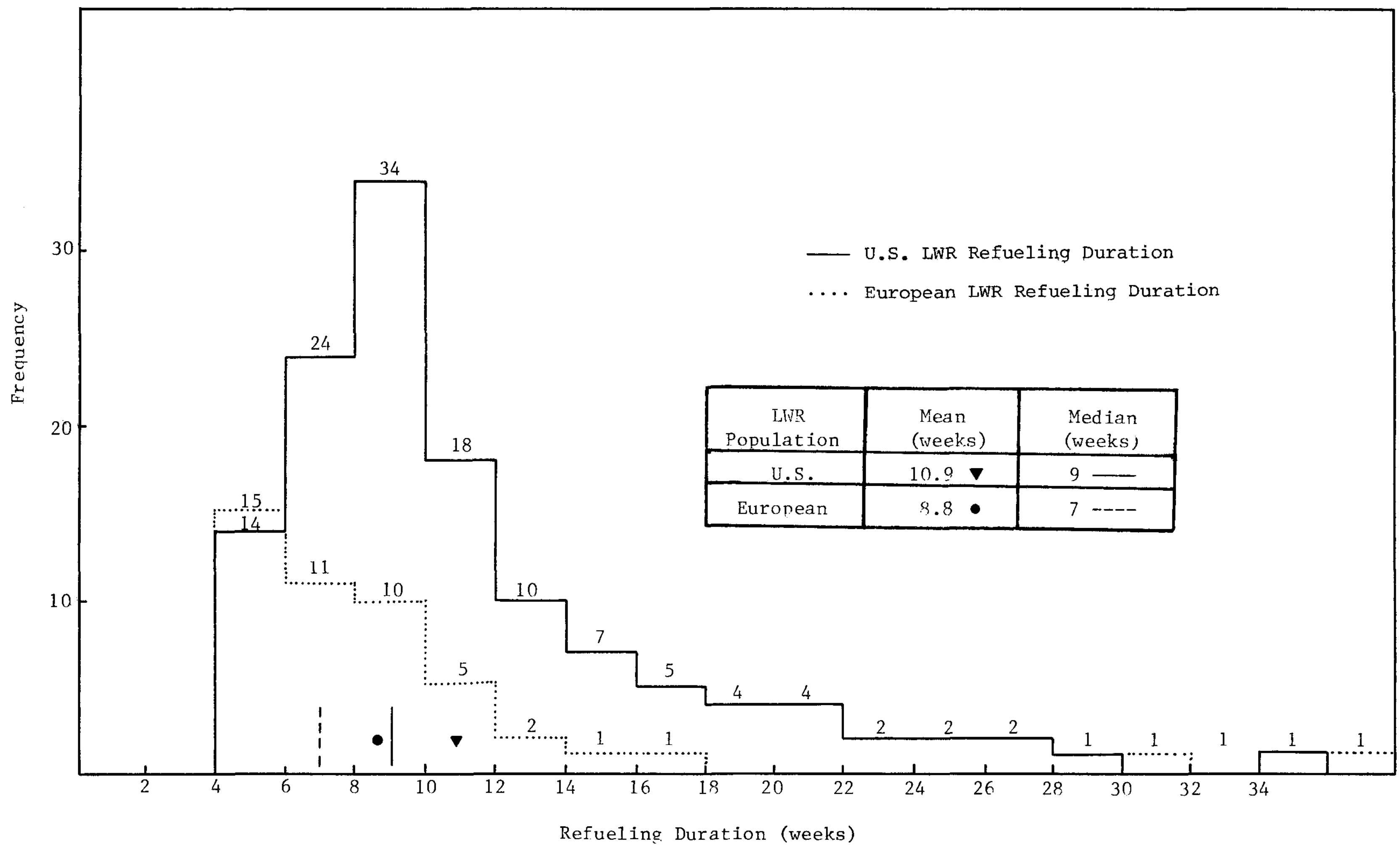


Figure 3.16. Refueling Durations: Comparison Between U.S. and European LWR's.

Section 4.0

CRITICAL PATH ANALYSIS OF REFUELING OUTAGES

4.1 Introduction

The purpose of this section is to review current operating experience data for typical refueling outages and to determine the critical path times associated with various operations. Thus far we have treated refueling outages as a single, homogeneous entity; however, refueling outages encompass a wide diversity of operations which must be accomplished while the plant is shutdown. They can be divided arbitrarily as follows:

a) Necessary operations to refuel the reactor

b) Repair and maintenance operations

c) Tests and inspections

d) Refueling related delays

The following definitions shall be used in this section for the discussion of the various aspects of refueling outages:

a) Refueling Operations - This category refers to the minimum time required to complete the refueling tasks. All other critical path operations have been taken out and only the tasks necessary to interchange fuel are considered.

b) Required Testing - Testing, of course, is a necessary part of nuclear plant operation; it has been separated out to define the extent of its impact on plant productivity.

c) Inspections - Inspections of plant equipment are necessary to prevent failures of key systems which may affect plant safety or operation. These items are separated out to indicate the extent of their impact, and show the potential benefit to be gained from a plant design and arrangement which facilitates inspections.

d) Refueling Equipment Failures - Some delays in refuelings have been attributed to failures in refueling equipment. There would be a direct gain in plant availability if the effect of refueling equipment failures on critical path events could be reduced through increased reliability or improved testing methods of the refueling equipment.

e) Dropped Items Into Reactor Vessel - Because of the difficulty in retrieving items which have fallen into the reactor vessel and the potential impact such an event has on plant operation, it is considered appropriate to include this as a separate category.

f) Maintenance - In addition to the refueling operations, it is generally considered that there is an extensive amount of maintenance occurring during refueling outages. This is in fact the case; work performed that is unrelated to refueling includes:

- preventive maintenance items
- required repairs
- plant modifications

However, much of this work is performed in parallel with refueling. This summary deals only with that maintenance which requires plant critical path time to complete.

The first category, refueling operations, has been further dissected to identify: (a) improvements which can be made; and, (b) the magnitude of the improvements' potential impact. However, this is not the primary purpose of this report. The Department of Energy (DOE) has a project [22] in progress to assess the ability to decrease refueling operation time by improvements in equipment and/or procedures.

The definitions used in the breakdown of the refueling operations are:

a) Time to Remove the Closure Head - This is the time from the unit's separation from the electrical grid until the closure head is removed. It includes operations such as:

PWR	BWR
Remove Turbine from Grid	Remove Turbine from Grid
Containment Purge	Cooldown
Cooldown	Remove Drywell Head
Disconnect Control Rod Drive Mechanisms (Piping and Electrical)	Remove Head Insulation
Remove Head Insulation	Detension Studs
Detension Studs	Remove Closure Head
Remove Closure Head	

b) Preparation for Fuel Movement - This aspect of the refueling operation is the transition phase from removal of the closure head until fuel movement is initiated. It involves:

PWR	BWR
Remove and Store Reactor Vessel Head	Remove and Store Reactor Vessel Head
Sealing Vessel-cavity annulus	Install Reactor Vessel Flange Protector
Fill Refueling Cavity	Remove and Store Steam Dryer
Remove Upper Internals	Install Steam Line Plugs
Install Guide Rings in Vessel Flange	Drain Steam Lines
	Unlatch and Remove Moisture Separator
	Flood Refueling Cavity
	Clean-up Water

c) Fuel Movement - This is the heart of the refueling operation; it involves shuffling fuel from one position to another within the core to optimize burnup and replacing spent fuel with fresh fuel or fuel partially burned in a previous cycle. In addition, during this time the fuel may be inspected. In BWRs, fuel sipping is used to identify leaking fuel assemblies. The fuel assemblies can be sipped either in-core or out-of-core. In PWRs, fuel is usually inspected visually, looking for mechanical damage and rod bow; however, PWRs do have the capability to sip fuel out-of core, if necessary.

d) Core Verification Through Closure Head Assembly - Much of the effort involved here is the reverse of the actions required in (b) above. In addition, the core assembly must be verified and checked to ensure that the proper fuel and control assemblies have been loaded with the correct orientation in the correct core locations.

e) Closure Head Assembly Through Criticality - This involves replacing shielding and insulation, hydrostatically testing the primary system, and reconnecting CRDMs and other piping.

f) Criticality Through Power - This is generally a short time and requires reactor heat-up and the synchronizing of the generator onto the grid.

Having defined the categories to be used in this report to subdivide the refueling outage, it is useful to summarize a breakdown of the contributing causes of refueling outage extensions. A simple, graphic representation of the selected sample of refuelings is shown below to provide a perspective on the above defined categories.

The idealizations of a rapid refueling alluded to earlier have not been found to hold true. Refuelings have been shown by operating experience to require significant organization and management efforts to even approach the ideal. As will be shown in Section 4.3, the actual refueling operations have been performed in an average of 34 days (52%). The repair and maintenance operations while requiring an average of 18 days per refueling outage or 27% are the most widely varying in nature and duration. In fact, for lengthy refueling outages (>4 months) most of the critical path controlling time is associated with repair of equipment (e.g., turbine, steam generators, reactor internals, feedwater spargers). Outages greater than 4 months in length have not been included in the above sample.

A fact not widely recognized is that required testing and inspections are taking an increasingly large amount of time, and since a great deal of this time is critical path time, it results in a lengthening of the refueling outages. According to the summary of refueling events above, testing and inspection accounts for approximately 20% of the refueling outage time. One particular test, the Type A containment leakage test, takes approximately 3-7 days for a PWR and therefore represents approximately 2% of the plant capacity factor for the year when it is required. The Type A containment leakage test is currently required to be performed approximately once every three years (3 times/10 years) (see Appendix C).

Refueling equipment malfunctions, procedure failures, and items dropped into the core represent a small contribution to the average refueling outage. However, since reporting of these events is not complete it is judged that this category may be underestimated. Nevertheless, this category is only a relatively small contributor to the outage time, but an important area where improvements can be made.

4.2 Population of Refuelings Considered for Detailed Investigation

There are limited data available in the public record regarding details of plant refuelings. The utility annual operating reports are the primary source of information which is used in this section to determine the times involved in performing various tasks during refueling outages. Some additional information is available through conferences and other limited studies which have been performed. Sections 4.3 and 4.4 include a summary of refueling operations and extensions of refueling outages based upon a limited sample of refuelings (21% of the total) for which adequate detail is available. Because the information used in compiling this report is taken from utility annual operating reports for which there are no strict guidelines, there is a wide scatter in the amount of detail provided for refueling outages. Some plants provide virtually no details of the refuelings; other plants give critical path items and key events. Therefore, some judgement has been exercised in assigning portions of the refueling outage to various categories.

Tables 4.1 and 4.2 summarize the selected refueling outages which have been used to assess the factors affecting refueling extensions:

Table 4.1: Summary of PWR Refueling Outages Used in Section 4

PWRs	No. of Refuelings Analyzed		Refueling Number				
		1	2	3	4	5	6
Connecticut Yankee	3	10.0(70)				8.6(75)	8.1(76)
Three Mile Island	1	13.7(76)					
Zion 1	1	11.6(76)					
Zion 2	1	11.4(77)					
Kewaunee	1	8.2(76)					
Point Beach 1	2			7.6(75)	7.7(76)		
Point Beach 2	1		4.2(76)				
Fort Calhoun	1		10.5(76)				
Robinson 2	2			5.7(75)	6.0(76)		
Surry 1	1			14.1(76)			
Surry 2	1		7.0(76)				
TOTAL	15	5	10				

Legend: ( ) - year of the refueling

X.X - length of refueling in weeks

Table 4.2: Summary of BWR Refueling Outages Used in Section 4

BWRs	No. of Refuelings Analyzed	Refueling Number 1	2	3	4	5	6
Dresden 2	1				10.3(76)		
Dresden 3	1				6.9(76)		
Millstone 1	2		9.4(74)		8.6(76)		
Peach Bot 2	1	12.7(76)					
Quad Cities 1	1		10.1(76)				
Quad Cities 2	1		7.7(76)				
Monticello	4	11.1(73)	9.6(74)	4.1(75)	9.9(75)		
Pilgrim 1	1	17.7(76)					
TOTAL	12	3			9		

( ) - year of the refueling

X.X - length of refueling in weeks

This sample will provide a qualitative indication of the types of events which are causing refueling extensions. Perhaps there is an overemphasis on first refuelings, which tend to be the longest; however, at this point in time, they are a large percentage of the overall population of refuelings (i.e., 35%) and therefore have been included here as representative of current reactor operating experience. From Section 3, it appears that the second through the seventh refuelings are equivalent in duration and therefore can be lumped together in a single population. The fallacy in this assumption may be that there are in-service inspection and surveillance requirements occurring every 3, 5 or 10 years which may make certain refuelings longer than others. For instance, the 10th, 20th, and 30th refuelings may be longer than others to enable performance of inservice inspections.

Because of the limited amount of data, it is important that we define how this population of data compares with the total population of refuelings which were discussed in Section 3. The distribution of refueling outage duration of the sample included in this section versus the entire population is shown in Figure 4.1. While this is not an exact representation of the distribution of the total population, the selected sample of refueling

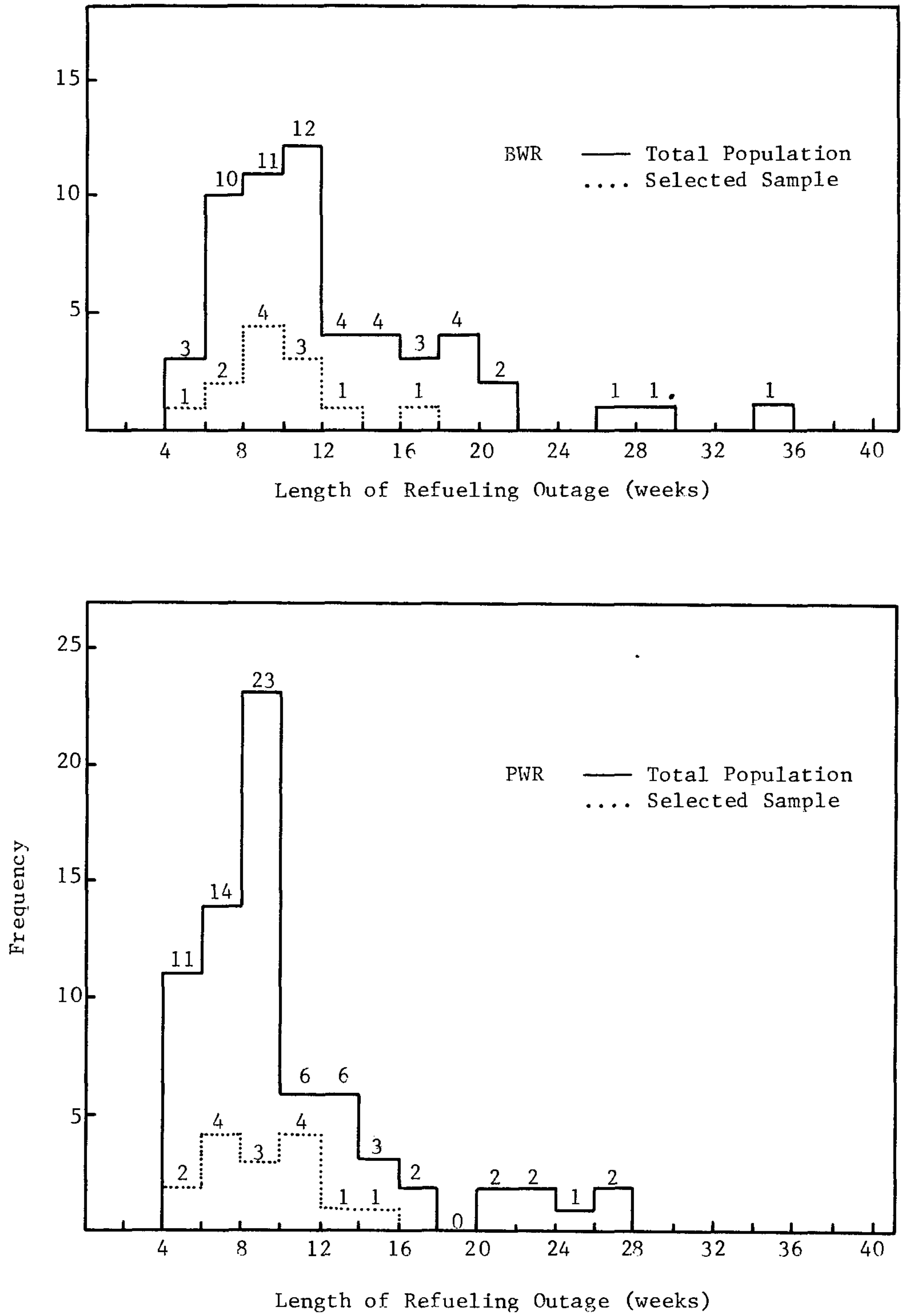


Figure 4.1 Frequency Histogram of the Length of Refueling Outages for BWRs and PWRs: Comparison of the Total Population versus the Group of Selected Refuelings.

outages does provide a representative sample which allows us to anwer questions concerning causes of refueling extensions and to evaluate methods which may be used to reduce the length of refueling outages.

It should be noted that some refuelings of long duration (i.e., greater than 3 months in length) have been included to allow an evaluation of the impact of lengthy refueling extensions on the assessment of average refueling outages. However, outages greater than 4 months (~3000 hours) are not represented in the sample considered in this section. These very long outages are not "typical" refueling outages and are dominated by non-refueling related problems (e.g., turbine, steam generators, condenser, core vibration, feedwater sparger, etc.). Therefore, the long duration refueling outages which are extended due to problems other than refueling related operations are not included here since they are judged to distort the main purpose of this report, which is to assess "normal" plant refuelings.

4.3 Detailed Review of Critical Path Events for Selected Refuelings

4.3.1 Limitations in the Critical Path Evaluation

In order to demonstrate the methodology used in the evaluation of the impact of various operations on the critical path refueling time, this section has dissected several refueling outages into their major critical path contributors. Each of the figures in this subsection display principal contributors to the critical path operations plus additional information if available. However, because of the lack of a consistent standard of reporting, in some cases the critical path time required for various operations has been estimated from the time required at other similar plants. In addition, in virtually all cases, the next most limiting work item in the critical path has not been reported by the utility and hence is not reflected in these figures. Therefore, the potential gain in critical path time associated with elimination or reduction in time of some "primary" operations is difficult to assess since parallel operations may occupy a significant amount of the time presently attributed to a "primary" operation. An approximate but realistic criterion which can be used to judge the amount of improvement which can be anticipated in reducing refueling outage time is obtained by looking at the shortest refueling outages which have occurred.

4.3.2 Evaluation of the Shortest PWR Refueling

The shortest PWR refueling in the U.S. data base* was the 1976 Point Beach 2 (497 MWe rated power) refueling which took only 29 days (see Figure 4.2). While the length of this refueling outage is remarkably short relative to the remainder of the refueling outage population, an even more impressive fact is that over the interval of time from the end of the first refueling until the end of the third refueling (28 months) the plant availability was 88%. Two refueling outages (totaling 11.1 weeks) accounted for 75% of the total plant unavailability over this period; major outages >100 hours accounted for 9%; and the remaining 16% were accounted for by short duration outages. This time frame corresponds to what is referred to in Section 3 as the period of "mature" plant operation. Nevertheless, a plant availability of 88% represents a significant achievement in plant performance.

The critical path time for the 1976 Point Beach 2 refueling outage, which was the unit's second refueling, is summarized in Figure 4.2. The categories of operation, which were defined in Section 4.1, are used to classify critical path time. There are some instances where arbitrary assignments have been made to these operational categories based upon comparison with other refueling outage information and the lack of specific information for Point Beach 2.

The problems with the evaluation of operating data are exemplified by comparing Table 4.3 with Figure 4.2. While Figure 4.2 gives the critical path times for completion of various operations, it does not provide a breakdown of the time which should be apportioned to various tasks which occur during the operations. For example, the time to remove the closure head takes 13 days from the time the generator is separated from the grid. Of that time, however, there is some critical path time involved in eddy current inspection of the steam generators and plugging of steam generator tubes. In addition, there is other work on leak testing of the steam generators, maintenance on the reactor coolant pumps, and various primary system in-service inspections.

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*PWRs greater than 150 MWe, through June 1977.

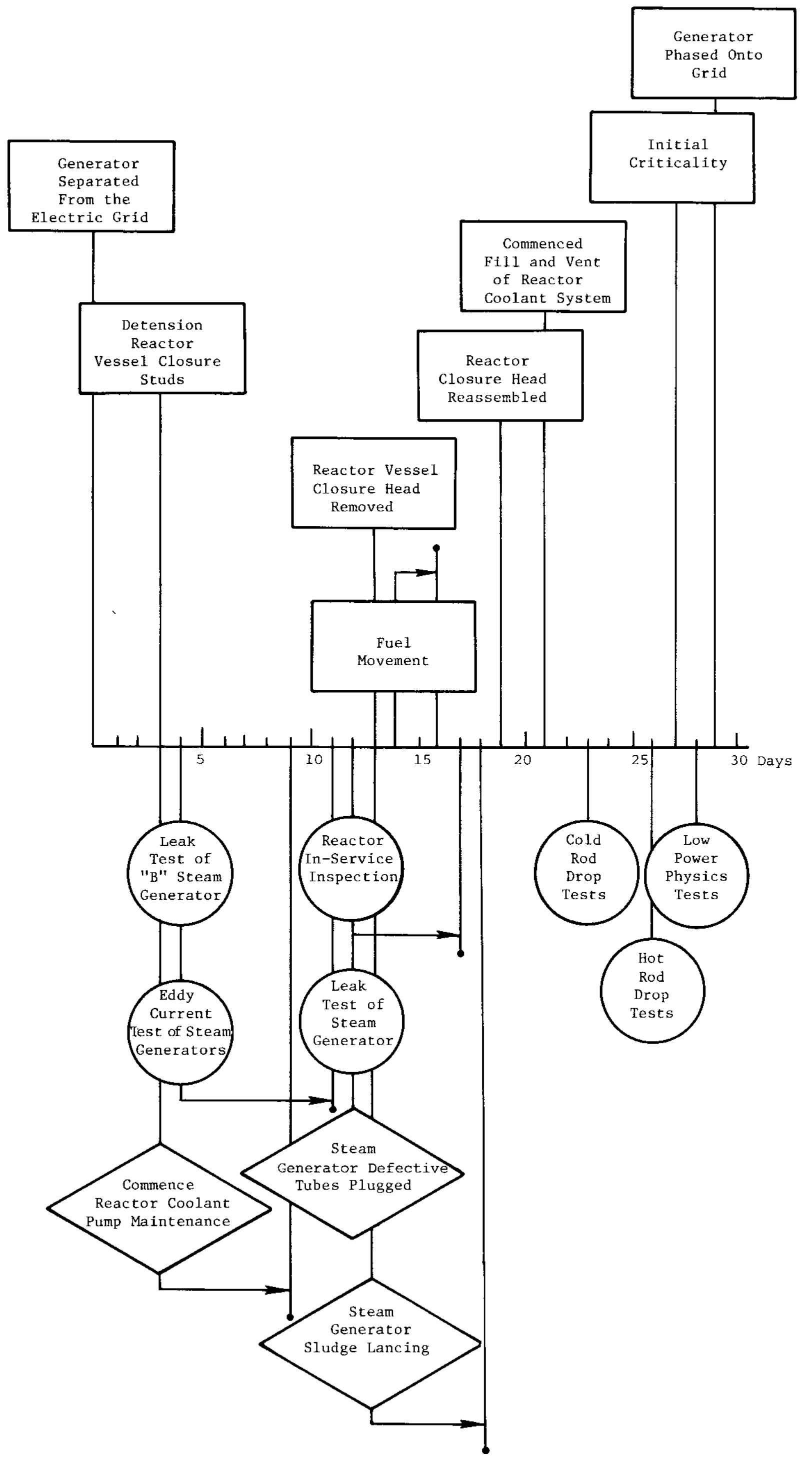


Figure 4.2. Graphical Summary of the 1976 Point Beach 2 Refueling Outage

Table 4.3: Summary of Critical Path Operations* Occurring During the 1976 Point Beach 2 Refueling Outage

Operation	Time (Days)				
	Complete Operation	Test	Inspection	Maint.	Estimated Time for Refueling Operations
Head Removal	13	0	7	1	5
Prepare to Remove Fuel	1	0	0	0	1
Fuel Movement	2	0	0	0	2
Head Reassembly	3	0	0	0	3
Head Assembly Through Criticality	8	2	0	0	6
Criticality Through Power Operations	2	1	0	0	1
TOTAL	29	3	7	1	18

*As noted in the beginning of section 4.3, the available data on refueling outages precludes a detailed critical path analysis (CPA). In lieu of the more sophisticated CPA, a much more simplistic approach has been used. The purpose of this analysis is not to estimate the potential time savings possible through elimination of certain operations, tests, or maintanance; it is meant only as a qualitative tool in assessing those areas which currently require critical path refueling outage time to accomplish. In this way it is hoped that those areas of refueling outages which are most fruitful to pursue can be clearly identified. It is important to emphasize that the approach of simple subtraction of times for various critical path tasks cannot accurately determine the critical path time savings associated with elimination of operations, only a more sophisticated CPA can do that. As will be shown in Section 4.4, the estimate of refueling operations using this approach is quite consistent for all the plants considered, indicating that the approach has a high degree of validity in identifying current refueling outage makeup.

Table 4.3 summarizes the estimated time necessary to complete the refueling operations if the testing, inspection, and maintenance items which could interfere with these operations are removed. It is estimated that the basic refueling operations would take 18 days, while inspections, maintenance, and testing cause an impact of approximately 11 days on the outage length.

Since this is one of the fastest refueling operations performed to date, it is judged that this approximates a minimum achievable refueling outage with the current design for refueling schemes. Factors which may tend to increase the length of this "minimum" projected outage when extrapolated to other plants are:

a) Larger plants tend to have slightly longer refueling outages; Point Beach 2 is rated at 497 MWe which is at the low end of the spectrum of commercial nuclear plants (see Section 3.4).

b) Other plants have shown a significant amount of required critical path maintenance necessary during refueling outages which Point Beach has been able to avoid.

c) The amount of time attributed to testing is on the low end of the typical distribution; for example, an integrated containment leak rate test was not performed.

4.3.3 Evaluation of the Shortest BWR Refueling

For BWR plants, one of the shortest refuelings was the Monticello refueling in January 1975 (see Figure 4.3). In the case of Monticello, the core was completely refueled, and the reactor was critical in 29 days. This minimum operational refueling length compares with the projected ideal refueling goals of approximately 10 to 20 days. However, the Monticello refueling of January 1975 was the first of two refuelings of 1975. Since the plant management knew a second refueling outage was required during 1975, many of the maintenance, test, and inspection items normally accomplished during refuelings were postponed until the fall refueling at Monticello. Therefore, while the Monticello refueling can serve as an example of minimum outage time, it would appear that an extension of this minimum refueling may not be able

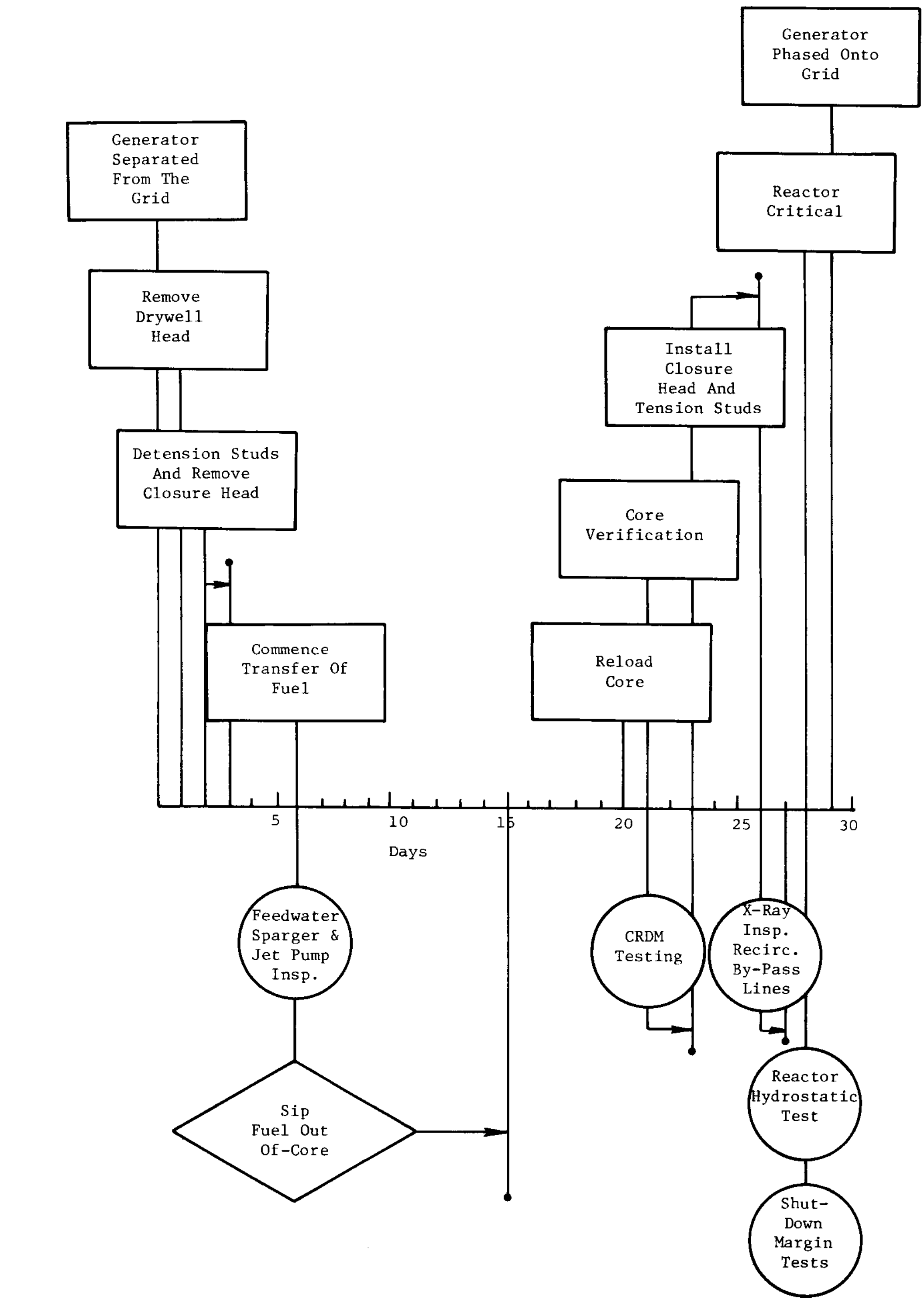


Figure 4.3 Graphical Summary of the January 1975 Monticello Refueling Outage

to be maintained on a regular basis, since additional necessary maintenance, tests, inspections, and repairs may be required.

Figure 4.3 is a graphical summary of the 1975 Monticello refueling. Table 4.4, below, also classifies the critical path time and the minimum estimated time for refueling operations. The categories of test, inspection, and maintenance have been factored out of each refueling operation time to estimate the time to perform the refueling operations.

Table 4.4: Summary of the Critical Path Operation* During the January 1975 Monticello Refueling

	Time (Days)				
Operation	Complete Operation	Test	Inspection	Maint.	Estimated Time For Refueling Operation
Head Removal	3	0	0	0	3
Prepare to Move Fuel	3	0	0	0	3
Fuel Movement	15	0	2	0	13
Head Reassembly	5	2	0	0	3
Head Assembly Through Criticality	2	1	0	0	1
Criticality Through Power Operation	1	1	0	0	0
TOTAL	29	4	2	0	23

*See Footnote to Table 4.3

As in the case of Point Beach 2, the refueling outage at Monticello was accomplished in a short period of time. The actual refueling operations plus required testing took 29 days. An even more remarkable fact is that if fuel sipping is not included in the "fuel movement" operation, then the refueling operation comprises only 13 days.

As a further benchmark comparison, consider the estimate of a typical refueling outage made by General Electric [5] for large boiling water reactors. Figure 4.4 gives a critical path summary of refueling operations and testing required during an equilibrium fuel cycle refueling. (Maintenance and inspections are not accounted for in the projection.) Table 4.5 compares the GE estimated "typical" refueling, the Monticello 1975 refueling, and the average refueling determined from the sample of 12 plants. The projected refueling outage time is based upon the time required for each individual action; it does not appear to properly account for the interaction of the many other activities occurring at the same time in the plant, nor does it project the time required for other actions, such as additional testing, inspections, or maintenance. In summary, the GE projection estimated 18 days to refuel a large BWR; operating experience shows that the fastest that a refueling has ever been accomplished is 29 days, while the average for the 12 selected plants is 41 days for comparable tasks (i.e., neglecting inspection and maintenance).

Table 4.5: Comparison of the Projected and Actual* Refueling Outage Lengths in BWRs

Operation	GE Estimate [5] Typical BWR Refueling (Days)	Monticello 1975 BWR Refueling (Days)	Average BWR Refueling from Op. Experience (Days)
Head Removal	2	3	3.4
Preparation to Move Fuel	1	3	2.3
Fuel Movement	6	13	19.8
Head Reass'y	6	3	5.3
Head Ass'y through Criticality	2	1	3.3
Criticality through Power Operation	0 (Est)	0	.4
Testing	1	4	7
Other	0	2	28
Total	18	29	69.5

*See Footnote to Table 4.3

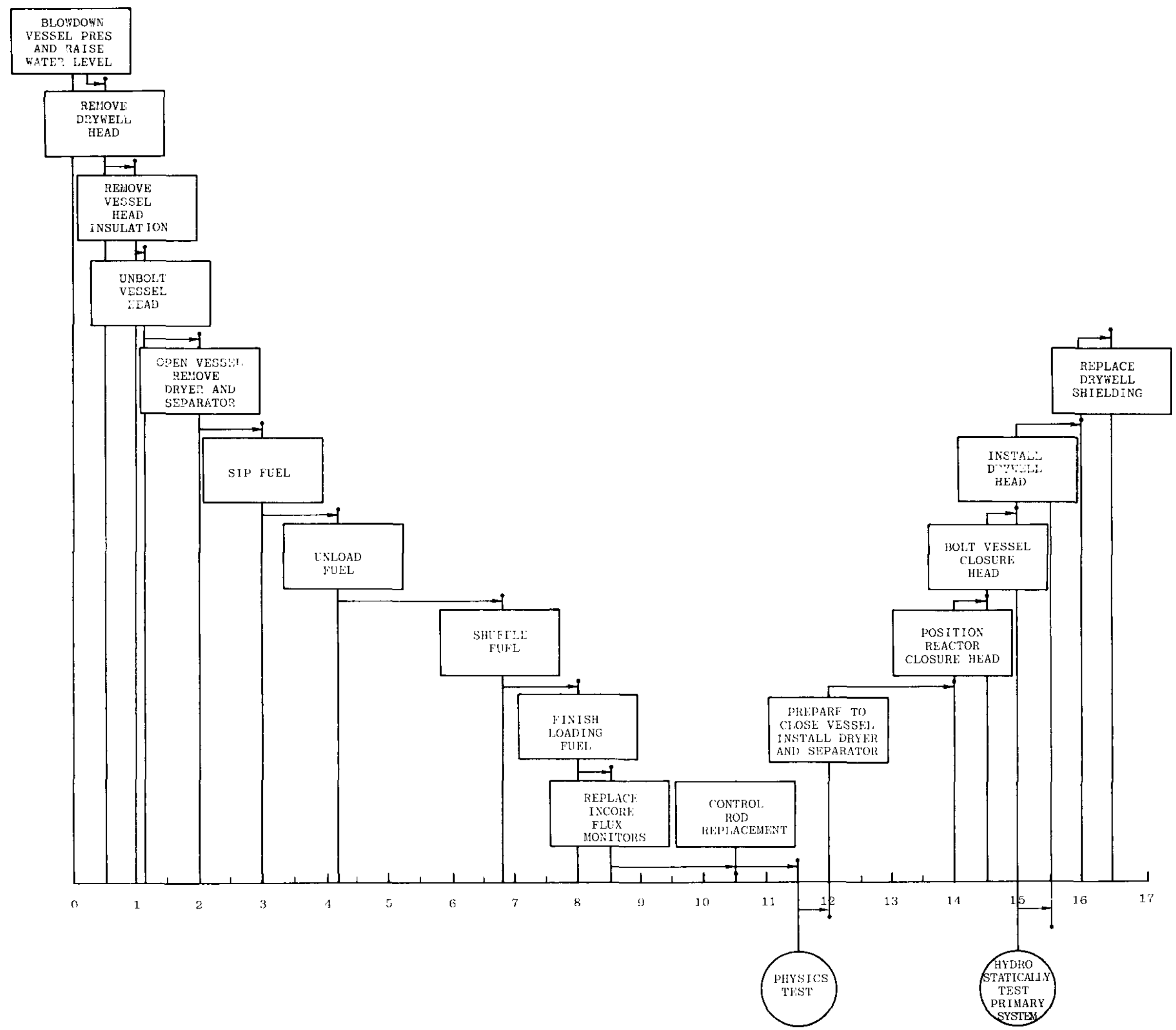


Figure 4.4. Summary of BWR Refueling Outage As Projected by General Electric in 1971[26]

4.3.4 Evaluation of an Extended Refueling Outage

Now that we have considered the shortest refueling outages recorded in U.S. operating history in units greater than 150 MWe, let us consider the other extreme - a case of one of the longer refuelings - Pilgrim 1976, and what contributed to the extension of that outage. Figure 4.5 and Table 4.6 summarize the operations which occurred in the critical path evaluation of the outage.

Table 4.6: Summary of Critical Path Refueling Operations* During the 1976 Pilgrim Refueling Outage

Operation	Time (Days)				
	Complete Operation	Test	Inspection	Maint.	Estimated Time for Refueling Operations
Head Removal	5	2	0	0	3
Prepare to Move Fuel	10	0	2	1	7
Fuel Movement	85	0	1	56	28
Head Reassembly	10	5	0	0	5
Head Assembly Through Criticality	13	2	0	0	11
Criticality Through Power Operation	1	0	1	0	0
TOTAL	124	0	4	57	54

* See Footnote to Table 4.3.

Some of the pertinent comparisons which can be made are those between refueling operations in the "shortest" and the "longest" refuelings. The principal difference is in the length of time required to move fuel. The Pilgrim 1 refueling required approximately 28 days to perform the movement of fuel, which is not accounted for by other critical path events. The longer time indicates that problems with identification of leaking fuel or fuel handling were probably the principal causes of extending

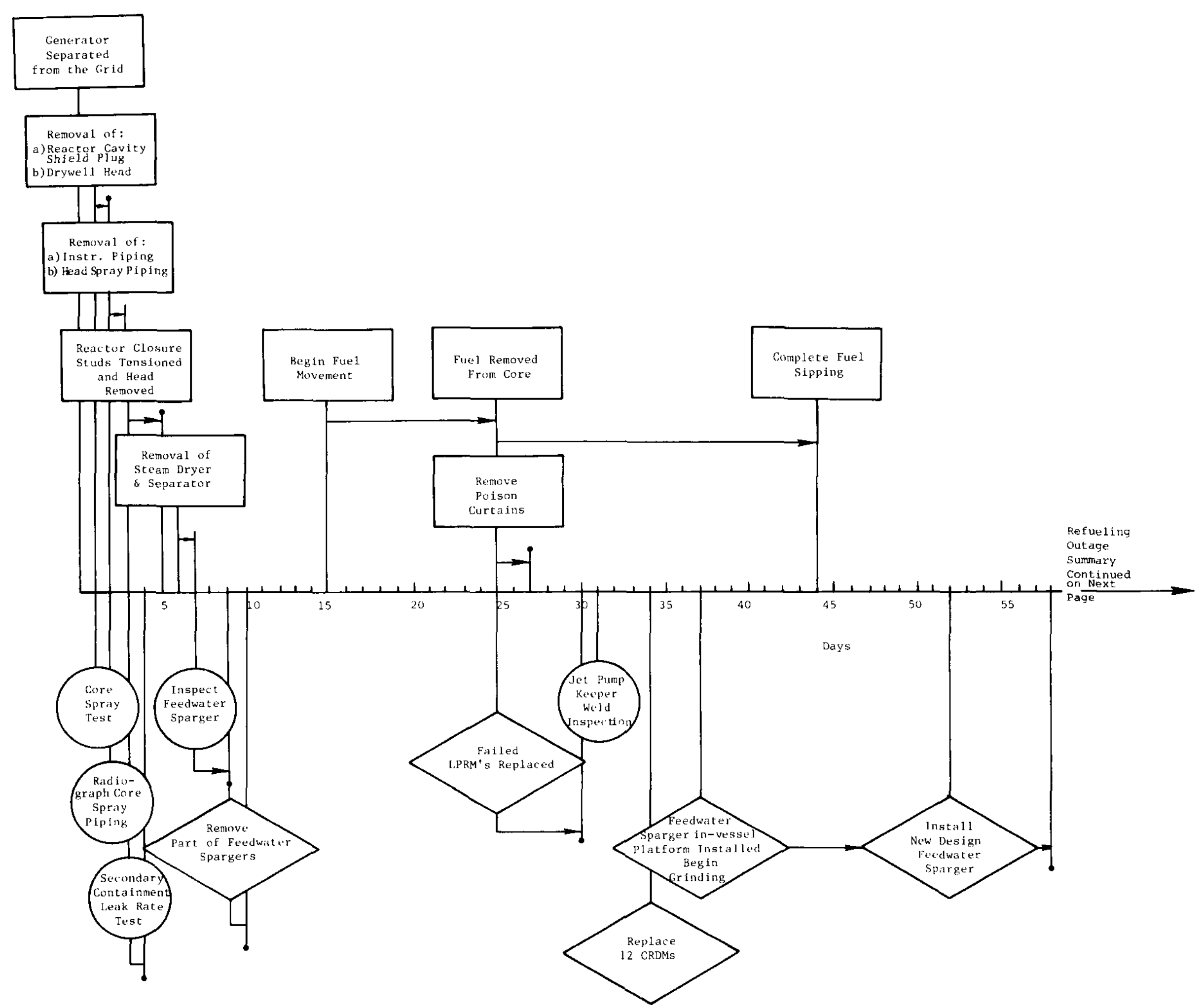


Figure 4.5 Graphical Summary of the 1976 Pilgrim Refueling Outage

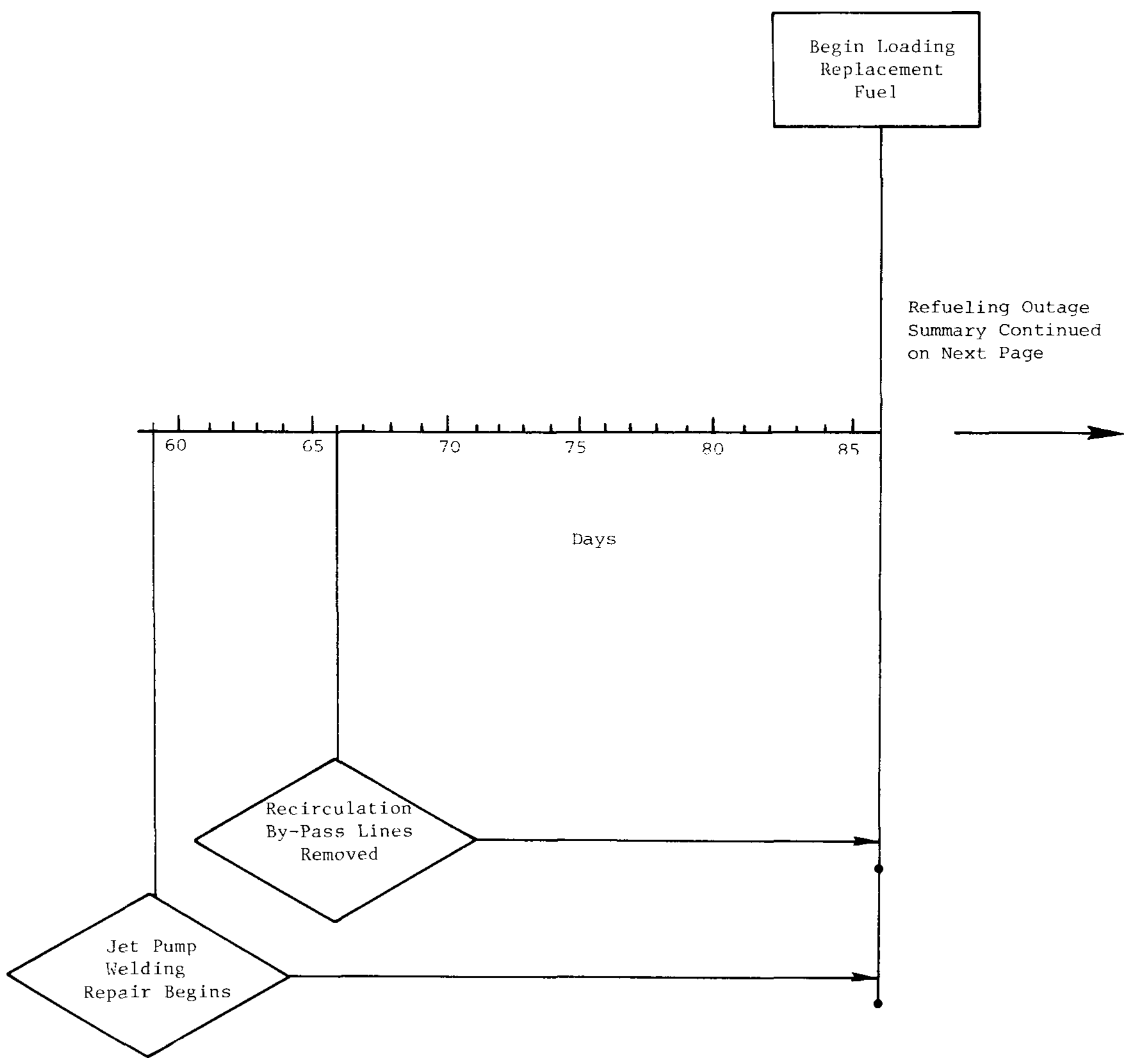
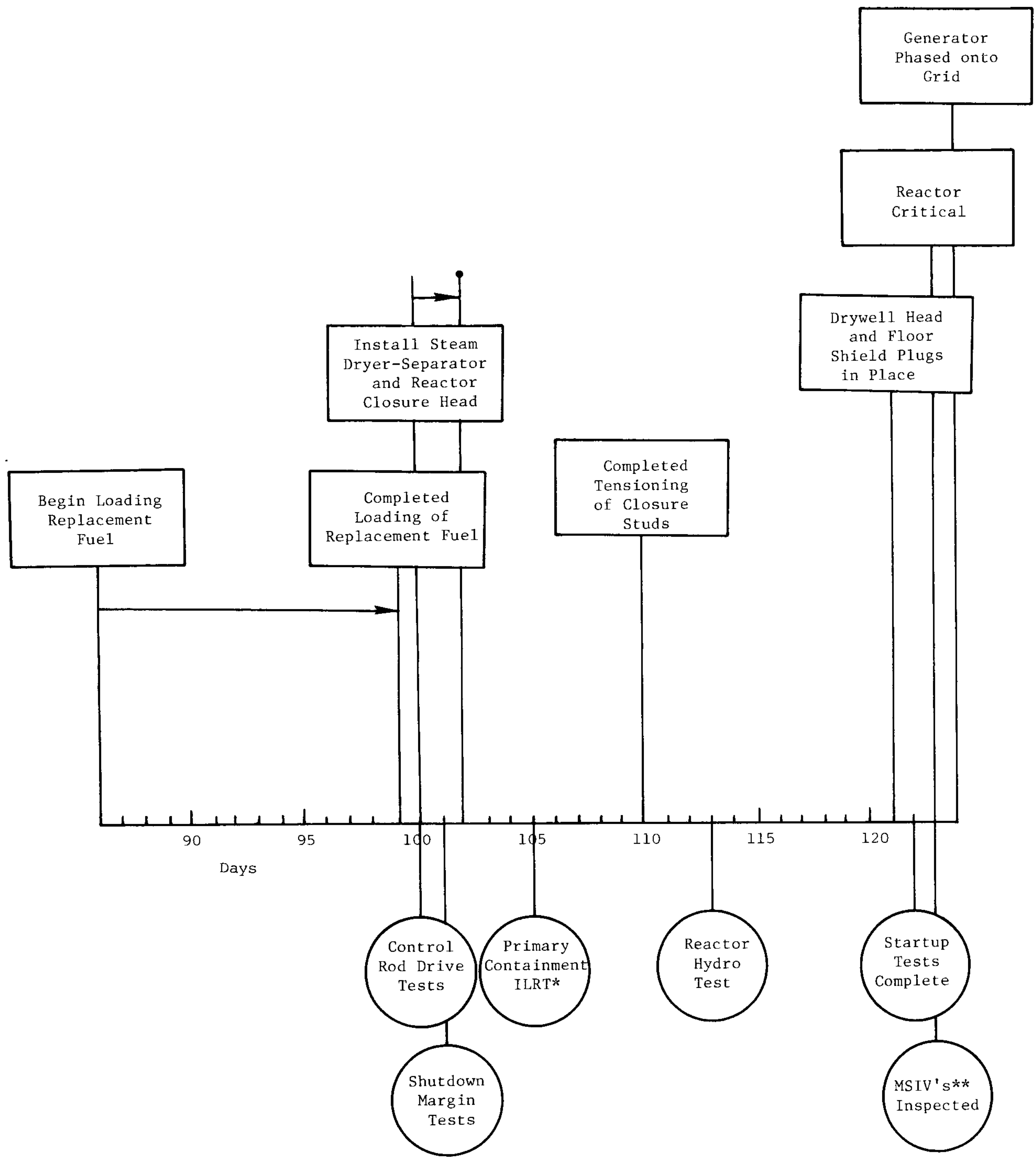


Figure 4.5. (Cont'd)



* ILRT - Primary containment integrated leak rate test

** MSIV - Main steam isolation valves

Figure 4.5. (Cont'd)

the time for this operation. In addition, the time from head assembly through initial criticality took 11 days in Pilgrim versus one in the Monticello outage. This dramatic difference indicates that there were some additional complications or maintenance items which arose, but were not reported, in the period between head assembly and initial criticality. Other than these two operations the estimated refueling times were comparable for Pilgrim and Monticello.

In summary, this evaluation of the 1976 Pilgrim refueling and its comparison with the shortest refueling outages indicate that the time for refueling operations estimated in Section 4.4 may be slightly overestimated because the utility data upon which the estimate is based does not contain all the delays incurred. Therefore, the refueling operations may actually account for an even smaller portion of the outage than suggested in Section 4.4 (i.e. less than 50%).

4.3.5 Evaluation of Typical Refueling Outages

Thus far we have considered both extremes of refueling outages, the shortest and the longest; the following is a brief summary of two "typical" refuelings. The term "typical" applies to the fact that the outage length is close to the mean value determined from Section 3.

The refuelings which are presented as typical refuelings are the following:

Plant	Plant Type	Year	Length of Outage (weeks)	No. of Refueling
Millstone 1	BWR	1976	8.6	Fourth
Zion 1	PWR	1976	11.6	First

Table 4.7 is a summary of the 1976 Millstone 1 (BWR) refueling, which is graphically presented in Figure 4.6. A comparison of the estimated time for refueling operations between the Millstone 1 "typical" refueling and the shortest BWR refueling (Monticello 1975) indicates that it required comparable times for the refueling operations. The major cause of the extension of the Millstone 1 refueling beyond that required for the shortest refueling was primarily related to maintenance which required

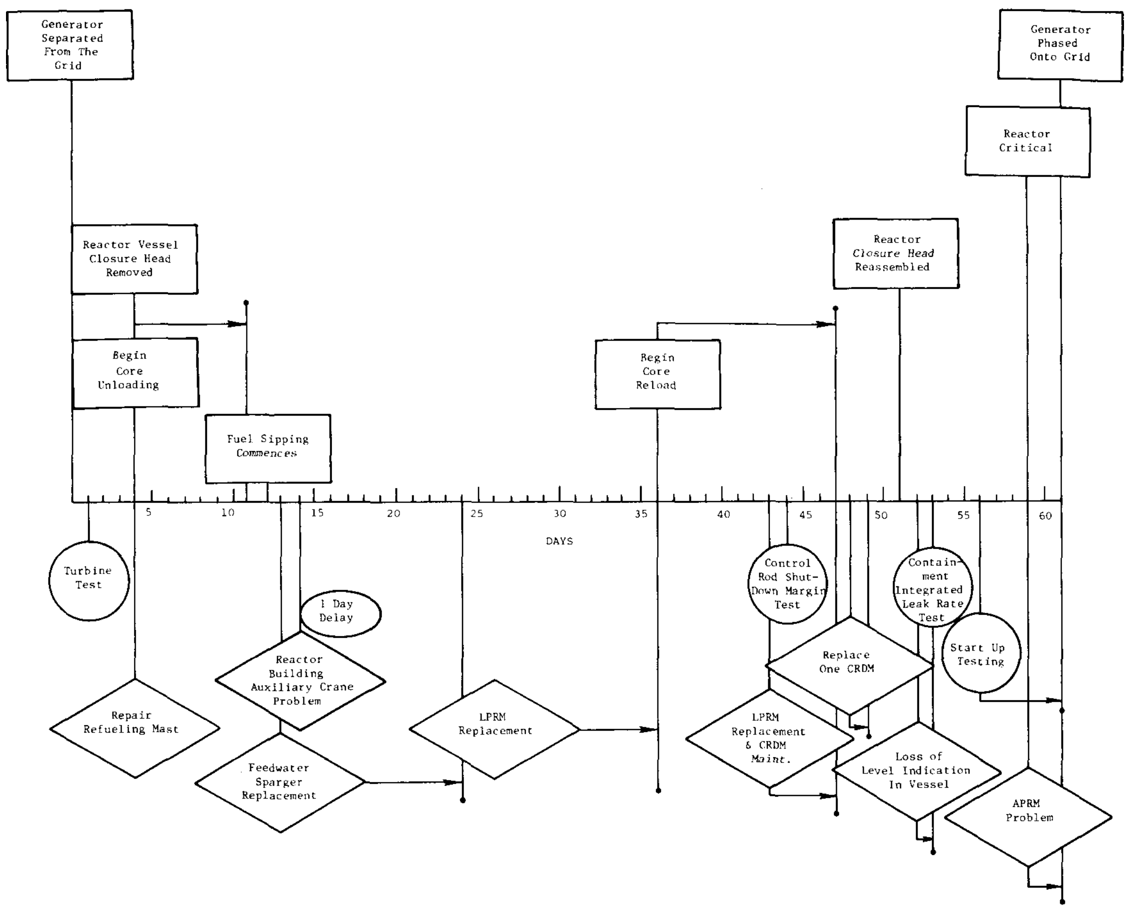


Figure 4.6. Graphical Summary of the 1976 Millstone 1 Refueling Outage

critical path time to complete (i.e., feedwater sparger replacement, LPRM replacement, and CRDM maintenance). Nearly 6 days of critical path refueling outage time was necessary for testing. In the case of the shortest BWR refueling outage, 5 days of the refueling outage time were required for testing and inspections.

Testing is a necessary part of the nuclear power program; however, experience has shown that it requires a significant fraction of the allotted outage time to complete existing test programs. It appears that a worthwhile contribution to power plant availability could be made if a method of reducing the impact of testing on outage time could be devised, such as performing testing in parallel with other critical path operations, developing new testing techniques which would reduce the time required to perform the testing, or demonstrating that longer intervals between testing can be justified.

Table 4.7: Summary of Critical Path Events* for the Millstone 1 1976 Refueling Outage

Operations	Time (Days)				
	Complete Operation	Test	Inspection	Maint.	Estimated Time for Refueling Operations
Closure Head Removal	4	0	0	0	4
Prepare to Move Fuel	0	0	0	0	0
Fuel Movement	43	0	0	25	18
Reassemble Closure Head	4	0	0	1	3
Closure Head Assembly Through Criticality	8	6	0	1	1
Criticality Through Power Operations	2	0	0	2	0
TOTAL	61	6	0	29	26

*See Footnote to Table 4.3

Table 4.8 and Figure 4.7 give a summary of the 1976 Zion 1 refueling, which was the first refueling at the Zion station. A comparison of the estimated time for refueling operations between the subject Zion refueling and the shortest PWR refueling (Point Beach 2) indicates that there are two operations which required substantially more time to perform at Zion than at Point Beach:

a) Fuel movement operation (9 days difference)
b) Closure head disassembly and assembly (6 days difference)

The apparent reasons for these differences are included here to demonstrate that the methodology used in this evaluation of refueling outage data is in fact reflecting actual refueling operation:

a) Fuel movement operations: There are two reasons for the large difference between Zion 1 and Point Beach 2 in the time required to move fuel:

   1) The principal reason for the longer time to move fuel at the Zion 1 1976 refueling is that a detailed characterization of 20 fuel assemblies was performed during the fuel shuffling operations. This characterization included:

      - Video taping
      - Rod bow measurements
      - Other dimensional measurements
      - Removal of two test rods from each of two removable rod assemblies
      - Measurement of grid cell spring forces
      - Reconstitution of the two test assemblies for a second cycle of irradiation

   2) The higher Zion 1 rating leads to a larger number of fuel assemblies to be handled (193 assemblies in Zion 1 versus 150 assemblies in Point Beach 2). This is judged to contribute a relatively small amount to the large difference.

b) Closure head assembly: The principal reasons for the difference in time required to remove the closure head between Zion and Point Beach are:

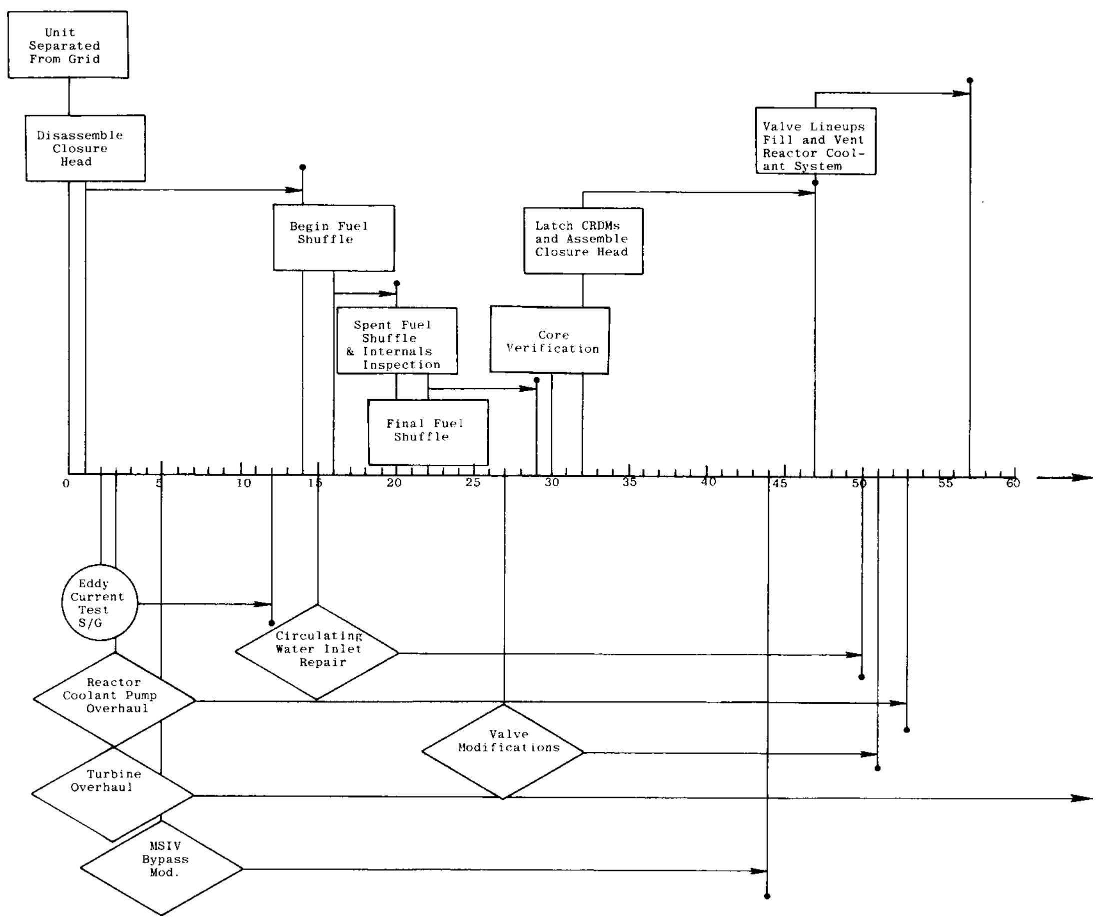


Figure 4.7. Graphical Summary of the 1976 Zion 1 Refueling Outage

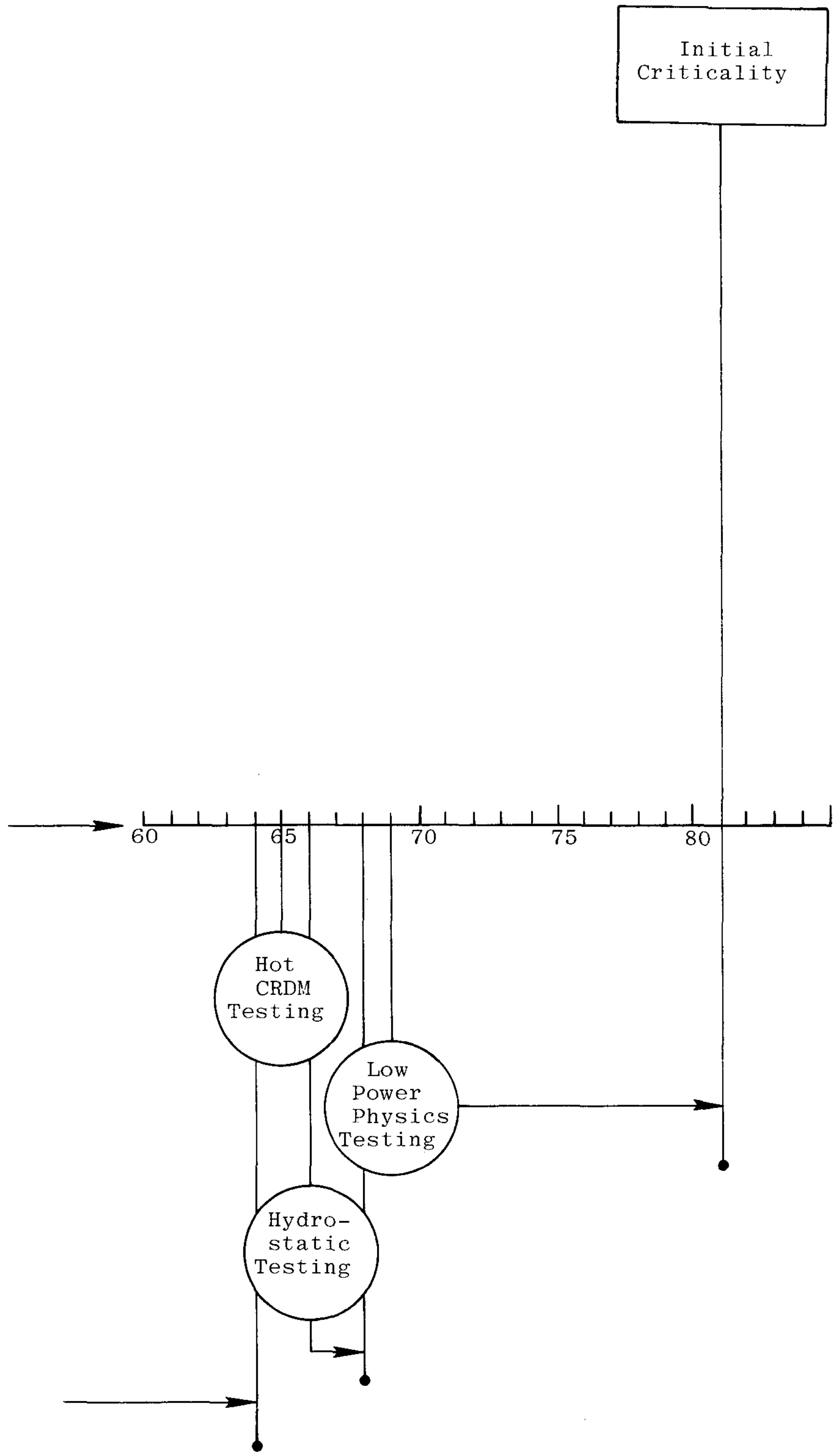


Figure 4.7 (Continued)

1) This was the first refueling at the Zion station.
2) There are more operations required in the larger Zion plant.
3) The time required at Point Beach 2 was very short relative to the time required at most other PWRs considered (see Section 4.4).
4) Extensive maintenance operations were occuring in parallel at Zion 1.

Table 4.8: Summary of Critical Path Events for the Zion 1 1976 Refueling Outage

Operation	Time (Days)				
	Complete Operation	Test	Inspection	Maint.	Estimated Time for Refueling Operations
Closure Head Removal	14	0	8	0	6
Preparation to Move Fuel	2	0	0	0	2
Fuel Movement	14	0	3	0	11
Closure Head Assembly	17	0	0	5	12
Closure Head Assembly Through Criticality	34	15	0	16	3
Criticality Through Power Operations	NA		0		0
TOTAL	81	15	11	21	34

4.3.6 Summary of Long Duration Refueling Outages

In addition to the 27 refueling outages which have been investigated in detail and are summarized in Section 4.4, there are a number of refuelings which exceed three months in duration and which have not been addressed in this section since the major cause of the outage may have resulted from maintenance, inspection, or repairs on plant components. Table 4.9 pro-

*See Footnote to Table 4.3

vides a tabulation of the plants, the refueling outage length, the date, and the cause of the refueling outage extension for refueling outages greater than 3 months.

Table 4.9a: PWR Refueling Outages Exceeding 3 Months in Duration

Plant	Duration (Hours/Weeks)	Date	Cause
Yankee Rowe	2472/14.7	1972	Turbine Generator Stator Windings
Point Beach	3762/22.4	1972-73	S/G/ Clad Repair Turbine Overhaul
Connecticut Yankee	3828/22.8	1973	Turbine Failure
Ginna	2737/16.3	1974	Turbine Blade Failure
Yankee Rowe	2553/15.2	1974	In-Core Instrument Replacement
Maine Yankee	2513/15	1974	Fuel Inspection
Oconee 1	3428/20	1975	Reactor Coolant Pump Seal
Fort Calhoun	2160/12.9	1975	In-Core Detector Replacement
Palisades	3365/20	1975-76	Steam Generator Tube Repairs
Rancho Seco	4536/27	1976	Reactor In-Core Specimen Tube Holder Generator Coil Replacement
Oconee 2	2304/13.7	1976	Reactor Surveillance Tube Holders
Three Mile Island	2304/13.7	1976	Surveillance Tube Holders
Surry 1	2362/14.1	1976-77	Steam Generator Inspection
San Onofre 1	4536/27	1976-77	Upgrade Safety-Related Systems Emergency Power Sources, Containment
Calvert Cliffs	2008/12	1977	Hydriding In-Core

Table 4.9b: BWR Refueling Outages Exceeding 3 Months in Duration

Plant	Duration (Hours/Week)	Date	Cause
Dresden 2	2160/12.9	1971	Plant Modification & Inservice Inspection
Millstone 1	4519/26.9	1972-73	Condenser Tube Replacement Feedwater Sparger Replacement
Dresden 3	2006/11.9 2044/12.2	1973 1974	Turbine Inspection/ Emergency Cooling System
Nine Mile Point	2264/13.5	1974	Plug In-Core LPRM Housing Feedwater Sparger & CDM Nozzle Repair
Quad Cities 1	2683/16	1974	Inverted Control Elements, Jet Pump
Quad Cities 2	2996/12.8	1974-75	Recirculation Pipe Inspection
Pilgrim 1	3026/18	1976	Sparger & Recirculation By Pass Line Replacement
Peach Bottom 2	2134/12.7	1976	Feedwater Sparger Replacement
Peach Bottom 3	2630/15.7	1976-77	Core Spray Line Repair
Oyster Creek	2497/14.9	1977	Feedwater Sparger Replacement

4.4 Summary of Refueling Operations

As noted in the introduction to Section 4, the largest segment of a typical refueling outage (~50%) is directly related to operations necessary to refuel the reactor; however, in pursuing methods of reducing the total outage time, it is necessary to know how this effort is apportioned among the various operations. Tables 4.11 and 4.12 provide the details of the length of time required for various operations for the selected refuelings. A summary table of the average time required is also given (Table 4.10). The comparison between PWRs and BWRs highlights the differences in refueling approaches in the two types of plants.

Because of the variations in PWR and BWR plant design, there can be substantial differences in the time required to perform similar tasks in PWRs and BWRs. From Table 4.10, it appears that PWR closure head removal and reassembly operations are taking longer than comparable BWR operations. However, in the area of fuel movement, the situation is reversed, and PWRs have a distinct advantage over BWRs based upon the operating histories from the selected sample of refueling outages. Figure 4.8 summarizes these comparisons between the average refueling operations of the selected PWR and BWR plants.

Table 4.10 Comparison of Average Times for Refueling Operations Between PWR and BWR Plants

	Average Time (Days)	
Refueling Operation	PWR	BWR
Closure Head Removal	8.5	3.4
Preparation to Move Fuel	2.4	3.2
Moving Fuel	9.3	16.3
Sipping Fuel	0	2.7
Poison Curtain Removal	0	.8
Reassemble Closure Head	6.9	5.3
Closure Head Reassembly Through Criticality	5.3	3.3
Criticality Through Power Operation	1.6	.4
Total	33.3	34.5

			Refueling Operations Categories**						
Plant	No. of Refueling	Year of Refueling	Closure Head Removal (Days)	Preparation To Move Fuel (Days)	Moving Fuel (Days)	Reassemble Closure Head (Days)	Closure Head Assembly Through Criticality (Days)	Criticality Through Power Operations (Days)	Total (Days)
Monticello	1*	1973	3	3	28	8	2	0	44
Monticello	2	1974	3	2	22	3	2	1	33
Monticello	3	1975	3	3	12	3	1	1	23
Monticello	4	1975	2	2	18	3	4	0	29
Millstone 1	2	1974	1	3	17	2	2	0	25
Millstone 1	4	1976	4	0	16	3	1	0	24
Dresden 2	4	1976	6	1	13	10	3	0	33
Dresden 3	4	1976	3	1	26	5	2	0	37
Quad Cities 1	2	1976	2	1	12	8	3	2	28
Quad Cities 2	2	1976	2	2	26	6	4	0	40
Peach Bottom 2	1*	1976	7	4	19	7	4	0	41
Pilgrim 1	1*	1976	5	6	28	6	11	1	57
Average	-	-	3.4	2.3	19.8	5.3	3.3	.4	34.5

* First refueling
** See footnote to Table 4.3.

Table 4.11. Summary of "Refueling Operations" for Selected BWRs

			Refueling Operations Categories **						
Plant	No. of Refueling	Year of Refueling	Closure Head Removal (Days)	Preparation To Move Fuel (Days)	Moving Fuel (Days)	Reassemble Closure Head (Days)	Closure Head Assembly Through Criticality (Days)	Criticality Through Power Operations (Days)	Total (Days)
Haddam Neck	1*	1970	12	5	9	9	7	0	42
Haddam Neck	5	1975	11	2	4	4	6	5	32
Haddam Neck	6	1976	18	3	9	2	3	0	35
Robinson 2	3	1975	2	1	11	5	5	1	25
Robinson 2	4	1976	8	3	6	7	6	1	31
Point Beach 1	3	1975	2	3	6	7	6	1	25
Point Beach 1	4	1976	7	0	6	1	4	3	21
Point Beach 2	2	1976	3	1	2	3	5	1	15
Surry 1	3	1976	10	2	17	8	2	1	40
Surry 2	2	1976	7	2	6	3	2	1	21
Zion 1	1*	1976	7	2	12	10	5	0	36
Zion 2	1*	1976	17	0	10	20	6	5	48
Three Mile Island	1*	1976	4	6	16	7	10	1	44
Kewaunee	1*	1976	4	4	10	9	7	1	35
Ft. Calhoun	2	1976	14	2	12	9	7	2	46
Average	-	-	8.5	2.4	9.3	6.9	5.3	1.6	34.2

* First refueling
** See footnote to Table 4.3

Table 4.12. Summary of "Refueling Operations" for Selected PWRs

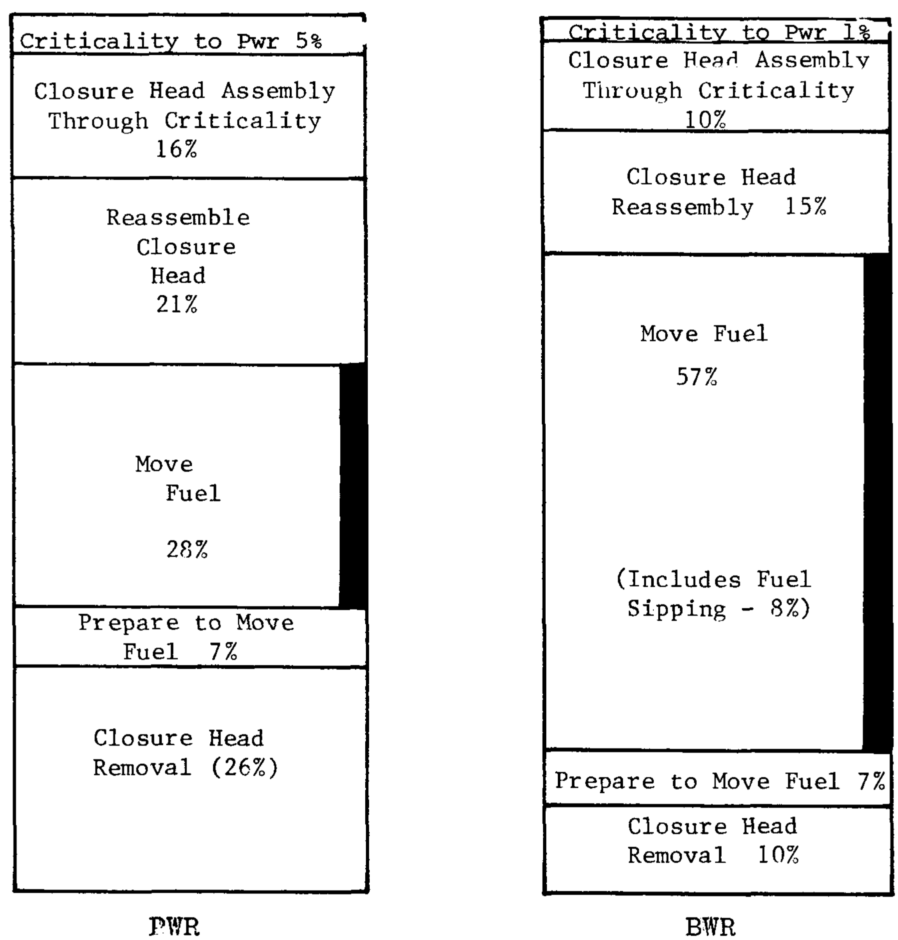


Figure 4.8. Comparison of Refueling Operations for Selected PWR and BWR Plants

Closure head removal and reassembly in PWR plants takes longer than in BWRs principally due to the amount of associated equipment which must be handled in PWR plants. Specifically, in PWR plants the control rod drive mechanisms (CRDMs) penetrate the top closure head, while in BWR plants the CRDMs penetrate the bottom closure head. Therefore, in PWR plants, the movement of fuel requires disconnecting all the CRDMs from their cabling and cooling piping in order to remove the closure head. In addition, because of the higher primary system pressure in PWR plants, the higher closure head preload requires additional time to detension and tension the closure studs. The disassembly and assembly of the closure head connections and the high closure head preload are the principal reasons for the extended time for this portion of the operation. For future reactors, Westinghouse has developed a closure head assembly schedule which is designed to reduce the time to perform this operation by utilizing a unitized head area arrangement which contains the studs as an integral part of the assembly, thereby avoiding the necessity of separate handling of the closure studs.

Fuel movement in BWRs takes appreciably longer than the comparable operation in PWRs. The reasons for the longer "fuel movement" times in BWRs are principally due to a combination of the following:

a) There are approximately 4 times the number of fuel assemblies in BWRs as in PWRs for the same rated power. For example, consider the following comparison of two 800 MWe units:

Plant	No. of Fuel Assemblies
BWR	720
PWR	157

b) BWRs sometimes reuse fuel channels. This requires some coordination effort and therefore potential delays in interchanging fuel channels during the fuel movement operation.

c) Leaking fuel has caused a larger percentage of operational problems in BWR plants than in PWRs. More "leakers" in a core leads to higher coolant activity and off-gas releases.

Since this may in turn lead to power deratings to limit the off-gas activity, it is prudent to remove the leaking fuel assemblies from the core. The best opportunity for removal of the fuel is during a refueling. However, since only part of the core is removed at each refueling, identification of the fuel assemblies containing leaking fuel rods becomes a necessary operation. Identification of leaking assemblies is performed by fuel assembly sipping. This may be performed in or out-of-core for BWRs and only out-of-core for PWRs. The sipping process can add significantly to the critical path time in BWRs either by:

1) requiring controlling time to sip fuel assemblies in-core
2) requiring controlling time to remove all fuel assemblies to allow out-of-core sipping

PWRs have not had a chronic problem with leaking fuel, and therefore all fuel assemblies are generally not sipped. Instead, only those assemblies removed from the core are sipped, and sipping is performed in non-critical path time.

4.5 Summary of Refueling Outages

Based upon the analysis described in Section 4.3, the refuelings for which detailed data is available as described in Section 4.2 are used to summarize the various aspects of a "typical" refueling outage. The goal of this summary is to identify those areas of the complex refueling operations which are most fruitful to pursue for potential decreases in the refueling outage length. An overview of this data can be obtained by considering a comparison of the average PWR and BWR refuelings in Table 4.13 below, which is also summarized in Figure 4.9. Tables 4.14 and 4.15 provide a listing of the critical path controlling time data which has been collected for each of the PWR and BWR refuelings.

Table 4.13. Relative Comparison of the Average PWR and BWR Refueling Operations Based Upon the Data Cited in Section 4.2

Category	Summary of Typical Refueling Outage			
	PWR		BWR	
	(Days)	%	(Days)	%
Refueling Operations	33.3	55%	34.5	49%
Required Testing	7	11%	6.9	10%
Inspection	6.5	11%	3.8	5%
Refueling Related Delays (Procedures or Equipment)	1.2	2%	1.8	3%
Items Stuck or Dropped in Core	.1	0%	.9	1%
Maintenance	13	21%	21.8	31%
TOTAL	61	100%	69.7	100%

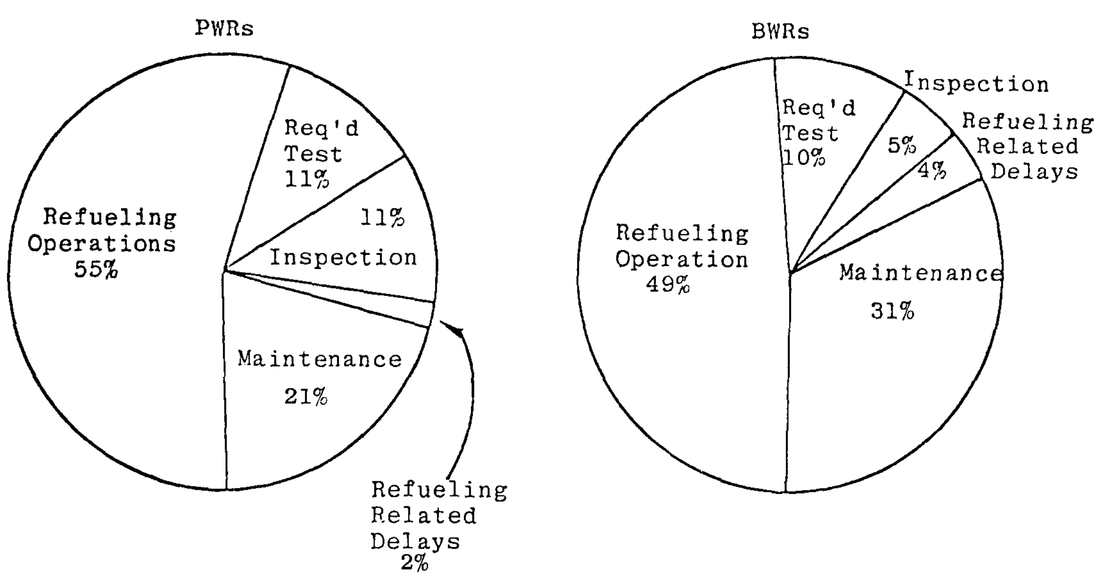


Figure 4.9: Graphical Summary of Typical Refueling Outages Based Upon a Selected Sample of Refuelings

Plant	No. of Refueling	Year of Refueling	Classification of Critical Path Times During The Refueling Outage: Required Refueling Operations (Days)	Required Testing (Days)	Inspection (Days)	Refueling Related Delays Procedure/ Equipment (Days)	Items Stuck or Dropped In-Core (Days)	Maintenance (Days)	Total (Days)
Haddam Neck	1[*]	1970	42	11[□]	17	1	0	0	71
Haddam Neck	5	1975	32	7	0	1	0	10	50
Haddam Neck	6	1976	35	10[□]	0	0	0	12	57
Robinson 2	3	1975	25	5	5	0	0	6	41
Robinson 2	4	1976	31	5	2	1	0	4	43
Point Beach 1	3	1975	25	5	7	7	1	3	48
Point Beach 1	4	1976	21	3	26	5	0	0	55
Surry 1	3	1976	40	0	5	0	0	53	98
Surry 2	2	1976	21	12[□]	0	1	0	16	50
Zion 1	1[*]	1976	36	3	13	0	0	19	71
Zion 2	1[*]	1977	48	11[□]	0	0	0	20	79
Three Mile Island	1[*]	1976	44	5	0	2	1	42	94
Kewaunee	1[*]	1976	35	6	6	0	0	7	54
Ft. Calhoun	2	1976	46	18[□]	8	3	0	0	75
Average	-	-		7	6.5	1.2	.1	13	63.5

[*]First plant refueling
[□]Includes Integrated Leak Rate Test (ILRT) of containment

Table 4.14. Summary of Selected PWR Refueling Outages

Plant	No. of Refueling	Year of Refueling	Classification of Critical Path Times During The Refueling Outage						
			Required Refueling Operations (Days)	Required Testing (Days)	Inspection (Days)	Refueling Related Delays Procedure/ Equipment (Days)	Items Stuck or Dropped In-Core (Days)	Maintenance (Days)	Total (Days)
Monticello	1[*]	1973	44	5[□]	3	2	6	16	76
Monticello	2	1974	33	8	10	7	1	8	67
Monticello	3	1975	23	3	3	0	0	0	29
Monticello	4	1975	29	9[□]	1	1	1	31	72
Millstone 1	2	1974	25	5	8	0	1	25	64
Millstone 1	4	1976	24	6[□]	0	3	0	28	61
Dresden 2	4	1976	33	9[□]	8	0	0	24	74
Dresden 3	4	1976	37	3	1	8	2	0	51
Quad Cities 1	2	1976	28	9[□]	6	0	0	29	72
Quad Cities 2	2	1976	40	8[□]	0	0	0	7	55
Peach Bottom 2	1[*]	1976	41	10[□]	0	1	0	39	91
Pillgrim 1	1[*]	1976	57	8	5	0	0	54	124
Average	-	-	34.5	6.9	3.8	1.8	.9	21.8	69.7

[*]First refueling
[□]Includes Integrated Leak Rate Test (ILRT) of containment

Table 4.15. Summary of Selected BWR Refueling Outages

It should be carefully noted that since very long refuelings have not been included in the group of selected refuelings (see Section 4.2), the above table is biased in that the overall percentage of maintenance may be underestimated. However, since we are most interested in the "typical" refueling, it is judged that Table 4.13 and Figure 4.9 represent an accurate summary of the events which comprise typical refuelings.

Based upon the simplistic breakdown of a typical refueling outage in Table 4.13, approximately one-half of the critical path time during a refueling outage is associated with operations not specifically required to refuel the plant, such as: a) maintenance (20-30%); b) required testing or inspections (15-20%); and c) refueling related delays (~4%). The other half of the outage time is associated with the actual refueling operation. Table 4.13 represents a composite, artificial plant. Actual refueling outages have been shown to vary appreciably for the individual plants which make up the average. Tables 4.14 and 4.15 give the details of each category considered in the refueling outage and the variation about the mean. For example, the time for refueling operations has varied from 18 days to 54 days. The critical path time associated with testing has varied from 0 to 18 days, and the time for inspection has varied from 0 to 26 days. Maintenance is the most widely varying component of the refueling outage, varying from 0 to 54 days.

While there is always a large number of maintenance and repair items performed during refuelings, utilities generally attempt to perform the maintenance during non-critical path time. However, there are some instances when the repair may interfere with the critical path work (e.g., in-core repairs, steam generator tube plugging in some plants) or may extend beyond the minimum refueling time (e.g., turbine repair). For example, there have been much longer refuelings than considered in this section which have been totally controlled by maintenance or repairs (e.g., the 1973 Haddam Neck refueling, which lasted approximately 160 days, required replacement of the turbine rotors). However, attempts to dissect the contributing causes of refueling extension due to specific types of maintenance would not be precise if based upon the limited data sample available because of the wide variation in the types of maintenance which can lead to extended outages, for example:

Typical PWR Maintenance	Typical BWR Maintenance
S/G Tube Plugging/Modification	Feedwater Sparger Replacement
In-Core Repair	Recirculation Pipe Replacement
Main Coolant Pump Repair/ Replacement	In-Core Repair
Turbine Blade Repair	Recirculation Pump Seal Repair
Generator Maintenance	Generator Maintenance
CRDM Maintenance	CRDM Maintenance
Circulating Water Pump Repair	MSIV Repairs
	Torus Modifications
	Snubbers Rebuilt
	Feedwater Pumps

Even the same maintenance operation at two plants can have significantly different impacts on the length of the outage. One example of this variability in impact of maintenance operations is in the case of steam generator tube repair. Westinghouse PWR plants with three loops have no loop isolation valves, which means that in their present configuration, steam generator (S/G) tube plugging or eddy current testing must be performed with the water level below that of normal refueling (i.e., below the reactor vessel nozzles). This means that a portion of the S/G work must be performed in critical path time, usually in series with head removal, therefore having a direct impact on plant availability. B & W has recently developed a technique which may reduce critical path time required for eddy current testing; the technique allows eddy current testing to be performed "wet".[34]

Possibly the most dramatic fact to be noted from Table 4.10 is the large percentage of refueling outage time associated with testing and inspection. The combination of these two categories accounts for approximately 20% of the "typical" refueling outage. In terms of plant capacity factor, this outage time represents nearly 4% of the total energy that can be produced in an entire year, which translates into approximately 12-14 days. It is important that utilities, component vendors, and regulatory agencies are aware of the contribution of testing and inspection to power plant availability. Many of these tests are essential to safe, reliable power operation; however, their impact on plant availability is an important cost factor which should be evaluated in the cost benefit equation of both the original plant projections and in the impact on planned operation. Alternative testing methods, less frequent testing, and on-line testing are items which should be factored into the considered plant design and arrangement. Layering additional test requirements on the utility can hamper its ability to operate efficiently with the end result being lost productivity. Safety cannot be relaxed or compromised. However, a question which does deserve consideration is, "What is the optimum balance between testing and power production?"

Section 5.0

EVALUATION OF EXTENDING THE REFUELING CYCLE

5.1 Potential for Increased Plant Availability

Since virtually all commercial nuclear power plants are base loaded units, replacement power must be provided when a nuclear reactor is taken off-line. In general, the replacement power will be generated by fossil fueled units at a substantially higher fuel cost. Recent estimates of replacement power costs are on the order of $250,000 to $800,000[2,29] per day for a 1000 MWe plant. In view of these high costs of alternative power generation, there is a strong economic incentive to maintain a high plant availability. As noted in the previous section, the fraction of lost plant availability due to refueling outages can range from 40% to 75%. This represents a significant target at which to shoot. The purpose of this section is to identify a method of increasing plant availability by altering the refueling cycle.

The annual refueling cycle has evolved as a compromise between: a) the frequent refueling theory which makes use of frequent refuelings to minimize the fuel enrichment requirements and b) the long duration refueling intervals (18-24 months) which may have higher fuel enrichment requirements but allow extended operation without requiring a shutdown.

The application of the frequent refueling theory to LWRs is a modification of the CANDU* reactor operation which uses heavy water as a moderator and continuous on-line refueling to minimize the excess reactivity requirements, and therefore, allows the use of natural uranium fuel. The frequent refueling theory as applied to LWRs reduces the amount of excess reactivity required, by requiring frequent refuelings. The goal of this theory is

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*CANDU - This is the Canadian heavy water moderated reactor design which uses natural uranium fuel, and therefore requires no enrichment facilities.

to incorporate a rapid refueling technique to reduce refueling outages to acceptable lengths, and therefore minimize fuel enrichment requirements.

Proponents of the opposite theory advocate long intervals between refuelings, and therefore,increasing the plant availability by reducing the total refueling outages of a plant. One "cost" of the longer intervals appears in the higher fuel costs needed to obtain sufficient excess reactivity to maintain criticality. The trade-off which has been made by the NSSS vendors and most utilities in the past is that an annual fuel cycle represents an "optimum" compromise between fuel cycle costs and plant availability costs. However, based upon operating experience, which indicates that refueling outages take significantly longer than originally anticipated, coupled with the rapid increase in replacement power costs, it appears desirable to reevaluate the decision to have approximately annual refuelings.

Previous estimates of the time necessary to refuel a reactor were 1 to 3 weeks. In reality, refueling outages include more than just refueling operations. The result is that the minimum refueling outage has taken 4 weeks and the mean refueling outage has taken approximately 9 weeks, which is 3 to 9 times the length anticipated. The original NSSS projected estimates of "refueling" times were the result of over-optimism on the speed with which a refueling could be performed, and the fact that all the operations occuring during a refueling outage were not included in the previous estimates (e.g., testing, inspection, and maintenance).
An additional constraint on the structure of ideal refueling cycles is that they should be integral units of six months. Since the nation as a whole has its peak electrical energy requirement during the summer* (followed closely by winter), the greatest percentage of electric generating capacity is planned to be available during the summer and winter months. For the summer peak periods, the capacity planned to be unavailable due to scheduled maintenance averages less than 2% (summers of 1976 thru 1979): The different electric reliability councils reporting a range from essentially zero to a maximum of only 4%. The U.S. average for the winter peak periods is about 9%, however, particularly severe winter weather in the midwestern and northeastern parts of the country can shrink the operating reserve to near zero in those

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*The peak demand on major electric utility systems of the 48 contiguous states during the summer of 1977 was approximately 35% higher than the peak demand during the spring of 1977.

regions. In any case, both summer and winter demand periods are times when the nuclear plant power generation is most necessary, and therefore utilities are anxious to avoid any outages during these peak power periods. Therefore, refueling outages, because of their length, are usually scheduled for spring or fall months when power demand is reduced,and replacement power can be provided more economically by the utility.

Using the operating experience from Sections 3 and 4, we shall now discuss a potential method of improving plant availability through an extension of the refueling cycle from the present 12 months to 18 months. The chief advantage of this concept is that it can provide an increase in the plant availability by reducing the scheduled outage time which translates directly into increased plant productivity. Figure 5.1 shows a typical three-year segment of a forty-year plant life. From Figure 5.1, the three-year cycle indicates that:

- For the annual fuel cycle, there is approximately 9.7 months of power production and 2.3 months of refueling outage each year.

- For the eighteen-month cycle, there is approximately 2.3 months of refueling outage each cycle and 15.7 months of power production, or on an annualized basis approximately 10.5 months per year of availability for power production.

This translates into an increase in days the plant is available of approximately 65 days over three years. This represents a substantial increase in plant availability, as indicated by the fact that an increase in availability of 6% per year represents savings of 5.4 to 13.2 million dollars per plant in replacement energy costs per year. Therefore, the potential savings in lengthening the refueling cycle are significant. There are, however, some potential drawbacks in lengthening the cycle which need to be considered (See Section 5.3).

In the idealized 18 month cycle, which is shown in Figure 5.1, the major assumption is that there is no increase in the fraction of outage time occurring outside refueling outages. This is judged to be a good assumption for two complementary reasons:

a) At present, an "average" mature nuclear plant incurs approximately 500 hours per year of major outage time outside of refuelings. While it is judged that this level of major outage time will decrease as experience increases, it appears that an allowance for this approximate level of outage time can account for any required plant maintenance which is not performed during refuelings.

b) Based upon the operating experience data from Section 5.2, it is shown that the fraction of lost capacity factor occurring outside PWR refuelings is approximately constant irregardless of the interval between refuelings. If this also holds true for the major outage contribution to lost capacity factor, then as the interval between refuelings is increased from 12 to 18 months the major outage contribution will increase from approximately 500 to 750 hours per interval between refueling.

Since most utility maintenance programs are geared to the annual refueling cycle, additional effort may be required to optimize a preventive maintenance program for the longer 18-month cycle. This optimization may lead to the conclusion that some preventive maintenance should still be performed on an annual schedule during other forced outages or during scheduled shorter duration outages between refuelings.

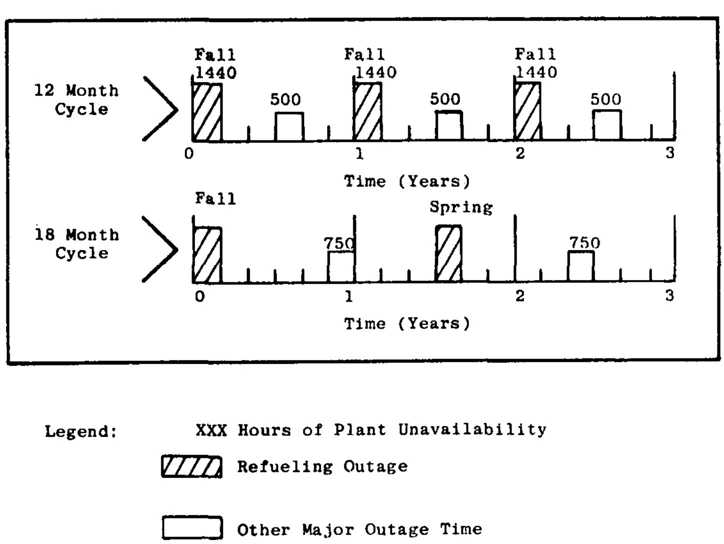

Figure 5.1. Comparison of the Plant Availability Time for a Typical Plant on an Annual Refueling Cycle Versus an Eighteen Month Refueling Cycle

Many of the current plant technical specifications are flexible enough to allow easy incorporation of the longer refueling cycle into the required test, inspection, and calibration schemes since their required frequency is based upon refueling cycles of up to 18 to 24 months.

The second big assumption in the extension of the refueling interval is that the fuel performance is adequate to allow operation over 18-month periods without forcing plant deratings to limit off-gas activity or primary coolant activity. Current information suggests that the newest fuel design for both PWR and BWR plants have substantially reduced fuel leakage rates; therefore, presently available fuel performance appears adequate to meet the longer cycles.

Because extending the refueling cycle from 12 months to 18 months may require changes in fuel enrichment, the decision to switch to the longer cycle must be accompanied by: long range planning as to the fuel loadings to be adopted; the adequacy of the enrichment capability needed to meet the demand; adequacy of fuels at higher burn-ups; and feasibility of increasing batch sizes at each refueling. For a typical PWR, we might anticipate increasing the batch size from 1/3 to 2/5 or more to increase the refueling cycle length in lieu of increasing fuel enrichment. Typical lead times in specifying fuel enrichment are on the order of three years.

5.2 Examples of Extended Cycles

The purpose of this section is to identify:

a) Operating experience data which supports the assertion that a gain in plant capacity factor is possible by extending refueling cycle length

b) Utilities which have already embarked on a program to increase the length of the refueling cycle

The feasibility of the 18 month cycle is supported to some extent by operating experience since there are many cases where plants have operated for extended calendar intervals (16 months of operation) and burnup (approximately 470 EFPD). However, in general, this has not been a repeating cycle in most plants but cases where circumstances have led to an extended interval.

For PWR plants, a regression analysis on the available operating data of plant energy produced between refuelings (see Figure 5.2) indicates that the same fraction of energy loss can be expected during 12-month cycles (10 month intervals) or 18 month cycles (16-month intervals). This loss in capacity factor is approximately 17-18% during these intervals. Therefore, the loss of capacity due to refueling represents an added burden which causes a loss of an approximately fixed amount of time. The annualized gain in capacity possible if refuelings are scheduled on an 18-month cycle is approximately 6%* better than if the refueling outages occurred annually.

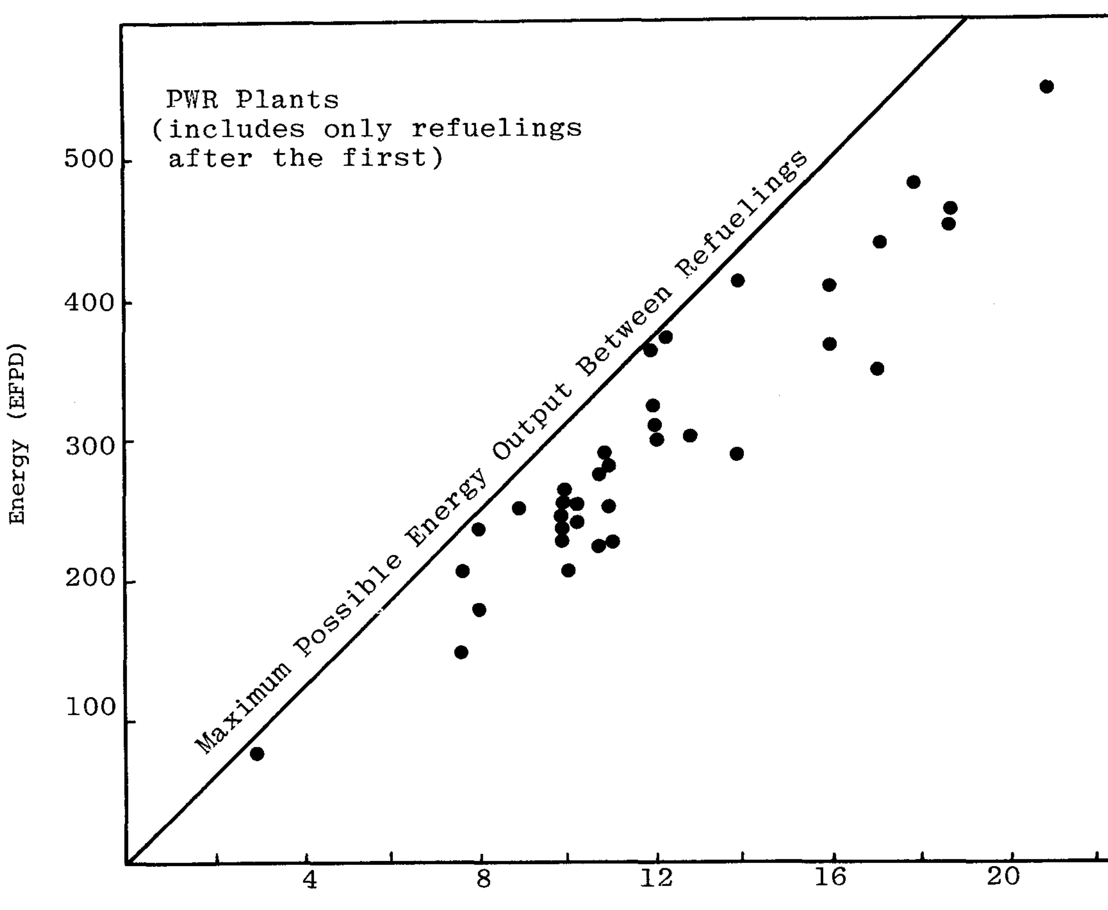

Figure 5.2. Comparison of PWR Energy Output Versus Calendar Months of Operation

*Assumes a 2.3 month refueling outage

In addition to the empirical evidence from operating experience for potential increased availability using longer fuel cycles, there are some utilities which have examined the problem, judged the 18 month refueling cycle to be superior to the annual refuelings; and have decided to implement a longer refueling cycle. Surry 1 and 2 are now on the first of their 18 month cycles; Nine Mile Point and Quad Cities are also using an 18 month cycle. Other units where longer cycles have evolved are Connecticut Yankee and San Onofre , which are two similar Westinghouse reactors using stainless steel clad fuel rods, and therefore, slightly atypical of other reactor plants which use zircaloy fuel cladding.

Before a large commitment is made to drastic changes in the fuel cycle length, it is prudent to have some "prototype" comparisons which put together all the factors of: longer intervals between refuelings; similar refueling outage lengths; and a constant fraction of outage time between refuelings. However, there are no plants which have operated with refueling cycles longer than 12 months for an extended length of time. Therefore, it is recommended that utilities do not extrapolate too far by extending the operating cycle beyond that with which we have some experience (i.e., not more than 18 months).

5.3 Advantages and Disadvantages of Longer Refueling Cycles

As with any decision affecting a nuclear power plant, changes in the length of the refueling cycle affect a wide variety of considerations. Since many nuclear facilities face unique problems or obstacles, the following discussion of various aspects of the impact of changing the fuel cycle on nuclear power plant operation is included to emphasize the many interrelated factors which must be considered before a decision is made to extend the refueling cycle.

From the standpoint of advantages of increasing the interval length between refuelings, we can cite the following potential advantages:

- <u>Increased plant availability.</u> The elimination of one refueling outage every three years translates into an increase of 6% in plant availability. A 6% increase in plant availability translates into savings of replacement power costs of approximately $5 to 10 million per year

- Reduction in the plant personnel radiation exposure. An additional argument for the increase in refueling intervals comes, not from an availability argument, but from a consideration of the number of men exposed to the levels of radiation involved in refueling operations. The current NRC regulations require a compliance with "as low as reasonably achievable" philosophy. Historically [19, 39], most radiation exposure at nuclear power plants occurs during refueling and maintenance operations. A reduction in the number of refuelings by increasing the interval between them could mean a reduction in the total man-rem exposure of operations and contractor personnel.

- Greater flexibility in fuel cycle: Planning for 18 month fuel cycles will enable a plant which is running well to stay on-line and available to produce base load power. Only "bad" things can happen when a plant is shutdown. This is a subjective judgement based upon a review of operating experience which indicates that it is desirable to maintain a smooth running plant at power as long as possible. The longer cycle will not preclude early shutdown for removal of possibly leaking fuel or other major maintenance. In other words, greater system flexibility is afforded by the change to longer cycles.

- Reduction in the number of heat-up-cool-down transients: An important variable in determing a nuclear power plant's lifetime is the number of large temperature transients from normal operating temperature to "cold iron" and back. A reduction in the number of refueling operations should result in a decrease in the number of such temperature cycles. This would be a direct benefit in terms of component lifetime.

- Plant security: This is an important aspect of nuclear power generation from the standpoint of public health and safety and the protection of expensive equipment. A decrease in the frequency of refueling outages will result in a reduction of 1/3 in time of exposure of the plant to outside contracting personnel and in-house maintenance personnel in vital areas of the plant particularly inside containment (e.g., reactor vessel, control rod drive mechanism, main coolant piping.) In addition, as concern over safety, safeguards, and prevention of sabotage increases, the restrictions on maintenance personnel will increase even more, resulting in an increase in the already staggering administrative constraints on workers and their actions and therefore on the length of refueling outages. A decrease in the number of refuelings will lessen the burden on the utilities in dealing with the administrative work load involved in ensuring that safeguard requirements are met during such an extended maintenance.

- Reduction in the amount of man power and plant time for regulatory review: The 18 month refueling cycle has another advantage - that of reducing the number of times the utility must interface with the NRC. Historically, each regulatory review has demonstrated the potential for creating additional back-fit requirements[31,32]. Because start-up from a refueling receives increased NRC attention, each recovery from refueling requires a significant effort on the part of plant management to satisfy NRC that the plant is being operated and maintained safely. If a utility can minimize these interfaces with NRC, plant management and operational personnel will have increased time available for plant operational needs.

There are, however, a number of variables which may detract from the advantages of increasing the refueling cycle length. Two examples of areas which require an evaluation by each utility with regard to its own particular needs are the following:

- Increased enrichment versus larger batch size. The principal trade-off in deciding whether to extend the refueling cycle length is in the method of ensuring adequate fuel to extend the cycle an additional 6 months. Two possible alternatives are:

1. Increasing the enrichment of the fuel assemblies.
2. Increasing the batch size exchanged during each refueling.

The first alternative, increasing fuel enrichment, has several uncertainties involved in it which require additional information. In particular, higher fuel enrichments may lead to: a) higher fuel burn-ups which have not been shown to be consistently achievable to date without increased risks of fuel failures; b) higher enrichment costs associated with the required higher fuel enrichment; c) higher power peaking which could reduce the core thermal margin. The second alternative, increasing the batch size, would avoid significantly higher burn-ups but would entail a more involved fuel management scheme to optimize performance. For both alternatives the fuel performance over an 18 month calendar period is of crucial importance.

A side issue which is not adequately discussed in the literature is the question of reduction in the number of spent fuel assemblies which must be handled in the back end of the fuel cycle. If the choice is made to increase the initial enrichment, there will be a decrease in the number of fuel assemblies which must be eventually disposed of over the life of the plant. This change is independent of the choice to lengthen the refueling cycle, however, it could be accomplished simultaneously.

- Increased forced outage time. The unknown in this evaluation is whether increasing the length between refuelings will lead to an increase in the forced outage time to perform needed maintenance or repair. Because experience is lacking in this area, it must be considered an unknown factor at this time (see also Section 5.2).

Section 6.0

CONCLUSIONS

Previous studies of nuclear plant outages have emphasized the necessity of planning in order to minimize outage time. The facts in this report are presented to aid in that planning by increasing the understanding of the make-up of refueling outages and of lost plant availability. Because each plant or small group of plants have unique problems, it is difficult to formulate generalized solutions for the entire industry by looking at only one or two plants. Therefore, this report summarizes a general review of a large number of refueling outages in an attempt to establish a pattern in the industry. The following conclusions are reached from the assessment of this population of refueling outages:

1. Refueling outages accounted for approximately 40% of the plant unavailability in U.S. LWRs during the period 1974 to 1977. However, the trend of refueling outages and other major outages indicates that during equilibrium fuel cycles (i.e., after the second year of commercial operation), refueling outages account for nearly 60% of the plant unavailability time (see Figure 6.1). Therefore, improvement in plant availability from current levels of 73% to levels approaching 90% as alluded to in the literature would appear to require a reduction in refueling outage time.

2. In order to reduce the impact of refueling outages on plant productivity, it is important to understand the causes contributing to the length of refueling outages. Based upon a selected group of LWR refueling outages, the critical path time can be divided into the following broad categories:

Operation	% of Refueling Time
Refueling operations	55%
Test	11%
Inspection	8%
Maintenance	26%

Figure 6.2 graphically emphasizes the amount of critical path time required to perform inspections and testing during a typical refueling outage. The largest contributor to the refueling outage is the time required for refueling operations, taking approximately 50% of the outage time. The remaining 50% of the "typical" outage is needed for maintenance, testing and inspections. While maintenance appears as a major contributor to the refueling outage length, it is shown in Section 4 that maintenance contributions to critical path time vary widely from refueling to refueling. The amount of critical path time associated with testing is also subject to variation as a function of the tests to be performed such as:

a) Emergency core cooling system tests
b) Containment leak rate tests
c) Control rod scram time tests
d) Shutdown margin tests
e) Hydrostatic tests
f) Low power physics tests

Of this testing, the largest single contributor is the integrated leak rate test of the containment. While this is generally required only every 3 years, it takes approximately 4-6 days of controlling path time to perform when it does occur, and therefore has a 10 to 20% effect on the length of a refueling outage.

3. Possibly the most dramatic fact to be noted from the above table is the large percentage of refueling outage time

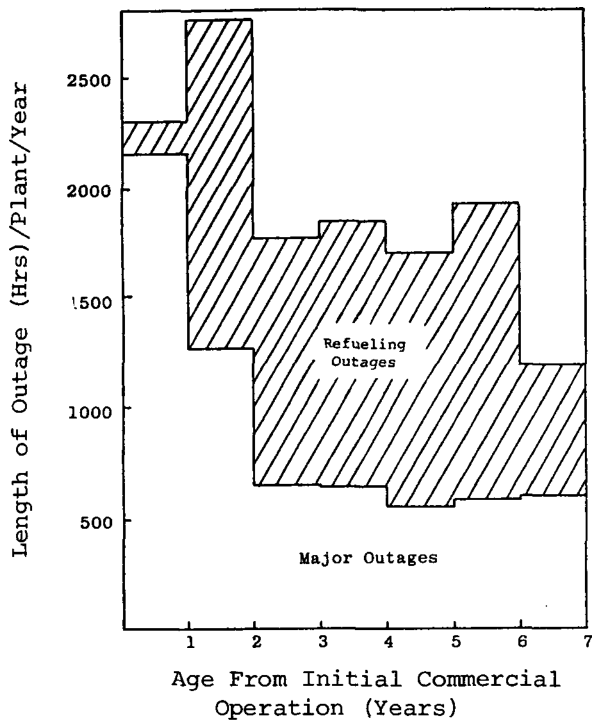

Figure 6.1. Distribution of LWR Outages as a Function of Plant Age.

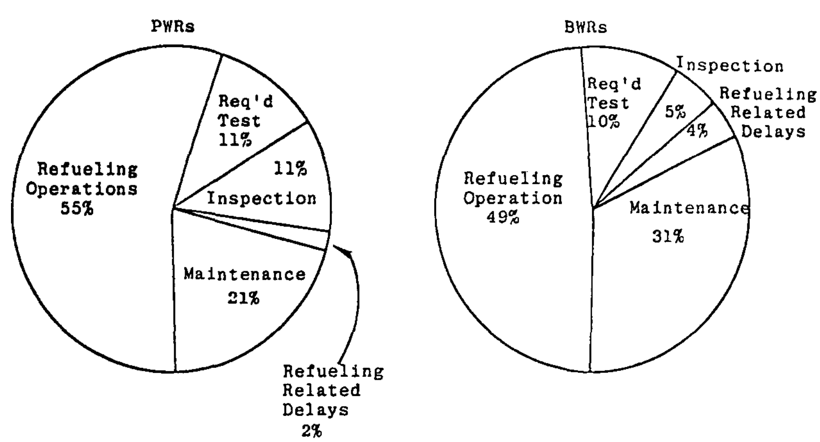

Figure 6.2. Graphical Summary of the Fraction of an Average Refueling Outage Attributed to Various Operations.

associated with testing and inspection. The combination of these two categories accounts for approximately 20% of the "typical" refueling outage. In terms of plant capacity factor, this outage time represents nearly 4% of the total energy that can be produced in an entire year, which translates into approximately 12-14 days. It is important that utilities, component vendors and regulatory agencies are aware of the contribution of testing and inspection to power plant availability. Many of these are essential to safe reliable power operation. However, their impact on plant availability is an important cost factor which should be evaluated in the cost benefit equation of both the original plant projections and in the impact on planned operation. Alternative testing methods, less frequent testing, and on-line testing are items which should be factored into the conceptual plant design and arrangement. Layering additional test requirements on the utility can hamper its ability to operate efficiently with the end result being lost productivity. Safety cannot be relaxed or compromised. However, a question which does deserve consideration is, "What is the optimum balance between testing and power production?"

4. The evaluation of a mature plant's performance is essential to the projection of nuclear power costs. As shown in Figure 6.1, the combined trend of major outages and refueling outages indicate a low plant availability during the first two years of commercial operation followed by an increased level of plant availability through the seventh year. The reasons for this trend are:

   a) The first two years of commercial operation incur the largest amount of major outage time, principally due to break-in problems; following this break-in period there is a period of relatively constant outage rate per plant.

b) The first refueling outage of a plant is significantly longer than subsequent refueling outages and generally occurs during the second year of commercial operation. Figure 6.3 shows a plot of the distribution of the average length of refueling outages as a function of refueling number. For both PWRs and BWRs from the 2nd through the 5th refuelings, the refueling outage duration is substantially less than for the first refueling. For PWRs, there is a slight improvement for each subsequent refueling; however, this trend is difficult to verify because of the increasingly poor statistics for the fifth, sixth, and seventh refuelings.

These two factors, combined with the fact that the existing operating data is dominated by relatively young plants (less than three years old) leads to a bias in the reactor performance data. While a reactor lifetime is anticipated to be 40 years and the first 2-3 years represents only 5% of the total plant time, the majority of the available data is from the initial two years of plant operation and represents a biased sample dominated by break-in problems. Therefore, any estimate of nuclear plant performance must account for this variation in plant availability with age.

5. A closer look at refueling outages indicates that the outage time is apportioned approximately the same in PWR and BWR refueling outages as shown in Figures 6.4 and 6.5. However, there are two principal areas of difference between PWR and BWR refueling outages:

   a) Closure head assembly and disassembly

   b) Fuel exchanging

   These are discussed in Section 4.

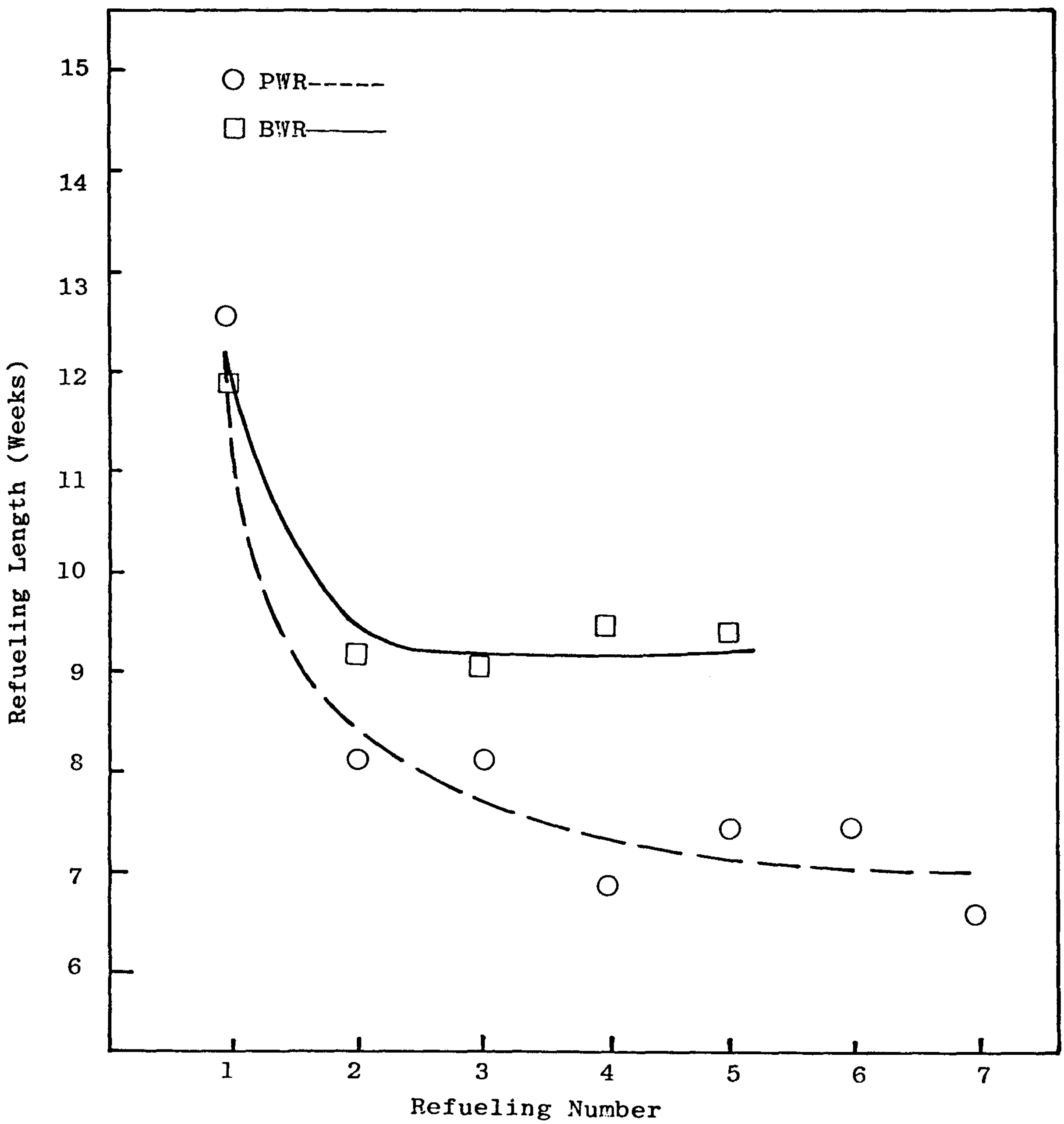

Figure 6.3. Refueling Length as a Function of the Number of Refuelings

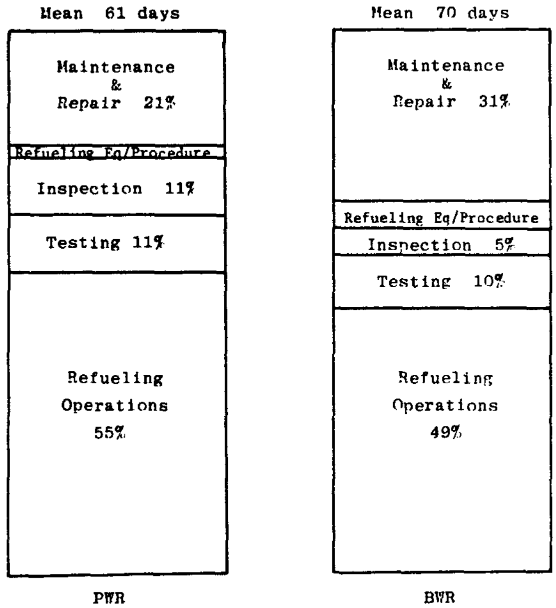

Figure 6.4. Comparison of the Components of a Refueling Outage for Selected PWP and BWR Plants.

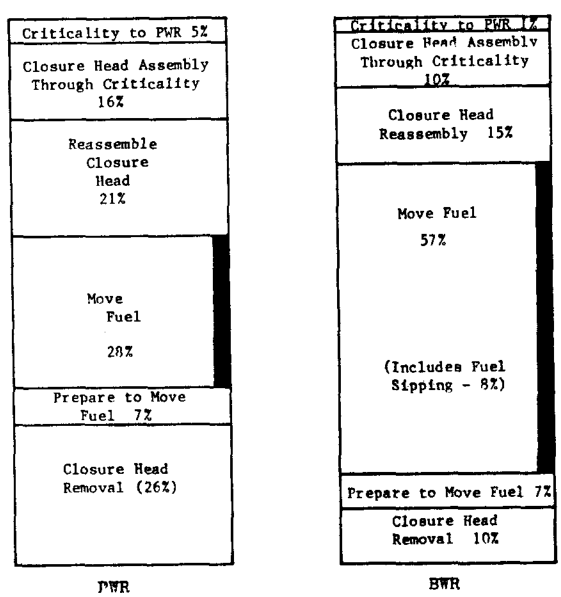

Figure 6.5. Comparison of Refueling Operations for Selected PWR and BWR Plants.

6. One method of reducing the impact of refueling outages on plant availability is to increase the fuel cycle length from 12 months to 18 months which eliminates one refueling outage every three years. As estimated in Section 5.1, increasing the fuel cycle length from 12 months to 18 months would increase plant availability by 6% per year.

7. A positive correlation between plant size and the length of refueling outages was determined using a simple linear regression analysis.

	Refueling Outage Duration (weeks)	
Plant Type	500 MWe Plant	1000 MWe Plant
PWR	Base (PWR)	Base +3.1 ± 3 weeks
BWR	Base (BWR)	Base + 6 weeks ± 4 weeks

The above table indicates that a 1000 MWe PWR takes an average of 3 weeks longer to refuel than 500 MWe plant, while a 1000 MWe BWR takes an average of 6 weeks longer than a 500 MWe unit. However, the limited amount of data available creates a large uncertainty in these estimates. Nevertheless, it seems clear that one can expect some increase in the outage time of larger plants over that of smaller units.

8. Based upon all the existing U.S. data and the limited amount of data available from European LWRs, it appears that European LWRs have a shorter mean and median refueling outage time than the U.S. LWR population.

	Refueling Outage Time (Weeks)	
	Mean	Median
U.S. LWR	10.9	8.8
European LWR	9.0	7.0

9. Utility projections of the length of an individual refueling outage have proven to be a difficult task. The operating experience data indicate that the median value of the length of a refueling outage is underestimated by approximately 1 to 3 weeks. There is, in addition, a small percentage of refueling outages which have long duration extensions caused by repair or maintenance needs discovered during the refueling outage. Just as there are a wide range of refueling outage durations, there are likewise a wide range of predictions because utilities attempt to anticipate the complicated operations which must be performed. However, it appears from the data (which is heavily biased by "first" refuelings) that the longer the anticipated refueling outage, the greater the uncertainty and the larger the underestimation in the refueling length.

10. A final word of caution with regard to the length of refueling outages - concern over safety, safeguards, and prevention of sabotage will increase the outage length due to: (a) additional administrative constraints on maintenance personnel and their actions; and (b) increased levels of testing. The result seems clear: refueling outages will tend to increase in length rather than decrease. This trend is hard to quantify and will be even more difficult to change.

Section 7.0

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APPENDIX A

SUMMARY OF MAJOR OUTAGES HISTORY BY PLANT

APPENDIX A

SUMMARY OF MAJOR OUTAGE HISTORY BY PLANT

The following are profiles of long duration outages (hours) for each plant included in this report (i.e., plants with ratings larger than 150 MWe).

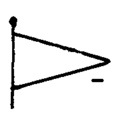
Legend of Symbols Used in This Appendix

▼ - Initial Criticality

■ - Commercial Operation

 - Refueling

◆ - Beginning of the Use of All Volatile Chemistry (AVT) in the Secondary Water Chemistry (PWRs only)

 - End of Data Used in this Study; June 31, 1977

( ) - Duration of Refueling in Hours

< > - Reasons for Extension of Refueling

Vendor Abbreviations

W - Westinghouse

GE - General Electric

CE - Combustion Engineering

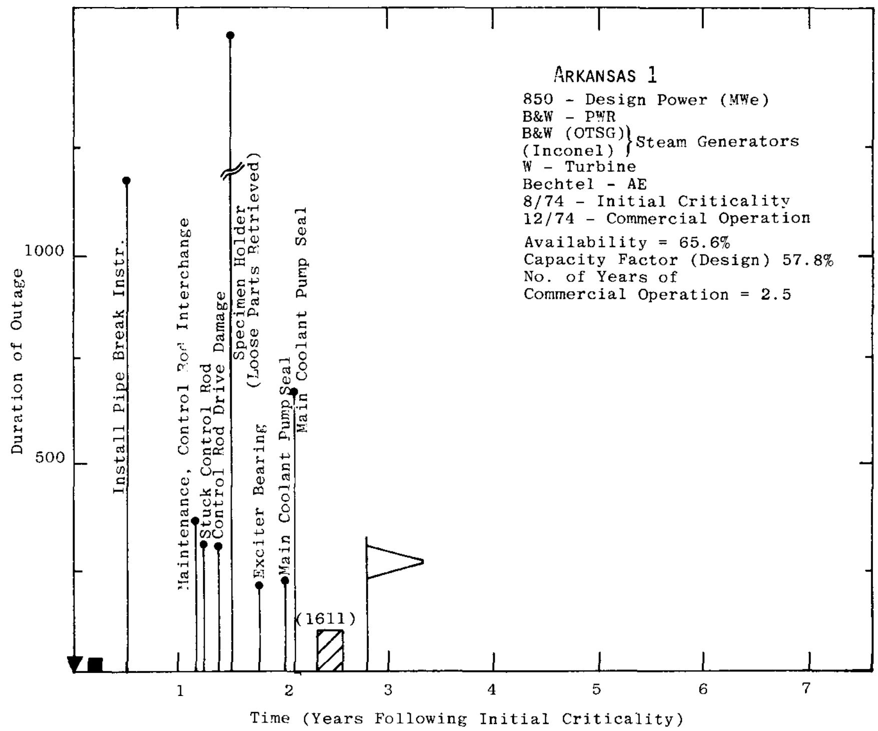
B&W - Babcock and Wilcox

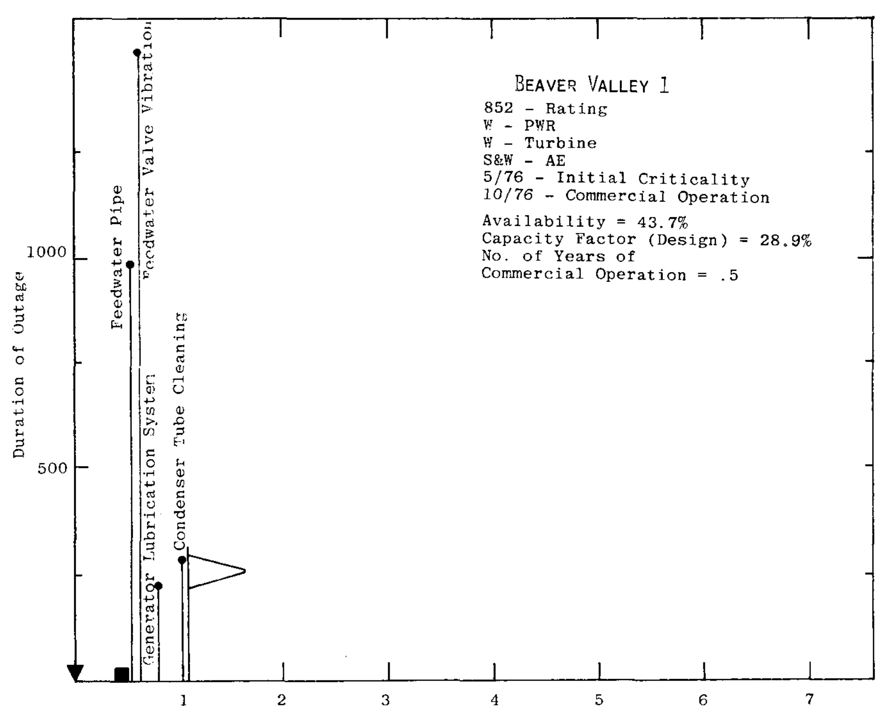
Plant Performance Parameters

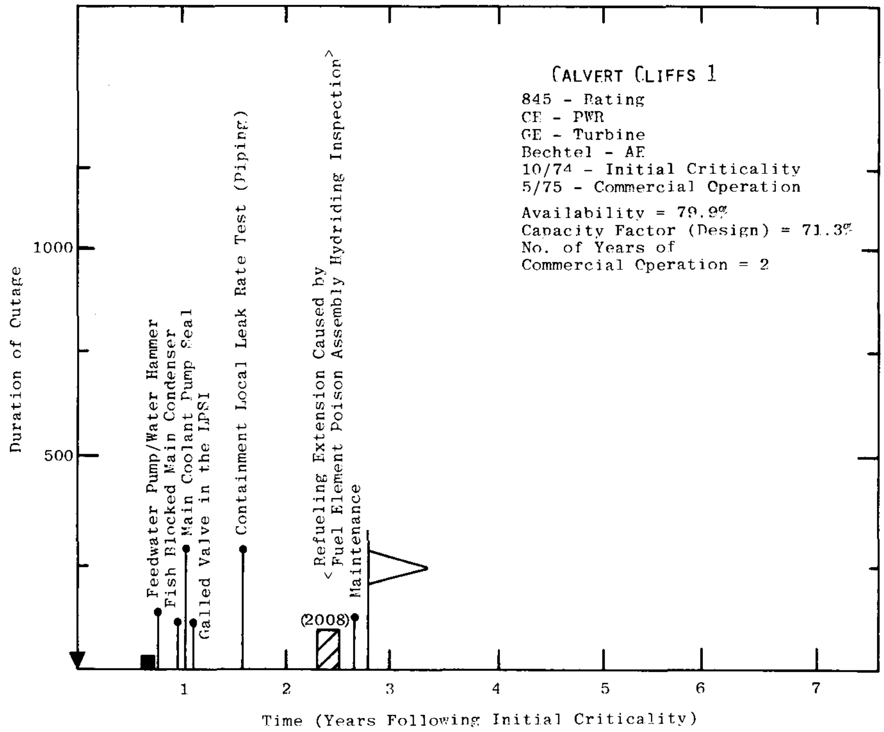
Availability - Cumulative Plant Availability Through June 1977

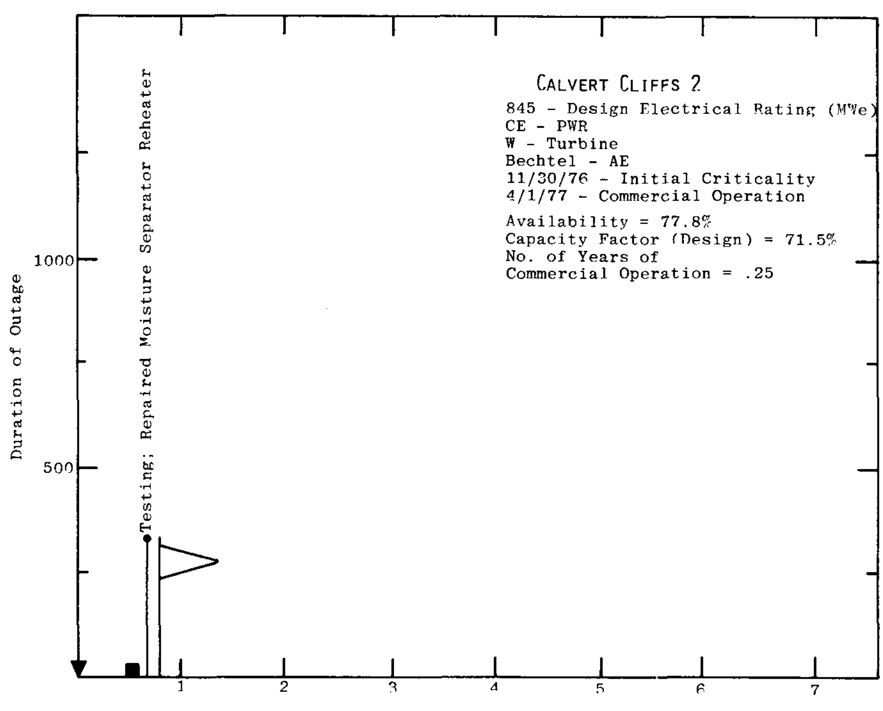
Capacity Factor - Cumulative Plant Capacity Factor Through June 1977 Based upon the Design Electrical Rating

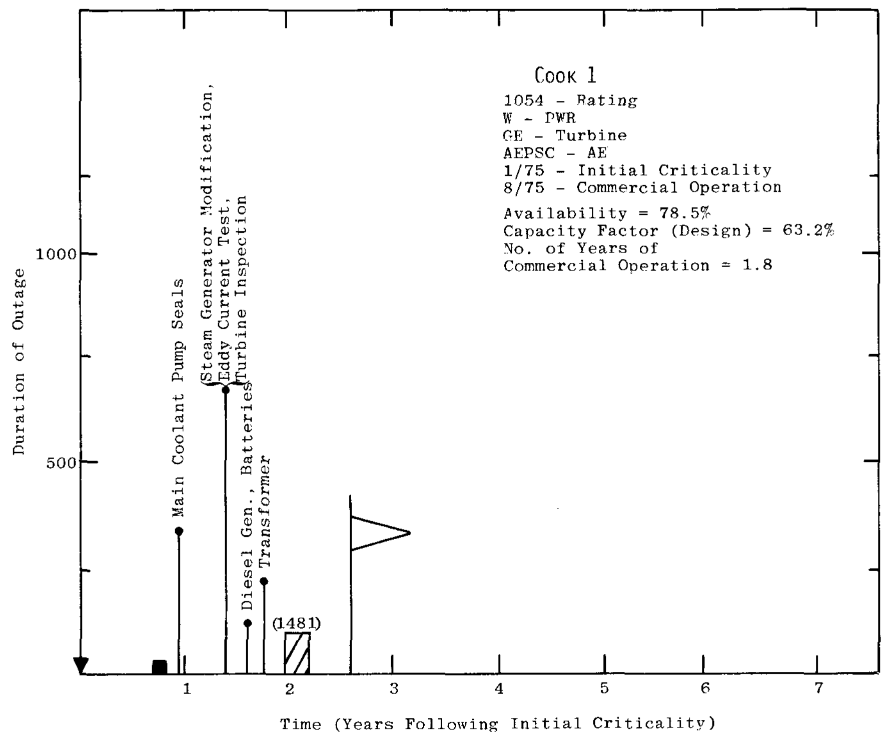
Architect Engineer Abbreviations		
AEPSC	-	American Power Service Corporation
B&R	-	Burns and Roe
Bechtel	-	Bechtel Corporation
Ebasco	-	Ebasco
Gilbert	-	Gilbert
G&H	-	Gibbs and Hill, Inc.
FPI	-	Flour Pioneer, Inc.
S&L	-	Sargent and Lundy Engineers
S&W	-	Stone and Webster
UE&C	-	United Engineers & Constructors

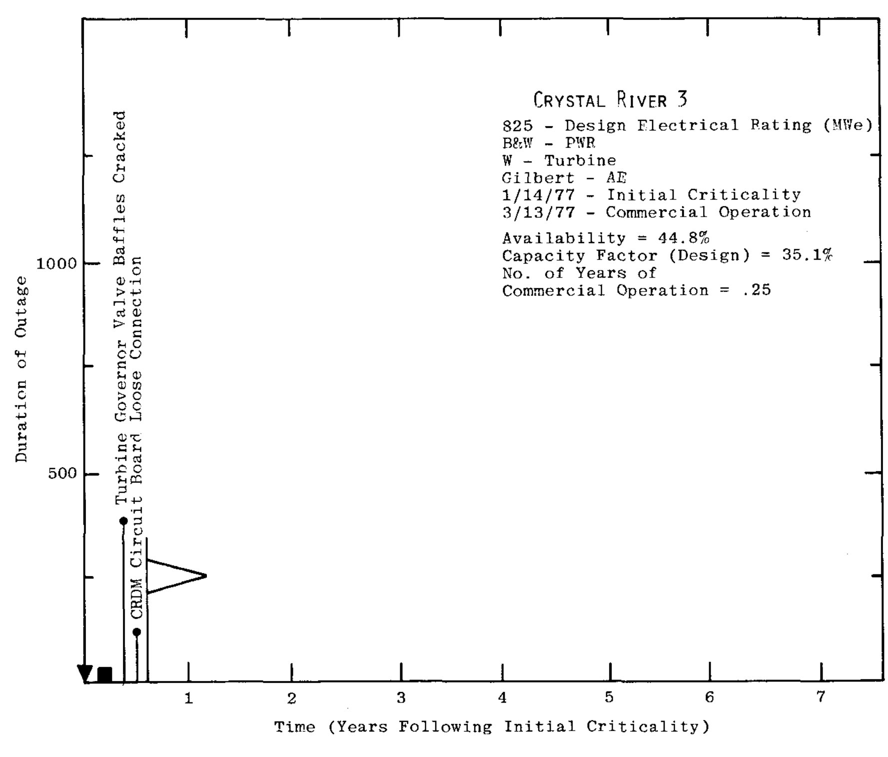

ARKANSAS 1
850 - Design Power (MWe)
B&W - PWR
B&W (OTSG)
(Inconel) Steam Generators
W - Turbine
Bechtel - AE
8/74 - Initial Criticality
12/74 - Commercial Operation
Availability = 65.6%
Capacity Factor (Design) 57.8%
No. of Years of
Commercial Operation = 2.5
Duration of Outage
1000
500
Install Pipe Break Instr.
Maintenance, Control Rod Interchange
Stuck Control Rod
Control Rod Drive Damage
Specimen Holder
(Loose Parts Retrieved)
Exciter Bearing
Main Coolant Pump Seal
Main Coolant Pump Seal
(1611)
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

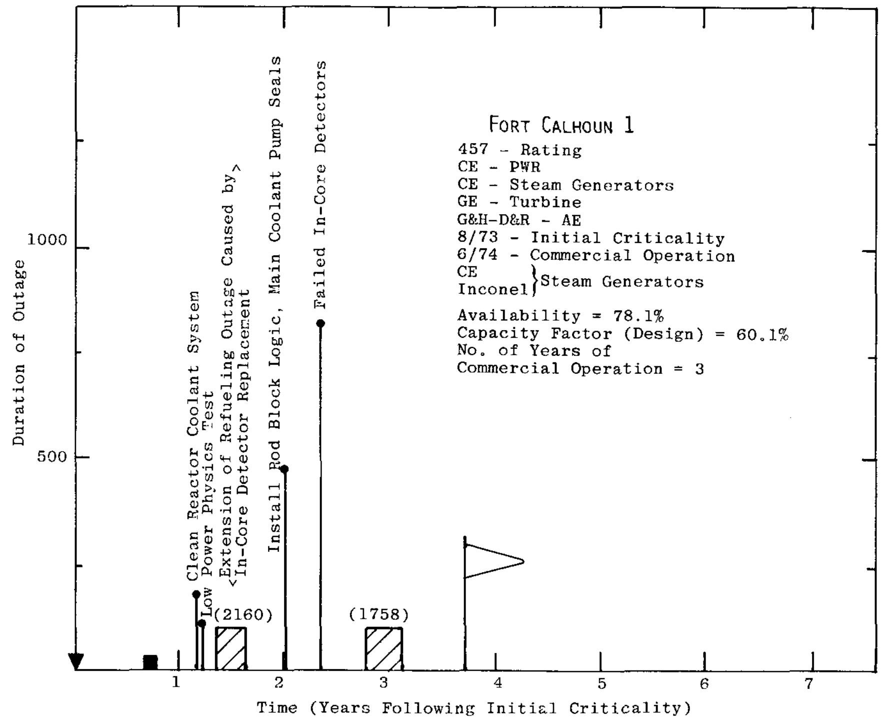

BEAVER VALLEY 1
852 - Rating
W - PWR
W - Turbine
S&W - AE
5/76 - Initial Criticality
10/76 - Commercial Operation
Availability = 43.7%
Capacity Factor (Design) = 28.9%
No. of Years of
Commercial Operation = .5
Duration of Outage
1000
500
Feedwater Pipe
Feedwater Valve Vibration
Generator Lubrication System
Condenser Tube Cleaning
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

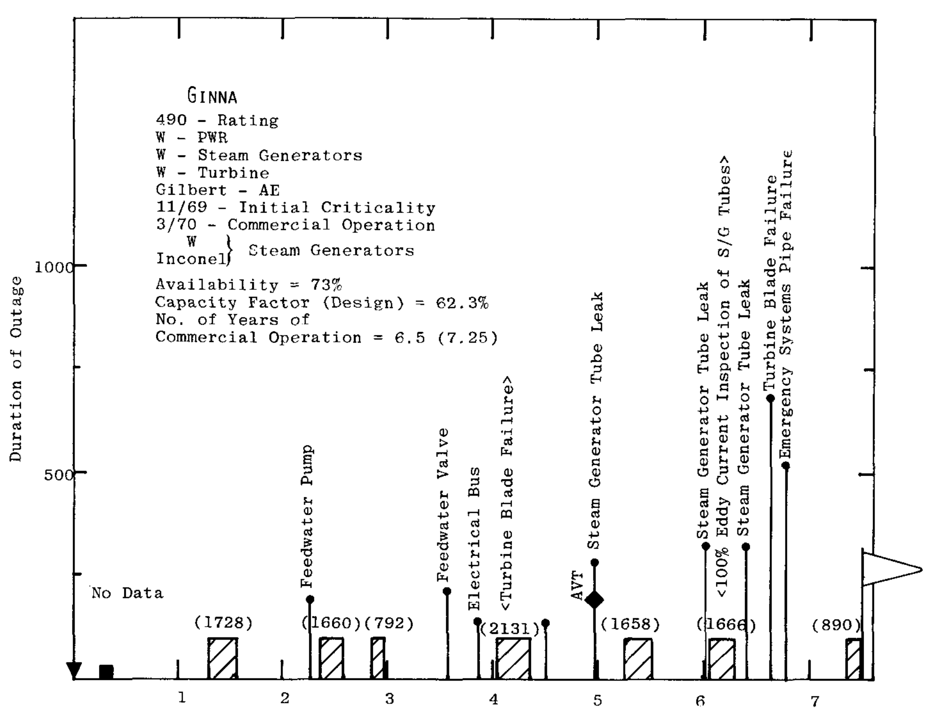

Calvert Cliffs 1
845 - Rating
CE - PWR
GE - Turbine
Bechtel - AE
10/74 - Initial Criticality
5/75 - Commercial Operation
Availability = 79.9%
Capacity Factor (Design) = 71.3%
No. of Years of
Commercial Operation = 2
Duration of Outage
1000
500
Feedwater Pump/Water Hammer
Fish Blocked Main Condenser
Main Coolant Pump Seal
Galled Valve in the LPSI
Containment Local Leak Rate Test (Piping)
Refueling Extension Caused by
< Fuel Element Poison Assembly Hydriding Inspection>
Maintenance
(2008)
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

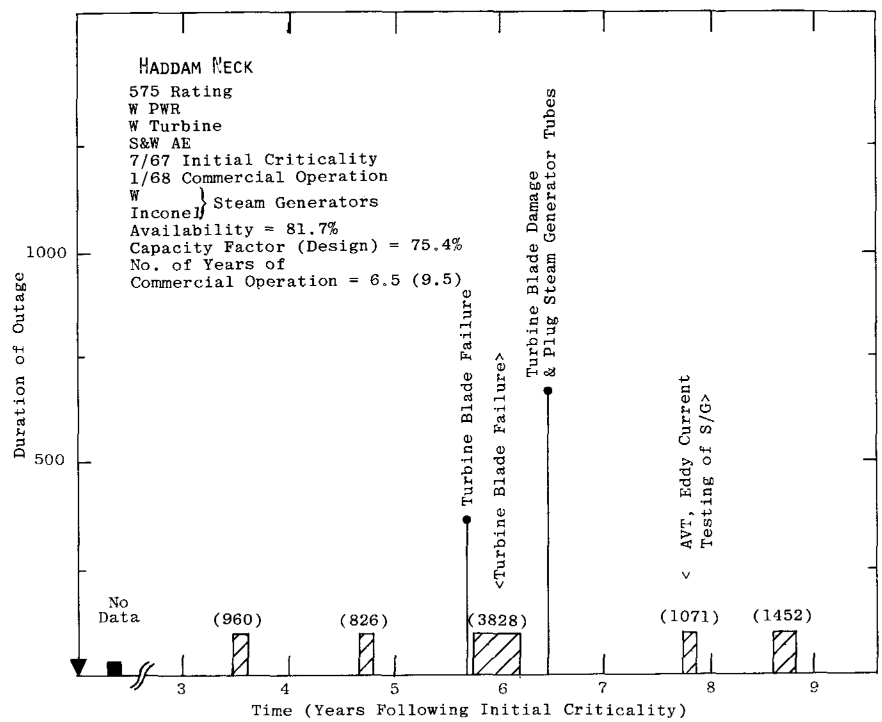

Calvert Cliffs 2
845 - Design Electrical Rating (MWe)
CE - PWR
W - Turbine
Bechtel - AE
11/30/76 - Initial Criticality
4/1/77 - Commercial Operation
Availability = 77.8%
Capacity Factor (Design) = 71.5%
No. of Years of
Commercial Operation = .25
Duration of Outage
1000
500
Testing; Repaired Moisture Separator Reheater
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)


Cook 1
1054 - Rating
W - PWR
GE - Turbine
AEPSC - AE
1/75 - Initial Criticality
8/75 - Commercial Operation
Availability = 78.5%
Capacity Factor (Design) = 63.2%
No. of Years of
Commercial Operation = 1.8
Duration of Outage
1000
500
Main Coolant Pump Seals
Steam Generator Modification,
Eddy Current Test,
Turbine Inspection
Diesel Gen., Batteries
Transformer
(1481)
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

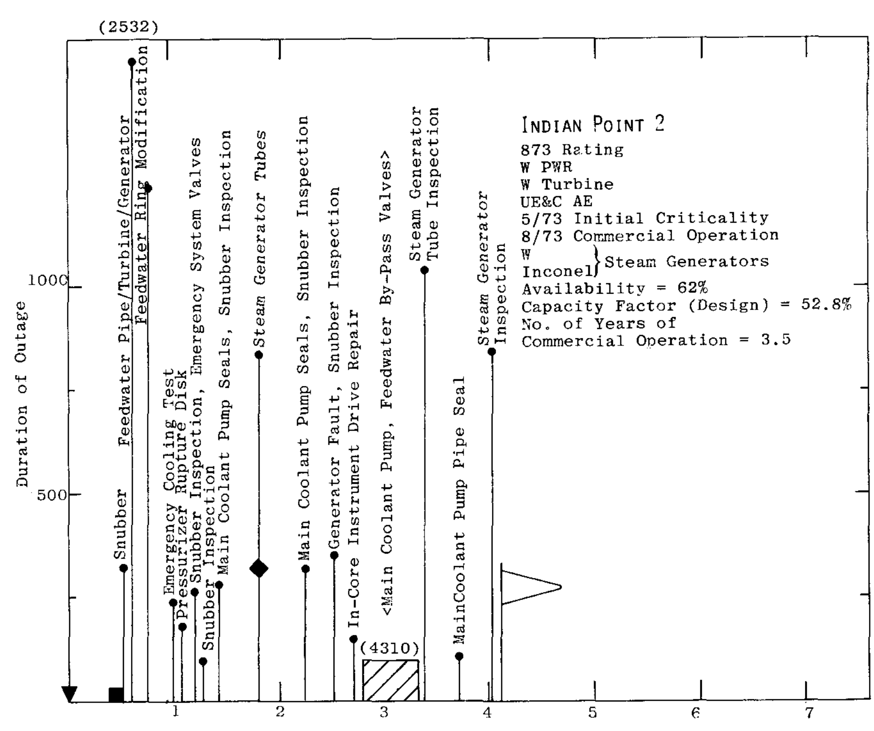

Crystal River 3
825 - Design Electrical Rating (MWe)
B&W - PWR
W - Turbine
Gilbert - AE
1/14/77 - Initial Criticality
3/13/77 - Commercial Operation
Availability = 44.8%
Capacity Factor (Design) = 35.1%
No. of Years of
Commercial Operation = .25
Duration of Outage
1000
500
Turbine Governor Valve Baffles Cracked
CRDM Circuit Board Loose Connection
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)


FORT CALHOUN 1
457 - Rating
CE - PWR
CE - Steam Generators
GE - Turbine
G&H-D&R - AE
8/73 - Initial Criticality
6/74 - Commercial Operation
CE
Inconel
Steam Generators
Availability = 78.1%
Capacity Factor (Design) = 60.1%
No. of Years of
Commercial Operation = 3
Clean Reactor Coolant System
Low Power Physics Test
<Extension of Refueling Outage Caused by>
In-Core Detector Replacement
Install Rod Block Logic, Main Coolant Pump Seals
Failed In-Core Detectors
(2160)
(1758)
Duration of Outage
1000
500
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

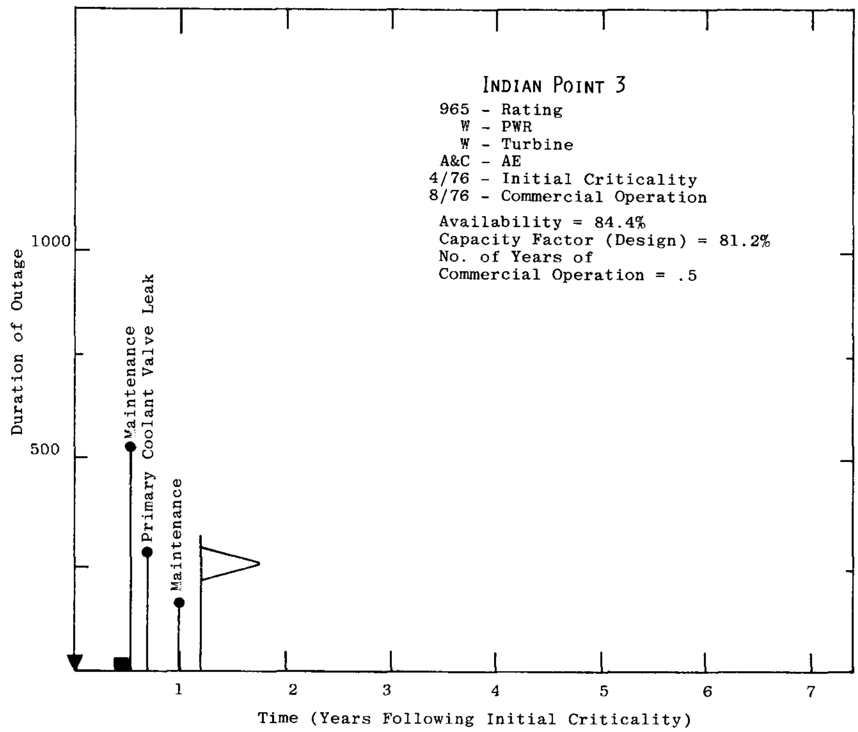

GINNA
490 - Rating
W - PWR
W - Steam Generators
W - Turbine
Gilbert - AE
11/69 - Initial Criticality
3/70 - Commercial Operation
W
Inconel
Steam Generators
Availability = 73%
Capacity Factor (Design) = 62.3%
No. of Years of
Commercial Operation = 6.5 (7.25)
No Data
Feedwater Pump
Feedwater Valve
Electrical Bus
<Turbine Blade Failure>
AVT
Steam Generator Tube Leak
Steam Generator Tube Leak
<100% Eddy Current Inspection of S/G Tubes>
Steam Generator Tube Leak
Turbine Blade Failure
Emergency Systems Pipe Failure
(1728)
(1660)
(792)
(2131)
(1658)
(1666)
(890)
Duration of Outage
1000
500
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

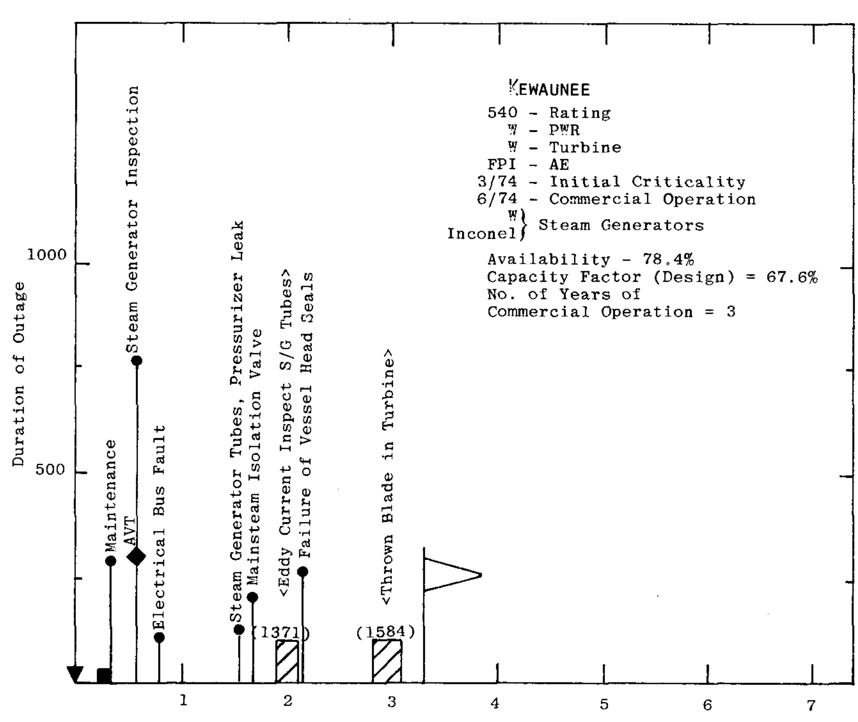


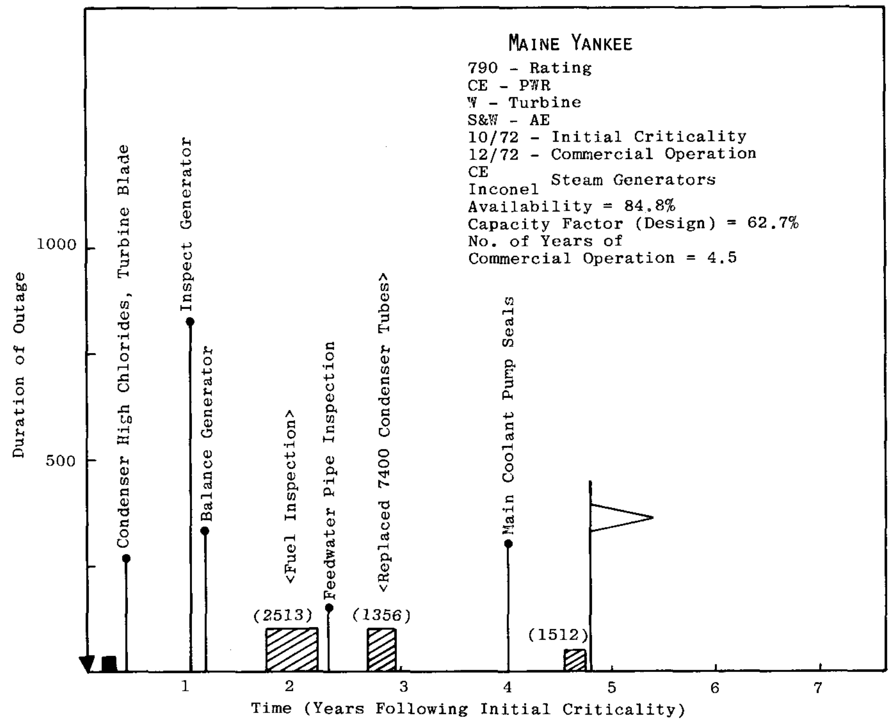
HADDAM NECK
575 Rating
W PWR
W Turbine
S&W AE
7/67 Initial Criticality
1/68 Commercial Operation
W
Inconel
Steam Generators
Availability = 81.7%
Capacity Factor (Design) = 75.4%
No. of Years of
Commercial Operation = 6.5 (9.5)
Duration of Outage
1000
500
No Data
(960)
(826)
(3828)
(1071)
(1452)
Turbine Blade Failure
<Turbine Blade Failure>
Turbine Blade Damage & Plug Steam Generator Tubes
< AVT, Eddy Current Testing of S/G>
3
4
5
6
7
8
9
Time (Years Following Initial Criticality)



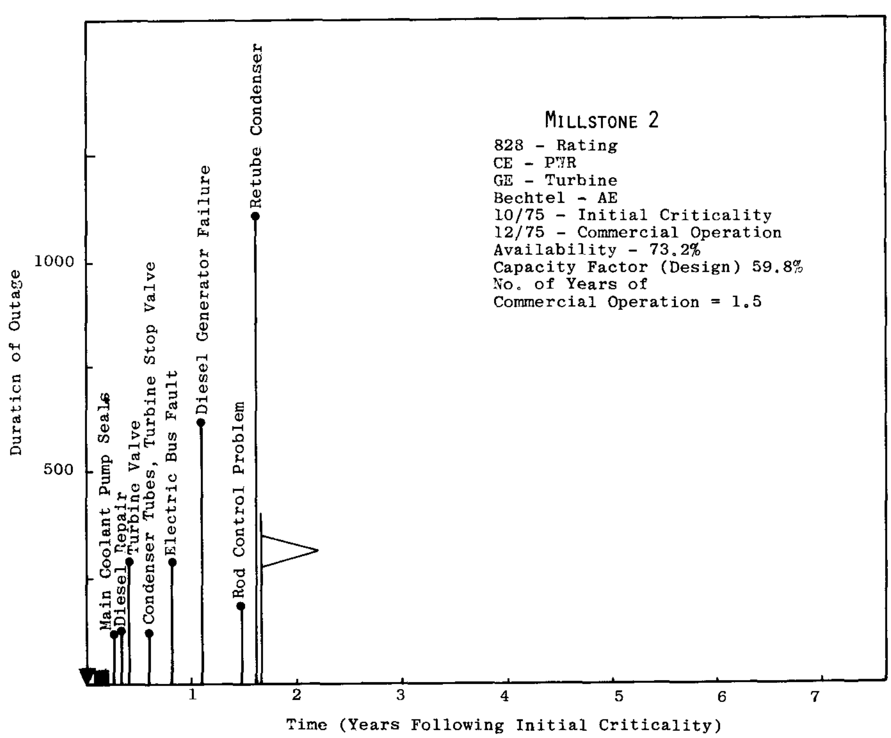
(2532)
Snubber
Feedwater Pipe/Turbine/Generator
Feedwater Ring Modification
Emergency Cooling Test
Pressurizer Rupture Disk
Snubber Inspection, Emergency System Valves
Snubber Inspection
Main Coolant Pump Seals, Snubber Inspection
Steam Generator Tubes
Main Coolant Pump Seals, Snubber Inspection
Generator Fault, Snubber Inspection
In-Core Instrument Drive Repair
<Main Coolant Pump, Feedwater By-Pass Valves>
(4310)
Steam Generator Tube Inspection
MainCoolant Pump Pipe Seal
Steam Generator Inspection
INDIAN POINT 2
873 Rating
W PWR
W Turbine
UE&C AE
5/73 Initial Criticality
8/73 Commercial Operation
W
Inconel
Steam Generators
Availability = 62%
Capacity Factor (Design) = 52.8%
No. of Years of
Commercial Operation = 3.5
Duration of Outage
1000
500
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)


INDIAN POINT 3
965 - Rating
W - PWR
W - Turbine
A&C - AE
4/76 - Initial Criticality
8/76 - Commercial Operation
Availability = 84.4%
Capacity Factor (Design) = 81.2%
No. of Years of
Commercial Operation = .5
Duration of Outage
1000
500
Maintenance
Primary Coolant Valve Leak
Maintenance
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

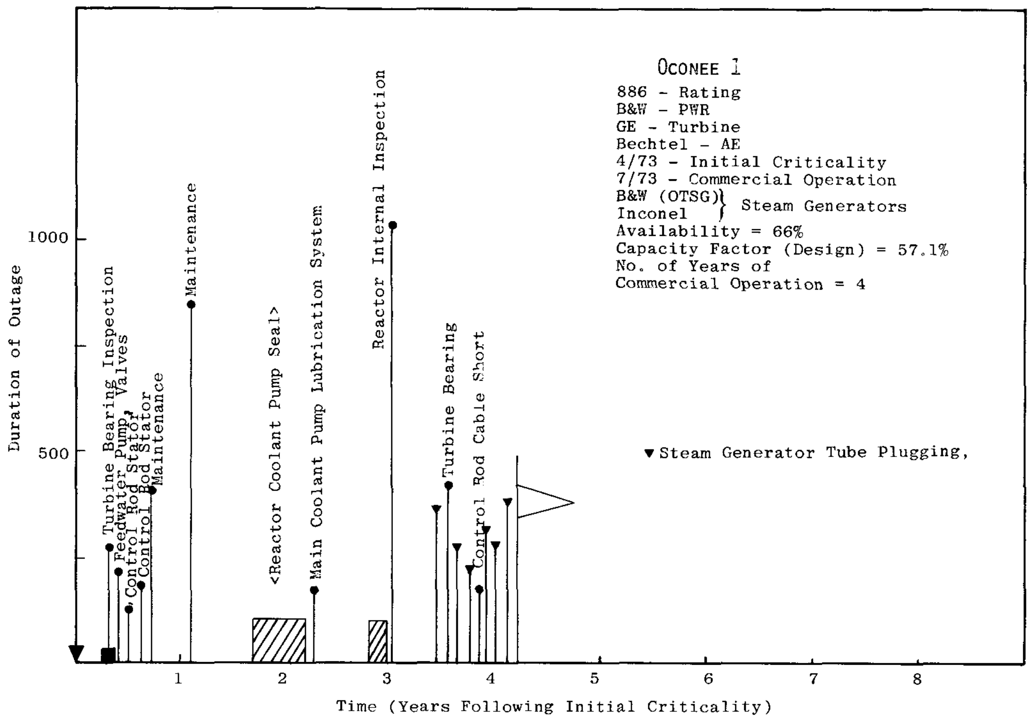

KEWAUNEE
540 - Rating
W - PWR
W - Turbine
FPI - AE
3/74 - Initial Criticality
6/74 - Commercial Operation
W
Inconel } Steam Generators
Availability - 78.4%
Capacity Factor (Design) = 67.6%
No. of Years of
Commercial Operation = 3
Duration of Outage
1000
500
Maintenance
AVT
Steam Generator Inspection
Electrical Bus Fault
Steam Generator Tubes, Pressurizer Leak
Mainsteam Isolation Valve
<Eddy Current Inspect S/G Tubes>
Failure of Vessel Head Seals
(1371)
<Thrown Blade in Turbine>
(1584)
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

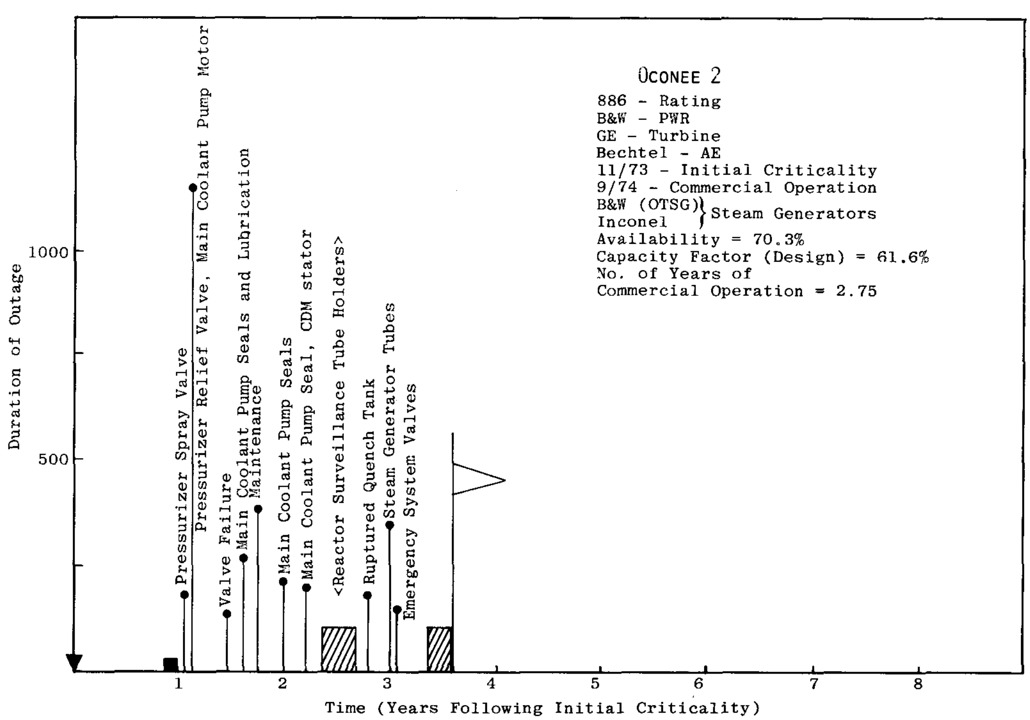


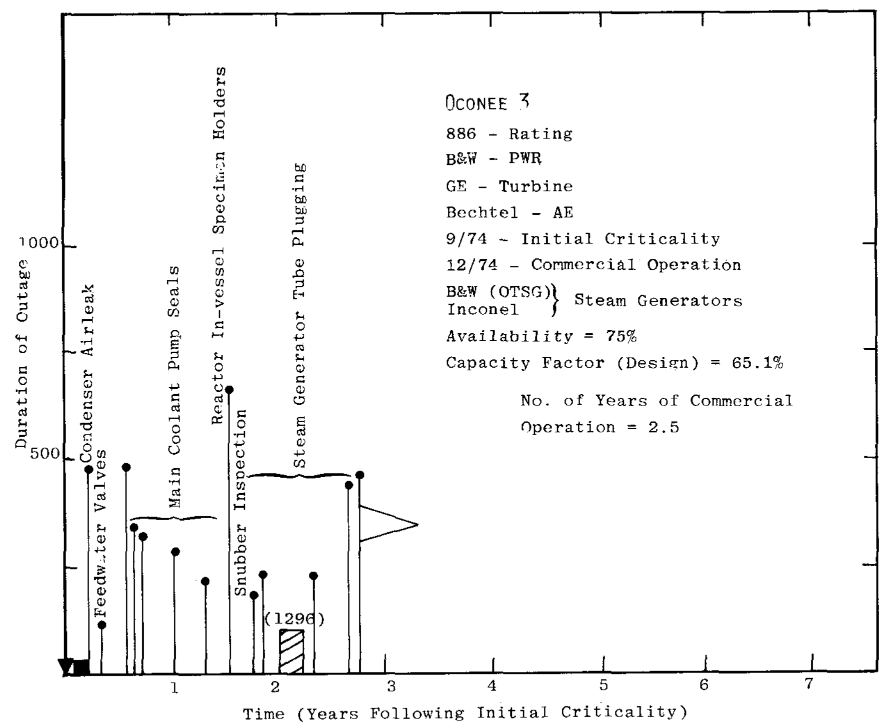
MAINE YANKEE
790 - Rating
CE - PWR
W - Turbine
S&W - AE
10/72 - Initial Criticality
12/72 - Commercial Operation
CE Inconel Steam Generators
Availability = 84.8%
Capacity Factor (Design) = 62.7%
No. of Years of Commercial Operation = 4.5
Duration of Outage
1000
500
Condenser High Chlorides, Turbine Blade
Inspect Generator
Balance Generator
<Fuel Inspection>
Feedwater Pipe Inspection
<Replaced 7400 Condenser Tubes>
Main Coolant Pump Seals
(2513)
(1356)
(1512)
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

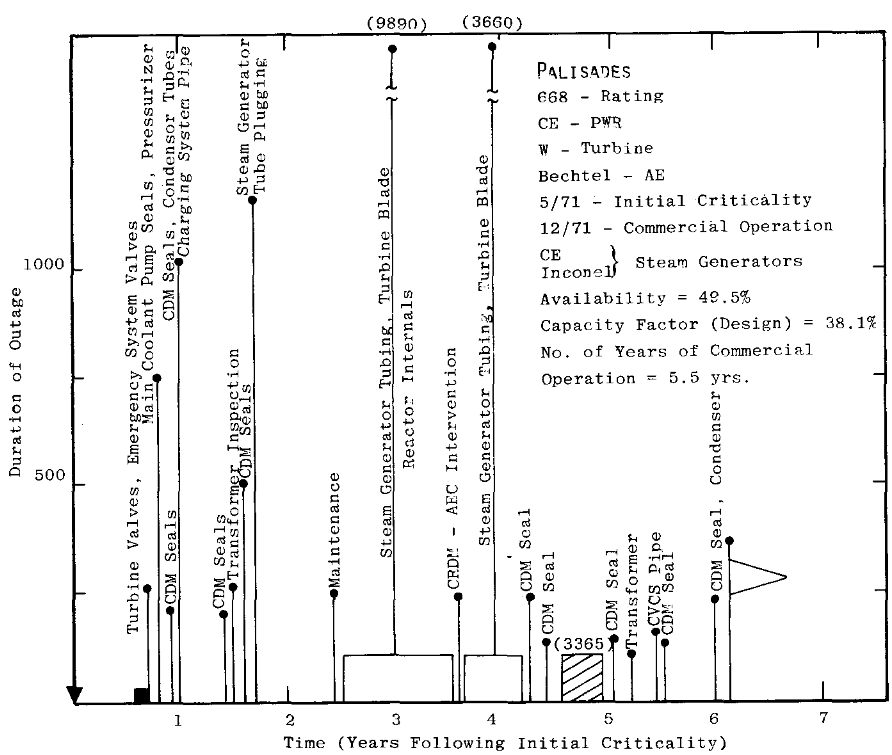


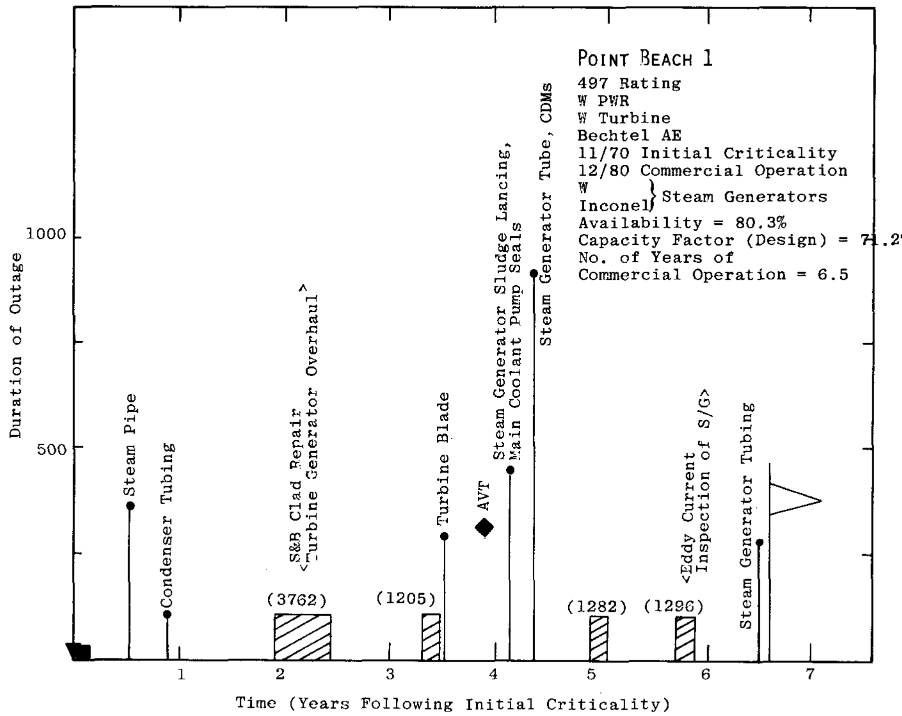
MILLSTONE 2
828 - Rating
CE - PWR
GE - Turbine
Bechtel - AE
10/75 - Initial Criticality
12/75 - Commercial Operation
Availability - 73.2%
Capacity Factor (Design) 59.8%
No. of Years of Commercial Operation = 1.5
Duration of Outage
1000
500
Main Coolant Pump Seals
Diesel Repair
Turbine Valve
Condenser Tubes, Turbine Stop Valve
Electric Bus Fault
Diesel Generator Failure
Rod Control Problem
Retube Condenser
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)


OCONEE 1
886 - Rating
B&W - PWR
GE - Turbine
Bechtel - AE
4/73 - Initial Criticality
7/73 - Commercial Operation
B&W (OTSG)
Inconel
Steam Generators
Availability = 66%
Capacity Factor (Design) = 57.1%
No. of Years of
Commercial Operation = 4
▼ Steam Generator Tube Plugging,
Turbine Bearing Inspection
Feedwater Pump, Valves
Control Rod Stator
Control Rod Stator
Maintenance
Maintenance
<Reactor Coolant Pump Seal>
Main Coolant Pump Lubrication System
Reactor Internal Inspection
Turbine Bearing
Control Rod Cable Short
Duration of Outage
1000
500
1
2
3
4
5
6
7
8
Time (Years Following Initial Criticality)

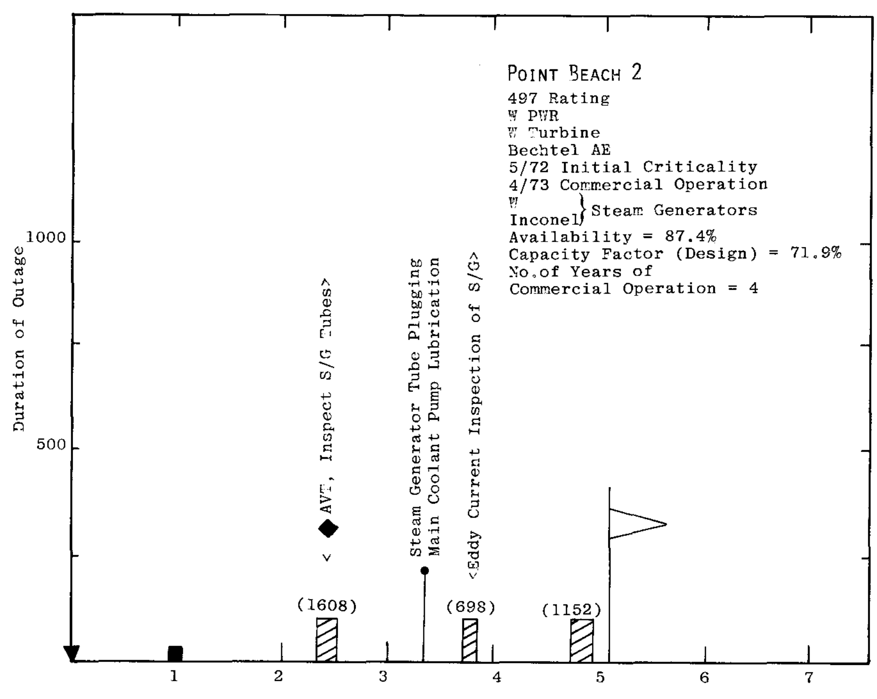

OCONEE 2
886 - Rating
B&W - PWR
GE - Turbine
Bechtel - AE
11/73 - Initial Criticality
9/74 - Commercial Operation
B&W (OTSG)
Inconel
Steam Generators
Availability = 70.3%
Capacity Factor (Design) = 61.6%
No. of Years of
Commercial Operation = 2.75
Pressurizer Spray Valve
Pressurizer Relief Valve, Main Coolant Pump Motor
Valve Failure
Main Coolant Pump Seals and Lubrication
Maintenance
Main Coolant Pump Seals
Main Coolant Pump Seal, CDM stator
<Reactor Surveillance Tube Holders>
Ruptured Quench Tank
Steam Generator Tubes
Emergency System Valves
Duration of Outage
1000
500
1
2
3
4
5
6
7
8
Time (Years Following Initial Criticality)


OCONEE 3
886 - Rating
B&W - PWR
GE - Turbine
Bechtel - AE
9/74 - Initial Criticality
12/74 - Commercial Operation
B&W (OTSG) Inconel } Steam Generators
Availability = 75%
Capacity Factor (Design) = 65.1%
No. of Years of Commercial Operation = 2.5
Condenser Airleak
Feedwater Valves
Main Coolant Pump Seals
Reactor In-vessel Specimen Holders
Snubber Inspection
Steam Generator Tube Plugging
(1296)
Duration of Outage
1000
500
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

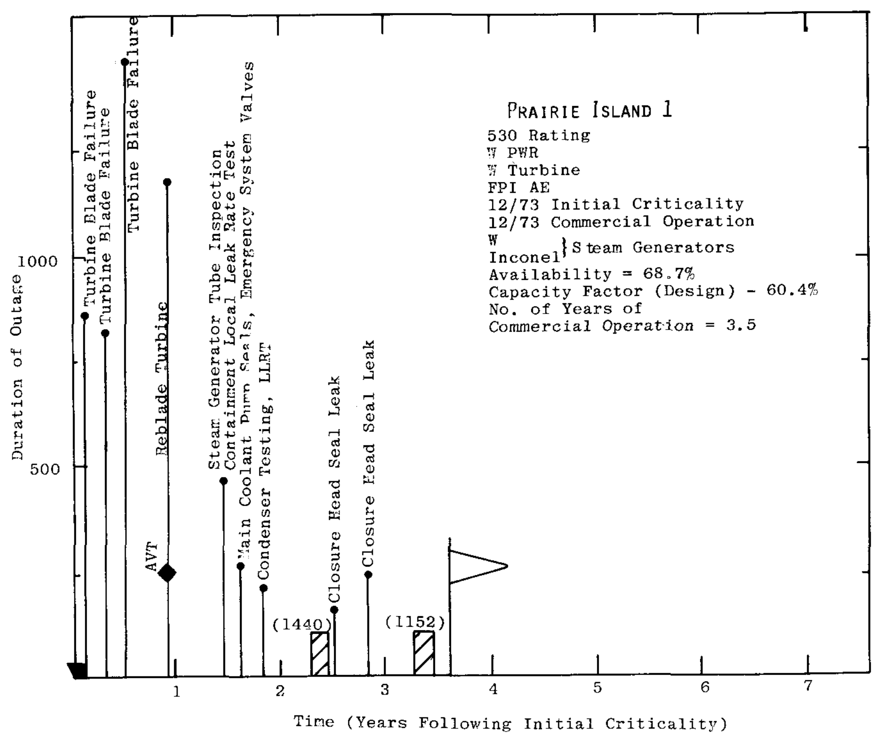

PALISADES
668 - Rating
CE - PWR
W - Turbine
Bechtel - AE
5/71 - Initial Criticality
12/71 - Commercial Operation
CE Inconel } Steam Generators
Availability = 49.5%
Capacity Factor (Design) = 38.1%
No. of Years of Commercial Operation = 5.5 yrs.
(9890)
(3660)
Turbine Valves, Emergency System Valves
Main Coolant Pump Seals, Pressurizer
CDM Seals
CDM Seals, Condensor Tubes
Charging System Pipe
Steam Generator Tube Plugging
CDM Seals
Transformer Inspection
CDM Seals
Maintenance
Steam Generator Tubing, Turbine Blade
Reactor Internals
CRDM - AEC Intervention
Steam Generator Tubing, Turbine Blade
CDM Seal
CDM Seal
(3365)
CDM Seal
Transformer
CVCS Pipe
CDM Seal
CDM Seal, Condenser
Duration of Outage
1000
500
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

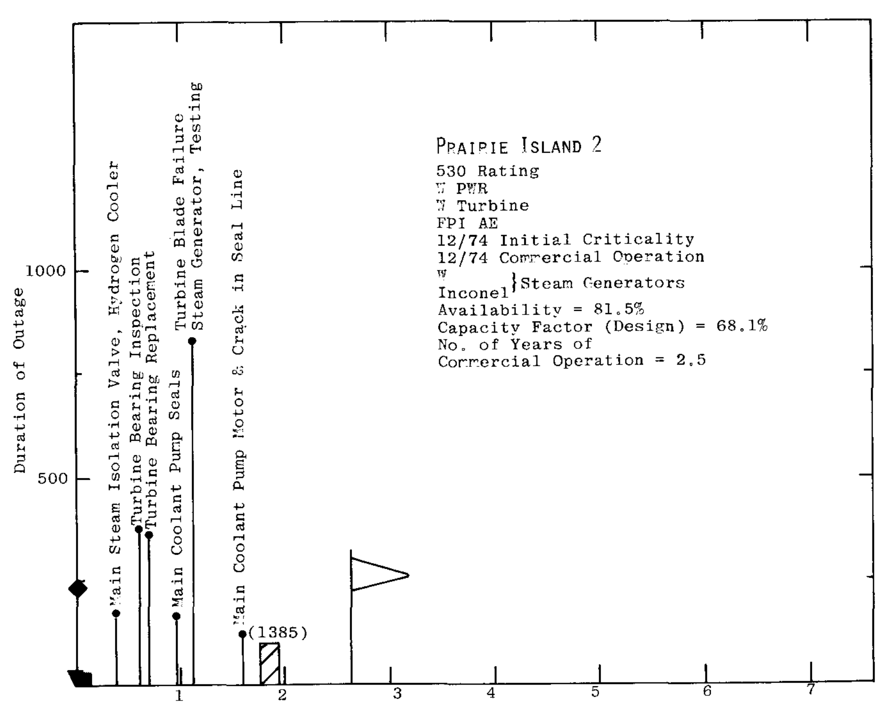


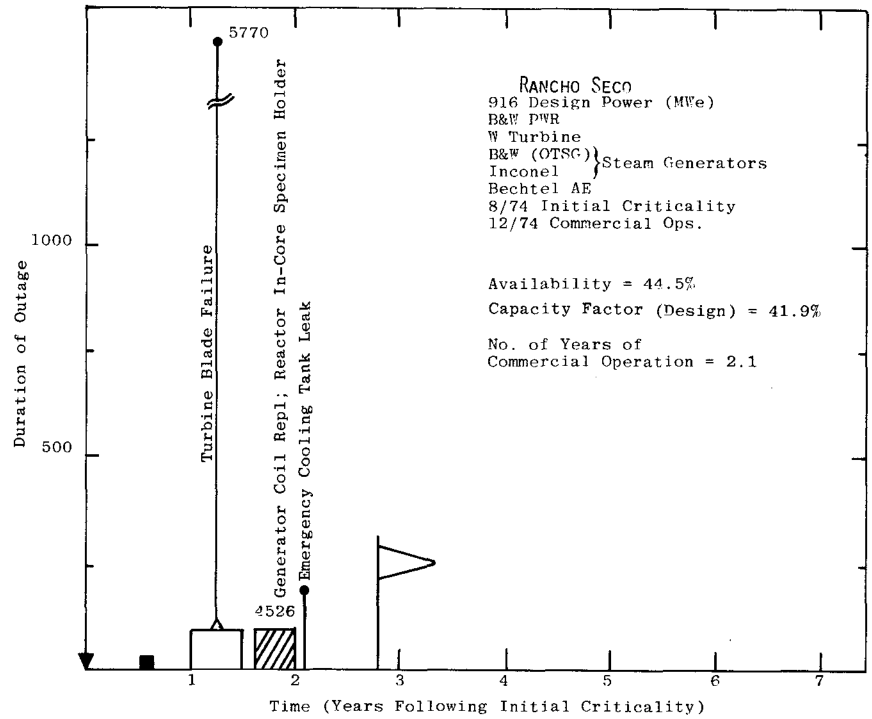
POINT BEACH 1
497 Rating
W PWR
W Turbine
Bechtel AE
11/70 Initial Criticality
12/80 Commercial Operation
W
Inconel
Steam Generators
Availability = 80.3%
Capacity Factor (Design) = 71.2%
No. of Years of
Commercial Operation = 6.5
Duration of Outage
1000
500
Steam Pipe
Condenser Tubing
S&B Clad Repair
<Turbine Generator Overhaul>
(3762)
(1205)
Turbine Blade
AVT
Steam Generator Sludge Lancing,
Main Coolant Pump Seals
Steam Generator Tube, CDMs
(1282)
(1296)
<Eddy Current
Inspection of S/G>
Steam Generator Tubing
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)



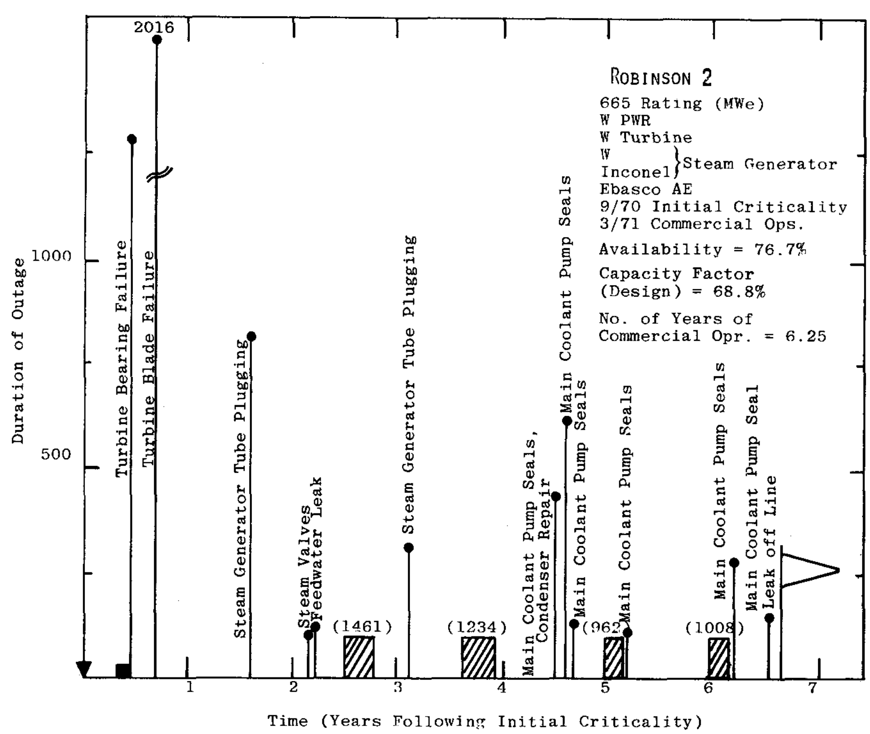
POINT BEACH 2
497 Rating
W PWR
W Turbine
Bechtel AE
5/72 Initial Criticality
4/73 Commercial Operation
W
Inconel
Steam Generators
Availability = 87.4%
Capacity Factor (Design) = 71.9%
No. of Years of
Commercial Operation = 4
Duration of Outage
1000
500
< AVT, Inspect S/G Tubes>
Steam Generator Tube Plugging
Main Coolant Pump Lubrication
<Eddy Current Inspection of S/G>
(1608)
(698)
(1152)
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)


Prairie Island 1
530 Rating
W PWR
W Turbine
FPI AE
12/73 Initial Criticality
12/73 Commercial Operation
W
Inconel } Steam Generators
Availability = 68.7%
Capacity Factor (Design) - 60.4%
No. of Years of
Commercial Operation = 3.5
Turbine Blade Failure
Turbine Blade Failure
Turbine Blade Failure
Reblade Turbine
AVT
Steam Generator Tube Inspection
Containment Local Leak Rate Test
Main Coolant Pump Seals, Emergency System Valves
Condenser Testing, LLRT
Closure Head Seal Leak
Closure Head Seal Leak
(1440)
(1152)
Duration of Outage
1000
500
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

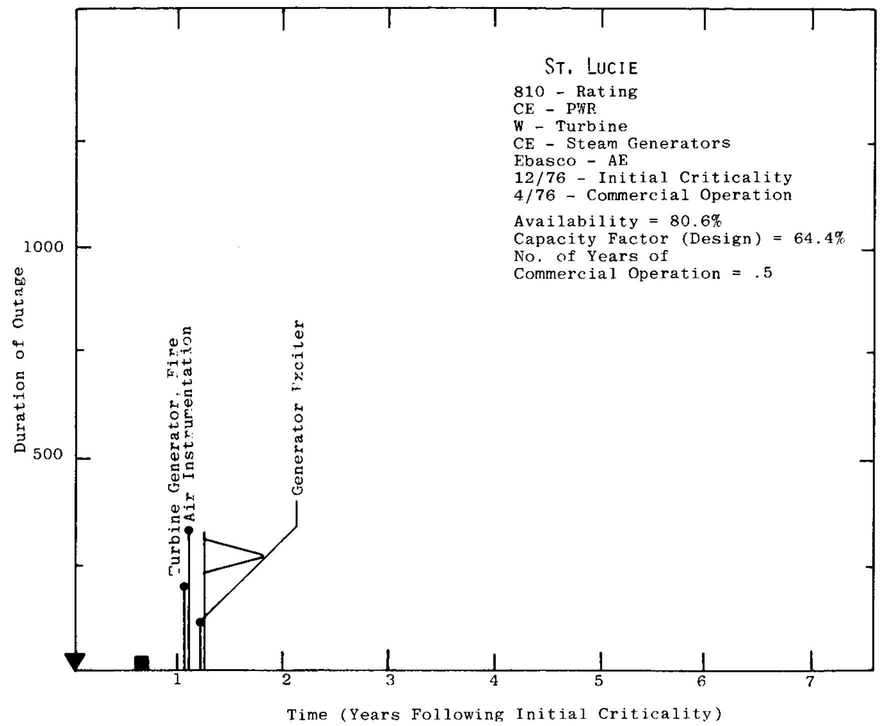

Prairie Island 2
530 Rating
W PWR
W Turbine
FPI AE
12/74 Initial Criticality
12/74 Commercial Operation
W
Inconel } Steam Generators
Availability = 81.5%
Capacity Factor (Design) = 68.1%
No. of Years of
Commercial Operation = 2.5
Main Steam Isolation Valve, Hydrogen Cooler
Turbine Bearing Inspection
Turbine Bearing Replacement
Main Coolant Pump Seals
Turbine Blade Failure
Steam Generator, Testing
Main Coolant Pump Motor & Crack in Seal Line
(1385)
Duration of Outage
1000
500
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

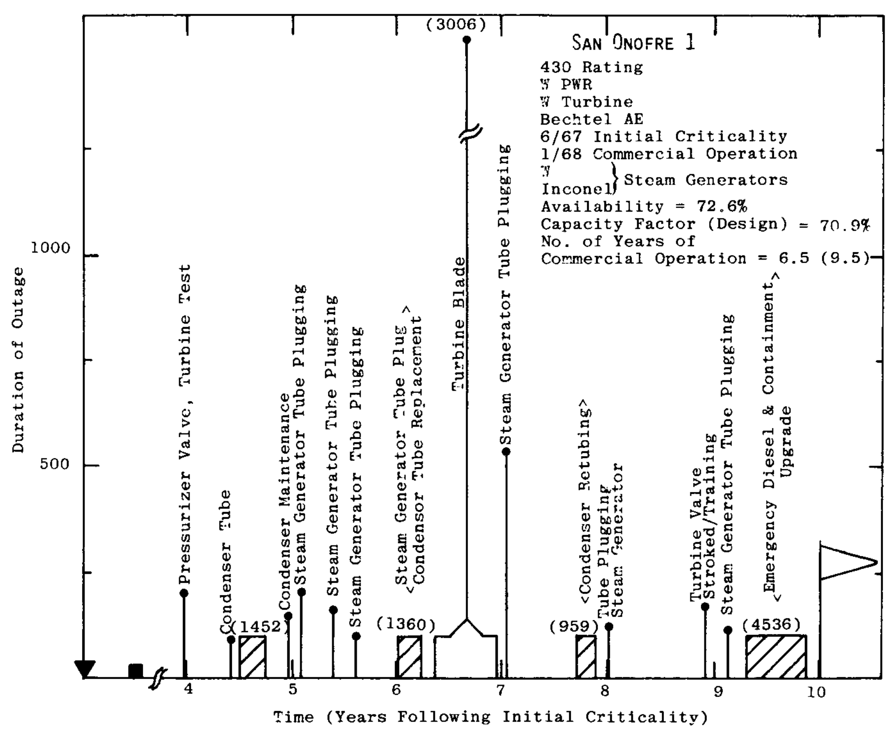


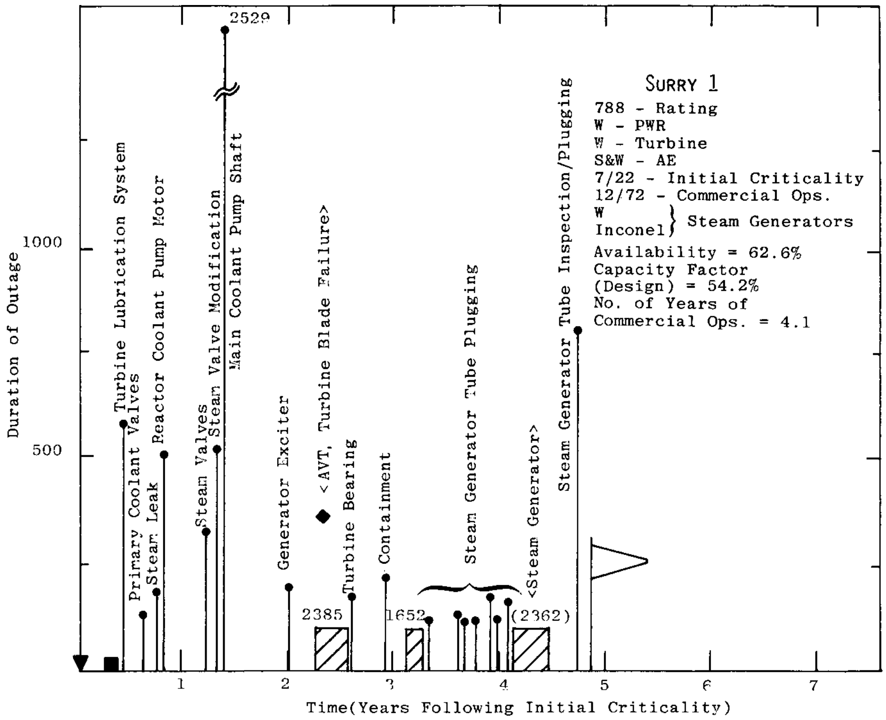
Rancho Seco
916 Design Power (MWe)
B&W PWR
W Turbine
B&W (OTSG) / Inconel } Steam Generators
Bechtel AE
8/74 Initial Criticality
12/74 Commercial Ops.
Availability = 44.5%
Capacity Factor (Design) = 41.9%
No. of Years of Commercial Operation = 2.1
5770
Turbine Blade Failure
4526
Generator Coil Repl; Reactor In-Core Specimen Holder
Emergency Cooling Tank Leak
1000
500
Duration of Outage
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

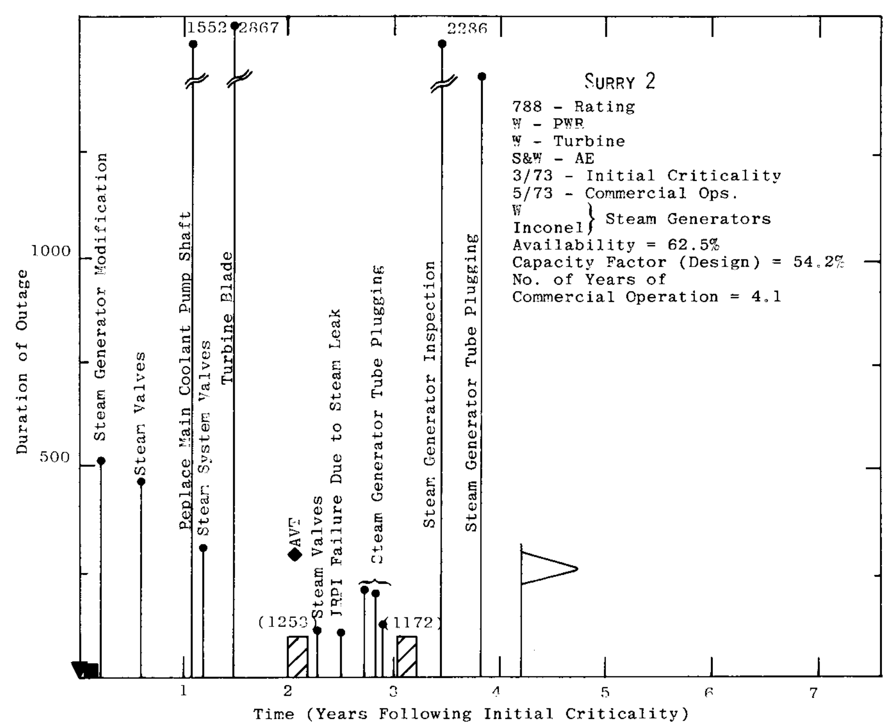


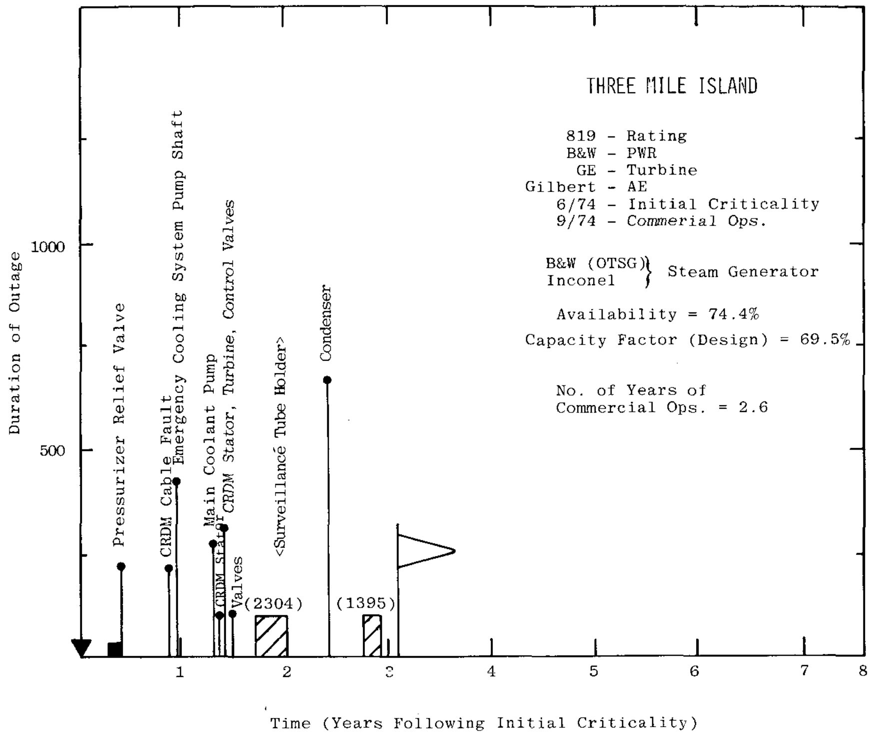
Robinson 2
665 Rating (MWe)
W PWR
W Turbine
W / Inconel } Steam Generator
Ebasco AE
9/70 Initial Criticality
3/71 Commercial Ops.
Availability = 76.7%
Capacity Factor (Design) = 68.8%
No. of Years of Commercial Opr. = 6.25
2016
Turbine Bearing Failure
Turbine Blade Failure
Steam Generator Tube Plugging
Steam Valves
Feedwater Leak
(1461)
Steam Generator Tube Plugging
(1234)
Main Coolant Pump Seals, Condenser Repair
Main Coolant Pump Seals
Main Coolant Pump Seals
(962)
Main Coolant Pump Seals
(1008)
Main Coolant Pump Seals
Main Coolant Pump Seal
Leak off Line
1000
500
Duration of Outage
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

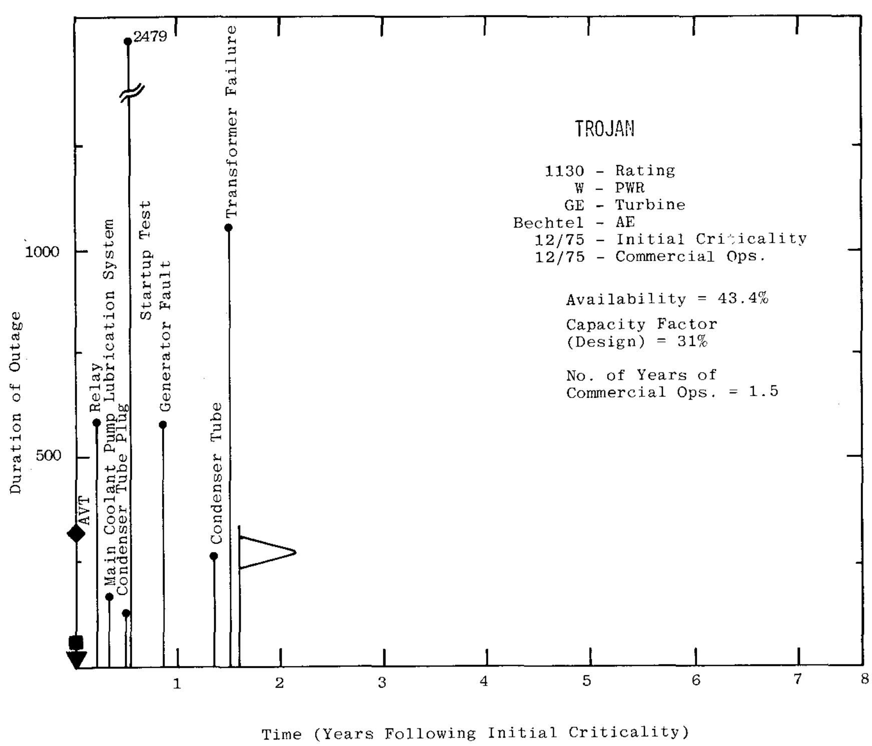

ST. LUCIE
810 - Rating
CE - PWR
W - Turbine
CE - Steam Generators
Ebasco - AE
12/76 - Initial Criticality
4/76 - Commercial Operation
Availability = 80.6%
Capacity Factor (Design) = 64.4%
No. of Years of
Commercial Operation = .5
Duration of Outage
1000
500
Turbine Generator, Fire
Air Instrumentation
Generator Exciter
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

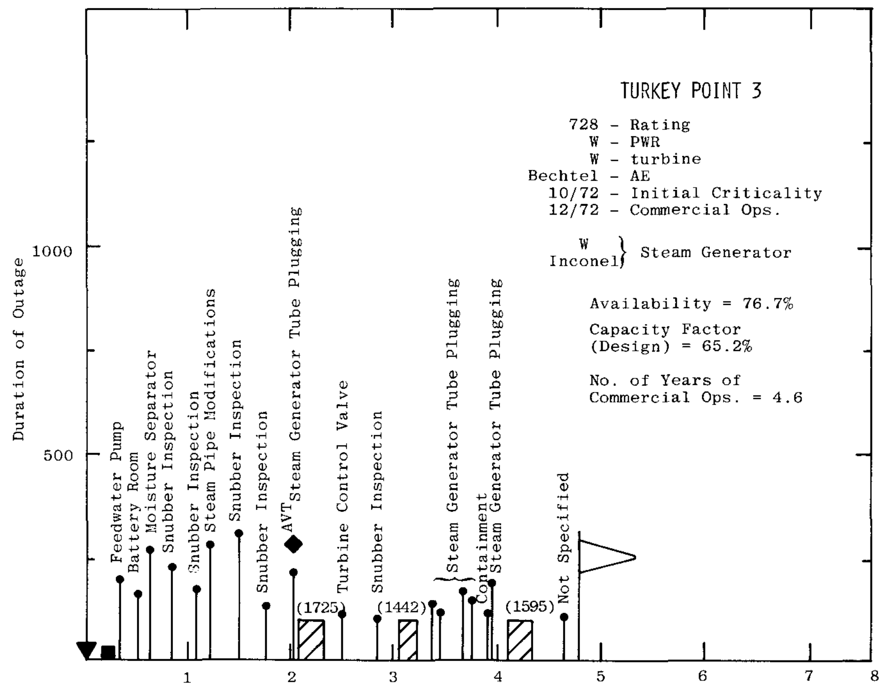

SAN ONOFRE 1
430 Rating
W PWR
W Turbine
Bechtel AE
6/67 Initial Criticality
1/68 Commercial Operation
W
Inconel } Steam Generators
Availability = 72.6%
Capacity Factor (Design) = 70.9%
No. of Years of
Commercial Operation = 6.5 (9.5)
Duration of Outage
1000
500
(3006)
Pressurizer Valve, Turbine Test
Condenser Tube
(1452)
Condenser Maintenance
Steam Generator Tube Plugging
Steam Generator Tube Plugging
Steam Generator Tube Plugging
Steam Generator Tube Plug
<Condensor Tube Replacement>
(1360)
Turbine Blade
Steam Generator Tube Plugging
<Condenser Retubing>
(959)
Tube Plugging
Steam Generator
Turbine Valve
Stroked/Training
Steam Generator Tube Plugging
<Emergency Diesel & Containment Upgrade>
(4536)
4
5
6
7
8
9
10
Time (Years Following Initial Criticality)


SURRY 1
788 - Rating
W - PWR
W - Turbine
S&W - AE
7/22 - Initial Criticality
12/72 - Commercial Ops.
W Inconel } Steam Generators
Availability = 62.6%
Capacity Factor (Design) = 54.2%
No. of Years of Commercial Ops. = 4.1
Duration of Outage
Time(Years Following Initial Criticality)
Turbine Lubrication System
Primary Coolant Valves
Steam Leak
Reactor Coolant Pump Motor
Steam Valves
Steam Valve Modification
Main Coolant Pump Shaft
2529
Generator Exciter
<AVT, Turbine Blade Failure>
Turbine Bearing
Containment
Steam Generator Tube Plugging
<Steam Generator>
Steam Generator Tube Inspection/Plugging
2385
1652
(2362)
500
1000
1
2
3
4
5
6
7

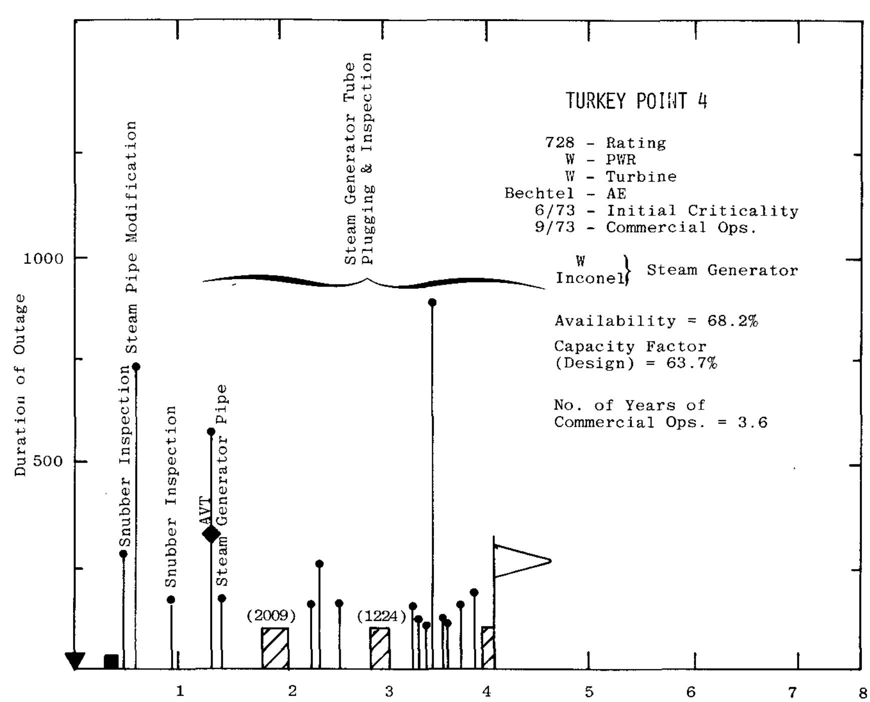

SURRY 2
788 - Rating
W - PWR
W - Turbine
S&W - AE
3/73 - Initial Criticality
5/73 - Commercial Ops.
W Inconel } Steam Generators
Availability = 62.5%
Capacity Factor (Design) = 54.2%
No. of Years of Commercial Operation = 4.1
Duration of Outage
Time (Years Following Initial Criticality)
Steam Generator Modification
Steam Valves
Replace Main Coolant Pump Shaft
Steam System Valves
Turbine Blade
1552
2867
2236
AVT
Steam Valves
IRPI Failure Due to Steam Leak
Steam Generator Tube Plugging
Steam Generator Inspection
Steam Generator Tube Plugging
(1253)
(1172)
500
1000
1
2
3
4
5
6
7


THREE MILE ISLAND
819 - Rating
B&W - PWR
GE - Turbine
Gilbert - AE
6/74 - Initial Criticality
9/74 - Commerial Ops.
B&W (OTSG) Inconel } Steam Generator
Availability = 74.4%
Capacity Factor (Design) = 69.5%
No. of Years of Commercial Ops. = 2.6
Duration of Outage
1000
500
Pressurizer Relief Valve
CRDM Cable Fault
Emergency Cooling System Pump Shaft
Main Coolant Pump
CRDM Stator, Turbine, Control Valves
Valves
Surveillance Tube Holder
Condenser
(2304)
(1395)
1
2
4
5
6
7
8
Time (Years Following Initial Criticality)

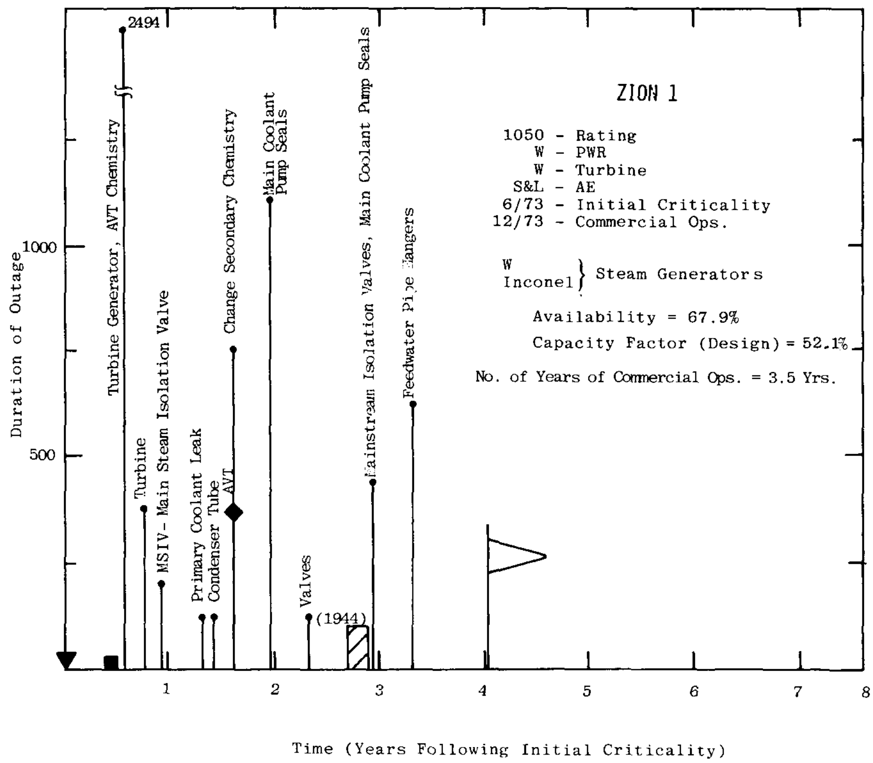

TROJAN
1130 - Rating
W - PWR
GE - Turbine
Bechtel - AE
12/75 - Initial Criticality
12/75 - Commercial Ops.
Availability = 43.4%
Capacity Factor (Design) = 31%
No. of Years of Commercial Ops. = 1.5
Duration of Outage
1000
500
2479
AVT
Relay
Main Coolant Pump Lubrication System
Condenser Tube Plug
Startup Test
Generator Fault
Condenser Tube
Transformer Failure
1
2
3
4
5
6
7
8
Time (Years Following Initial Criticality)

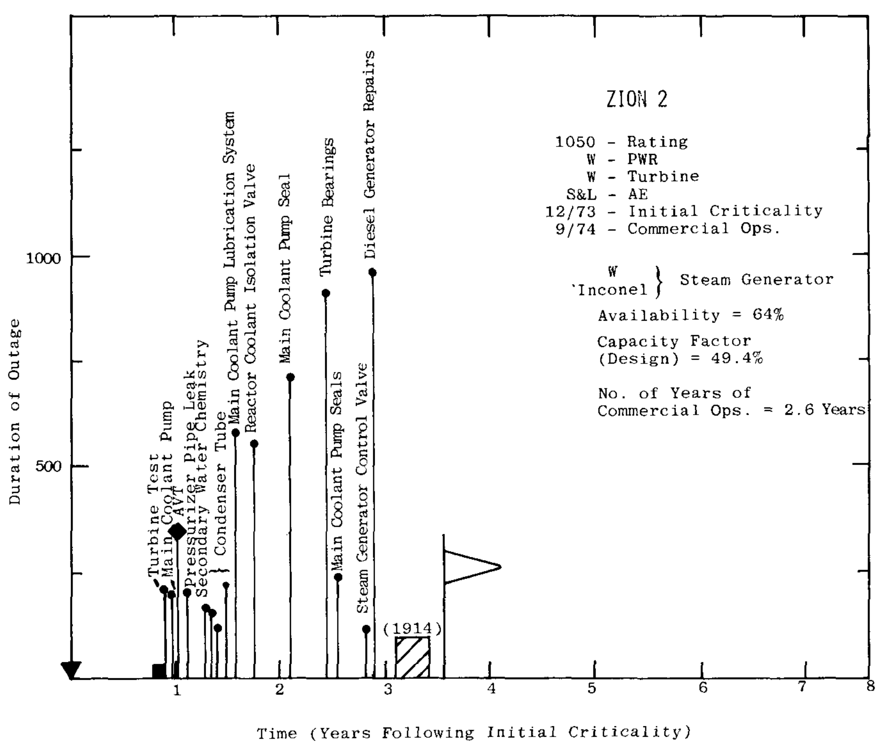


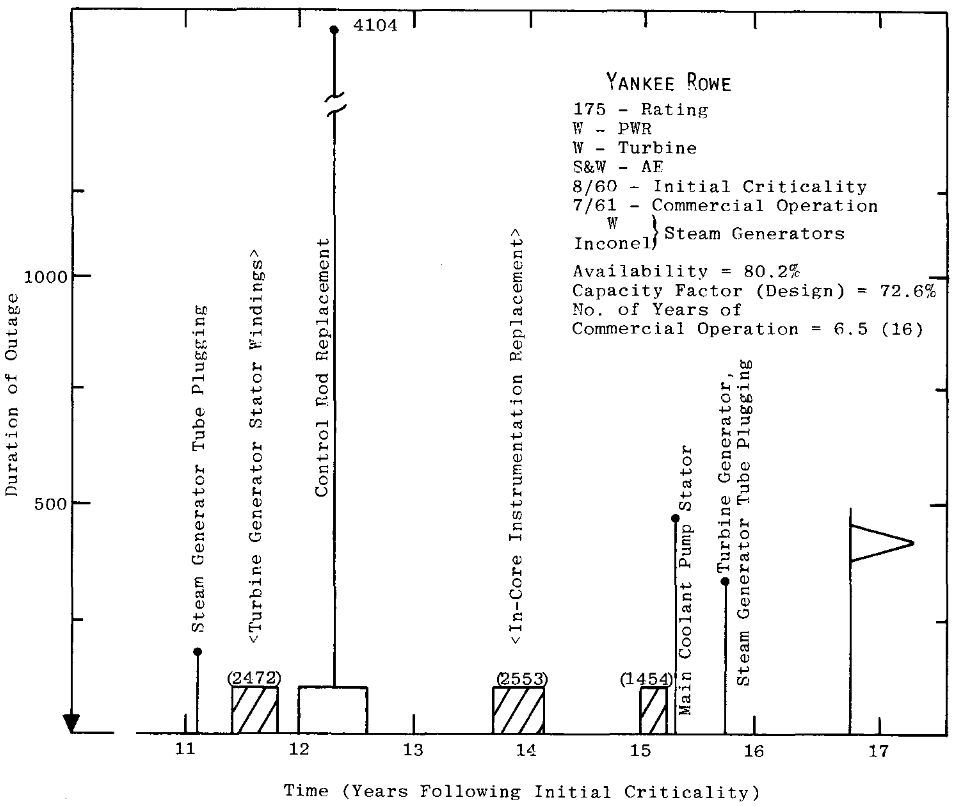
TURKEY POINT 3
728 - Rating
W - PWR
W - turbine
Bechtel - AE
10/72 - Initial Criticality
12/72 - Commercial Ops.
W Inconel } Steam Generator
Availability = 76.7%
Capacity Factor (Design) = 65.2%
No. of Years of Commercial Ops. = 4.6
Duration of Outage
1000
500
Feedwater Pump
Battery Room
Moisture Separator
Snubber Inspection
Snubber Inspection
Steam Pipe Modifications
Snubber Inspection
Snubber Inspection
AVT
Steam Generator Tube Plugging
Turbine Control Valve
Snubber Inspection
Steam Generator Tube Plugging
Containment
Steam Generator Tube Plugging
Not Specified
(1725)
(1442)
(1595)
1
2
3
4
5
6
7
8

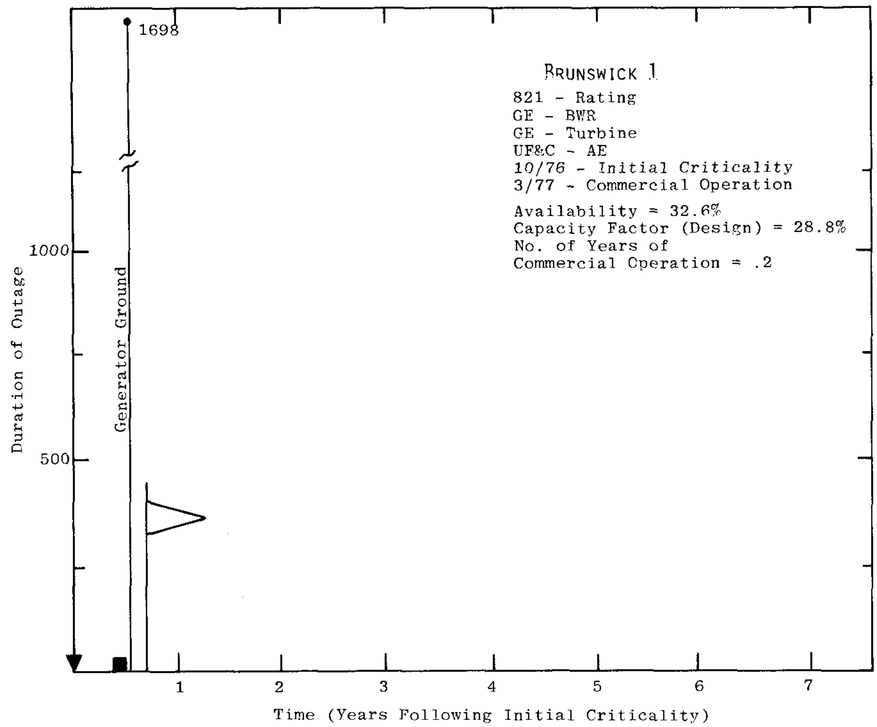


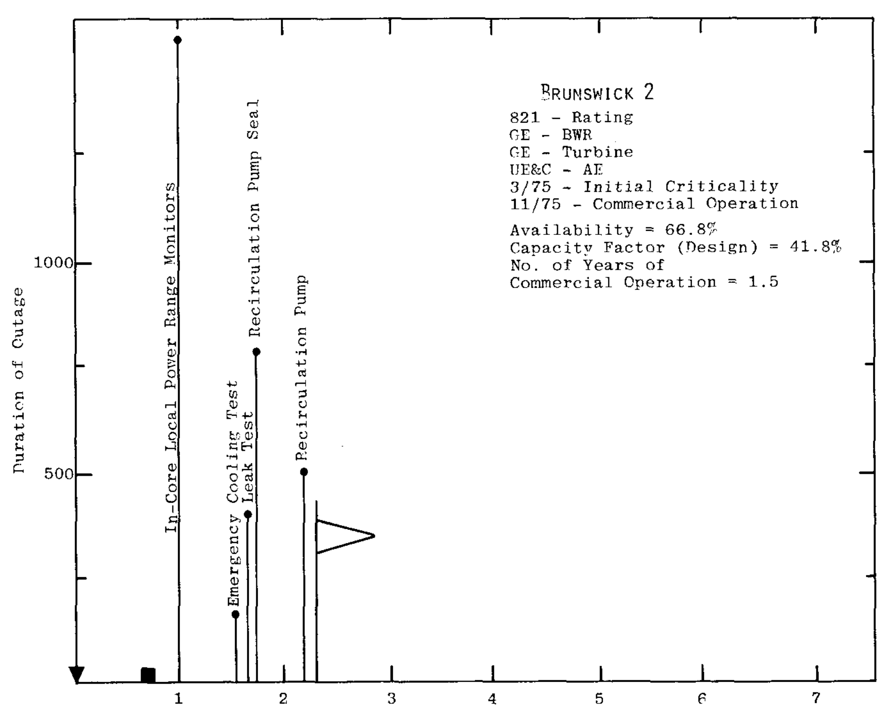
TURKEY POINT 4
728 - Rating
W - PWR
W - Turbine
Bechtel - AE
6/73 - Initial Criticality
9/73 - Commercial Ops.
W Inconel } Steam Generator
Availability = 68.2%
Capacity Factor (Design) = 63.7%
No. of Years of Commercial Ops. = 3.6
Duration of Outage
1000
500
Snubber Inspection
Steam Pipe Modification
Snubber Inspection
AVT
Steam Generator Pipe
Steam Generator Tube Plugging & Inspection
(2009)
(1224)
1
2
3
4
5
6
7
8
Time (Years Following Initial Criticality)

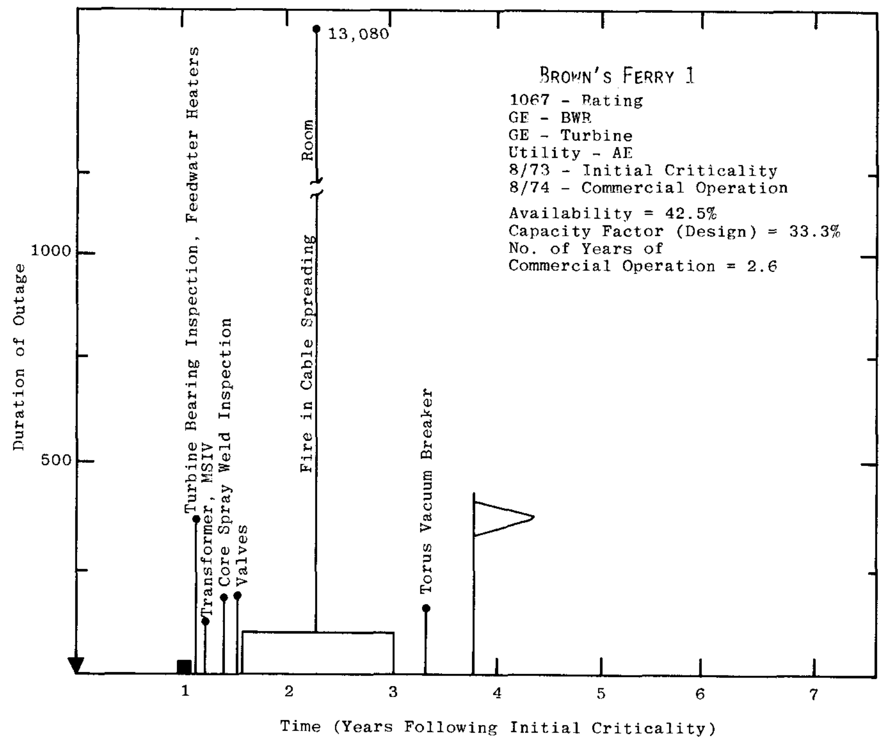

ZION 1
1050 - Rating
W - PWR
W - Turbine
S&L - AE
6/73 - Initial Criticality
12/73 - Commercial Ops.
W
Inconel
Steam Generators
Availability = 67.9%
Capacity Factor (Design) = 52.1%
No. of Years of Commercial Ops. = 3.5 Yrs.
Duration of Outage
Time (Years Following Initial Criticality)
2494
Turbine Generator, AVT Chemistry
Turbine
MSIV- Main Steam Isolation Valve
Primary Coolant Leak
Condenser Tube
AVT
Change Secondary Chemistry
Main Coolant Pump Seals
Valves
(1944)
Mainstream Isolation Valves, Main Coolant Pump Seals
Feedwater Pipe Hangers
1000
500
1
2
3
4
5
6
7
8

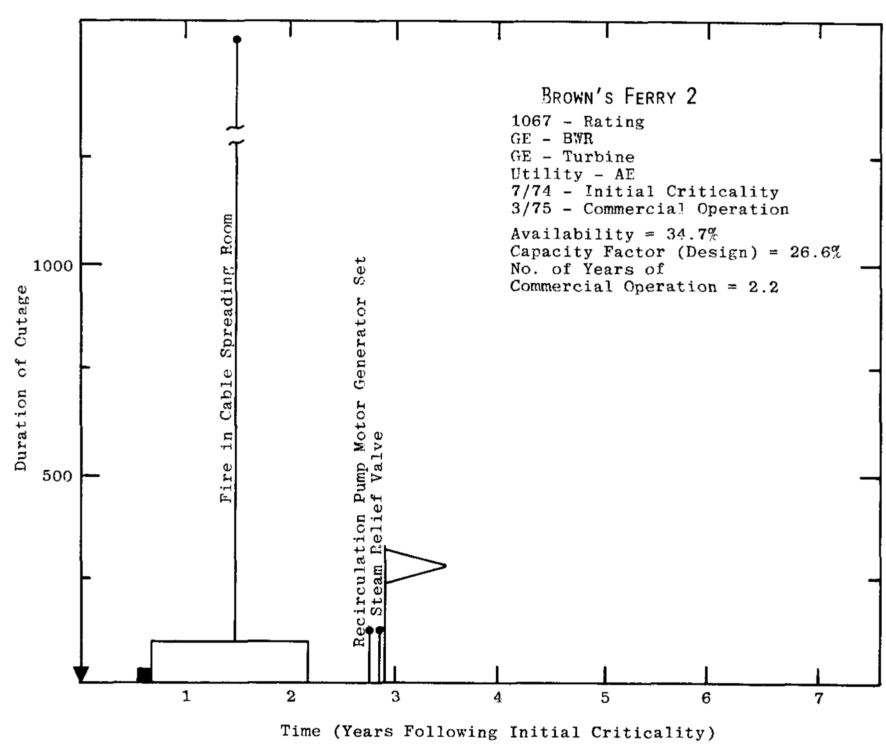

ZION 2
1050 - Rating
W - PWR
W - Turbine
S&L - AE
12/73 - Initial Criticality
9/74 - Commercial Ops.
W
Inconel
Steam Generator
Availability = 64%
Capacity Factor (Design) = 49.4%
No. of Years of Commercial Ops. = 2.6 Years
Duration of Outage
Time (Years Following Initial Criticality)
Turbine Test
Main Coolant Pump
AVT
Pressurizer Pipe Leak
Secondary Water Chemistry
Condenser Tube
Main Coolant Pump Lubrication System
Reactor Coolant Isolation Valve
Main Coolant Pump Seal
Turbine Bearings
Main Coolant Pump Seals
Steam Generator Control Valve
Diesel Generator Repairs
(1914)
1000
500
1
2
3
4
5
6
7
8

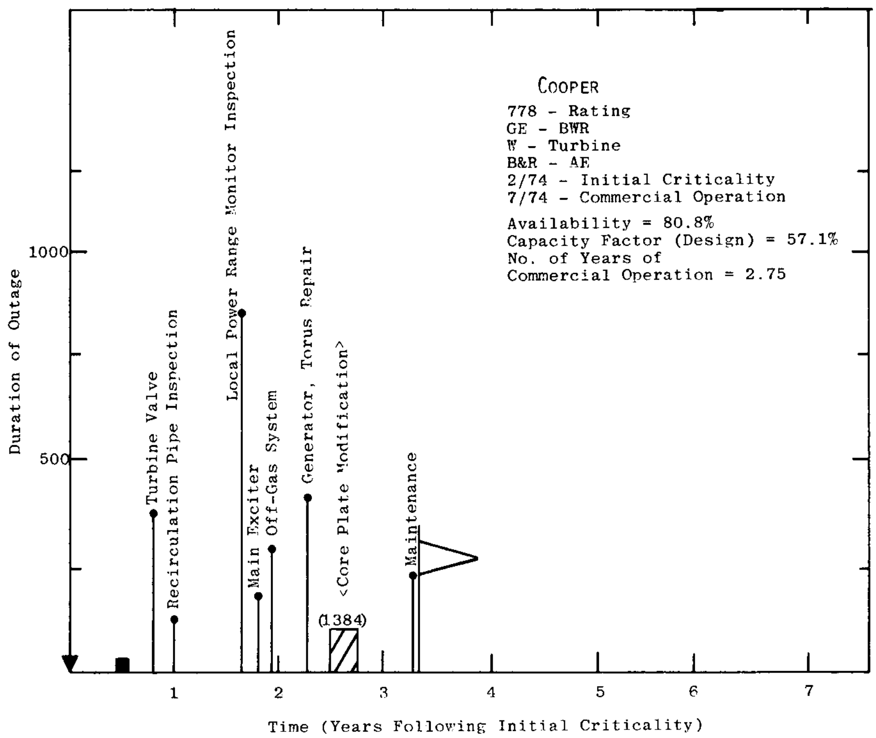

4104
YANKEE ROWE
175 - Rating
W - PWR
W - Turbine
S&W - AE
8/60 - Initial Criticality
7/61 - Commercial Operation
W
Inconel } Steam Generators
Availability = 80.2%
Capacity Factor (Design) = 72.6%
No. of Years of
Commercial Operation = 6.5 (16)
Steam Generator Tube Plugging
<Turbine Generator Stator Windings>
Control Rod Replacement
<In-Core Instrumentation Replacement>
Main Coolant Pump Stator
Turbine Generator, Steam Generator Tube Plugging
(2472)
(2553)
(1454)
1000
500
Duration of Outage
11
12
13
14
15
16
17
Time (Years Following Initial Criticality)

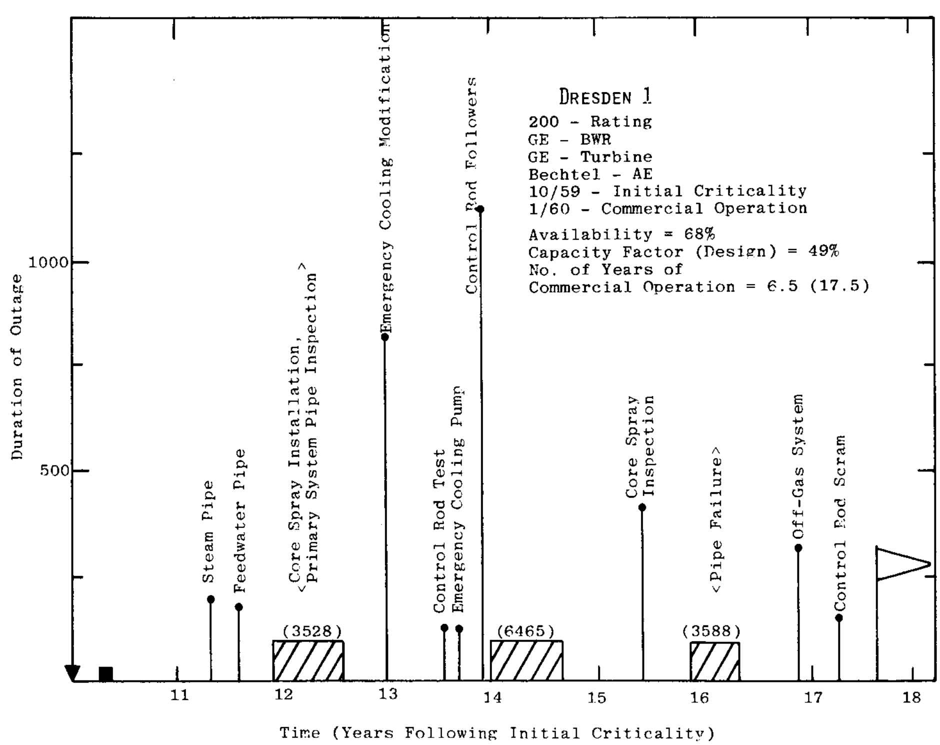

1698
BRUNSWICK 1
821 - Rating
GE - BWR
GE - Turbine
UE&C - AE
10/76 - Initial Criticality
3/77 - Commercial Operation
Availability = 32.6%
Capacity Factor (Design) = 28.8%
No. of Years of
Commercial Operation = .2
Generator Ground
Duration of Outage
1000
500
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

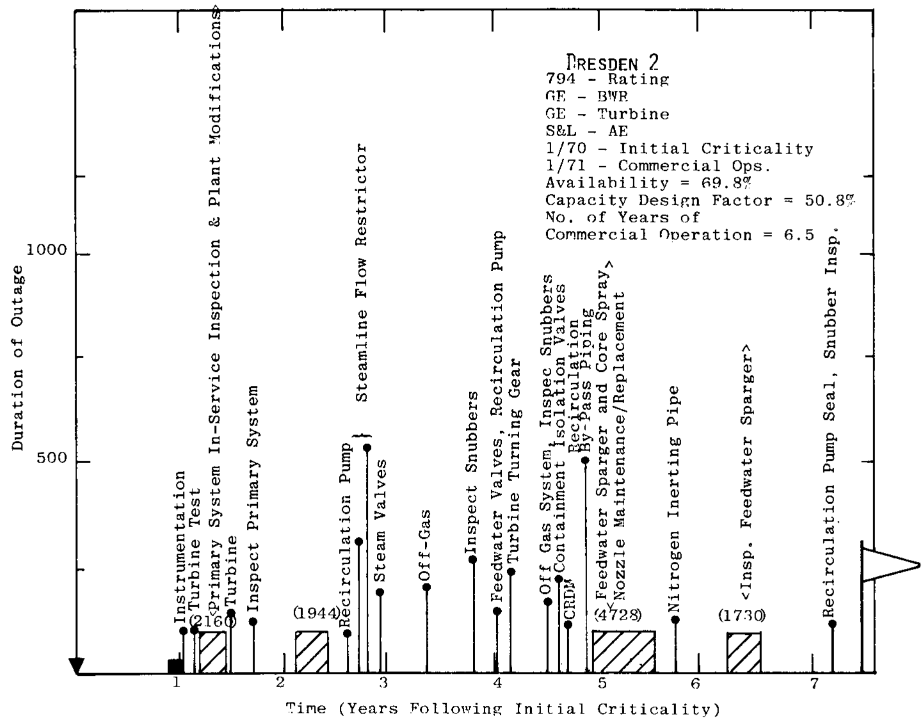

BRUNSWICK 2
821 - Rating
GE - BWR
GE - Turbine
UE&C - AE
3/75 - Initial Criticality
11/75 - Commercial Operation
Availability = 66.8%
Capacity Factor (Design) = 41.8%
No. of Years of
Commercial Operation = 1.5
In-Core Local Power Range Monitors
Emergency Cooling Test
Leak Test
Recirculation Pump Seal
Recirculation Pump
Duration of Outage
1000
500
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

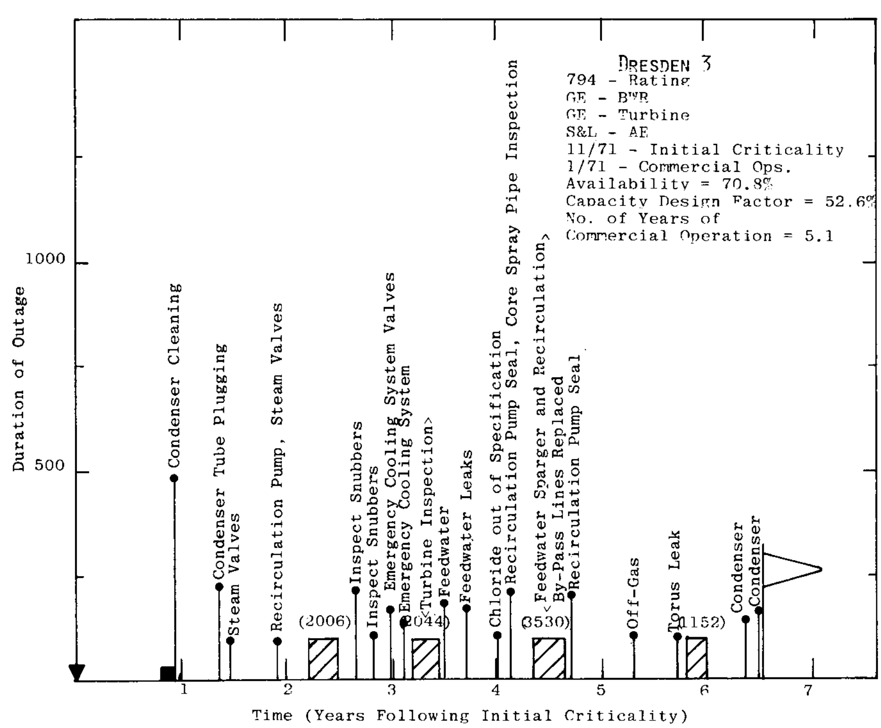

13,080
BROWN'S FERRY 1
1067 - Rating
GE - BWR
GE - Turbine
Utility - AE
8/73 - Initial Criticality
8/74 - Commercial Operation
Availability = 42.5%
Capacity Factor (Design) = 33.3%
No. of Years of
Commercial Operation = 2.6
Turbine Bearing Inspection, Feedwater Heaters
Transformer, MSIV
Core Spray Weld Inspection
Valves
Fire in Cable Spreading Room
Torus Vacuum Breaker
Duration of Outage
1000
500
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

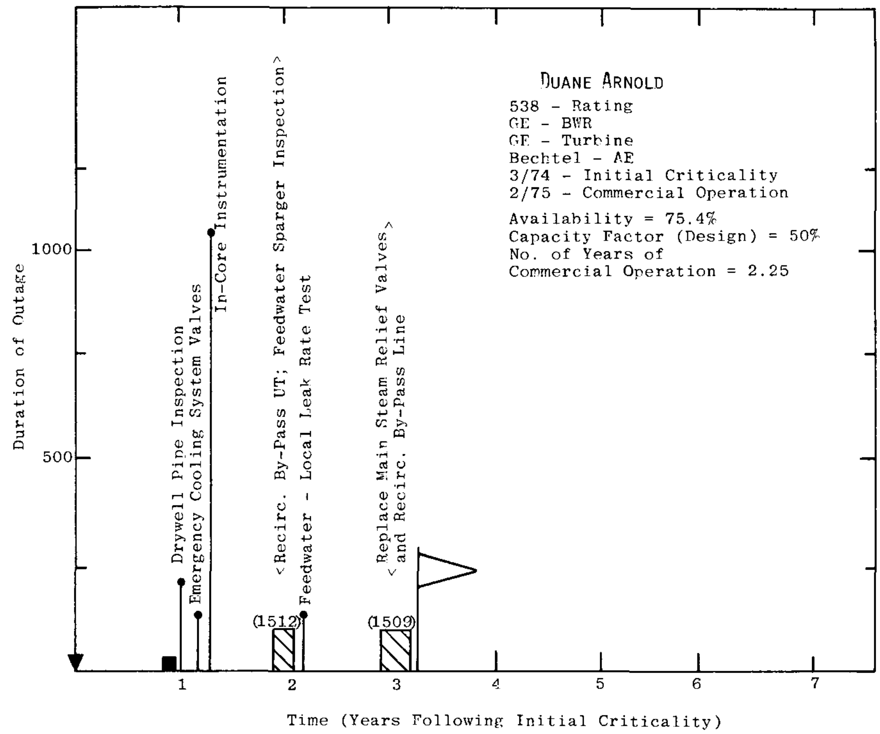

BROWN'S FERRY 2
1067 - Rating
GE - BWR
GE - Turbine
Utility - AE
7/74 - Initial Criticality
3/75 - Commercial Operation
Availability = 34.7%
Capacity Factor (Design) = 26.6%
No. of Years of
Commercial Operation = 2.2
Fire in Cable Spreading Room
Recirculation Pump Motor Generator Set
Steam Relief Valve
Duration of Outage
1000
500
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

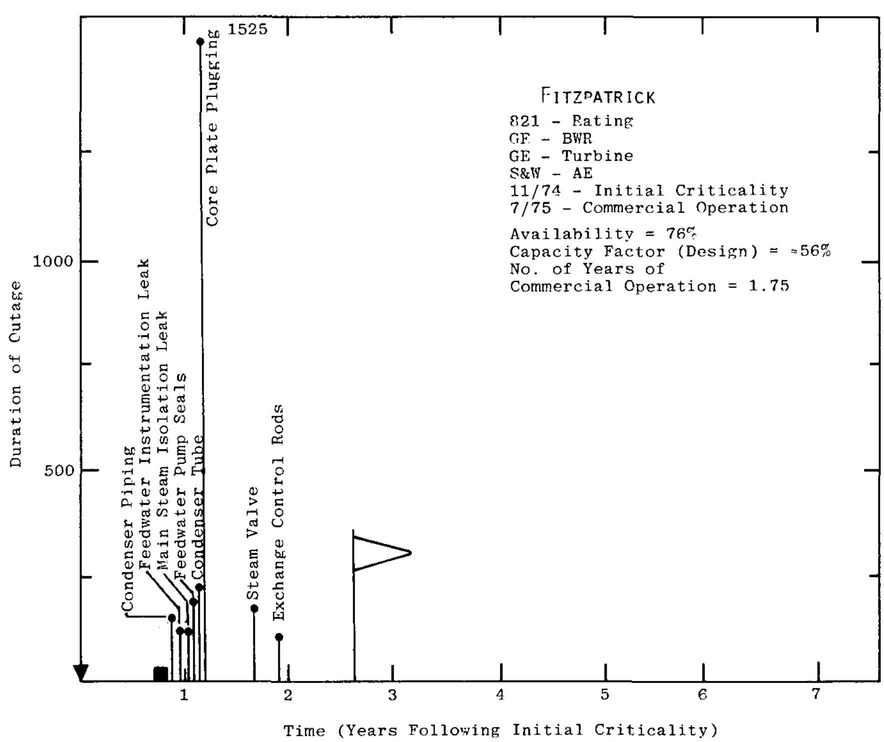

COOPER
778 - Rating
GE - BWR
W - Turbine
B&R - AE
2/74 - Initial Criticality
7/74 - Commercial Operation
Availability = 80.8%
Capacity Factor (Design) = 57.1%
No. of Years of
Commercial Operation = 2.75
Turbine Valve
Recirculation Pipe Inspection
Local Power Range Monitor Inspection
Main Exciter
Off-Gas System
Generator, Torus Repair
<Core Plate Modification>
(1384)
Maintenance
Duration of Outage
1000
500
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

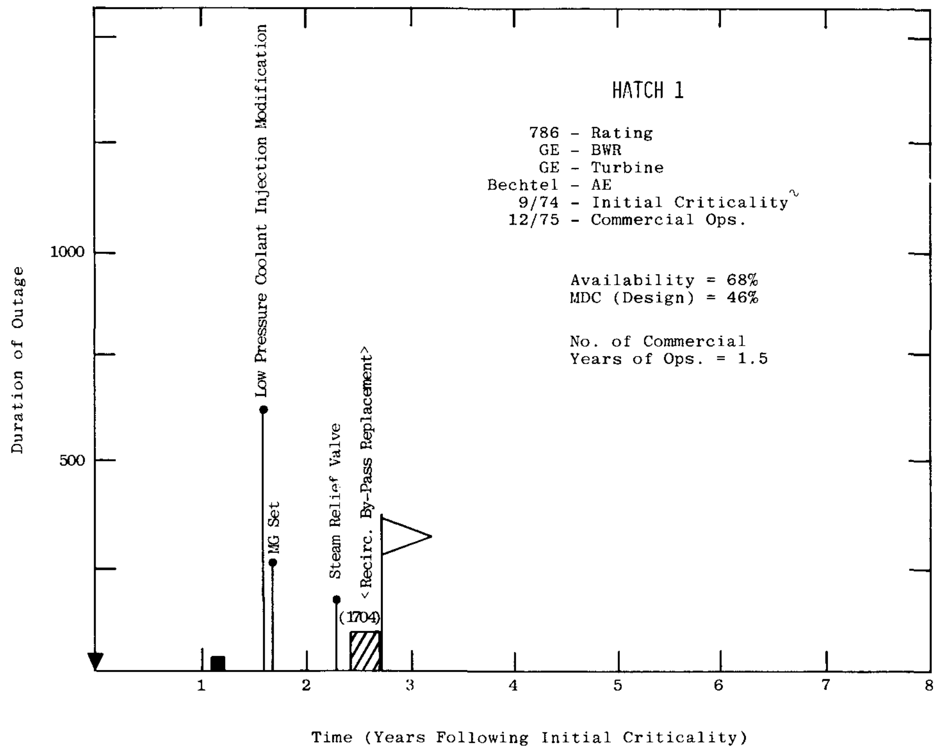

DRESDEN 1
200 - Rating
GE - BWR
GE - Turbine
Bechtel - AE
10/59 - Initial Criticality
1/60 - Commercial Operation
Availability = 68%
Capacity Factor (Design) = 49%
No. of Years of
Commercial Operation = 6.5 (17.5)
Steam Pipe
Feedwater Pipe
Core Spray Installation,
<Primary System Pipe Inspection>
(3528)
Emergency Cooling Modification
Control Rod Test
Emergency Cooling Pump
Control Rod Followers
(6465)
Core Spray
Inspection
<Pipe Failure>
(3588)
Off-Gas System
Control Rod Scram
Duration of Outage
1000
500
11
12
13
14
15
16
17
18
Time (Years Following Initial Criticality)

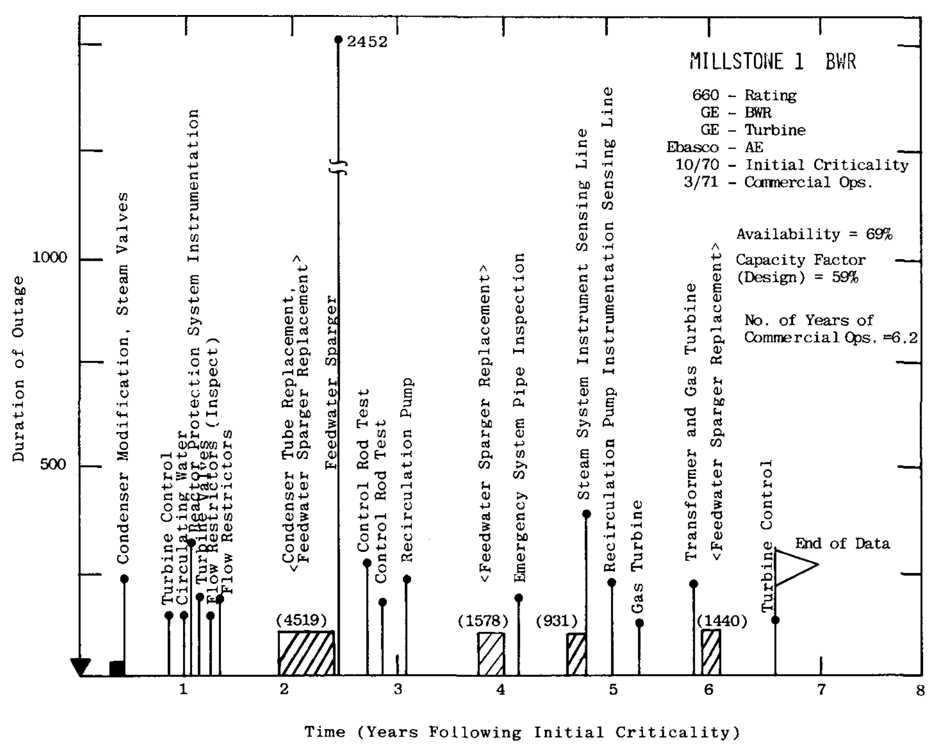

DRESDEN 2
794 - Rating
GE - BWR
GE - Turbine
S&L - AE
1/70 - Initial Criticality
1/71 - Commercial Ops.
Availability = 69.8%
Capacity Design Factor = 50.8%
No. of Years of
Commercial Operation = 6.5
Duration of Outage
Time (Years Following Initial Criticality)

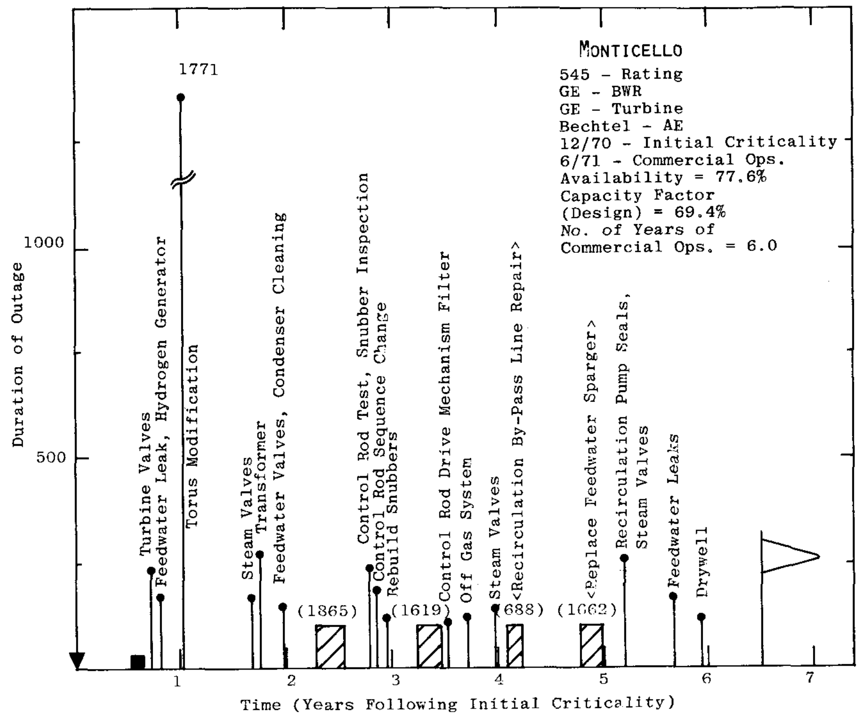

DRESDEN 3
794 - Rating
GE - BWR
GE - Turbine
S&L - AE
11/71 - Initial Criticality
1/71 - Commercial Ops.
Availability = 70.8%
Capacity Design Factor = 52.6%
No. of Years of
Commercial Operation = 5.1
Duration of Outage
Time (Years Following Initial Criticality)

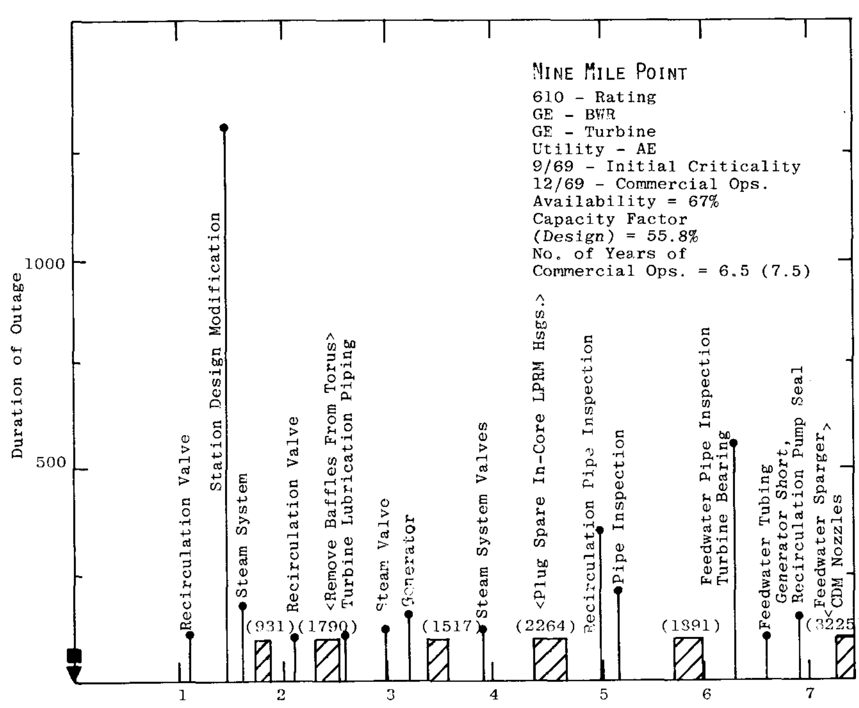

DUANE ARNOLD
538 - Rating
GE - BWR
GE - Turbine
Bechtel - AE
3/74 - Initial Criticality
2/75 - Commercial Operation
Availability = 75.4%
Capacity Factor (Design) = 50%
No. of Years of
Commercial Operation = 2.25
Duration of Outage
1000
500
Drywell Pipe Inspection
Emergency Cooling System Valves
In-Core Instrumentation
<Recirc. By-Pass UT; Feedwater Sparger Inspection>
Feedwater - Local Leak Rate Test
Replace Main Steam Relief Valves
and Recirc. By-Pass Line
(1512)
(1509)
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

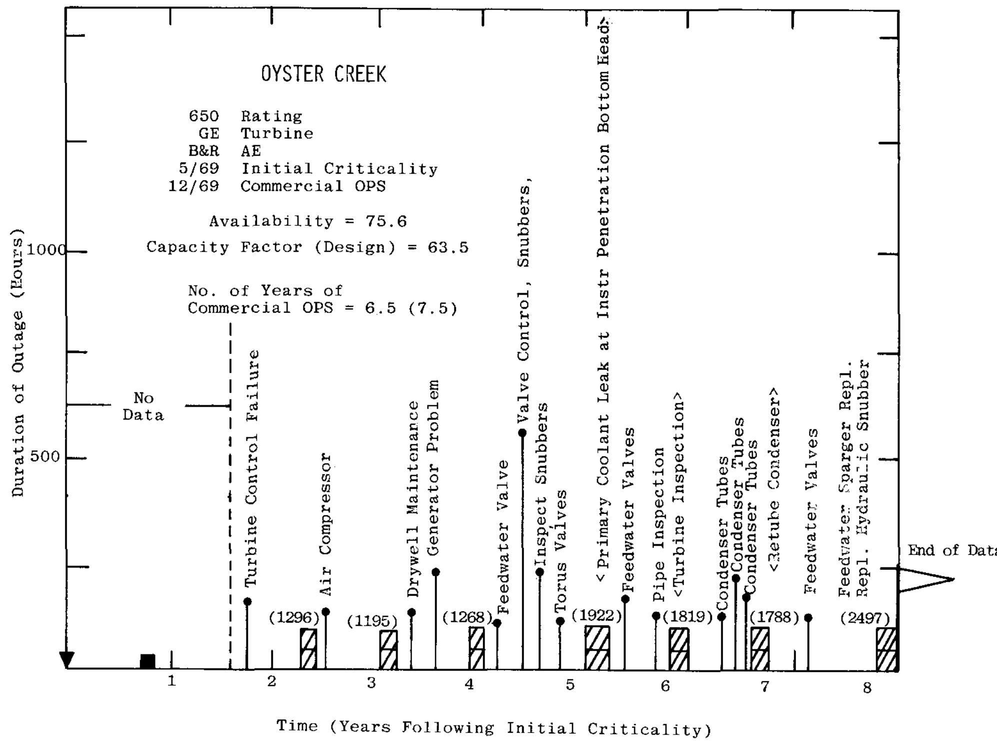

FITZPATRICK
821 - Rating
GE - BWR
GE - Turbine
S&W - AE
11/74 - Initial Criticality
7/75 - Commercial Operation
Availability = 76%
Capacity Factor (Design) = ≈56%
No. of Years of
Commercial Operation = 1.75
Duration of Outage
1000
500
1525
Core Plate Plugging
Condenser Piping
Feedwater Instrumentation Leak
Main Steam Isolation Leak
Feedwater Pump Seals
Condenser Tube
Steam Valve
Exchange Control Rods
1
2
3
4
5
6
7
Time (Years Following Initial Criticality)

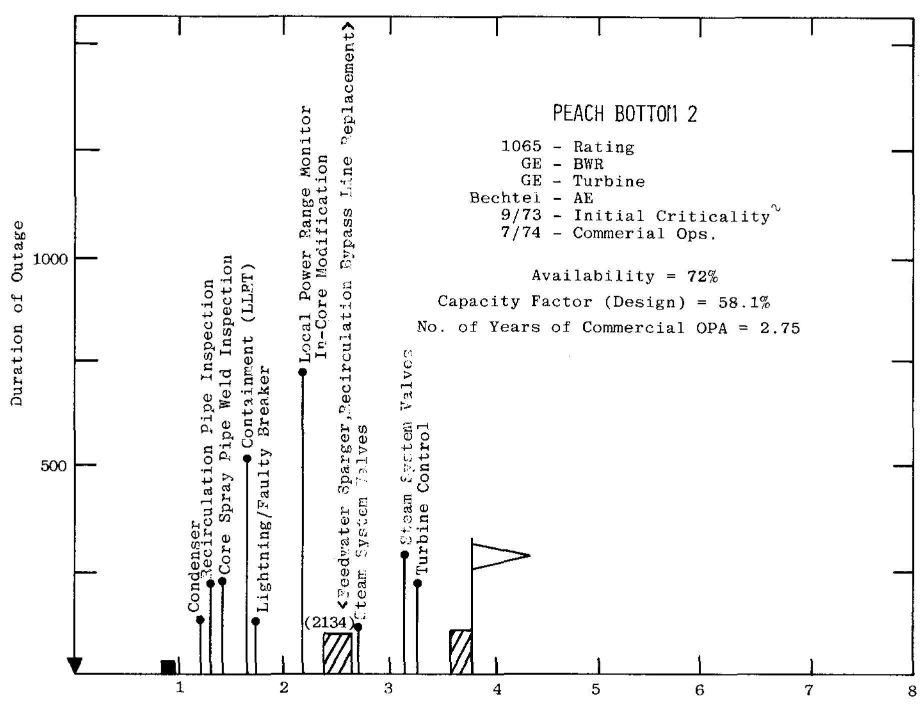

HATCH 1
786 - Rating
GE - BWR
GE - Turbine
Bechtel - AE
9/74 - Initial Criticality
12/75 - Commercial Ops.
Availability = 68%
MDC (Design) = 46%
No. of Commercial Years of Ops. = 1.5
Low Pressure Coolant Injection Modification
MG Set
Steam Relief Valve
<Recirc. By-Pass Replacement>
(1704)
Duration of Outage
1000
500
1
2
3
4
5
6
7
8
Time (Years Following Initial Criticality)

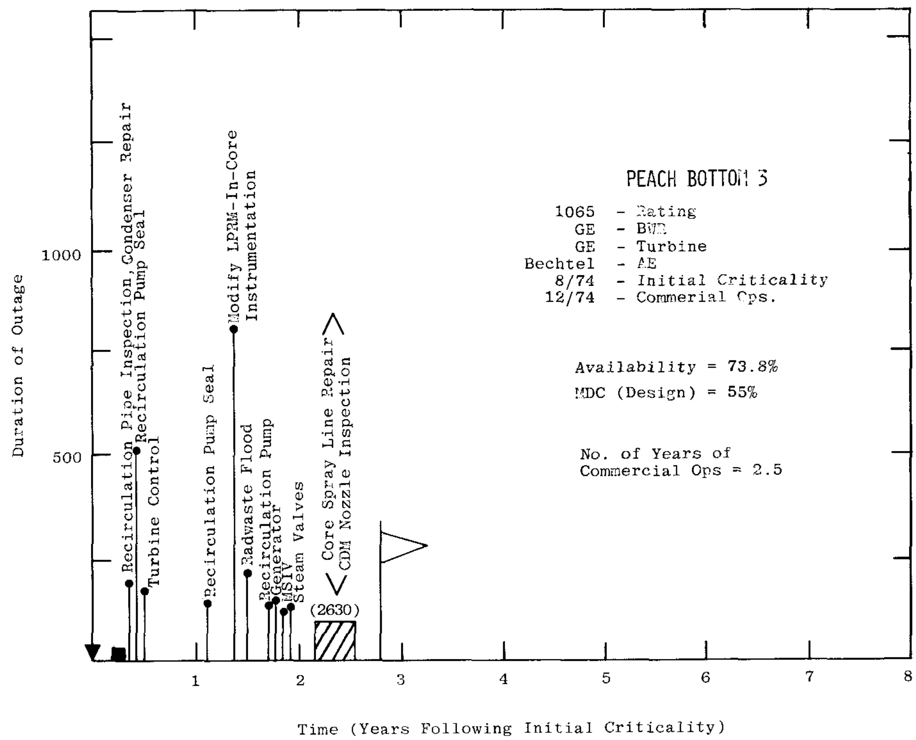

MILLSTONE 1 BWR
660 - Rating
GE - BWR
GE - Turbine
Ebasco - AE
10/70 - Initial Criticality
3/71 - Commercial Ops.
Availability = 69%
Capacity Factor (Design) = 59%
No. of Years of Commercial Ops. =6.2
2452
Condenser Modification, Steam Valves
Turbine Control
Circulating Water
Reactor Protection System Instrumentation
Turbine Valves (Inspect)
Flow Restrictors
Flow Restrictors
<Condenser Tube Replacement, Feedwater Sparger Replacement>
Feedwater Sparger
Control Rod Test
Control Rod Test
Recirculation Pump
<Feedwater Sparger Replacement>
Emergency System Pipe Inspection
Steam System Instrument Sensing Line
Recirculation Pump Instrumentation Sensing Line
Gas Turbine
Transformer and Gas Turbine
<Feedwater Sparger Replacement>
Turbine Control
End of Data
(4519)
(1578)
(931)
(1440)
Duration of Outage
1000
500
1
2
3
4
5
6
7
8
Time (Years Following Initial Criticality)

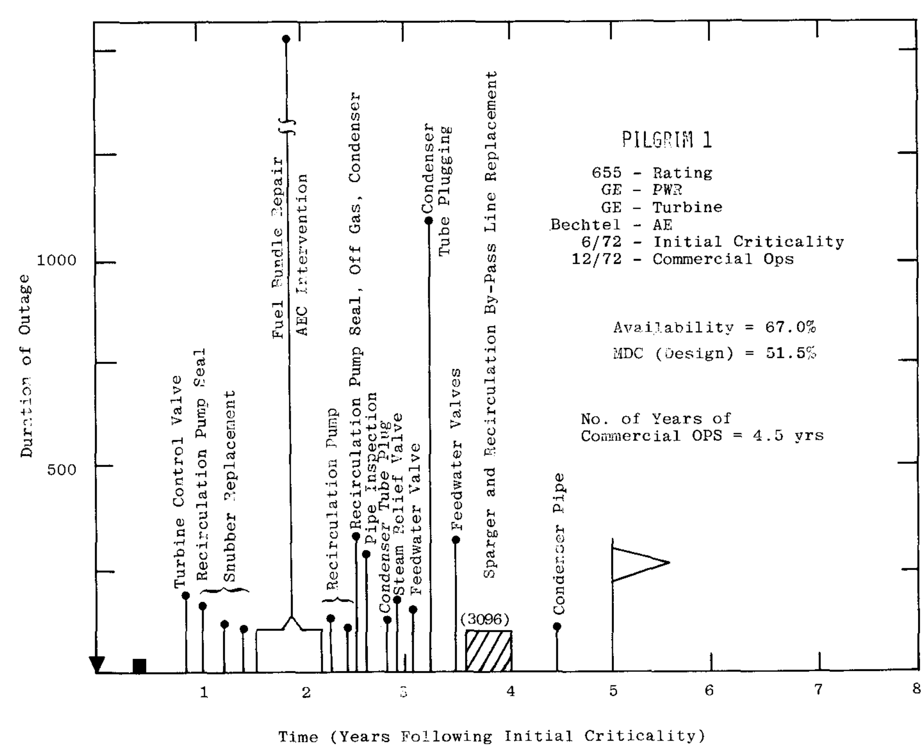

MONTICELLO
545 - Rating
GE - BWR
GE - Turbine
Bechtel - AE
12/70 - Initial Criticality
6/71 - Commercial Ops.
Availability = 77.6%
Capacity Factor
(Design) = 69.4%
No. of Years of
Commercial Ops. = 6.0
Duration of Outage
Time (Years Following Initial Criticality)
1771
(1865)
(1619)
(688)
(1662)
Turbine Valves
Feedwater Leak, Hydrogen Generator
Torus Modification
Steam Valves
Transformer
Feedwater Valves, Condenser Cleaning
Control Rod Test, Snubber Inspection
Control Rod Sequence Change
Rebuild Snubbers
Control Rod Drive Mechanism Filter
Off Gas System
Steam Valves
<Recirculation By-Pass Line Repair>
<Replace Feedwater Sparger>
Recirculation Pump Seals,
Steam Valves
Feedwater Leaks
Drywell

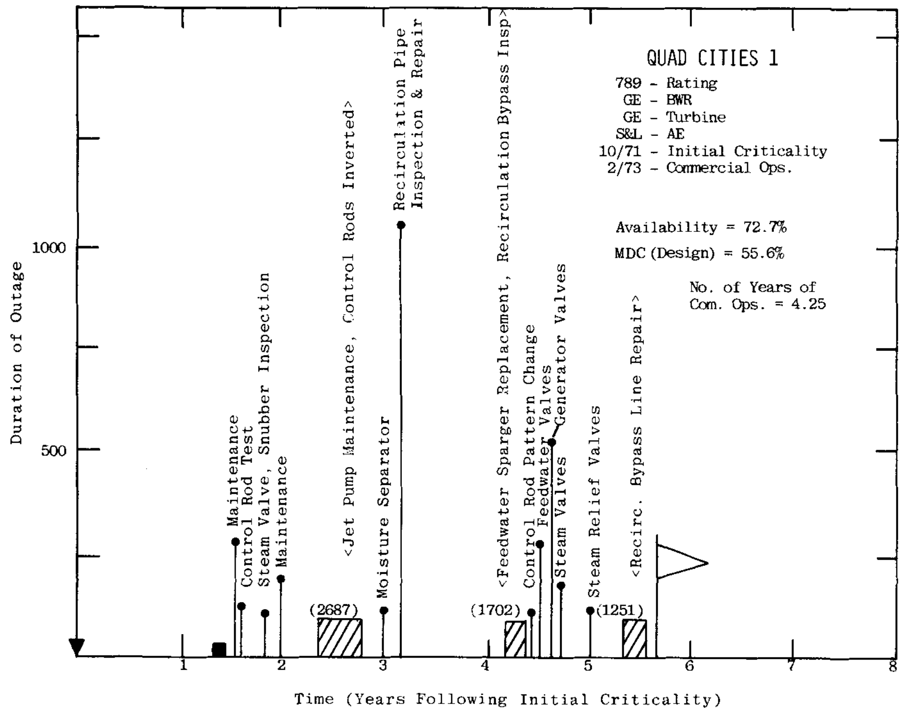

NINE MILE POINT
610 - Rating
GE - BWR
GE - Turbine
Utility - AE
9/69 - Initial Criticality
12/69 - Commercial Ops.
Availability = 67%
Capacity Factor
(Design) = 55.8%
No. of Years of
Commercial Ops. = 6.5 (7.5)
Duration of Outage
Time (Years Following Initial Criticality)
(931)
(1790)
(1517)
(2264)
(1391)
(3225)
Recirculation Valve
Station Design Modification
Steam System
Recirculation Valve
<Remove Baffles From Torus>
Turbine Lubrication Piping
Steam Valve
Generator
Steam System Valves
<Plug Spare In-Core LPRM Hsgs.>
Recirculation Pipe Inspection
Pipe Inspection
Feedwater Pipe Inspection
Turbine Bearing
Feedwater Tubing
Generator Short,
Recirculation Pump Seal
<Feedwater Sparger,
CDM Nozzles>

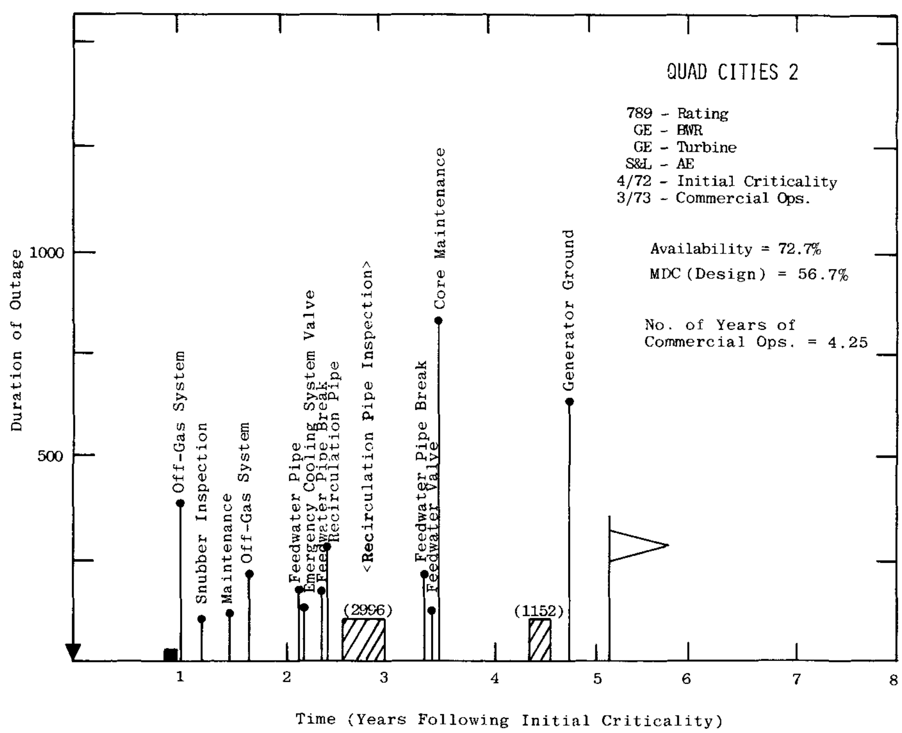

OYSTER CREEK
650 Rating
GE Turbine
B&R AE
5/69 Initial Criticality
12/69 Commercial OPS
Availability = 75.6
Capacity Factor (Design) = 63.5
No. of Years of Commercial OPS = 6.5 (7.5)
Duration of Outage (Hours)
1000
500
No Data
Turbine Control Failure
(1296)
Air Compressor
(1195)
Drywell Maintenance
Generator Problem
(1268)
Feedwater Valve
Valve Control, Snubbers,
Inspect Snubbers
Torus Valves
(1922)
< Primary Coolant Leak at Instr Penetration Bottom Head>
Feedwater Valves
Pipe Inspection
(1819)
<Turbine Inspection>
Condenser Tubes
Condenser Tubes
Condenser Tubes
(1788)
<Retube Condenser>
Feedwater Valves
(2497)
Feedwater Sparger Repl.
Repl. Hydraulic Snubber
End of Data
1
2
3
4
5
6
7
8
Time (Years Following Initial Criticality)

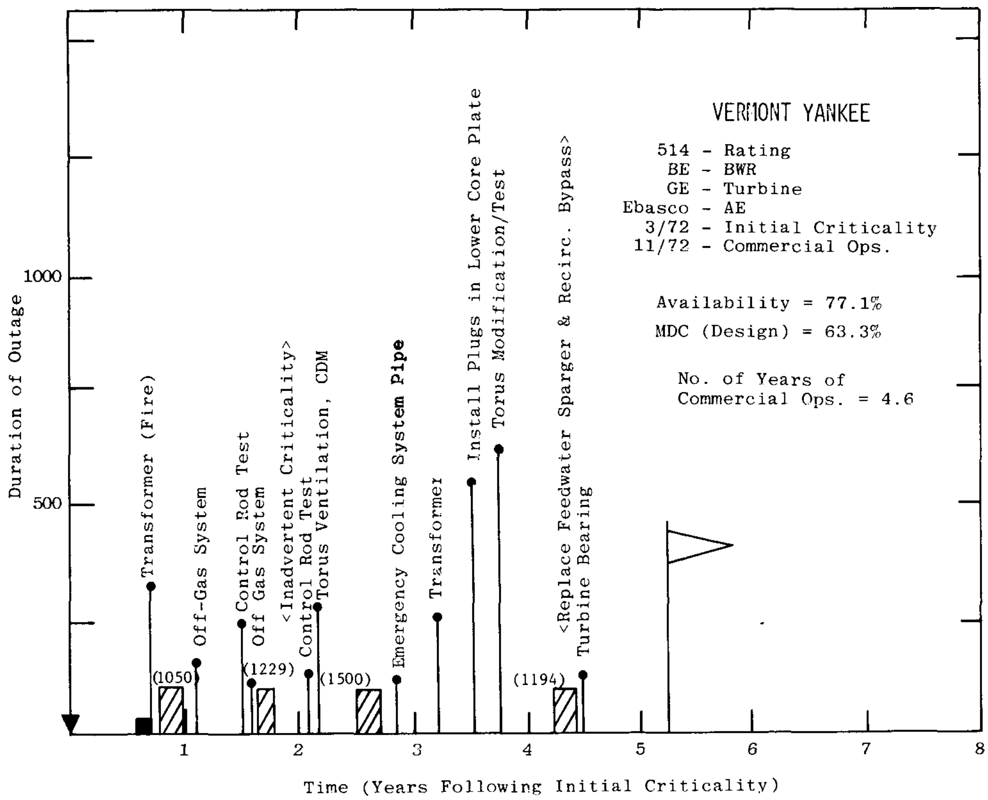

PEACH BOTTOM 2
1065 - Rating
GE - BWR
GE - Turbine
Bechtel - AE
9/73 - Initial Criticality
7/74 - Commerial Ops.
Availability = 72%
Capacity Factor (Design) = 58.1%
No. of Years of Commercial OPA = 2.75
Duration of Outage
1000
500
Condenser
Recirculation Pipe Inspection
Core Spray Pipe Weld Inspection
Containment (LLRT)
Lightning/Faulty Breaker
Local Power Range Monitor
In-Core Modification
(2134)
<Feedwater Sparger, Recirculation Bypass Line Replacement>
Steam System Valves
Steam System Valves
Turbine Control
1
2
3
4
5
6
7
8
Time (Years Following Initial Criticality)


PEACH BOTTOM 3
1065 - Rating
GE - BWR
GE - Turbine
Bechtel - AE
8/74 - Initial Criticality
12/74 - Commerial Ops.
Availability = 73.8%
MDC (Design) = 55%
No. of Years of
Commercial Ops = 2.5
Recirculation Pipe Inspection, Condenser Repair
Recirculation Pump Seal
Turbine Control
Recirculation Pump Seal
Modify LPRM-In-Core
Instrumentation
Radwaste Flood
Recirculation Pump
Generator
MSIV
Steam Valves
Core Spray Line Repair
CDM Nozzle Inspection
(2630)
Duration of Outage
1000
500
1
2
3
4
5
6
7
8
Time (Years Following Initial Criticality)


PILGRIM 1
655 - Rating
GE - PWR
GE - Turbine
Bechtel - AE
6/72 - Initial Criticality
12/72 - Commercial Ops
Availability = 67.0%
MDC (Design) = 51.5%
No. of Years of
Commercial OPS = 4.5 yrs
Turbine Control Valve
Recirculation Pump Seal
Snubber Replacement
Fuel Bundle Repair
AEC Intervention
Recirculation Pump
Recirculation Pump Seal, Off Gas, Condenser
Pipe Inspection
Condenser Tube Plug
Steam Relief Valve
Feedwater Valve
Condenser
Tube Plugging
Feedwater Valves
Sparger and Recirculation By-Pass Line Replacement
(3096)
Condenser Pipe
Duration of Outage
1000
500
1
2
3
4
5
6
7
8
Time (Years Following Initial Criticality)


QUAD CITIES 1
789 - Rating
GE - BWR
GE - Turbine
S&L - AE
10/71 - Initial Criticality
2/73 - Commercial Ops.
Availability = 72.7%
MDC (Design) = 55.6%
No. of Years of
Com. Ops. = 4.25
Duration of Outage
Time (Years Following Initial Criticality)
Maintenance
Control Rod Test
Steam Valve, Snubber Inspection
Maintenance
<Jet Pump Maintenance, Control Rods Inverted>
Moisture Separator
Recirculation Pipe
Inspection & Repair
<Feedwater Sparger Replacement, Recirculation Bypass Insp>
Control Rod Pattern Change
Feedwater Valves
Generator Valves
Steam Valves
Steam Relief Valves
<Recirc. Bypass Line Repair>
(2687)
(1702)
(1251)


QUAD CITIES 2
789 - Rating
GE - BWR
GE - Turbine
S&L - AE
4/72 - Initial Criticality
3/73 - Commercial Ops.
Availability = 72.7%
MDC (Design) = 56.7%
No. of Years of
Commercial Ops. = 4.25
Duration of Outage
Time (Years Following Initial Criticality)
Off-Gas System
Snubber Inspection
Maintenance
Off-Gas System
Feedwater Pipe
Emergency Cooling System Valve
Feedwater Pipe Break
Recirculation Pipe
<Recirculation Pipe Inspection>
Feedwater Pipe Break
Feedwater Valve
Core Maintenance
Generator Ground
(2996)
(1152)


VERMONT YANKEE
514 - Rating
BE - BWR
GE - Turbine
Ebasco - AE
3/72 - Initial Criticality
11/72 - Commercial Ops.
Availability = 77.1%
MDC (Design) = 63.3%
No. of Years of
Commercial Ops. = 4.6
Duration of Outage
1000
500
Transformer (Fire)
Off-Gas System
Control Rod Test
Off Gas System
<Inadvertent Criticality>
Control Rod Test
Torus Ventilation, CDM
Emergency Cooling System Pipe
Transformer
Install Plugs in Lower Core Plate
Torus Modification/Test
<Replace Feedwater Sparger & Recirc. Bypass>
Turbine Bearing
(1050)
(1229)
(1500)
(1194)
1
2
3
4
5
6
7
8
Time (Years Following Initial Criticality)

APPENDIX B

EUROPEAN LIGHT WATER REACTORS (>150 MWe) CONSIDERED IN THIS REPORT FOR COMPARISON PURPOSES

APPENDIX B European Light Water Reactors (>150 MWe) Considered in this Report for Comparison Purposes

Plant	LWR	MWe	Date of Commercial Operation	Country
Ardennes (Chooz)	PWR	305	4/67	France
KKS Stade	PWR	630	5/72	Germany
KRB Gundremminger	BWR	237	1/67	Germany
KWL Lingen	BWR	256	10/68	Germany
KWO Obrigheim	PWR	328	3/69	Germany
Trino Vercellese	PWR	260	1/65	Italy
Kerncentrale Borssele	PWR	447	10/74	Netherlands
Jose Cabrera (Zorita-1)	PWR	153	8/69	Spain
Santa Maria DeGarona	BWR	440	5/71	Spain
Oskarshamn-1	BWR	440	2/72	Sweden
Oskarshamn-2	BWR	580	12/74	Sweden
Atomkraftwerk Beznau 1	PWR	350	9/69	Switzerland
Atomkraftwerk Beznau 2	PWR	350	12/71	Switzerland
Kernkraftwerk Muhleberg	BWR	306	11/72	Switzerland

APPENDIX C

SUMMARY OF TYPICAL TECHNICAL SPECIFICATION TEST REQUIREMENTS AFFECTING REFUELING OUTAGES

APPENDIX C

SUMMARY OF TYPICAL PLANT TESTS PERFORMED DURING REFUELING OUTAGES

This appendix presents a summary of the typical tests required by plant technical specifications or NRC standards to be performed at frequencies set by the refueling outages. This summary is not meant to be a complete list of the testing, inspection, and calibration requirements, but rather a description of the principal testing requirements which have contributed to refueling outage extensions. Many of these tests are specified to be performed every operating cycle. The reason for tying refueling outages to the frequency of testing is that many of the tests must be performed while the plant is shutdown and the refueling outage represents a reasonably regular interval where the plant is available for such shutdown testing. Of course, much of the testing is necessary for the safe operation of the plant. However, the large amount of testing also creates an additional burden on the utility and the ability to minimize critical path time.

Perhaps a quantitative representation of the approximate amount of requirements added to nuclear plants over the past 8 years will lead to a better appreciation of the magnitude of the problem. The layering of additional requirements on nuclear power plants has been referred to elsewhere as a case of "regulatory excess".(31) In this appendix, the only point which needs to be made is that, in some cases, the benefit from additional testing may become prohibitively expensive in terms of the lost plant productivity. However, there is no good way to quantify the effects of increased regulatory action on plant productivity, especially during refueling outages. Therefore, we refer here to a qualitative assessment(31) which has compared the increase in regulatory requirements as a function of calendar year. From Figure C-1, note there is a steep upward acceleration in regulatory pronouncements in 1975-76. An average of three new requirements per month were issued in 1976, each with significant impact on NSSS design. Balance of plant impacts are not indicated here.

In this appendix the testing, inspection, and calibration requirements which are considered to potentially impact on the length of refueling outages are the following:

Core

- Core Verification
- Scram Timing of Control Rods
- Shutdown Margin Tests
- Fuel Inspections
- Power Distribution Maps

Primary System

- Hydrostatic Testing
- Instrument Calibration
- In-Service Inspection of Steam Generator Tubes (PWRs)
- In-Service Inspection of Primary System Welds

Primary Containment

- Local Leak Rate Tests
- Integrated Leak Rate Tests
- Main Steam Isolation Valve Testing (BWRs)
- Leak Test of the Drywell to Suppression Chamber Structure
- Pressure Suppression Chamber Test

- Standby Gas Treatment System

Safety Related Systems Tests

Pump and Valve Tests

Secondary Containment Tests

Turbine/Generator Inspections

The following is a brief summary description of some of the tests or inspections which have been noted to cause refueling outage extensions:

Core

a) Core Verification - usually involves underwater TV camera video tape of each core location for subsequent independent checks.

b) Scram Timing of Control Rods - involves ensuring that the time to scram the control rods is within the technical specifications after core refueling. Involves setting operation conditions

c) Shutdown Margin Test - involves ensuring that there is adequate negative reactivity shutdown margin in the control elements to shutdown the core under the worst postulated accident (e.g., one control element stuck out of the core)

d) Fuel Inspections - may involve sipping or visual exams for fuel bow or distortion.

e) Power Distribution Map - involves constant power operation at various levels during power ascension to ensure proper in-core power distributions.

Primary System

a) Hydrostatic Tests - of primary, secondary and safety-related systems usually require a high pressure within a specified temperature range for a given period of time within a specified leakage limit.

b) Instrument Calibration - involves checking set points and calibration of safety-related equipment. This is usually accomplished with minimum impact on critical path time.

c) Inservice Inspection of Pressurized Water Reactor Steam Generator Tubes (Regulatory Guide 1.83): The inspections to identify trends in steam generator tube wall thickness include the following:

 (1) Preservice inspection of all tubes in the steam generators to obtain baseline information

 (2) Major changes in secondary water chemistry (e.g., phosphate to volatile) should also be followed by a baseline inspection of all tubes

 (3) Subsequently at least 3% of steam generator tubes should be inspected at each inspection

 (4) Frequency:

  (a) First in-service inspection performed after 6 effective full power months but before 24 calendar months.

  (b) Subsequent in-service inspections should not be less than 12 months or more than 24 calendar months apart.

d) In-service inspection of class 1, 2 and 3 component pressure boundaries (as delineated in the ASME Boiler and Pressure Vessel Code Section XI)

(1) Components subject to inspection are:

(a) Pressure Vessels

(b) Piping

(c) Pumps - monthly

(d) Valves

(2) Types of Tests

(a) Hypostatic/Pressure Test (4 hours duration)

(b) Weld Inspections

(c) Visual Inspections

(3) Frequency

(a) 100% Weld Inspection shall be completed during each 10 year inspection period.

Primary Containment

a) Standard Review Plan (US Nuclear Regulatory Commission NUREG 75/087) Containment Leakage Rate Tests

(1) Containment Integrated Leakage Rate Test (Type A Test): perform at 3 equal intervals during each 10 year period

(2) Containment Penetration Leakage Rate Test (Type B Test) perform during each shutdown for refueling but not longer than 2 years. Air locks should be tested every 6 months.

(3) Containment Isolation Valve Leakage Test (Type C Test): perform during each shutdown for refueling but not at longer intervals than 2 years.

Safety System

a) Safety System Surveillance Tests - involve emergency core cooling systems and flow rate tests, logic system functional tests, pump and valve operation tests and actuation tests (usually at low pressure and high pressure). Plug relief valve actuation testing. In addition, the many containment safety systems are required to be tested during refueling outage, such as, isolation, continuous spray, plus main steam isolation valves

b) Diesel generator - initiated by simultaneous signals which simulate safety injection; coincident with loss of all normal on- and off-site power; start rapidly; and also, supply all engineered safety feature loads.

c) Battery - once each operating cycle, the station batteries shall be subjected to a rated load discharge test. The specific gravity and voltage of each cell shall be determined after the discharge and logged

Valves

a) Valves (Section XI: IWV)

IWV-2110 Categories of Valves

Categories of valves subject to the rules of this subsection are defined as:

1) Category A - valves for which seat leakage is limited to a specific maximum amount in the closed position for fulfillment of their function

2) Category B - valves for which seat leakage in the closed position is inconsequential for fulfillment of their function

3) Category C - valves which are self-actuating in response to some system characteristic, such as pressure (relief valves) or flow direction (check valves)

4) Category D - valves which are actuated by an energy source capable of only one operation, such as rupture disks or explosive actuated valves

5) Category 3 - valves which are normally locked (or sealed) open or locked (or sealed) closed to fulfill their function