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AVAILABILITY ANALYSIS OF UNITED STATES BWR IV ELECTRICAL GENERATION PLANTS*

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Abstract

Availability, as quantified by power output levels, from all active U.S. BWR IV plants were analyzed over a seven and a half year period to determine the operational characteristics of these plants throughout an operating cycle. The operational data were examined for infant mortality, end of cycle decreased availability, and seasonal availability variations. Scheduled outages were also examined to determine the industry's current approach to planning maintenance outages. The results of this study show that nuclear power plants do suffer significant infant mortality following a refueling outage. And while they do not suffer an end of cycle decrease in availability, a mid-cycle period of decreased availability is evident. This period of decreased availability is due to a combination of increased forced unavailability and seasonally scheduled maintenance and refueling outages. These findings form the start of a rational approach to increasing plant availability.

1. INTRODUCTION

This study was conducted as part of an ongoing study at the Massachusetts Institute of Technology to examine the forced unavailability of nuclear power generation facilities. This research has been performed under the funding and sponsorship of INEEL.

2. DATA ANALYSIS TECHNIQUE

2.1. Capacity Factor

The purpose of this study was to examine plants operational availability during a refueling cycle and how the availability relates to the capacity factor. In general, the capacity factor, defined as the ratio of the actual electrical energy produced to the theoretical electrical energy which could have been produced over a given time period, is defined by the following equation:

$$\textbf{Capacity Factor} = \frac{\textbf{MWe output}}{\textbf{MWe theoretical}} \qquad (1)$$

The time period used for this study is an operating cycle which is defined as:

$$\textbf{Operating Cycle Length} = \textbf{Refueling Outage Length} + \textbf{Refueling cycle Length} \qquad (2)$$

The capacity factor during an operating cycle then is given by:

$$\textbf{Capacity Factor} = \frac{(\textbf{Refueling Cycle Length}) \times (\textbf{Refueling Cycle Availability})}{(\textbf{Refueling Cycle Length}) + (\textbf{Refueling Outage Length})} \qquad (3)$$

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where

$$\textbf{Refueling Cycle Availability} = \frac{\textbf{MWoutput}}{\textbf{MWrated}} \text{ or}$$
$$= \textbf{percentage of maximum power output}$$

The operating cycle capacity factor depends on three factors: refueling cycle availability, refueling outage length, and refueling cycle length. The independent effect of these three variables on capacity factor is shown in Fig. 1 for assumed changes in refueling cycle availability from 89% to 97%, refueling outage from 78 days to 30 days, and refueling cycle length from 18 months to 24 months. The zero point reference capacity factor in Fig. 1 of 77.25% is an average of U.S. BWR IV plants from 1990 through May, 1997. Notice that the operating cycle capacity factor goes from 77.25% to 84.65% when availability increases, to 83.80% when the refueling outage is reduced and to 80.10% when the refueling cycle is extended.

Increasing the availability during the refueling cycle gives the greatest gains. However U.S. refueling cycle availability performance has been historically low. Although decreasing the length of the refueling outage gives nearly the same gain in capacity factor, there are intensive industry efforts to reduce it already underway. Hence, refueling cycle availability and refueling cycle length are investigated further. First, the method of analysis is presented.

2.2. Plant Availability Data

Operating data from all U.S. BWR IV plants were examined from January, 1990 through May, 1997. All U.S. BWR IV plants were included in the study with the exception of Shoreham, which was decommissioned in 1987, and Brown's Ferry 1 and 2 which were shutdown for the majority of the time period. Of the remaining 17 plants, the time period which encompassed the long NRC-imposed shutdowns for Brunswick 1, Brunswick 2, and Cooper Station were ignored.

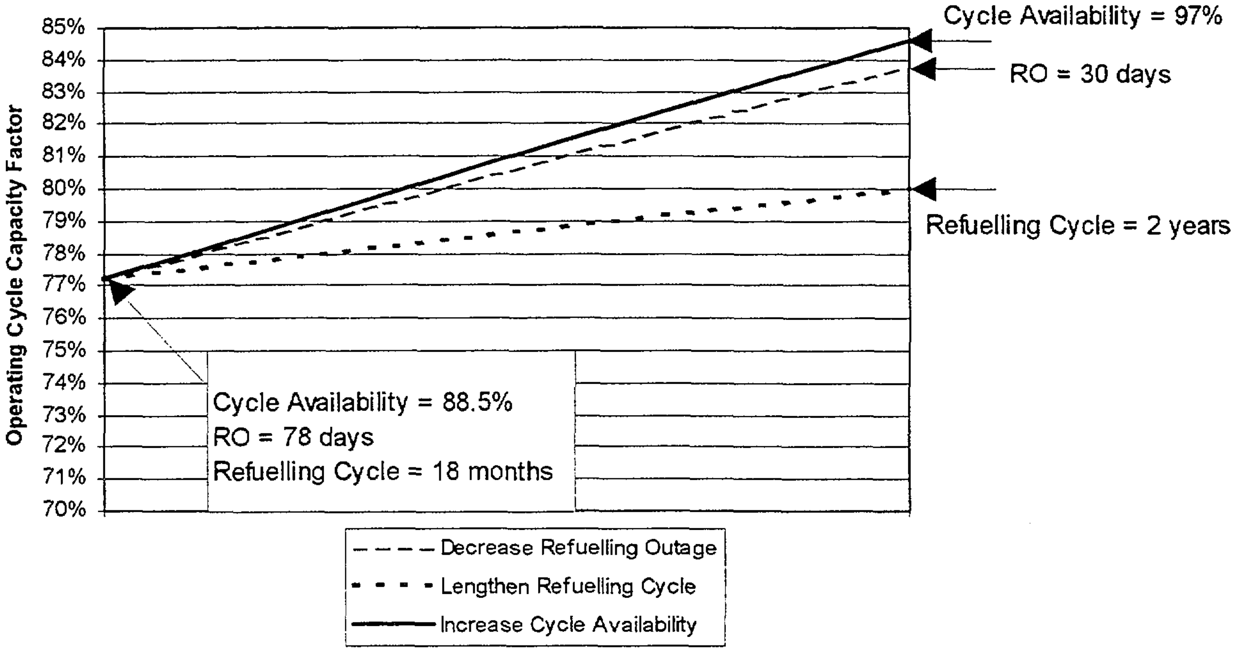

FIG. 1. How the Operating Cycle Capacity Factor changes by independently varying refueling cycle length, refueling cycle availability, and refueling outage length.

The daily refueling cycle availability was derived from NRC monthly "gray book" data [1]. The gray book data lists, for each plant, the daily average power output by the plant for the 24 hour period. The daily average power outputs were transformed into a daily percentage of maximum power output, or daily availability. Then the plant data were split into refueling cycles, rather than months. It was then necessary to re-align the refueling cycles such that all plant data were examined for beginning of cycle and end of cycle performance.

2.3. Refueling Cycle Availability Analysis

All refueling cycle starts were aligned by calling the first day of the refueling cycle for each plant day "1". As shown in Fig. 2, the refueling cycles were "left- justified" by aligning the first day of each refueling cycle. A vertical average at any given day during the refueling cycle gives the average availability for all plants on that day of the refueling cycle. This method accurately accounts for the performance of each plant during the beginning of a

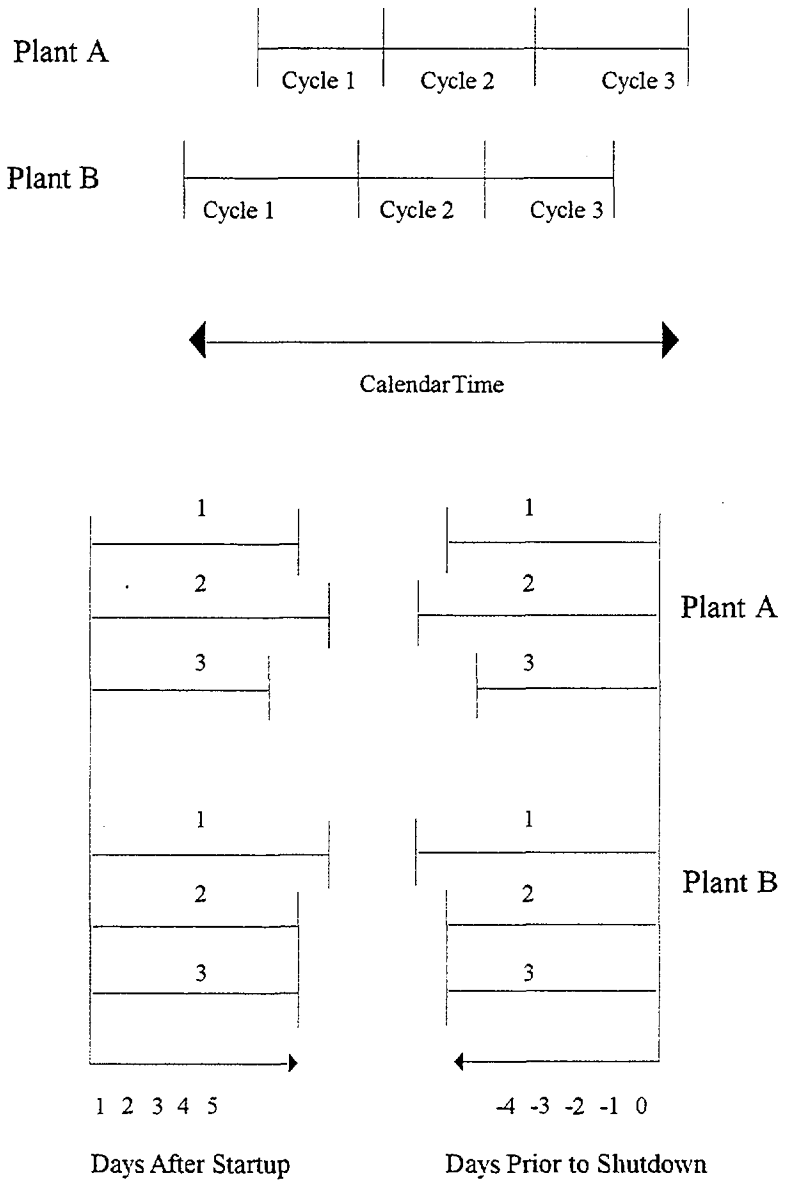

FIG. 2. Sample data which shows how refueling cycle data was transformed from calendar time to a time scale based upon the number of days after the start of the refueling cycle and the number of days before the plant shutdown for the following refueling outage.

refueling cycle. In a second analysis, the refueling cycles were "right- justified" such that the refueling cycles end on the same day. This method is used to show the availability of every plant during the end of the refueling cycle.

3. US BWR IV PLANT START OF REFUELING CYCLE AVAILABILITY

3.1. Availability at the Start of a Refueling Cycle

Fig. 3 presents the daily and cumulative availability for "left-justified" data. In Fig. 3, day 1 along the x-axis represents the average availability of all U.S. BWR IV plants on the first day of the refueling cycle. Notice that daily availability is significantly depressed during the beginning of the refueling cycle. This effect can be directly attributed to infant mortality, which is defined as early failures in a system where the failure rate decreases with time [2]. While infant mortality is usually only applied to single component failures, in an assembly of many components the entire assembly, in this case the plant, exhibits infant mortality as the collective effects of individual components performance. The depression in daily availability corresponding to an increase in forced unavailability which occurs mid-cycle between days 210 and 390 will be examined in detail later.

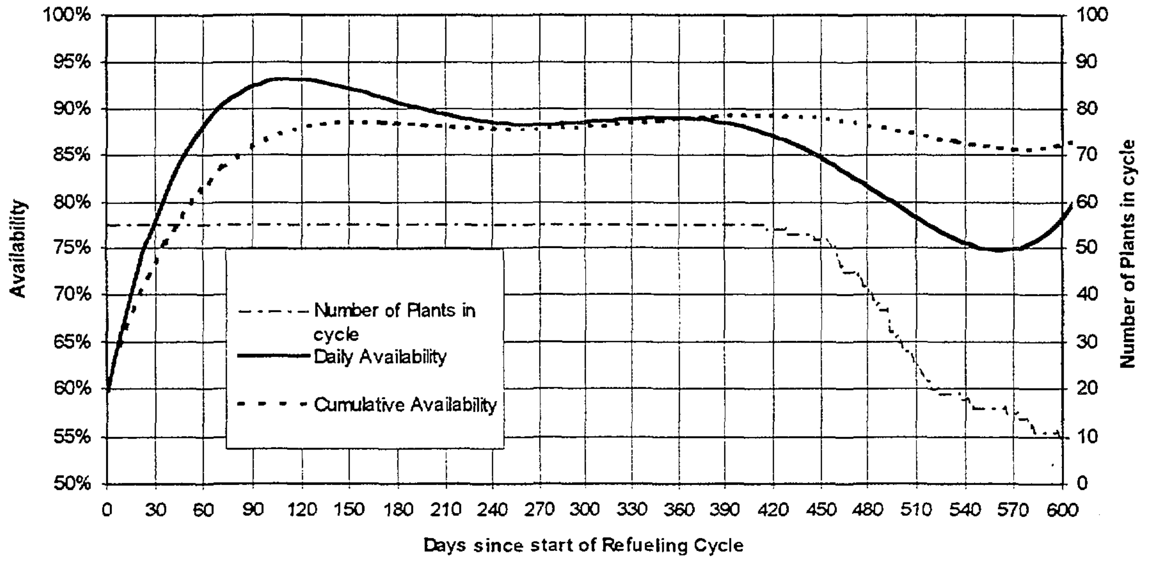

FIG. 3. The average of all BWR IV plant's daily and cumulative availability during a refueling cycle. The bottom line shows the number of plants not in a refueling outage -- as plants shutdown for a refueling outage this line drops accordingly.

The bottom line of Fig. 3 shows the number of plants still in-cycle. When a plant enters a refueling outage the number of plants in cycle represented by the bottom line drops, and the that plant is no longer considered in the industry average. Thus the daily availability near the end of the refueling cycle on the right hand side of Fig. 3 is not indicative of all plants near the end of the refueling cycle since there are fewer plants remaining in-cycle. Also, this segment of data may be skewed downwards as most plants experience some degree of end of cycle coastdown. When a plant starts the next refueling cycle, its availability is restarted at day 1.

The cumulative availability at any day contains the history of all of the daily availabilities preceding that day. The equation for cumulative availability is given by

$$\textbf{Cumulative Average at time T} = \frac{1}{T}\int_0^T \left[\text{DailyAvailability}(t)\right]dt \qquad (4)$$

When equation (4) is discretized, it becomes:

$$\textbf{Cumulative Average at time T} = \frac{1}{T}\sum_{i=1}^{T} (\textbf{Daily Availability})_i \qquad (5)$$

3.2. Effect of Eliminating Infant Mortality

A plant that eliminates infant mortality will see a significant increase in refueling cycle availability, and hence an increase in capacity factor. To show this, the first 120 days of daily availability data shown in Fig. 3 were parametrically increased to constant values between 87% and 100% . The BWR IV average refueling cycle length of 540 days was used for the rest of the calculation. Fig. 4 shows how this artificial boost in performance increased the operating cycle capacity factor by increasing the refueling cycle availability.

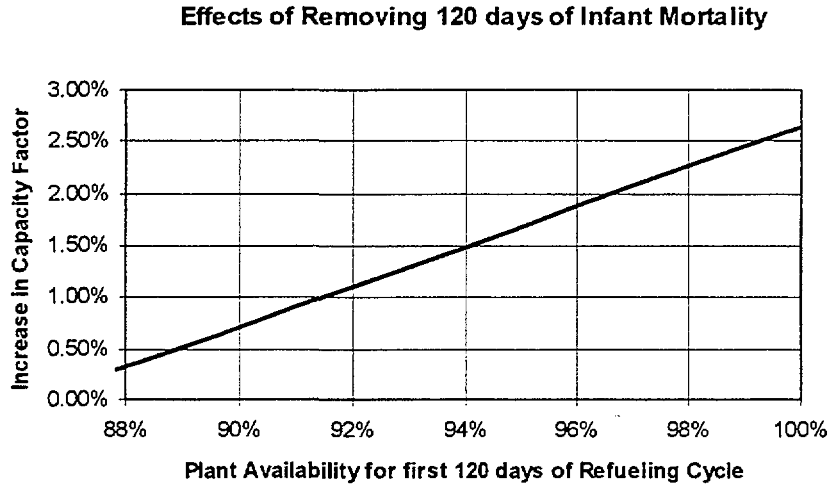

FIG. 4. By artificially setting the daily availability to different values over the first 120 days of the refueling cycle, the refueling cycle availability increases, which equates to increased operating cycle capacity factor.

4. US BWR IV END OF REFUELING CYCLE AVAILABILITY

4.1. Availability at the End of a Refueling Cycle

As previously stated, the data in Fig. 3 are invalid near the end of the refueling cycle. Therefore, the so-called "right- justified" analysis was used to accurately portray how each plant operates at the end of the refueling cycle. The coastdown effect was removed from the data by matching the maximum power output level reported in the NRC database to the daily power output level. All outages and major power reductions were left in the data. In this manner, plant availability was not unduly decreased due to core life, but was decreased due to operating casualties and outages. Fig. 5 shows the resulting daily availability.

Fig. 6 amplifies a portion of Fig. 5 and shows the daily availability data of every BWR IV plant over the last 180 days of each plant's refueling cycle. The cumulative availability curve shown in Fig. 6 was derived by subtracting 180 days from the average refueling cycle length of 532 days, and finding the cumulative availability at the 352nd day of the refueling cycle from the "left-justified" data in Fig. 3. The cumulative availability for the first 352 days of operation is 88.72%, and the cumulative availability during the final 180 days is found using equation 4 by combining the first 352 days of operation from Fig. 3 and the last 180 days of operation from Fig. 6. Using this method, the cumulative availability for the last 180 days of

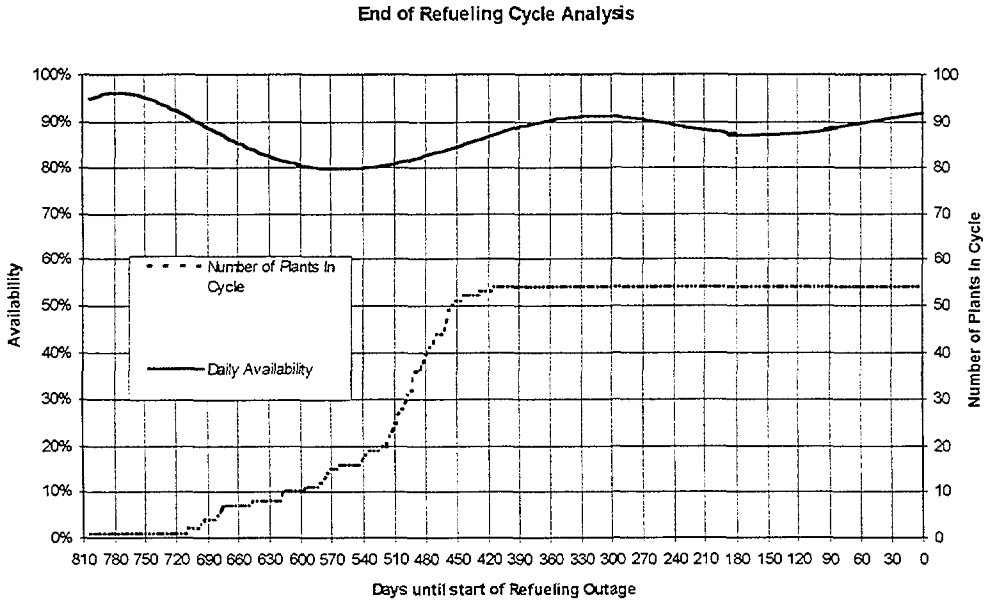

FIG. 5. The average of all BWR IV plant's daily availability using a "right-justified" alignment whereby all plants finish the refueling cycle on the same day, day 0.

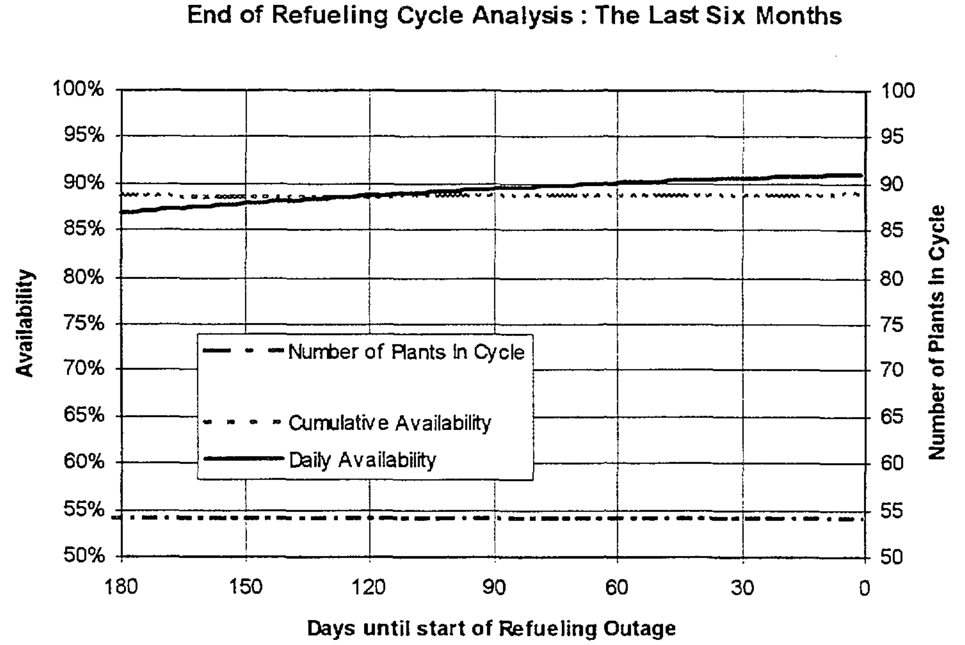

FIG. 6. Daily and Cumulative availability for all plants during the last 180 days of the refueling cycle. Note how the daily availability curve is higher than the cumulative availability curve.

operation contains the beginning of cycle history. It is significant to note that over the last four months of operations, the daily availability curve is greater than the cumulative availability. This means that the plants are operating better at the end of the refueling cycle than previously. This increase in performance may result from the mid-cycle availability decrease. That is, equipment breakdowns occur in the middle of the refueling cycle and not at the end of the refueling cycle. Significantly, for the cycle lengths examined, the mid-refueling cycle breakdown period is not followed by a subsequent breakdown or wear out period prior to the plants shutting down. A plant with an extended core could sustain the higher level of performance seen in the end of cycle period and increase availability and capacity factor.

Extending the refueling cycle length will increase the refueling cycle availability if it is assumed that the daily availability remains higher than the cumulative availability. This is a reasonable assumption based on a case study conducted at M.I.T. with a BWR IV plant [Brodeur, 1997] which showed that less than 20% of component failures are age related. Another M.I.T. study [Moore, 1996], showed that specific components, such as the main feedwater pump, are not age limited. Furthermore, this assumption is supported by the recent decision to operate British Advanced Gas Reactors which refuel on-line on three year operating cycles. If the refueling cycle is artificially extended 180 days to 2 years, and the daily availability during the extended 180 day period is maintained at 90.7% (the availability on the last day of actual refueling cycle operations), the cumulative and daily availability can be plotted as shown in Fig. 7.

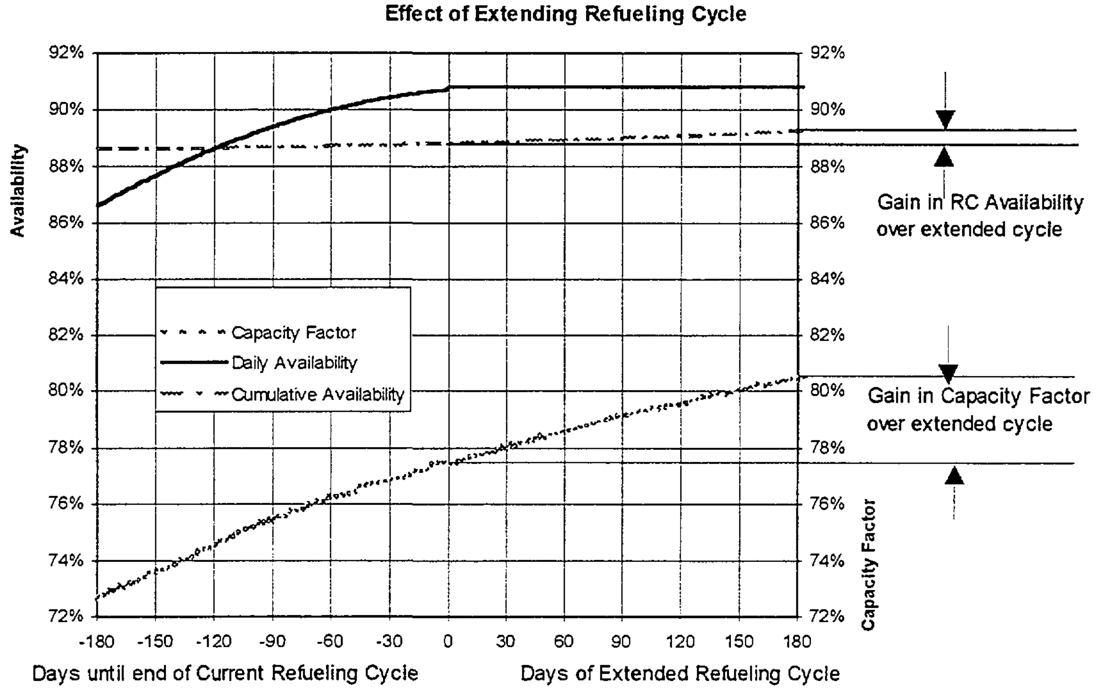

FIG. 7. The refueling cycle here is artificially extended 180 days, and the daily availability is set to 90.7%. Notice that the cumulative availability increases since the daily availability is always higher. The increase in cumulative availability corresponds to an increase in refueling cycle availability, which leads to the increase in operating cycle capacity factor.

Here the cumulative availability includes the first 352 days of operations from the "left-justified" data, the final 180 days of availability from the "right-justified" data, and the artificial availability from the extended data.

Fig. 7 shows that the refueling cycle availability increases 0.75% due to the high daily availability achieved in the extended operational period. Since capacity factor depends upon both refueling cycle availability and refueling cycle length, there is a non-linear increase in capacity factor with an extended refueling cycle. The capacity factor increases 2.80% with extended refueling cycle. This non-linear relationship is the basis for an economic advantage to extending the current 18 month refueling cycle.

The preceding paragraphs have shown that eliminating infant mortality and extending the length of the refueling cycle can increase the operating cycle capacity factor. The large dip in daily availability in the middle of the refueling cycle shown in Fig. 3 must be explained to complete the discussion of refueling cycle availability.

5. US BWR IV PLANT MID-CYCLE REDUCED AVAILABILITY

5.1. Mid-cycle Daily Availability Dip

The mid-cycle dip in daily availability is due to a mix of seasonally scheduled maintenance and an increase in forced unavailability. The seasonal effects are shown by re-examining the daily availability using the original calendar time scale. Instead of finding the daily availability as a function of the number of days since the start of the refueling cycle, this analysis yields the daily availability as a function of calendar day.

5.2. Seasonal Effects upon Daily Availability

Fig. 8 shows the monthly availability for U.S. BWR IV plants. While the data deviate greatly, there are relative peaks during the heavy demand, late summer and winter periods and reduced availability during the lesser demand spring and fall months. This pattern suggests that perhaps plants are taking a scheduled maintenance outage prior to and following the summer months. This hypothesis is confirmed by plotting in Fig. 9 the percentage of plants in a scheduled outage status. There are a significant number of scheduled outage days in March,

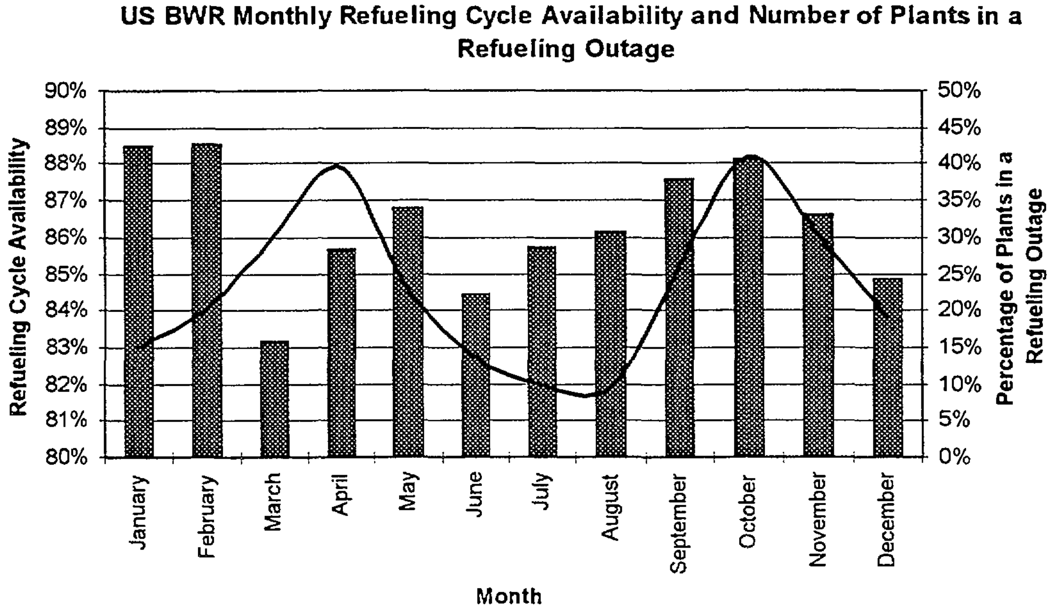

FIG. 8. The bars show the monthly variation in availability for U.S. BWR IV plants. Notice the high peak during the late summer, early fall months and winter months. The line corresponds to the percentage of plants in a refueling outage. Notice that it takes 4 to 6 months for availability to peak after plants come out of the refueling outage.

April, November, and December, and very few scheduled outage days from May through September. The availability dip in June can not be explained as being due to scheduled outages: even when full power days lost to scheduled outages occurring in June are added to the monthly availability of Fig. 8, the resulting availability is significantly below May. Rather than scheduled outages, the low availability in June is due to infant mortality. As the line which shows the percentage of plants in a refueling outage status decreases in Fig. 8, plants are exiting the refueling outage and starting a refueling cycle. Notice the high number of plant starts in April and May, which drive the availability low in June, and low in July and August relative to the higher performance of September and October. The same is true for the high number of plant starts in October and November, which drive availability low in November and December.

5.3. Increased Forced Unavailability in the middle of the refueling cycle

Not all of the decrease in mid-refueling cycle availability is due to seasonally planned maintenance outages and infant mortality. Some of this decrease is due to an increase in forced unavailability during the middle of the refueling cycle. This effect is shown by removing all scheduled outages from the refueling cycle data, and examining the data along a refueling cycle axis, similar to Fig. 3.

The results, shown in Fig. 10, still show the dip in daily availability in the mid-cycle time period. This suggests that plants are suffering a period of increased forced unavailability, and are forced to shutdown to fix problems. Fig. 10 also shows that scheduled outages are evenly distributed throughout the refueling cycle, and are not being heavily utilized to overcome the mid cycle increase in forced unavailability.

5.4. Implications of Seasonal Maintenance on Capacity Factor

Seasonally-adjusted planned maintenance can be used to offset the effects of mid-cycle increased forced unavailability. The first benefit of planned maintenance is that plants undergo less traumatic infant mortality following a planned maintenance outage. Fig. 11 compares the daily availability following a scheduled outage compared to the daily availability following a

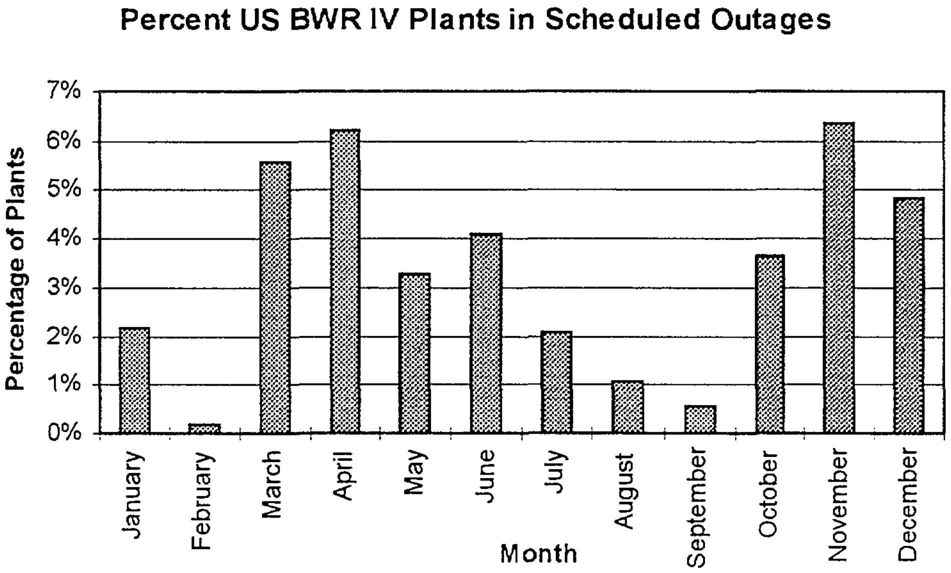

FIG. 9. Monthly variation in the percentage of plants in a scheduled outage status. Notice the large peaks in spring and late fall. The large increase in June is unexplainable.

refueling outage. Notice that the infant mortality period following a scheduled outage is not as prolonged or pronounce as that following a refueling outage. Second, planned, conditional maintenance could reduce the incidence of forced outages during the middle of the refueling cycle. Third, as a plant reduces the forced unavailability, and plans for outage periods, fuel usage can be optimized to match the economic benefits of operating during peak demand periods, and the coastdown period can be optimized. And finally, a plant that plans outages is in control of the outage, and not being controlled by the outage.

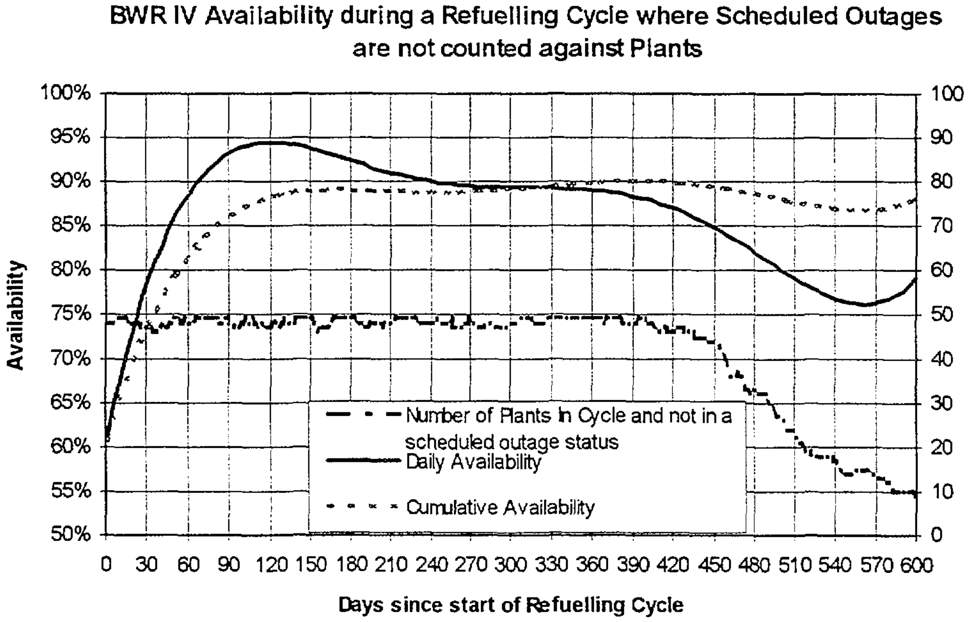

FIG. 10. Daily availability during the refueling cycle with schedule outages removed. If the mid-cycle dip in daily availability had been due purely to seasonal scheduled outages, the daily availability would have remained flat. The fact that the dip persists suggests that plants suffer a mid-cycle increase in forced unavailability.

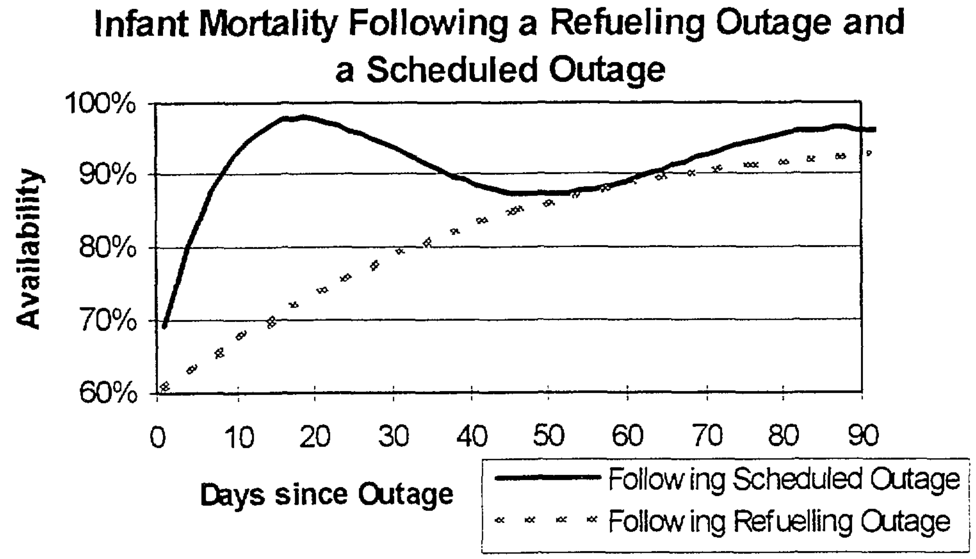

FIG. 11. Daily Availability following a scheduled outage and following a refueling outage. Notice that the infant mortality following a scheduled outage is much less severe (in magnitude and length of time) than the infant mortality following a refueling outage.

6. CONCLUSIONS

6.1. Conclusions and Recommendations for Improved Availability

This paper showed how the operating cycle capacity factor is affected by refueling outage length, refueling cycle length, and refueling cycle availability. Refueling cycle availability is affected by infant mortality, seasonally-adjusted scheduled maintenance outages, and forced outages. Increasing refueling cycle availability to 97% can increase operating cycle capacity factor over 7%. This goal can be realized:

(1) Reducing the forced unavailability following a refueling outage. Elimination of infant mortality leads to a 2.5% gain in operating cycle capacity factor as shown in FIG. 4.

(2) Implementing conditional, seasonally-planned maintenance. While scheduled outages occur seasonally as shown in Fig. 9, they do not occur at strategic times within the refueling cycle to prevent increases in forced unavailability, as seen from Fig. 10. A rational maintenance outage can reduce forced unavailability by fixing equipment before it breaks, and at a time that is economically convenient for the plant. Scheduling outage time also allows for better core life planning.

(3) Seeking extended refueling cycles through new, longer core designs. Operational data show that the balance of plant will not reduce availability if core life is extended. Rather, high availabilities would be maintained which would non-linearly increase capacity factor. Fig. 7 shows this beneficial, non-linear increase.

REFERENCES

[1] United States Nuclear Regulatory Commission Monthly Operating Report for United States Nuclear Facilities, 1989-1997

[2] RAMAKUMAR,R., *Engineering Reliability: Fundamentals and Applications*. Prentice Hall, New Jersey (1993) 482 pp.

Addendum to "Availability Analysis of United States BWR IV Electrical Generation Plants" by D. H. Renick, F. Li and N. E. Todreas

by, D. L. Brodeur, Department of Nuclear Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139

This addendum is attached to modify the findings of the attached paper. These new insights are the results of continued research in the area of BWR/IV US nuclear power plant reliability. Detailed findings are presented in MIT report to INEEL, "A Study of US Nuclear Power Boiling Water Reactor, Class IV, Operating Performance, 1992-1997" by David L. Brodeur and Virginia T. Angus. Reporting inconsistencies in the daily average power data used for the original paper were noted and overcome by establishing the maximum generation for any plant within an operating cycle as 100% capacity. Additionally the time frame of the study was restricted to five and a half years, January 1992 to June 1997, to reflect more current operating trends.

Figure 3A portrays the same information as Figure 3 of the paper using the refined data. The daily mean capacity data has been shown in addition to the fitted curves. It is noted that the mean daily capacity for the first seven days is discontinuous with that of the remainder of the operating cycle. For the first seven days the mean daily capacity increases linearly from zero to eighty five percent. After day seven the mean capacity is much more random exhibiting the impact of individual plant failures. The linear response during the first seven days can be attributed to the lengthy process of power accession and testing following the refueling outage. The thin 21 day moving average line has been added to observe the changes in daily mean capacity. It is a connection of the daily mean capacities for the first seven days and an expanding 21 day average after day seven. The average expands such that day nine is a three day average, day 10 a five day average up to day 18 and greater when the average is held at 21 days. The heavy solid line is then a sixth

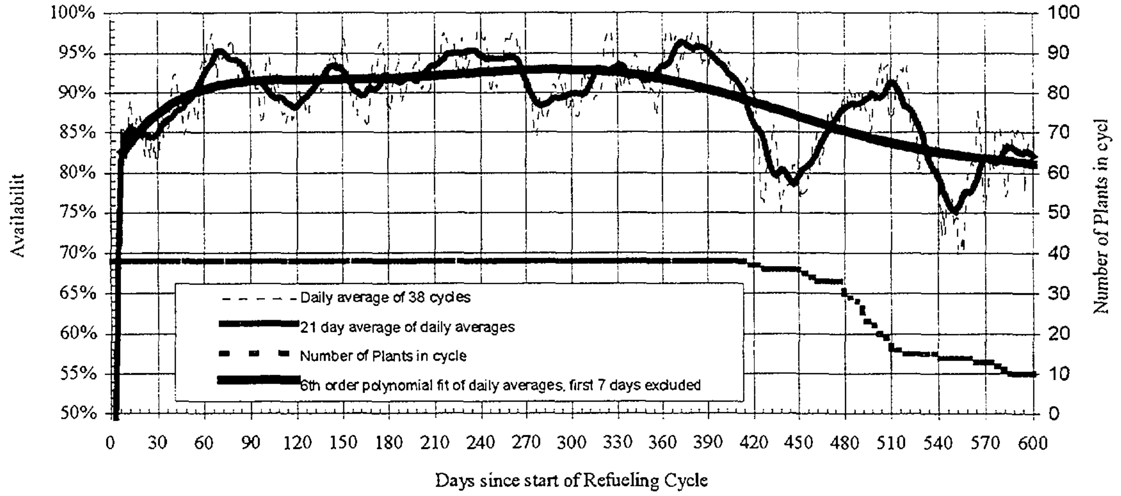

Figure 3A. The average of all BWR/4 plant's daily and cumulative availability during a refueling cycle. The bottom line shows the number of plant operating cycles averaged – as plants shutdown for a refueling outage this line drops accordingly.

order best fit of the 21 day average data. It is observed that this line is a good fit to the daily mean capacity data. This line replaces the solid line of figure 3 in the original paper and is representative of the daily capacity.

There are four regions noted of daily mean capacity performance. As discussed earlier during the first seven days capacity is linearly increasing from 0 to 85%. This is attributed to the start up process and not plant reliability failures. From day eight to day 90 the mean daily capacity is observed to increase from 85% to 92%. This is attributed to early cycle plant failures, the infant mortality reported in the original paper. Note that this is an observable but small effect. From day 90 until day 330 mean daily capacity is noted to be relatively constant at 92%. This period marks the optimum mid-cycle operating period. After day 330 the mean daily capacity is observed to steadily decline.

Of significance, the large period of decreased early cycle capacity, reported earlier as infant mortality, has been much diminished. The cumulative cycle performance is observed to slowly climb to greater than 90% during the mid-cycle period of steady performance. The end of cycle declining daily capacity is observed to drag the cumulative capacity down to below 80% by day 600. The lesser impact of the early cycle decreased performance is noted by the proximity of the cumulative capacity to the mean daily capacity by the end of the mid-cycle plateau (92 versus 90%). In comparison, the entire cycle cumulative capacity falls by greater than 10% as a result of the constantly declining end of cycle performance. As noted in the original paper, it is unclear whether this declining performance is the result of the end of cycle fuel coast down or declining plant reliability.

To examine the end of cycle performance the mean operating cycle data is again examined in a right justified manner, similar to the original paper. The daily capacity reported by plants has been carefully modified to reflect the percentage of power that could be generated as limited by fuel coast down. The heavy line of figure 5A is a third order best fit curve of the mean daily coast down modified capacity. The other points and

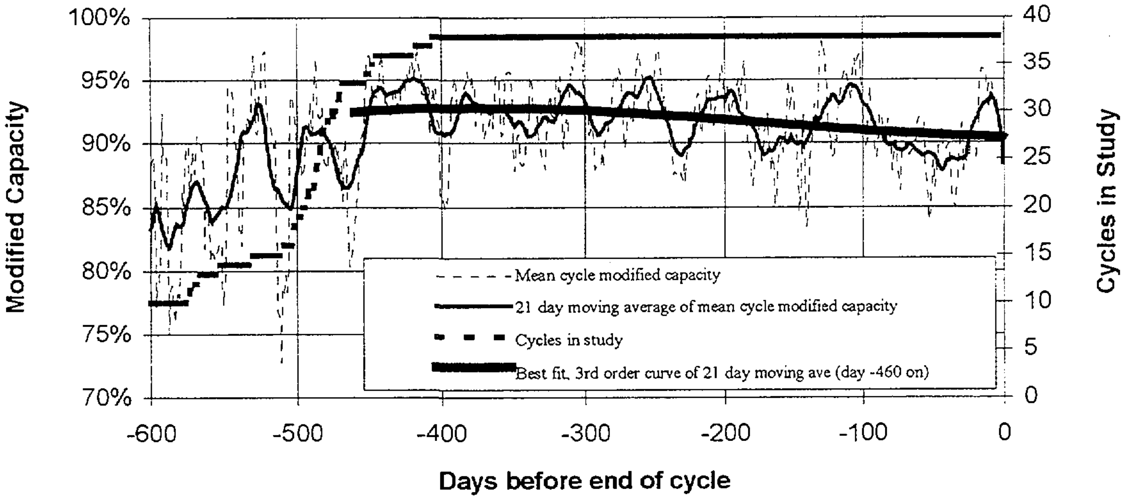

Figure 5A. The average of all BWR/4 plant's daily modified capacity using a "right justified" alignment whereby all plants finish the operating cycle on the same day, day 0.

curves are similar to those of figure 3A. It is noted that the capacity, modified to remove the effects of coast down, slowly declines in performance from 92.5% 460 days before the common end of cycle point to 90% by the end of cycle. This degradation is not as significant as the fuel coast down effects but does reflect an increasing difficulty of plant reliability with increasing cycle length. This finding is contrary to that of the attached paper.

The observations noted in this paper resulted from a detailed examination of each cycle's data and from a requirement that raw data be plotted along with fitted curves. For this reason the above figures contain the raw data, averaged data and then fitted curves. A lesson has been learned to cautiously view fitted curves for which the raw data is no longer visible.