INIS
TRN AU8104868

AAEC/E496

AAEC/E496

AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

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by

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July 1980

ISBN 0 642 59694 8

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ABSTRACT

Operating data on all commercial nuclear power plants of the PWR, HWR, BWR and GCR types in the Western World are analysed statistically to determine whether the explanatory variables size, year of operation, vintage and reactor supplier are significant in accounting for the variation in capacity factor. The results are compared with a number of previous studies which analysed only United States reactors. The possibility of specification errors affecting the results is also examined.

Although, in general, the variables considered are statistically significant, they explain only a small portion of the variation in the capacity factor. The equations thus obtained should certainly not be used to predict the lifetime performance of future large reactors.

National Library of Australia card number and ISBN 0 642 59694 8

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PWR TYPE REACTORS; HEAVY WATER COOLED REACTORS; BWR TYPE REACTORS; GCR TYPE REACTORS; NUCLEAR POWER PLANTS; PERFORMANCE; RELIABILITY; ECONOMICS; NUCLEAR POWER; STATISTICAL MODELS

CONTENTS

1. INTRODUCTION

The total cost of supplying a unit of electricity from a plant consists of three components - capital charges, fuel charges, and operation and maintenance charges. Unlike fossil-fuelled plants, where the fuel charge is the major expense, the capital charge term dominates for nuclear plants. The capital charge is evaluated by applying a capital annual charge rate, which covers depreciation, interest, insurance and taxes, to the total fixed cost of the plant and dividing this by the electricity generated per annum.

The capacity factor has always played an important role in determining the economic viability of any energy project.

Plant capacity factor is a measure of the total electrical energy actually produced by a plant during a given period, compared to the energy it might have produced had it operated at the licensed design power level for the entire period. It is expressed as a percentage.

$$\text{Capacity factor} = \frac{\text{total electricity generated (MWh)}}{\text{licensed capacity rating (MWe)} \times \text{period (h)}}$$

$$= \frac{\text{available hours}}{\text{period}} \times \frac{\text{total electricity generated}}{\text{licensed capacity rating} \times \text{available hours}}$$

The first term refers to the availability of plant. Although the second term depends mainly on system requirements it is also affected by the plant being available but operating at a reduced power level owing to equipment malfunction, or to load following as needed.

Plant availability factor is the percentage of the total time in a given period during which the plant was producing electricity or was capable of producing electricity.

Therefore, high energy production, as indicated by a high capacity factor, lowers the average capital charge. Moreover, a lower than normal capacity factor may indicate poor reliability.

When making a decision regarding the type of plant to be installed (nuclear, fossil-fired steam, hydro or gas turbine, etc.) an electricity utility needs to consider the capacity factor at which the plant can be expected to operate. Utilities require baseload stations to maintain continuous operation, except for brief periods when shutdown occurs because of maintenance, refuelling or forced outages. It follows that for baseload stations a high availability, which is reflected by a high capacity factor, is important.

In this study the capacity factor has been used as a measure of power station performance because uniform comprehensive data are generally not available for other measures of performance. However, it must be remembered that the annual capacity factor of a plant is affected by the availability of both the nuclear and conventional components of the plant as well as by total system requirements. Since nuclear plants generally have the lowest operating costs of the electricity system and so are usually baseloaded, the capacity factor should be a reasonable measure of availability after allowing for scheduled outages.

For some time there has been much controversy about the comparative performances of nuclear and conventional power plants, and the relationship between performance and size of plant. In Australia, these issues were first raised during the proceedings of the Ranger Uranium Environmental Inquiry [Fox 1975/76]. Arguments were presented by Roberts [1976] and Marshall [1975] which, in general, reflected those originally developed by Comey [1974].

Comey, in his initial study, examined the performance of all nuclear power plants larger than 100 MWe which were operating in the United States. His work indicated that the capacity factors of nuclear plants reached a peak after three to four years of operation, and then declined linearly. In a series of articles prompted by Comey's original work, the merits of his findings were questioned by Margen and Lindhe [1975] and Netschert [1975]. Using Comey's data, Margen and Lindhe showed that there was no significant statistical reduction in performance after six or seven years of service; however, they did observe a decrease after eleven or twelve years. They noted that three prototype reactors were responsible for the performance figures during this period, and that the outage of only one of these units sharply affected the average for the whole year. Whereas Comey's initial study had used only year of operation as the explanatory variable, Netschert also considered the variation of capacity factor with unit size. In turn, Comey [1975] responded by claiming that Netschert's figures showed a clear drop in capacity factor as reactor size increased.

Roberts [1976], in his submission to the Ranger Inquiry, examined the 1975 performance of all United States reactors larger than 300 MWe. His analysis predicted a loss of 4.6 percentage points* in capacity factor for every 100 MWe added. This would indicate an absolute decrease in energy output for reactors larger than 1036 MWe. Symonds [1976] challenged the validity of Robert's findings on the grounds that there were insufficient data for the larger sized reactors. He demonstrated that Robert's results were highly sensitive to minor changes in the data. Symonds also pointed out that an analysis of world data showed that reactor performance was relatively independent of age, after the settling-in period, and that records of the United States and the European plants support this observation. He cited studies by Kohn [1975] and Moraw et al. [1975] which supported his conclusions.

This topic was expanded by Komanoff [1976], who examined the 1975 performance of all United States reactors larger than 450 MWe. He investigated the relationship between capacity factor and a number of explanatory variables including size, year of operation and vintage or year of commissioning. Komanoff found that nuclear capacity factors declined with increasing unit capacity. PWR capacity factors declined 3.4 percentage points per 100 MWe increase, and BWR capacity factors declined 3.3 percentage points per 100 MWe increase. His results also indicated that PWR performance improved with age but that BWR performance did not. Finally he found that performance did not improve with vintage by which he meant the year in which a reactor was commissioned. (In the present study, vintage is given a value equal to the number of years since startup.)

Rebuttals of these claims were made by Perl [1977] and Simard [1977] who questioned the statistical significance of Komanoff's results. A discussion of Komanoff's study and Perl's criticism is presented in Appendix A.

An extensive analysis has been carried out by the authors in an attempt to clarify the conflicting claims of previous authors, and also to extend the study to encompass a wider range of nuclear power plant operating experience. This analysis covered all reactors operating commercially in the Western World of the types: gas cooled (GCR), pressurised water (PWR), boiling water (BWR) and heavy water (HWR). Various regression equations were fitted to the data to determine the influence on capacity factor of a number of explanatory variables such as year of operation, vintage, size and reactor supplier. The results of this analysis are discussed in Section 3.

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* This is the absolute difference between percentages.

Correct use of a classical linear regression model will depend on assumptions concerning the random disturbance term in the equations. The possibility that these assumptions may be invalid is examined in Section 4.

The results of the study are compared with those obtained by Komanoff and Roberts from US data. We conclude that while the equations estimated in the various studies may be useful in making some inferences concerning the effect of the above factors, their use in predicting the lifetime performance of large reactors is not recommended.

2. DATA BASE

A data base (listed in Appendix B) was established containing the operating history of all published commercial nuclear plants in the Western World to December 1978. Only those reactors with at least one full year of commercial operation were considered. The capacity factors were evaluated on a calendar year basis, counting the calendar year of startup, or part thereof, as the first year of operation. This first year was subsequently omitted in all analyses. A summary of the data base by reactor type is given in Table 1.

Use of the present type of analysis to project the future performance of large reactors can be criticised because the historical data include few large plants and these have only operated for a limited period. As Symonds [1976] pointed out in relation to Robert's submission, the addition of just one more large reactor can greatly influence the results. The extensive data base used in the present study does overcome this problem to some extent. For example, whereas Komanoff's original data base contained only two PWRs of size greater than 1000 MWe and none at all in the range 900-1000 MWe, the present data base contains eight PWRs of size greater than 1000 MWe and seven in the 900-1000 MWe range. For BWRs, Komanoff's data base contained three reactors of size greater than 1000 MWe, compared to five in the present data base. (Neither data base contains any BWRs in the range 900-1000 MWe as yet.) Moreover, Komanoff's data base contained only two BWRs and one PWR with more than five years of operation, compared to 21 BWRs and 15 PWRs in the data base of this study.

TABLE 1

CONTENTS OF DATA BASE

Type	Size (MWe)	No. of Reactors	No. of Reactor Years of Operation
GCR	0-199	17	308
GCR	200-499	12	160
GCR	500-799	7	57
HWR	0-199	3	32
HWR	200-499	3	22
HWR	500-799	6	29
PWR	0-199	4	65
PWR	200-499	12	97
PWR	500-799	13	79
PWR	≥800	30	121
BWR	0-199	5	67
BWR	200-499	11	103
BWR	500-799	14	83
BWR	≥800	15	67
TOTAL	-	152	1290
AVERAGE	560	-	8.5

3. RESULTS

The preferred equation for each reactor type is

PWR

$$CF = 77.4 - \underset{(3.7)}{0.021S} + \underset{(0.9)}{2.423Y} + \underset{(0.7)}{0.242Y^2} - \underset{(1.7)}{0.020Y^3}$$

$$- \underset{(7.4)}{2.827V} + \underset{(2.6)}{6.68MW} + \underset{(4.1)}{21.7MS} \qquad R^2 = 0.28$$

where CF = capacity factor (per cent)
S = size (MWe)
Y = year of operation
V = vintage
MW = 1 if reactor supplied by Westinghouse
0 otherwise
MS = 1 if reactor supplied by Siemens
0 otherwise

R^2 is the coefficient of determination; the t-values are given in brackets below the estimated coefficients.

BWR

$$CF = 41.1 - \underset{(3.1)}{0.021S} + \underset{(3.2)}{10.62Y} - \underset{(2.4)}{1.047Y^2} + \underset{(1.7)}{0.027Y^3}$$

$$- \underset{(2.2)}{1.175V} + \underset{(3.2)}{10.14MG} \qquad R^2 = 0.13$$

where MG = 1 if reactor supplied by General Electric
0 otherwise

HWR

$$CF = 10.8 + \underset{(4.3)}{0.081S} + \underset{(6.2)}{6.20Y} - \underset{(1.0)}{1.28V} \qquad R^2 = 0.49$$

GCR

$$CF = 103.6 - \underset{(8.6)}{0.103S} + \underset{(4.2)}{7.124Y} - \underset{(2.1)}{0.378Y^2} + \underset{(0.8)}{0.005Y^3}$$

$$- \underset{(5.7)}{3.114V} + \underset{(5.5)}{12.79MU} \qquad R^2 = 0.42$$

where MU = 1 if reactor supplied by UKAEA
0 otherwise

The main conclusions derived from this study were:

(a) For GCRs, PWRs and BWRs, capacity factor decreased with increase in size - but for the HWR it increased with size. For both PWR and BWR the capacity factor decreased by 2.1 percentage points per 100 MWe increase in capacity. The possibility of a non-linear relationship between capacity factor and size was investigated but rejected on statistical grounds.

(b) On average, the most recent reactors performed best. The relationship between capacity factor and year of operation was linear for the HWR but, for the other three reactor types, a third degree polynomial gave the best results. Performance improved with year of operation for the HWR, but for the BWR, PWR and GCR it reached a maximum in the 7th, 12th and 13th years respectively.

(c) Although the individual regression coefficients were significant, the coefficient of determination (R^2) for each equation was low, indicating that a large portion of the variation in capacity factor was not explained by the regression equation. This makes predictions based on the equations most uncertain.

(d) Under the assumption that capacity factor decreases with size, it can be shown mathematically that total energy production (capacity factor x size) will reach a maximum. However, the estimated equations indicate that this would occur only at plant sizes considerably larger than those presently envisaged.

(e) The results indicate that the reactors built by some manufacturers appear to have performed significantly better, on average, than the same type of reactor supplied by other manufacturers.

(f) The results were virtually unchanged when S, the size variable was divided into the four discrete ranges:

. Small	$S < 200$ MWe
. Medium	$200 \leq S < 500$ MWe
. Medium-large	$500 \leq S < 800$ MWe
. Large	$S \geq 800$ MWe

(g) In Section 1 vintage was defined, for a particular reactor, as the period from reactor startup to the time of this study. As an alternative, we redefined vintage as the cumulative number of reactors of the same type built. However, for this variable the estimated coefficient was insignificant, with a sign opposite to that expected.

(h) Some data on availability factors were obtainable for United States reactors. However, when availability factors were used as the dependent variable in the equations the fit was, in all cases, worse than when capacity factors were used. This surprising result could have been caused by the limited amount of data which may also have contained errors.

(i) Lapides [1978] has shown that the performance of nuclear units improves after each year of operation. He demonstrated that second cycle power operations were substantially better than first cycle operations and so on, until a plateau was reached after three or four cycles. We attempted to incorporate this effect directly by assigning a number to each refuelling cycle. However, in all cases, the estimated coefficient was insignificant.

4. RELIABILITY OF ESTIMATED EQUATIONS

After a regression equation has been fitted to data, the usual procedure is to determine the significance of the estimated coefficients. The importance of this step is that any inference made on the basis of the equations will be reliable only if the coefficients have been properly estimated. Usually, a coefficient is said to be significant if the ratio of the coefficient to its estimated standard error is greater than two (approximately). This test applies only if certain assumptions concerning the data are correct. The use of ordinary least squares for regression analysis, together with a detailed description of the effect of specification errors, is given in Kmenta [1971].

Of particular relevance to the present study is the possibility that the capacity factor for one year may be dependent on that for other years. If this effect, termed autoregression, is present, the significance test is not applicable. Autoregression usually occurs when factors are omitted that are important in explaining the variation in some quantity. As discussed later, this is likely to be the case for the equations considered here.

The data for individual reactors were tested for the presence of autoregression. However, there were so few plants with enough years of operation for the standard test to be meaningful that no firm conclusions could be reached. The test on the data for some reactors did indicate autoregression but this was not a universal result.

Another problem which might affect the reliability of the estimated equations in the present study is that the variation in the capacity factor may become larger with increasing plant size. For example, this could result if the increasing complexity of larger plants causes more frequent unscheduled outages. This effect, termed heteroskedasticity, occurs when the variance of the random disturbance term is not constant over the range of an explanatory variable. The estimated residuals from the equations were used to derive estimates of the variance of the disturbance term for different ranges of the independent variable, size. A comparison of these estimates produced inconclusive results suggesting that the variance for the smaller prototype reactors was greater than for the more recent, fully commercial units. However, for the commercial plants, there did not appear to be any increase in operational variability with increasing reactor size.

The consequence of either heteroskedasticity or autoregression is to render the estimated coefficients unbiased but inefficient. This means that although 'reasonable' estimates of the parameters have been obtained the significance of these estimates cannot be properly tested. These specification errors can be corrected by the use of a technique called generalised least squares which, however, requires estimation of the correlation parameter for the disturbances for each reactor. As previously noted, the majority of reactors have only a few annual readings, making estimation unsatisfactory.

The aim of the study has been to estimate the separate effects of several explanatory variables particularly size, vintage and year of operation. However, these variables may be highly correlated because reactors of the same type tend to become progressively larger with time. When this happens it becomes difficult to estimate the separate effect of each variable on the variation in the capacity factor.

The extent of this problem, which is termed multicollinearity, can be gauged by considering the correlation between variables in the sample. For example, the square of the simple correlation coefficient between vintage and size for the four reactor types ranged from 0.52 to 0.84. The dependence between the variables was reduced by considering worldwide data rather than data for one country alone. For instance, the simple correlation coefficient squared between size and vintage, for worldwide PWRs was 0.52, compared to a value of 0.64 for PWRs in the United States. When more than two variables were considered the correlation between them did not increase appreciably.

Multicollinearity does not signify incorrect results but, when present to a high degree, causes the estimated regression coefficients to have large variances, that is, to become unreliable.

As indicated by the above example, the correlation between variables was not excessive for the worldwide data so multicollinearity did not affect interpretation of the results.

5. SUMMARY

This study has used statistical regression methods to analyse operating data for all commercial nuclear power stations of the PWR, BWR, HWR and GCR types. While the results from an analysis of historical data may be useful in drawing inferences concerning the effect of some factors on past performance they should not be used to project lifetime performance of future large nuclear power reactors.

The effects of some factors on nuclear power plant performance have been examined. Capacity factor has been used as a measure of performance because there are no worldwide data on the availability of the nuclear component of plants. However, the capacity factor depends not only on the availability of plant but also on total system requirements. The performance, as indicated by the capacity factor, may be lowered by the failure of conventional equipment (for example, the generator) or by running the plant at less than full capacity at times of low demand. This would occur for utilities which have nuclear plants as a significant fraction of their total installed capacity. When total system demand is low some of these plants may be assigned to standby or load-following duty.

The analysis has shown a significant vintage effect for all reactor types in that the performance of the more recently commissioned reactors is better than that of the earlier ones. Performance has also improved with operating experience. It was found that performance decreased with increasing size of plant, in the range two to three percentage points per 100 MWe increase in capacity for the light water reactors (BWR and PWR). For HWR plants the more recent, larger reactors showed improved performance over the earlier, smaller ones. There was no evidence to support the view that total energy production, for a particular reactor, reached a maximum at sizes comparable to those presently envisaged.

If, as Komanoff has done, the derived equations are used to project the lifetime performance of large reactors, it must be stressed that the chosen variables and their forms, as specified for the estimated equations, explain only a small amount of the historical variation in the capacity factors. This means either that some variables which are important in explaining the variation have been neglected or that the remaining variation results from the effect of numerous small factors. This has important consequences for the error bands which must be attached to any prediction. For example, consider a 1000 MWe PWR with all other variables at their mean values in the sample. At a 95 per cent confidence level, the mean value of the capacity factor for all such reactors would be predicted as 50 ± 6 per cent while the capacity factor for an individual reactor in the group would be predicted as 50 ± 40 per cent. Further uncertainty arises in prediction when the variables, size and year of operation, used in the projection are considerably greater than their mean values in the available sample.

Komanoff used the results from his study to support the view that conventional power plants were operationally superior and cheaper to run over their lifetimes than nuclear power stations. In his initial study, Komanoff found that both the PWR and BWR had a size related drop in capacity factor of 3.4 percentage points per 100 MWe increase in capacity. In a subsequent update of his study, incorporating plant data for 1977, Komanoff [1978] noted an improvement in the average capacity factor of operating nuclear plants. He also revised the size-related drop in capacity factor to 2.5 percentage points per 100 MWe for the PWR, and 3.2 percentage points per 100 MWe for the BWR; these decreases are larger than those we obtained using a wider range of data.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the helpful discussions held with Dr J.L. Symonds and Mr P. Essam during the course of this work. Thanks are also due to Mr J.R. Fredsall for assistance in establishing the data base.

7. REFERENCES

Comey, D. [1974] - Will Idle Capacity Kill Nuclear Power? The Bulletin of the Atomic Scientists, 30, No.9, November, pp.23-28.

Comey, D. [1975] - Points Versus Trends. The Bulletin of the Atomic Scientists, 31, No.8, October, pp. 44-45.

Daniel, C. and Wood, F. [1971] - Fitting Equations to Data. John Wiley and Sons, Inc. New York.

Fox, R.W. [1975-6] - Proc. of the Ranger Uranium Environmental Inquiry. Australian Government Publishing Service, Canberra.

Kmenta, J. [1971] - Elements of Econometrics. MacMillan Publ. Co. Inc., New York.

Kohn, H. [1975] - Reactor Performance Evaluations. Power Engineering, 79, No.12, December, pp. 52-55.

Komanoff, C. [1976] - Power Plant Performance. Council on Economic Priorities Publication, S6-1, New York.

Komanoff, C. [1978] - Nuclear Power Plant Performance, Update 2. Report in Nuclear News, 21, No.10, pp. 31-32.

Lapides, M. [1978] - Predicting Generating Unit Performance. EPRI Journal, 3, No.3, April, pp.26-30.

Margen, P. and Lindhe, S. [1975] - The Capacity of Nuclear Power Plants. The Bulletin of the Atomic Scientists, 31, No.8, October, pp.38-40.

Marshall, P. [1975] - see Fox, R.W. [1975-6] pp.4230-4260.

Moraw, G., Pinter, M., and Szeless, A. [1975] - Verfugbarkeit von Kernkraftwerken mit Leichtwasser-reaktoren. Atomwirtschaft, November, pp.558-565.

Netschert, B. [1975] - Use of Capacity Factor in the Nuclear Debate. The Bulletin of the Atomic Scientists, 31, No.8, October, pp.42-43.

Perl, L. [1977] - Review and Critique of the Council on Economic Priorities Study - Power Plant Performance. National Economic Research Associates, Inc., March.

Roberts, A. [1976] - see Fox, R.W. [1975-6] pp.8195-8243.

Simard, R. [1977] - A Critique of the Council on Economic Priorities Text, Power Plant Performance - Nuclear and Coal Capacity Factors and Economics. ORNL/TM5846, April.

Symonds, J.L. [1976] - see Fox, R.W. [1975-6] pp. 8220-8243.

APPENDIX A

DISCUSSION OF KOMANOFF'S STUDY OF COMMERCIAL NUCLEAR REACTORS

I. KOMANOFF'S STUDY

In his study for the Council on Economic Priorities (CEP), Komanoff [1976] analysed the performance of commercial nuclear reactors installed in the United States during the years 1968 to 1974. Of the 38 reactors in his data base, 24 were PWRs ranging in capacity from 450 MWe to 1050 MWe, and 14 were BWRs in the range 514 MWe to 1098 MWe. He regressed the capacity factor on the explanatory variables, unit size, unit age and year of initial commercial operation. He also examined the effects of unit duplication. According to Komanoff, the capacity factor variation in the data base was best described by the following equations:

$$\text{PWR} \quad CF = 93.48 - \frac{1}{4.22 \times \log(1+AGE)} - 3.368 \times (MWe/100) \qquad R^2 = 0.21$$

$$\text{BWR} \quad CF = 79.30 - 3.287 \times (MWe/100) \qquad R^2 = 0.11$$

where AGE is the year of operation.

These equations show that capacity factors have been inversely related to unit size. PWR capacity factors have declined at an average rate of 3.4 percentage points per 100 MWe increase in capacity and BWRs at an average rate of 3.3 percentage points per 100 MWe increase. Capacity factors for PWRs increased in the early years of operation. BWRs, however, showed no tendency for the capacity factor to alter as reactors became older. It should be noted that these conclusions about age are based on units in the CEP data base, only two of which had accumulated as many as eight years of commercial operation. Komanoff claimed that there was evidence to show that the operating reliability of power plants generally started to deteriorate at, or before, the tenth year. He cited as examples of this trend, the three nuclear plants in the 200 MWe class which had operated for at least ten years and each of which has suffered significant capacity factor reduction since then. These units were not in the CEP data base.

According to Komanoff there was no statistically significant vintage effect for either the PWRs or BWRs, although there was some evidence to suggest that duplicate PWRs installed about a year after identical reactors, at the same site, have operated at significantly higher capacity factors than their predecessors.

The CEP study showed that PWRs have operated at an average capacity factor of 61.6 per cent, almost 6 percentage points higher than the BWRs' capacity factor of 55.9 per cent. For the individual manufacturers, Westinghouse PWRs have operated at an average capacity factor of 64.7 per cent, while the General Electric BWRs have operated at an average capacity factor of 55.9 per cent. Komanoff suggested that, given the inverse relationship between capacity factor and size, some of this difference could be attributed to the larger average size of General Electric reactors, compared with those from Westinghouse.

Komanoff used his estimated equations to predict the behaviour of future nuclear reactors. In particular, he calculated the expected lifetime average capacity factor for large nuclear units and related this to the cost of producing power from these reactors. He then compared the relative economics of nuclear and coal-fired plants, and found the latter to be superior.

In a subsequent update of his study, incorporating plant data for 1977, Komanoff [1978] noted an improvement in the average capacity factor of operating nuclear plants. He also revised the size-related drop in capacity factor to 2.5 percentage points per 100 MWe for PWRs, and 3.2 percentage points per 100 MWe for BWRs.

II. PERL'S REVIEW OF THE KOMANOFF STUDY

Perl [1977] has published, for the Atomic Industrial Forum, an extensive review and critique of the study made by Komanoff for the CEP. Perl claimed that predictions of future capacity factors using Komanoff's equations would be unreliable. To substantiate this argument he made the following points.

- Komanoff's data had too much variability to explain reactor performance by a regression equation. The CEP study used data on existing nuclear reactors, with capacity factors ranging widely from 14 to 77 per cent, to generalise about the future performance of large reactors over their lifetime. Komanoff's model explained only 20 per cent of the variation in historic performance of PWRs, and 11 per cent of BWRs. At a 95 per cent confidence level, the model was capable of estimating the average performance of PWRs, ± 9 percentage points, and the capacity factor for individual PWRs, ± 30 percentage points.

- The CEP data base consisted mainly of information on reactors which were smaller than those used to predict future performance. There were only five operating reactors of 1000 MWe or larger, none of which had operated for more than two years. Despite this, Komanoff projected capacity factors over a ten-year period of their life. It should be noted that the error of prediction increases dramatically as the values of the explanatory variables become further removed from their mean values in the sample. In addition, Komanoff's model assumed that reactor performance declined linearly with size. The CEP model ignored the influence of improvements in nuclear performance which may occur as both utilities and reactor manufacturers learn by experience. That is, Komanoff did not allow for a 'learning curve' or vintage effect.*

- There is evidence that capacity factors of nuclear plants vary over their operating lives, but historical data are heavily dominated by plants which have operated only for a few years. Of the 38 United States reactors operating in 1975, 12 had operated for only one year, and only 11 had operated for more than three years. If capacity factors of nuclear plants improve with age, then the use of historical data on the initial performances of reactors to project lifetime performances will result in understated future reliability. Conversely, if capacity factors deteriorate over the lives of these plants, historical data will give an overstated power plant reliability.

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* Komanoff did, in fact, consider a vintage effect but he found that the estimated regression coefficient was not significantly different from zero.

- Given the large number of variables which potentially influence the nuclear capacity factor, it becomes extremely difficult to estimate their individual effects with precision. In particular, size, year of operation, and vintage all appear to influence the nuclear capacity factor. However, these three factors are all highly correlated. Plants of recent vintage all tend to be large and have few years of operation.

- The CEP study used regression analysis to estimate the parameters of its capacity factor model. In estimating the parameters of this model, each year of operation of the 38 nuclear reactors in the data base was taken as an independent observation of reactor performance. Analysis of the data suggests substantial correlation in the year-to-year performance of individual reactors.

APPENDIX B

DATA BASE

The data used in the study are listed below. For each reactor the country, reactor supplier, gross size (MWe), type of reactor and number of years of operation are given, followed by the capacity factor for each year including the first year of operation. The -1.0 indicates that the capacity factor is not known for that year.

```
ARGE SIEM  340  HWR     4  34.7  84.5  86.3  54.9
BELG ACEC  410  PWR     4   8.1  74.9  76.2  82.7
BELG ACEC  410  PWR     3  41.8  72.3  75.7
BELG FRAM  920  PWR     3  44.9  58.0  76.4
CANA AECL  788  HWR     2  -1.0  57.6
CANA AECL  788  HWR     2   5.1  66.1
CANA AECL  220  HWR    12  -1.0   3.9  44.9  22.2  47.7  54.9  17.8
                           55.6  63.3  71.6  60.0  43.9
CANA AECL  540  HWR     7  53.7  47.2  93.2  72.5  80.8  93.6  86.0
CANA AECL  540  HWR     7  43.5  55.3  69.8  88.7  86.5  94.1  91.4
CANA AECL  540  HWR     6  36.1  85.1  44.3  58.5  94.5  95.8
CANA AECL  540  HWR     5  80.5  94.3  24.8  69.6  91.5
FRAN ACEC  319  PWR    12  -1.0  19.3   3.3   0.0  47.4  69.0  76.5
                           76.1  55.5  75.0  51.3  91.7
FRAN CEA    77  HWR    12   0.0   0.0   0.0   0.0   0.0  35.6  75.9
                           68.3  87.4  80.3  82.4  76.2
FRAN UNDI  560  GCR     6  27.8  51.9  63.0  58.1  71.3  72.6
FRAN UNDI  240  GCR    14  -1.0  14.3  28.5  64.5  62.2  84.2  81.3
                           55.3  75.6  79.3  77.9  69.3  50.2  44.6
FRAN UNDI  500  GCR    12   0.8   3.0  24.4  20.6  28.4  44.4  56.5
                           23.2   1.3  54.3  36.4  58.7
FRAN SACM   40  GCR    20   0.0   0.0   0.0   0.0  63.3  64.2  67.0
                           84.4  74.2  90.7  97.5  94.4  88.1  94.7
                           97.5  82.1  79.9  81.0  87.6  81.6
FRAN SACM   40  GCR    19   0.0   0.0   0.0  63.3  64.2  67.0  84.4
                           74.2  90.7  97.5  94.4  88.1  94.7  97.5
                           82.1  79.9  81.0  87.6  81.6
FRAN UNDI  500  GCR     9  25.4   4.0  50.4  74.9  44.4  72.4  71.0
                           59.4  54.8
FRAN UNDI  530  GCR     7  35.0  62.0  82.5  64.7  83.6  72.5  71.7
GERM AEG   805  BWR     2  26.4  49.1
GERM GE    250  BWR    12  10.3  47.9  46.7  57.4  84.2  90.9  83.0
                           78.8  87.6  86.5  58.4   3.6
GERM AEG   268  BWR    10  26.0  77.9  59.6  60.4  31.4  56.7  20.5
                           70.2  72.5   1.2
GERM AEG   670  BWR     7   0.0   0.0  45.0   8.3  31.2  65.4  64.6
GERM SIEM 1200  PWR     4  16.8  80.0  51.7  62.4
GERM SIEM 1300  PWR     2   8.6  75.2
GERM KWUR  855  PWR     2  42.4  70.3
GERM SIEM  345  PWR    10   5.7  65.8  83.8  74.6  79.4  86.9  85.0
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Continued

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                                 90.3   77.2   75.1
GERM SIEM  662  PWR      6       56.5   71.2   91.8   82.3   94.1   93.6
GERM SIEM   58  HWR     13       -1.0   14.9   17.1   20.7   34.2   84.6   65.9
                                 85.4   19.7   72.2   72.8   87.1   65.5
INDI GE    200  BWR      9       24.5   62.1   51.0   24.8   43.1   47.5   52.9
                                 65.9   56.8
INDI GE    200  BWR      9       24.5   62.1   51.0   24.8   71.2   34.1   52.8
                                 64.9   71.5
INDI AEAE  220  HWR      6        0.0    0.0   50.5   34.3   46.7   27.5
ITAL GE    160  BWR     15        0.0   52.5   68.9   58.3   65.5   73.6   84.3
                                 53.0   82.3   31.8   73.1   54.5   35.8   86.4
                                 34.3
ITAL WEST  272  PWR     14        8.4   38.9   71.0   27.1    0.0    0.0   52.2
                                 56.9   83.3   59.7   68.7   96.5   66.5   76.6
ITAL TNPG  210  GCR     16        0.0   17.5   83.9   82.5   78.9   86.2   83.9
                                 27.0   64.7   45.9   65.4   37.7   54.8   54.1
                                 54.3   58.5
JAPA GETO  460  BWR      8       -1.0   45.8   64.2   55.0   42.8    0.0   41.2
                                  0.0
JAPA GE    784  BWR      6        0.0    0.0   55.8    9.4   63.4    0.8
JAPA TOSH  784  BWR      4       -1.0    0.0   72.4   32.8
JAPA TOSH  540  BWR      4       -1.0   44.3   56.5   50.3
JAPA HITA  460  BWR      5        0.0   76.5   76.7   73.0   49.1
JAPA GE    357  BWR      9        3.2   60.8   60.4   72.6   80.3   61.1   33.5
                                 66.5   36.4
JAPA MHI   559  PWR      3       40.2   78.5   84.0
JAPA WEST  340  PWR      8       42.8   59.1   51.2   34.5   14.3    0.0    0.0
                                  0.0
JAPA MHI   500  PWR      6       48.6   60.7   75.2    6.4   68.6   39.8
JAPA MHI   826  PWR      2       38.6   65.4
JAPA WEST  826  PWR      4       47.0   72.8   46.5    5.6
JAPA MHI   826  PWR      4       -1.0   46.8   54.7   69.0
JAPA GEC   166  GCR     13       -1.0   23.7   46.1   59.9   61.9   59.2   67.8
                                 67.4   70.2   67.2   69.0   70.0   67.6
NETH GEGK   54  BWR     10       10.1   66.8   77.7   85.6   68.9   78.8   59.8
                                 86.8   91.1   80.5
NETH KWUR  477  PWR      5       27.3   73.3   69.9   82.3   79.6
PAKI CGE   137  HWR      7        0.4   19.4   38.1   48.6   45.5   40.6   28.1
SPAI GE    460  BWR      7       37.6   66.3   61.5   59.0   72.0   74.9   47.8
SPAI WEST  160  PWR     10       10.2   56.5   65.8   71.8   64.0   65.4   76.5
                                 80.9   79.1   85.1
SPAI GC    518  GCR      6       28.5   69.3   83.0   77.2   75.4   75.0
SWED ASEA  590  BWR      3       30.8   71.4   54.6
SWED ASEA  460  BWR      8        0.0    1.5   35.1   50.9   33.5   69.5   64.0
                                 69.0
SWED ASEA  590  BWR      4        9.6   61.0   58.6   68.0
SWED ASEA  792  BWR      5       -1.0    1.1   16.9   32.1   52.3
SWED WEST  822  PWR      4        4.8   45.8   61.8   60.7
SWIT GETS  336  BWR      7       -1.0   30.0   71.7   66.1   83.6   84.0   86.7
SWIT WEST  364  PWR      9       32.4   61.0   53.3   44.0   55.0   76.9   81.5
                                 83.4   84.9
SWIT WEST  364  PWR      7       25.3   82.4   72.9   82.6   83.3   86.6   88.0
BRIT TNPG  167  GCR     17       -1.0   28.1   43.2   50.9   86.3   73.7   85.9
                                 88.9   87.1   88.4   87.2   77.5   84.9   79.9
                                 80.5   80.3   73.7
BRIT TNPG  167  GCR     16       28.1   43.2   50.9   86.3   73.7   85.9   88.9
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                                     87.1  88.4  87.2  77.5  84.9  79.9  80.5
                                     80.3  73.8
BRIT TNPG  187   GCR        17      -1.0  29.3  61.0  72.6  78.9  75.2  82.4
                                     74.3  76.2  55.4  56.2  64.9  59.3  61.7
                                     62.7  62.2  61.7
BRIT TNPG  187   GCR        16      -1.0  22.3  61.0  72.6  75.2  82.4  74.3
                                     76.2  55.4  56.2  64.9  59.3  61.7  62.7
                                     62.3  61.7
BRIT UKAE   60   GCR        22      28.2  49.2  28.9  69.8  66.9  74.7  81.2
                                     84.2  82.7  82.9  79.7  80.6  88.6  87.6
                                     93.5  85.6  90.9  88.8  88.8  38.8   0.0
                                      0.0
BRIT UKAE   60   GCR        22      27.4  49.2  28.9  69.8  66.9  74.7  81.2
                                     84.2  82.7  82.9  79.7  80.6  88.6  87.6
                                     93.5  85.6  90.9  88.8  88.8  77.4  79.1
                                     64.6
BRIT UKAE   60   GCR        20      28.7  69.8  66.9  74.7  81.2  84.2  82.7
                                     82.9  79.7  80.6  88.6  87.6  93.5  85.6
                                     90.9  88.8  88.8  77.4  79.3  64.6
BRIT UKAE   60   GCR        20      29.7  69.8  66.9  74.7  81.2  84.2  82.7
                                     82.9  79.7  80.6  88.6  87.6  93.5  85.6
                                     90.9  88.8  88.8  77.4  79.3  64.6
BRIT UKAE   60   GCR        20      28.5  30.2  58.2  70.3  82.1  84.2  82.7
                                     87.3  79.7  92.4  88.6  87.5  93.5  85.6
                                     91.8  91.5  91.1  88.0  89.2  80.8
BRIT UKAE   60   GCR        19      30.0  58.2  70.3  82.1  84.2  82.7  87.3
                                     79.7  22.8   0.0  43.7  93.5  85.6  91.8
                                     91.5  91.1  88.0  89.2  80.8
BRIT UKAE   60   GCR        19      30.2  58.2  70.3  82.1  84.2  82.7  87.3
                                     79.7  92.4  88.6  87.5  93.5  85.6  91.8
                                     91.5  91.1  88.0  89.4  81.0
BRIT UKAE   60   GCR        19      29.7  58.2  70.3  82.1  84.2  82.7  87.3
                                     79.7  92.4  88.6  87.5  93.5  85.6  91.8
                                     91.5  91.1  88.0  89.4  81.0
BRIT TNPG  285   GCR        13      12.6  68.6  77.2  69.2  76.5  63.6  68.2
                                     68.4  66.7  64.8  68.4  63.7  58.6
BRIT TNPG  285   GCR        13      87.9  68.6  77.2  69.2  76.1  63.6  68.2
                                     68.4  66.7  64.8  68.4  63.7  58.6
BRIT EEBT  330   GCR        14      -1.0  42.2  73.7  74.4  70.2  66.3  36.0
                                     11.8  49.8  47.7  62.9  60.9  65.1  66.1
BRIT EEBT  330   GCR        14      -1.0  42.2  73.7  74.4  70.2  66.3  36.0
                                     11.8  49.8  47.7  62.9  60.9  65.1  66.1
BRIT GEC   180   GCR        15      -1.0  47.4  79.4  77.9  77.7  78.3  85.4
                                     83.7  81.7  72.7  71.0  78.2  86.8  74.0
                                     89.3
BRIT GEC   180   GCR        14      47.0  79.4  77.9  77.7  78.3  85.4  83.7
                                     81.7  72.7  71.0  78.2  76.6  88.9  71.6
BRIT TNPG  313   GCR        11      -1.0  34.1  53.5  46.4  57.7  52.4  47.8
                                     51.2  54.3  57.0  59.1
BRIT TNPG  313   GCR        11      -1.0  34.1  53.5  46.4  57.7  52.4  47.8
                                     51.2  54.3  57.1  59.1
BRIT EEBT  325   GCR        13      -1.0  28.4  50.1  63.3  61.4  63.7  68.3
                                     56.9  60.9  65.2  71.5  71.1  69.5
BRIT EEBT  325   GCR        13      -1.0  28.4  50.1  63.3  61.4  63.7  68.3
                                     56.9  60.9  65.2  71.5  71.1  69.5
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BRIT APC    290  GCR    14  -1.0  46.1  27.6  51.4  73.0  66.0  66.9
                            66.9  62.2  39.8  73.4  71.4  70.1  69.6
BRIT APC    290  GCR    14  -1.0  46.1  27.6  51.4  73.0  66.0  66.9
                            66.9  62.2  39.8  73.4  71.4  70.1  69.7
BRIT EEBT   670  GCR     9  -1.0   0.0  14.7  40.4  23.6  44.0  16.2
                            49.3  50.8
BRIT EEBT   670  GCR     8  -1.0  14.7  40.4  23.6  44.0  16.2  49.4
                            50.8
BRIT TNPG   660  AGR     2  17.5  20.9
BRIT TNPG   660  AGR     2  -1.0   0.0
BRIT TNPG   660  AGR     2  -1.0  21.5
BRIT TNPG   660  AGR     2  30.2  33.3
BRIT UKAE    40  AGR    16  -1.0   0.0   0.0   0.0  66.4  71.6  62.5
                            66.2  63.3  65.9  55.0  52.8  32.5  44.5
                            56.5  49.6
USA  GE      75  BWR    16  19.6  19.8  31.0  29.1  55.2  80.6  68.3
                            64.2  58.0  51.6  58.1  67.7  54.1  46.8
                            39.4  58.1
USA  GE    1097  BWR     5  -1.0  59.0  14.7  14.0  54.2
USA  GE    1097  BWR     4  24.2  15.2  16.8  66.8
USA  GE    1097  BWR     2  36.6  77.6
USA  GE     834  BWR     2  -1.0  35.9
USA  GE     834  BWR     3  24.7  35.6  34.9
USA  GE     801  BWR     4  30.4  56.9  54.1  67.2
USA  GE     210  BWR    19  -1.0  15.0  30.1  67.9  53.8  56.4  55.3
                            80.1  46.4  52.5  47.2  77.6  35.3  63.0
                            33.1  21.1  40.5  55.1  37.7
USA  GE     840  BWR     8  17.0  38.1  45.8  71.4  48.8  42.5  62.6
                            51.1
USA  GE     838  BWR     7  16.2  70.4  52.8  46.2  31.8  57.9  74.4
USA  GE     597  BWR     4  34.5  47.2  51.1  59.2
USA  GE     849  BWR     4  -1.0  29.9  57.6  54.2
USA  GE     813  BWR     4   2.4  45.4  61.0  54.9
USA  GE      65  BWR    15  33.7  66.7  47.7  29.1  59.7  81.8  68.3
                            75.6  60.7  66.3  77.2  66.7  69.7  36.2
                             0.0
USA  ALIS    55  BWR    11  -1.0   0.6  16.0  27.8  43.6  53.1  44.4
                            69.1  58.1  38.6  20.5
USA  GE     682  BWR     8   4.5  62.7  55.3  33.0  63.1  68.2  65.9
                            84.4
USA  GE     580  BWR     8  -1.0  28.8  73.1  67.1  60.1  59.4  82.1
                            73.3
USA  GE     640  BWR     9   3.8  34.2  54.1  59.6  64.2  60.3  56.1
                            75.7  54.2
USA  GE     650  BWR     9   9.2  63.0  69.7  79.0  65.3  66.8  57.4
                            70.2  59.3
USA  GE    1100  BWR     5  -1.0  54.3  55.0  60.1  43.8
USA  GE    1100  BWR     4  28.4  57.1  65.2  51.8
USA  GE     685  BWR     6  25.4  70.6  34.2  44.9  42.0  46.2
USA  GE     832  BWR     7  -1.0  34.6  70.5  50.5  62.9  50.2  52.5
USA  GE     832  BWR     6  29.3  74.8  64.6  37.3  64.0  64.2
USA  GE     537  BWR     6  11.7  41.3  56.5  79.8  72.5  78.8
USA  BABW   902  PWR     4  99.6  65.1  51.5  67.6
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USA   WEST   888   PWR      2   10.8   39.7
USA   CE     880   PWR      2   10.5   81.7
USA   CE     880   PWR      4   -1.0   60.1   85.6   66.2
USA   WEST  1090   PWR      3   48.9   74.0   52.5
USA   CE     480   PWR      5   37.9   61.0   52.5   55.4   73.2
USA   WEST   450   PWR      9    5.8   58.7   72.8   65.2   91.0   56.5   81.1
                                55.3   81.2
USA   WEST   600   PWR     11   21.4   60.3   73.0   70.7   83.6   85.9   48.4
                                86.9   82.3   80.4   80.1
USA   BABW   163   PWR     16   13.3   66.8   43.8   80.2   85.9   22.6   14.8
                                26.5   26.7   94.4   87.2    0.0   94.4    0.0
                                 0.0    0.0
USA   WEST   902   PWR      5    5.9   44.7   64.8   30.3   68.2
USA   WEST  1005   PWR      2   49.0   65.3
USA   WEST   560   PWR      4   50.3   71.7   72.4   75.8
USA   CE     830   PWR      6   25.5   49.2   52.1   65.4   85.8   74.4
USA   CE     860   PWR      3    8.9   63.5   60.3
USA   BABW   922   PWR      5   38.9   52.3   69.0   52.3   51.8
USA   BABW   922   PWR      5   13.1   26.2   64.7   55.1   50.1
USA   BABW   922   PWR      4   27.5   65.5   61.8   68.2
USA   CE     723   PWR      7    0.0   30.0   39.7    1.5   41.5   48.0   85.2
USA   WEST   524   PWR      8   27.8   75.0   67.2   63.2   72.1   67.0   77.6
                                84.0
USA   WEST   524   PWR      6    7.4   69.2   72.9   85.8   85.9   82.7
USA   WEST   560   PWR      5    6.6   32.5   80.0   71.0   80.5
USA   WEST   560   PWR      4    2.2   69.2   58.5   84.2
USA   BABW   966   PWR      4    9.6   31.6   27.2   73.0
USA   WEST   739   PWR      8    0.8   39.7   78.4   61.5   78.2   67.9   79.1
                                69.2
USA   WEST  1132   PWR      2    0.2   39.9
USA   WEST   450   PWR     11   16.8   34.4   69.7   81.3   80.4   82.6   60.8
                                83.9   86.4   66.2   62.4
USA   WEST   100   PWR     21   -1.0    0.0    0.0   30.6   40.2   42.1   45.1
                                 2.9   41.4   67.0   60.8   46.9   39.1   44.1
                                34.1   29.5   30.2    3.5    0.0    0.0   15.4
USA   CE     840   PWR      2   12.2   77.2
USA   WEST   824   PWR      6   11.3   51.0   48.5   57.1   64.1   72.8
USA   WEST   824   PWR      5   54.1   38.5   73.7   48.8   64.6
USA   BABW   876   PWR      4   59.3   77.1   60.5   75.8
USA   WEST  1178   PWR      3    0.2   23.0   66.9
USA   WEST   728   PWR      6    5.0   54.9   60.7   71.9   71.4   73.9
USA   WEST   728   PWR      5   39.3   71.8   65.9   62.4   60.6
USA   WEST   185   PWR     18    5.8   56.9   45.6   61.9   77.5   63.3   84.6
                                83.1   79.7   74.7   78.9   93.7   42.5   68.6
                                60.1   78.4   82.2   67.3
USA   WEST  1085   PWR      5   14.3   39.2   55.0   51.8   57.7
USA   WEST  1085   PWR      5   -1.0   15.0   53.8   52.8   70.3
USA   CE     862   PWR     15    0.0    0.0    0.0   13.4   27.2   52.4   51.9
                                35.8   34.7   39.9   60.6   53.4   45.3   32.9
                                58.8
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