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Energy and Environment Division

Power Plant Reliability-Availability and State Regulation

A.V. Nero and I.N.M.N. Bouromand

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POWER PLANT RELIABILITY-AVAILABILITY AND STATE REGULATION

A. V. Nero and I.N.M.N. Bouromand

Volume 7

of

HEALTH AND SAFETY IMPACTS OF

NUCLEAR, GEOTHERMAL, AND FOSSIL-FUEL

ELECTRIC GENERATION IN CALIFORNIA

Energy and Environment Division
Lawrence Berkeley Laboratory
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Berkeley, California 94720

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Vol. 1: "Health and Safety Impacts of Nuclear, Geothermal, and Fossil-Fuel Electric Generation in California: Overview Report," by the entire staff, Lawrence Berkeley Laboratory Report LBL-5924. Includes "Executive Summary" for the project.

Vol. 2: "Radiological Health and Related Standards for Nuclear Power Plants," by A.V. Nero and Y.C. Wong, Lawrence Berkeley Laboratory Report LBL-5285.

Vol. 3: "A Review of Light-Water Reactor Safety Studies," by A.V. Nero and M.R.K. Farnaam, Lawrence Berkeley Laboratory Report LBL-5286.

Vol. 4: "Radiological Emergency Response Planning for Nuclear Power Plants in California," by W.W.S. Yen, Lawrence Berkeley Laboratory Report LBL-5920.

Vol. 5: "Control of Population Densities Surrounding Nuclear Power Plants," by A.V. Nero, C.H. Schroeder, and W.W.S. Yen, Lawrence Berkeley Laboratory Report LBL-5921.

Vol. 6: "Health Effects and Related Standards for Fossil-Fuel and Geothermal Power Plants," by G.D. Case, T.A. Bertolli, J.C. Bodington, T.A. Choy, and A.V. Nero, Lawrence Berkeley Report LBL-5287.

Vol. 7: "Power Plant Reliability-Availability and State Regulation," by A.V. Nero and I.N.M.N. Bouromand, Lawrence Berkeley Laboratory Report LBL-5922.

Vol. 8: "A Review of Air Quality Modeling Techniques," by L.C. Rosen, Lawrence Berkeley Laboratory Report LBL-5998.

Vol. 9: "Methodologies for Review of the Health and Safety Aspects of Proposed Nuclear, Geothermal, and Fossil-Fuel Sites and Facilities," by A.V. Nero, M.S. Quinby-Hunt, et al., Lawrence Berkeley Laboratory Report LBL-5923.

POWER PLANT RELIABILITY-AVAILABILITY AND STATE REGULATION

ABSTRACT

Data from the Edison Electric Institute annual report on equipment availability are briefly examined with a view to determining the breadth of effort which would be required to reduce outage time caused by equipment difficulties. For nuclear units for several size categories of fossil units, and for gas turbine units, the basic data are examined to establish the basic operating experience and related outage and availability rates, and to assign outages to major plant systems. Related data giving detailed outage causes are grouped to yield data on component failure versus outage time, information that is required to determine the possible impace of research and regulatory efforts on reliability and availability.

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1. Introduction

The reliability of electric generating facilities may have important effects on both plant safety and the cost of electricity. Component and system failures can lead to unsafe conditions in or around the plant and can lead to plant unavailability and increased generation costs.

For most power plants, interested regulatory agencies do not concern themselves with the detailed design of a plant, except for areas with well-defined safety significance. This includes many design areas for nuclear power plants, which are reviewed and licensed by the Nuclear Regulatory Commission (NRC), and relatively few areas of geothermal and fossil-fuel plants. However, Occupational Safety and Health Administration (OSHA) regulations apply to many areas in conventional industrial facilities, including power plants. Areas covered by the California OSHA regulations include boiler and pressure vessels, petroleum handling, and areas pertaining directly to worker health and safety.

Whether more detailed regulation of power plant design and operation would increase safety or decrease costs is a question of interest to agencies responsible for review of proposed electric generating facilities, such as the California Energy Resources Conservation and Development Commission (ERCDC). The purpose of this report is to examine the narrow question of whether efforts directed specifically at the reduction of component and system failures could result in improvements in these areas. We do not attempt to resolve the question, but — on the basis of historical data — attempt to indicate the extent of efforts which would be required to make improvements in safety and cost.

2. The Current Data and Other Studies

The technologies of interest in this work are nuclear, geothermal, and fossil-fuel power plants. However, the Edison Electric Institute, in its periodic reports on power plant performance,[1] devotes primary attention to nuclear and fossil-fuel plants, and these are the types which will be examined below. Geothermal plants are also important in California; limited data are available on these plants. However, the data are not in a form that is readily comparable with the other plant types. Since, moreover, the basic plant design is significantly different in that it does not include a steam supply system, in this report we restrict our attention to the more conventional and widely-used system.

The Edison Electric Institute (EEI) assembles data from utilities throughout the United States. The data of primary interest in the basic EEI report[1] are concerned with plant availability or, conversely, outage rates. This information is relatively closely connected with "reliability", and only distantly related to plant, worker, or public safety. The connection between these areas is obscured partly by the fact that each of them is affected differently by ancillary matters, such as how the plant is actually operated internally and how it is connected with the electric generating network as a whole. An example of the first of these matters would be the importance that is attached to instances when a particular monitoring system becomes inoperative: is the plant shut down completely, partially, or not at all? As for external matters, a plant's position within the generating network determines whether it is used as a base load plant or not: to some extent, the degree to which this alters the balance between availability and service hours will be apparent in the information below.

Appendices to this report define many of the terms used below, but several of the more important ones should be specified here. We have already referred to reliability, availability, and outages. <u>Reliability</u> has an intuitive significance, but is difficult to specify precisely; so the others will be used hereafter. <u>Availability</u> is the percentage of time that a plant is available for use, whether or not it is actually used. <u>Outage time</u> is the time during which a plant is removed from service for equipment-related reasons and may be either forced (complete or partial, depending on the percentage reduction in output that is necessary), maintenance (indicating that the required service was able to be postponed for a time), or planned (indicating periodic maintenance that is intrinsic to the particular plant type). An additional term of some importance from the point of view of overall availability is <u>capacity factor</u>, the ratio of actual energy output for a period to output if the plant had been run continuously at full capacity.

A large amount of work has recently been done on various aspects of plant reliability and availability. These have usually been directed to questions of cost or to increased availability. The report of the Council on Economic Priorities[2] is a good example of the former category. This report compares cost of coal-fired plants with nuclear plants, including both pressurized-water and boiling-water types; the cost comparisons include consideration of expected capacity factors, based on an analysis of historical data. However, the conclusions of the report have been criticized because the plant types are broken down in so much detail that each category has few examples, so that the statistical significance of the results is questionable. Substantial work directed more to system reliability, emphasizing nuclear systems, is being performed at the Electric Power Research Institute, and has resulted in several reports.[3]

The intention of this brief report is more to characterize the breadth of component failures than to perform any detailed analysis. For this reason, we have confined our attention to the EEI report on availability,[1] which does not distinguish between different types of nuclear plants or different types of fossil-fuel plants. Further analysis of the specific types would be necessary to yield detailed information on how to improve reliability or availability. Our purpose is less ambitious.

We begin with a brief look at the availability of major plant types, then proceed to an identification of the major outage causes by broad system categories. Finally, more detailed information, assigning outages to specific component failure categories, is used to identify where major sources of outage time arise. The major plant types considered are nuclear and fossil-fuel units. Although the EEI report separately considers gas turbines, jet engines, and diesels. Of the last three types, gas turbines are included below. Fossil units should be regarded to include coal, oil, and gas-fired steam plants and are not distinguished in this work. The primary focus in what follows is, as just suggested, outage time. We also include information on number of occurrences. The first is directly relevant to availability, and both are related to reliability.

3. Overall plant data

The data used are taken exclusively from the current Edison Electric Institute report on equipment availability for the ten years 1965 to 1974.[1] and a supplementary report.[4] To gain an appreciation of the overall reliability of electric generating units, data indicating the basic operating experience (stated in terms of unit-year averages) were abstracted from that report. These data are summarized, for fossil-fuel units in various size categories, for all fossil-fuel units, for nuclear units, and for gas turbine units, in Table 3-1. For the same unit categories, outage and availability rates derived from operating experience are shown in Table 3-2.

The basic distinction between the information given as "operating experience" and that given as "rates" is that the first is stated in terms of time periods in hours (see Appendix II) while the rates are percentages obtained as ratios (see Appendix III) of appropriate time periods. These same ratios will be used in the discussion of sections 4 and 5 on system and component outage rates.

Basic operating experience

Although attention is usually given only to the outage and availability rates, it is useful to examine first the basic operating experience. These data indicate the manner in which the different plant types are used and also provide direct clues indicating the vintage of the various plants. Table 3-1 gives "service hours", the average time during which units are actually operated; the table also gives "available hours", which is the sum of service hours and "reserve shutdown hours", the time during which the plant was available, but not needed (for economic or similar reasons). For all the fossil-fuel and nuclear categories, the service hours are within 5% of the available hours, indicating that these units are used whenever possible, i.e., as "base load" units. (However, this interpretation is not entirely unambiguous since planned outages may be scheduled during periods when the plant was not needed.) On the other hand, the gas turbine units were used for only a small portion of their available time, indicating that they were used for supplying peak loads.

The "total outage hours" given in Table 3-1 is the sum of forced, maintenance, and planned outages. The sum of outage hours and available hours yields "period hours", the total clock time during which the plant had been completed and con-

Table 3-1: Basic Operating Experience for Electric Generating Units, 1965-1974

CATEGORY	NO. OF UNITS	NO. OF UNIT YEARS	PERIOD HOURS (PH)*	SERVICE HOURS (SH)*	AVAILABLE HOURS (AH)*	TOTAL OUTAGE HOURS (OH)*
Fossil (130-199 MWe)	259	1899	8756.	7512.	7752.	1004.
Fossil (200-389 MWe)	247	1686	8636.	7273.	7366.	1269.
Fossil (390-599 MWe)	111	555	8438.	6604.	6666.	1772.
Fossil (600 & Above MWe)	81	285	8088.	5730.	5934.	2154.
Fossil (all units)	945+	6274	8659.	7118.	7475.	1184.
Nuclear	43	123	7955.	5827.	6017.	1939.
Gas Turbine	570	2199	8097.	1243.	7071.	1027.

* Average per unit year

+ Because this includes units smaller than 130 MWe, it does not equal the sum of the individual fossil categories given nected to the overall electric generating system. This period would be one year (no less than 8760 hours) but for the fact that the number of "units years" includes the year in which each plant began operation. Note that for large fossil units (600 MWe minimum), nuclear units, and gas turbines, the period hours is about 8000, substantially less than 8760, indicating that a significant portion of the unit years counted were the actual start-up years for those units. This indirectly indicates that the units in these categories are, on the average, rather young, a fact that is substantiated by a comparison of the number of unit years in these categories with the number of units. Such a comparison shows that these units had only operated about three years, on the average, a significant contrast with fossil units under 600 MWe, which operated twice as long, on the average. Thus large fossil units, nuclear units, and gas turbine units are relatively recent additions to total electric generating capacity.

Outage and availability rates

The basic operating experience given above is converted into more convenient ratios, which indicate directly the degree to which each class of unit achieves certain goals. Generally speaking, these goals are low outage rates or high "operation" ratios. Several of these rates and ratios, all expressed in percentages, are given in Table 3-2, and a brief examination shows that there is no direct correlation between outage rates and operating ratios (either availability or capacity factor). Any possible correlation is destroyed largely because of the distinctive operating characteristics and purposes of the various plant categories.

Three outages rates are shown in the table. The forced outage rate, the ratio of forced outage hours to service hours plus forced outage hours, directly indicates the probability that the plant would be forced out of operation when it was definitely needed. The "equivalent" forced outage rate modifies the simple forced outage rate to take consideration of the times when it is only necessary to reduce the output of the plant, rather than to take it out of service entirely. For the fossil and nuclear unit categories these two rates maintain a relatively consistent percentage difference. (The ratio of the "equivalent forced" to the "forced" outage rates varies from 1.34 to 1.44 for the specific fossil categories, with 1.36 for fossil "all units". The ratio for nuclear is 1.36.) The third outage rate given is a total outage rate, and therefore includes consideration of scheduled (i.e., maintenance and planned) outages. As a result, it is some

Table 3-2 Outage and Availability Rates for Electric Generating Units, 1965-1974 (given as unit year averages)

CATEGORY	FORCED OUTAGE RATE (%)	EQUIVALENT FORCED OUTAGE RATE (%)	TOTAL OUTAGE RATE (%)	CAPACITY FACTOR (%)	OPERATING AVAILABILITY (%)
Fossil (130-199 MWe)	3.6	4.8	11.8	72.5	88.5
Fossil (200-389 MWe)	5.3	7.6	14.8	71.1	85.3
Fossil (390-599 MWe)	9.5	12.9	21.2	63.4	78.9
Fossil (600 & Above MWe)	15.8	21.8	27.3	58.1	73.3
Fossil (all units)	5.03	6.8	14.3	66.8	86.3
Nuclear	11.5	15.6	25.0	59.6	75.6
Gas Turbine	32.3	32.8	45.2	12.9	87.3

measure of the total "unavailability" of the plant, and is derived somewhat independently of periods when the plant is shut down for economic or similar reasons. (However, as noted above, it may not be completely independent, since a planned outage may be scheduled for a time when the plant is not needed.)

The "operating" ratios given are operating availability and capacity factor. The first is the ratio of available hours to period hours, a simple ratio, but one which is not simply related to reliability, although it is often interpreted to be similar. The relationship is obscured by the inclusion of reserve shutdown hours in available hours. The second operating ratio, capacity factor, is the ratio of the measured output of electrical energy from a plant category to the output that would result from operating the plants at their full rated output for 100% of the period considered. Capacity factor is therefore reduced from 100% by any reduction of plant output for any reason. Because reserve shutdown is one such reason, capacity factor is also not a measure of reliability. It is more directly a measure of service time, modified by periods of reduced output, such as partial outages or load following. Even though operating availability and capacity factor are not direct measures of reliability, they are among the parameters that are useful for planning purposes (i.e., consideration of how many units will be needed to meet any particular demand).

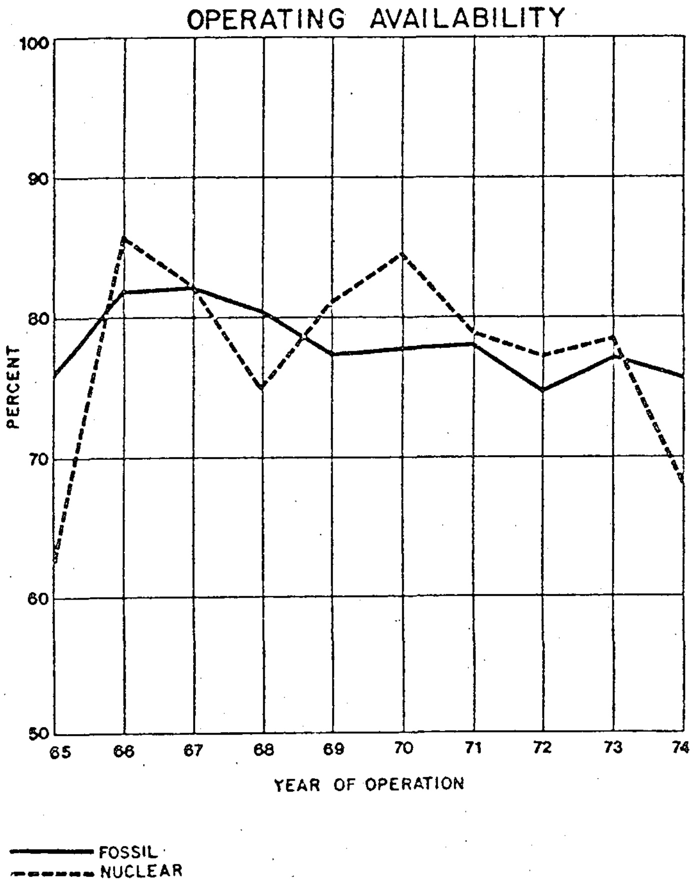
From the data given in Table 3-2, we note first that, for fossil units, outage rates increase with unit size (power) and, conversely, operating ratios decrease with size. This does not necessarily imply that large units inherently have more outage or operating difficulties. As noted above, average plant operating experience (years of operation) decreases with unit size, so that larger outage rates may be related to lesser operating experience rather than to larger unit size. There is no way to choose between these possibilities on the basis of the aggregate data of the EEI reports. Such a choice could be made using data broken down by age of plant.

A comparison is often made between nuclear and fossil units. Since nuclear units are relatively large, such a comparison should only consider the larger fossil units, the natural competitors with nuclear units. The average unit size of the 58 nuclear units licensed to operate on June 30, 1976 was about 750 MWe. The average for the 43 units included in the data of the EEI report being considered was certainly slightly lower, probably close to the minimum of the largest fossil-unit size range (600 MWe and larger). As already noted, the nuclear category and the fossil $\geq$ 600 MWe category even have similar operating experience: 3 and 3 1/2 years per unit, respectively. So a comparison seems appropriate and yields the observation that the nuclear category has somewhat lower forced (11.5 vs 15.8%) and total (25.0 vs 27.3%) outage rates and somewhat higher operating availability (75.6% vs 73.3%) and capacity factor (59.6 vs 58.1%) than the largest fossil units. If the comparison is made with the next smallest fossil size (390 to 599 MWe), the situation is exactly reversed, and by about the same amount for each parameter. Since the average nuclear unit size really lies close to 600 MWe, the dividing line between the two fossil categories noted, one must conclude that this data does not suggest how to choose, on the basis of performance, between nuclear units and fossil units of comparable size. They are comparable. Any choice would have to be made on the basis of more complete data, perhaps categorizing units more specifically by plant type, size, and age.[2]

These observations are based on the ten year EEI data.[1] The same report also displays the forced outage rate and operating availability by year of operation for nuclear units and for the sum of the two largest fossil-unit categories. These data are shown in figure 3-1; the number of units as a function of year is also given. Year-to-year variations are apparent, especially for nuclear, with its smaller sample (i.e., number of units), but no clear trend for the future is apparent. To check this, monthly data[5] on operating nuclear plants for the year September 1975 through August 1976 were averaged, yielding a forced outage rate of 14.5%, above that given in Table 3-2, but less than the 18 to 19% given for 1974 in Figure 3-1. The year's unit availability and unit capacity (comparable to the operating availability and capacity factor, respectively) were 68.8% and 62.6%, respectively. The first is less than the Table 3-2 datum and comparable to the 1974 result in Figure 3-1, which was lower than the ten-year average. The 62.6% figure is actually higher than the ten-year average, suggesting the possibility that "unit capacity" may be calculated differently than capacity factor or that nuclear units are less often placed on reserved shutdown now than in the past. (Capacity may simply have been more effectively utilized.) Regardless of the details, though, the yearly data--like the ten-year data--shows little difference between nuclear units and large fossil units. In any case, in examining yearly data--especially for nuclear--one must be aware that noticeable changes in average numbers can be caused by changes in the status of one or few nuclear units, such as the fire at the Brown's Ferry facility. (See LBL 5286).

Comparison of Fossil Units 390 MW and Above to All Nuclear Units

UNIT YEAR AVERAGES
1965–1974



SAMPLE TABLE

Year of Operation	Fossil–390 MW and Above No. of Units	Nuclear No. of Units
1965	15	3
1966	21	5
1967	32	6
1968	52	7
1969	76	7
1970	88	9
1971	104	11
1972	128	11
1973	151	22
1974	173	42

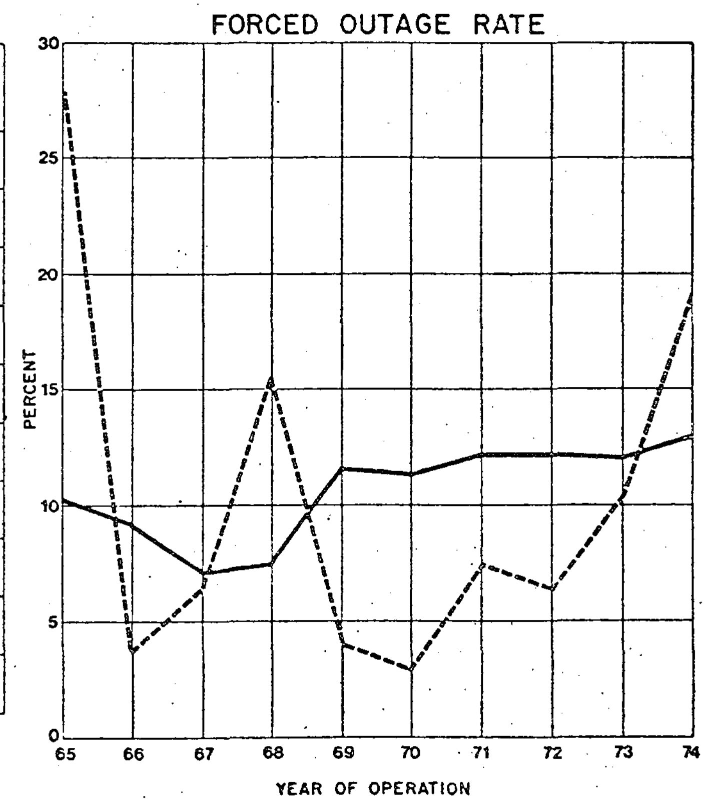


Figure 3-1 (Reproduced from reference 1)

We do not compare with the gas turbine data because--as noted above--these are used for a different purpose; they experience few service hours and have large outage rates. (Their operating availability is high because of large reserve shutdown periods.) Considering the large outage rates, leaving economic factors aside, one would not want to rely on these gas turbine units for base load operation.

Other Analyses

As we have emphasized above, these data are not unambiguous in their interpretation, either as regards the reliability of large generating units or as regards a comparison of nuclear and fossil units. The data are also deficient, as noted, in that the fossil fuel information does not distinguish between fuels. It would not be surprising if plants burning coal, a more difficult fuel to use than oil or gas, had poorer than average operating experience.

Other analyses of operating data have been performed,[2-3] often for the purpose of comparing alternative technologies with a view to predicting future reliability or availability. However, the data are limited--they are essentially the same data as examined here--and more detailed analyses can be confounded by imponderable factors. For example, examination and comparison of operating experience by age of plant may yield results subject to varied interpretations, depending on whether one assumes that the learning experience (reliability vs experience with plant operation) observed for older units can be applied to the present and future generations of plants, with increased size and possibly new features, such as the prospect of large and complex emission control systems for fossil units.

The difficulty of interpreting available data makes the information summarized above and also treated in other analyses an imperfect basis for making general planning decisions, such as the number of units needed, or for making particular choices, such as between fossil (or coal) and nuclear. We do note that the data base yearly becomes larger. In the present discussion, though, we refrain from suggesting any particular conclusion useful for planning. Instead, we proceed to the following sections to present data that may serve as the information base for making choices intended to improve reliability.

4. Outage Data by Major System

Determination of the reasons for outages (unavailability) of electric generating plants usefully begins with an assignment of outage causes to the major systems making up the plant. For any plant based on steam generation, the plant may be divided into a steam generating system and the energy conversion systems. The latter category is common to this entire class of plants and consists basically of a steam-driven turbine, an electric generator driven by the turbine, and a condenser which removes waste heat and converts the steam exiting the turbine into (liquid) water for return to the steam supply system.

One alternative to a steam-based system is a gas turbine unit, in which the gases resulting from combustion of fossil fuels are used directly to drive the turbine. In an advanced form of this concept, the gases exiting from the turbine generate steam to drive a steam turbine, giving rise to the term "combined cycle."

Of the purely steam-driven systems, units are distinguished by the form of the steam supply system. Fossil fuel units use a boiler, consisting of a burner in which combustion of coal, oil, or gas takes place in proximity to water-filled tubes in which steam is raised. Nuclear units use a reactor in which nuclear fuel generates heat that is transferred to water flowing around the fuel; steam may be raised in this water itself (in a boiling-water reactor) or in secondary water contained in a steam generator (as in a pressurized-water reactor system).

Thus for steam-based units, the major systems are the boiler or reactor, the turbine, the generator, and the condenser. For pure gas-turbine systems, only the turbine and condenser (if any) are identifiable as major systems.

For the four fossil-unit size categories, nuclear units, and gas-turbine units, data from the basic EEI report[1] on forced, maintenance, planned, and total outages are given by unit and major system in Tables 4-1 to 4-6. The unit outage hour data are the same as those given in Table 3-1.

The "total outage hours" given in Table 3-1 is the sum of unit forced, maintenance, and planned outages. A similar sum has been performed for the major systems themselves, but care should be taken in interpreting the results because maintenance or planned outage of a single system may not be the cause of a unit outage: more than one system may be removed from service simultaneously.

Table 4 -1 FOSSIL UNITS 1965-1974

(FORCED OUTAGES)

UNIT YEAR AVERAGE

Cause Code \ Size	130-199 MWe	200-389 MWe	390-599 MWe	600 & Above MWe
BOILER	5. *	6.	7.	10.
	193.	273.	396.	589.
	68%	66%	56%	54%
TURBINE	1.	1.	2.	2.
	48.	79.	170.	207.
	17%	19%	24%	19%
CONDENSER	0.	0.	0.	0.
	3.	7.	13.	14.
	1%	2%	2%	1%
GENERATOR	0.	0.	1.	1.
	16.	23.	58.	209.
	6%	6%	8%	19%
OTHER	1.	1.	2.	3.
	23.	33.	67.	76.
	8%	8%	10%	7%
UNIT	6.	8.	12.	17.
	282.	413.	701.	1082.
	100%	100%	100%	99%

* Three numbers for each entry are 1) number of occ. 2) outage hours 3) percentage of total

Table 4-2 Fossil Units 1965-1974

(MAINTENANCE OUTAGES)

UNIT YEAR AVERAGE

Cause Code \ Size	130-199 MWe	200-389 MWe	390-599 MWe	600 & Above MWe
BOILER	2. *	2.	2.	2.
	163.	242.	299.	285.
	40%	37%	41%	29%
TURBINE	1.	1.	1.	2.
	90.	150.	168.	242.
	22%	23%	23%	25%
CONDENSER	1.	1.	0.	1.
	50.	83.	66.	115.
	12%	13%	9%	12%
GENERATOR	1.	1.	1.	1.
	60.	94.	100.	165.
	15%	14%	14%	17%
OTHER	1.	1.	1.	1.
	46.	88.	92.	166.
	11%	13%	13%	17%
UNIT	3.	4.	4.	3.
	203.	281.	335.	332.
	50%	43%	46%	34%

* Three numbers for each entry are 1) number of occ. 2) outage hours 3) percentage of total

Table 4-3 FOSSIL UNITS 1965-1974

(PLANNED OUTAGES)

Cause Code \ Size	130-199 MWe	200-389 MWe	390-599 MWe	600 & Above MWe
BOILER	1. *	1.	1.	1.
	428.	499.	597.	563.
	33%	30%	28%	33%
TURBINE	1.	1.	1.	1.
	352.	419.	571.	487.
	27%	25%	27%	29%
CONDENSER	0.	0.	0.	0.
	178.	261.	314.	165.
	14%	16%	15%	10%
GENERATOR	0.	0.	0.	0.
	235.	316.	391.	315.
	18%	19%	18%	19%
OTHER	0.	0.	0.	0.
	111.	175.	249.	162.
	9%	10%	12%	10%
UNIT	1.	1.	1.	1.
	519.	575.	736.	739.
	40%	34%	35%	44%

* Three numbers for each entry are 1) number of occ. 2) outage hours 3) percentage of total

FOSSIL UNITS

Table 4-4 TOTAL (FORCED + MAINT. + PLANNED OUTAGES) 1965-1974

UNIT YEAR AVERAGE

Cause Code \ Size	130-199 MWe	200-389 MWe	390-599 MWe	600 & Above MWe
BOILER	8. * 784. 39	9. 1014 37	10. 1292. 36	13. 1437. 38
TURBINE	3. 490. 25%	3. 648. 24%	4. 909. 27%	5. 936. 25%
CONDENSER	1. 231. 12%	1. 351. 13%	0. 393. 11%	1. 294. 8%
GENERATOR	1. 311. 16%	1. 433. 16%	2. 549. 15%	2. 689. 18%
OTHER	2. 180. 9%	2. 296. 11%	3. 408. 11%	4. 404. 11%
UNIT	10. 1004. 50%	13. 1269. 46%	17. 1772. 50%	21. 2153. 57%

* Three numbers for each entry are 1) number of occ. 2) outage hours 3) percentage of total

As a result, the sum of system maintenance (or planned) outage hours exceeds the unit maintenance (or planned) outage hours.

Each entry in Table 4-1 to 4-6 gives the average number of occurrences per unit year,* the average outage time (in hours), and a percentage, the ratio of outage time to the sum of outage time assigned to all systems. Because of the possibility of simultaneous system outages, the unit (maintenance, planned and total) outage hours is often less than 100% of the sum of system outage hours.

The forced outage data for the four fossil categories are given in Table 4-1. In this case, the ambiguity due to simultaneous system outages does not occur (a forced outage essentially always occurs due to failure of a single critical system), so that unit outage hours does equal the sum of system outages.

For all of the unit categories of Table 4-1, boiler failure is the primary cause of outage time. As was noted in section 3, the forced outage time increases strongly with unit size. Boiler outage time also increases, but not as significantly. In contrast, the generator contribution to outages increases markedly for the largest fossil category. For these units, forced outages due to turbine and generator difficulties, together, become comparable to boiler outage times. As units become smaller, boiler-induced outages have an increased tendency to dominate.

For maintenance and planned outages, no single system dominates in fossil units, although the boiler is still the most important. Furthermore, the rough statement may be made for all systems and for the overall units that maintenance and planned outage hours increase only slightly, if at all, as unit size increases. This contrasts strongly with the forced outage data.

The total outage data for fossil units, given in Table 4-4, sums the above data, and hence obscures the distinctions we have just made. On the other hand, it does give summary information on outages of the major systems. For the largest fossil units, for example, boiler outage hours is clearly largest (1437), but turbine (936) and generator (689) are certainly comparable. However, this comparison is unambiguous only for forced outages, where overlapping outages do not occur.

Turning to the nuclear-unit data in Table 4-5, we note that the reactor

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*Although the number of occurrences is given, attention in our discussion is only given to outage times.

Table 4-5

NUCLEAR UNITS FOR 1965-1974
(OUTAGES)

UNIT YEAR AVERAGE

Outage / Cause Code	FORCED OUTAGE	MAINTENANCE OUTAGE	PLANNED OUTAGE	TOTAL OUTAGE
REACTOR	4. *	1.	2.	7.
	408.	299.	763.	1470.
	54%	54%	61%	57%
TURBINE	2.	1.	0.	3.
	195.	131.	259.	585.
	26%	24%	21%	23%
CONDENSER	1.	0.	0.	1.
	30.	53.	76.	159.
	4%	10%	6%	6%
GENERATOR	0.	0.	0.	0.
	50.	41.	95.	186.
	7%	7%	8%	7%
OTHER	2.	0.	0.	2.
	73.	26.	66.	165.
	10%	5%	5%	6%
UNIT	8.	3.	3.	14.
	756.	336.	846.	1938.
	100%	61%	67%	76%

* Three numbers for each entry are 1) number of occ. 2) outage hours 3) percentage of total

0 0 0 0 4 7 0 5 8 2 3

GAS TURBINE FOR 1965-1974
(OUTAGES)

Table 4-6

UNIT YEAR AVERAGE

Outage / Cause Code	FORCED OUTAGE	MAINTENANCE OUTAGE	PLANNED OUTAGE	TOTAL OUTAGE
GAS TURBINE	10. *	5.	1.	16.
	503.	205.	182.	890.
	86%	87%	92%	87%
GENERATOR	1.	1.	0.	2.
	54.	16.	6.	76.
	9%	7%	3%	7%
OTHER	1.	1.	0.	2.
	29.	15.	9.	53.
	5%	6%	5%	5%
UNIT	12.	7.	2.	21.
	590.	234.	198.	1022.
	100%	99%	100%	100%

* Three numbers for each entry are: 1) number of occ. 2) outage hours 3) percentage of total

causes the same percentage of forced outage time as does the boiler for the largest fossil units. However, the nuclear units do not show the large generator forced outage time exhibited by the largest fossil units. Turbine outages are similar. As to the other categories, planned outages are dominated by the reactor because of the substantial refueling time. Curiously, the percentage distribution of outage times among majors systems is similar for forced, maintenance, and planned outages.

Comparable data for gas turbines are given in Table 4-6. These units are simpler, with fewer major systems identified. Outages of the turbine completely dominate the unit outage times.

For the steam-based systems, fossil-fuel and nuclear, the general pattern is clear, i.e., that the steam-supply system is most responsible for outage time, but that the turbine is also comparatively important, as (for the large fossil units) is the generator. The next section attempts to break down very detailed outage cause data into several broad failure classes for the steam supply (boiler or reactor) and turbine systems.

5. Outage Data by Component Categories: Bases for Improved Reliability?

Detailed outage cause data is given in a subsidiary Edison Electric Institute report[4] that is to be associated with the report[1] on which sections 3 and 4 are based. Outage causes are divided into a large number of categories, somewhat too large a number to grasp easily. For the purposes of our discussion, we have grouped the categories for boiler or reactor and turbine into a small number of "component" classes, as indicated in Appendix IV.* Data for these component classes, as well as the undivided generator, condenser, and other categories, are given in Tables 5-1 and 5-2 for the moderately large and largest fossil units and in Table 5-3 for nuclear units. Data is given for forced and for the sum of all (forced, maintenance, planned, and "equivalent" partial) outages. Again, average number of occurrences, outage hours, and percentage (of the summed outage hours) for all components are given.

The component classes indicated in Appendix IV are formed in a somewhat arbitrary manner, but this is difficult to avoid. An attempt was made to associate similar components or functions. We will not discuss all the

*Because there was no obviously superior way to form the classes, their composition, as indicated in the appendix, should be examined carefully.

Table 5-1. Fossil Units, 390 - 599 MWe
Component Outages, 1965 - 1974
(555 unit-years, 111 units)

	FORCED OUTAGES			FORCED, MAINT., PLANNED & EQUIV. PARTIAL-OUTAGES		
COMPONENT	NO. OCC.	O.H.	%	NO. OCC.	O.H.	%
BOILER						
General	0.9	51.	7.3	2.2	695.	18.3
Tubes	3.1	228.	32.6	4.0	292.	7.7
Air Handling	0.3	17.	2.4	3.0	88.	2.3
Valves and Pipes	0.3	12.	1.8	1.2	37.	1.0
Fuel and Waste Systems	1.9	57.	8.2	16.0	201.	5.3
Operational Difficulties	0.3	20.	2.9	7.2	61.	1.6
Miscellaneous	0.4	9.	1.2	1.6	69.	1.8
Sub Total (Boiler)	7.	394.	56.	35.	1443.	38.
TURBINE						
General	0.2	32.	4.6	1.4	605.	15.9
Nozzles, Shafts, Blades	0.5	61.	8.7	1.2	122.	3.2
Turbine Control	0.8	56.	7.9	1.7	91.	2.4
Piping	0.1	11.	1.5	0.7	22.	0.6
Miscellaneous	0.1	10.	1.4	0.4	104.	2.7
Sub Total (Turbine)	2.	170.	24.	5.	944.	25.
GENERATOR	1.	58.	8.	2.	551.	14.
CONDENSER	0.	13.	2.	7.	417.	11.
OTHERS	2.	66.	10.	9.	476.	12.
TOTAL	12.	701.	100.	58.	3831	100.

Table 5-2. Fossil Units, 600 MWe and Above
Component Outages, 1965 - 1974
(285 unit-years, 81 units)

COMPONENT	FORCED OUTAGES			FORCED, MAINT., PLANNED & EQUIV. PARTIAL-OUTAGES		
	NO. OCC.	O.H.	%	NO. OCC.	O.H.	%
BOILER						
General	1.7	134.	11.9	4.0	767.	18.0
Tubes	2.8	248.	22.0	4.0	286.	6.7
Air Handling	0.4	31.	2.8	6.0	118.	2.7
Valves and Pipes	0.5	16.	1.4	1.8	30.	0.7
Fuel and Waste Systems	3.4	105.	9.3	42.6	262.	6.2
Operational Difficulties	0.5	31.	2.8	24.6	113.	2.6
Miscellaneous	0.7	22.	2.0	3.4	112.	2.6
Sub Total (Boiler)	10.	587.	52.	86.	1688.	40.
TURBINE						
General	0.4	34.	3.0	2.2	619.	14.5
Nozzles, Shafts, Blades, etc.	0.5	70.	6.2	1.9	148.	3.5
Turbine Control	1.1	87.	7.7	3.4	142.	3.3
Piping	0.1	7.	0.6	0.1	14.	0.3
Miscellaneous	0.2	8.	0.7	0.6	68.	1.6
Sub Total (Turbine)	2.	206.	18.	8.	992.	23.
GENERATOR	1.	244.	22.	3.	737.	19.
CONDENSER	0.	14.	1.	8.	321.	8.
OTHERS	3.	76.	7.	17.	515.	12.
TOTAL	16.	1127.	100.	122.	4252.	100.

Table 5-3. Nuclear Units
Component Outages, 1965 - 1974
(123 unit-years, 43 units)

COMPONENT	FORCED OUTAGES NO. OCC.	FORCED OUTAGES O.H.	FORCED OUTAGES %	FORCED, MAINT., PLANNED & EQUIV. PARTIAL-OUTAGES NO. OCC.	FORCED, MAINT., PLANNED & EQUIV. PARTIAL-OUTAGES O.H.	FORCED, MAINT., PLANNED & EQUIV. PARTIAL-OUTAGES %
NUCLEAR REACTOR						
General	0.1	10.	1.3	0.6	172.	5.9
Primary Cooling System (without steam gen.)	1.0	164.	21.7	2.4	266.	9.1
Steam generator	0.1	91.	12.0	0.6	162.	5.5
Control Rods	0.5	19.	2.4	4.9	221.	7.6
Refueling	0.0	2.	0.3	0.4	549.	18.7
Auxiliary Emergency Cooling System	0.6	47.	6.2	1.1	82.	2.8
Containment and Related Systems	0.1	5.	0.6	0.2	14.	0.4
Radioactivity Control	0.1	2.	0.2	0.6	37.	1.3
Instrumentation Control System	1.4	59.	7.8	5.0	174.	6.0
Miscellaneous	0.1	6.	0.8	1.5	57.	2.0
Sub Total (Reactor)	4.	405.	54.	17.	1734.	59.
TURBINE						
General	0.1	6.	0.8	0.6	330.	11.2
Nozzles, Shafts, Blades, etc.	0.6	88.	11.7	1.8	114.	3.9
Turbine Control	0.8	83.	11.0	1.4	93.	3.2
Piping	0.2	7.	0.9	0.5	19.	0.6
Miscellaneous	0.3	11.	1.4	1.1	38.	1.3
Sub Total (Turbine)	2.	195.	26.	5.	594.	20.
GENERATOR	0.	50.	7.	1.	186.	6.
CONDENSER	1.	30.	4.	6.	188.	6.
OTHERS	2.	73.	9.	5.	220.	8.
TOTAL	9.	753.	100.	34.	2922.	99.

resulting data, but comment only on dominant contributors to outages.

For boilers, the major forced outage cause is boiler tube difficulties. For total outage hours, fuel and waste-related systems assume comparable importance, but a firm interpretation cannot be made, because the "general" category (which can mean that more than one component caused difficulties) is so large.

For turbines, the forced outage time is essentially contributed equally by internal turbine components (nozzles, shafts, blades, etc.) and by "turbine control." However, for the total outage time, the "general" category dominates, probably indicating general overhaul.

For the nuclear units, responsibility for reactor forced outage time is primarily due to the primary cooling system, steam generator, and auxiliary cooling systems. Although these are important contributors to the total outage time, the largest single contributor is refueling (as noted in the previous section); control rod contributions become comparable to the primary cooling system and steam generator.

A brief look at tables 5-1 to 5-3 and a comparison with the constituents of each component class, as given in Appendix IV, makes it clear that the outages result from a broad range of failures, the only easily identifiable class for fossil-fuel plants being the boiler tubes.

As a result, implementation of improvements in design, construction, or operation to reduce failures, and hence outages, requires a broad and sustained effort. This type of effort is suitable for the utilities and their contractors or for substantial engineering groups at research or regulatory institutions. (An example is the effort at the Electric Power Research Institute.[3]) It is not clear whether any such effort can be performed directly at state regulatory agencies such as the ERCDC. Indirect influence can be exerted through the exercise of oversight during the review process. The expense to the ERCDC and to the utilities of more direct involvement would have to be compared with the estimated benefit from such involvement.

References

1. Edison Electric Institute, "Report on Equipment Availability for the Ten Year Period 1965-1974", EEI Publication 75-50, November 1975.

2. Council on Economic Priorities, "Power Plant Performance", 1976.

3. G.S. Lellouche and M.E. Lapides, "Risk Assessment and Reliability Engineering", paper presented at the American Nuclear Society - Canadian Nuclear Society Joint Meeting, Toronto, Canada, June 1976; M.E. Lapides, "Nuclear Unit Productivity Analysis", Electric Power Research Institute Report EPRI SR-46, August 1976; S.L. Basin, R.R. Fullwood, and W.L. Lavallee, "Summary of Nuclear Power Plant Operating Experience for 1975", Electric Power Research Institute Report EPRI NP-263, October 1976.

4. Edison Electric Institute, "Report on Equipment Availability: Fossil and Nuclear Component Cause Code Summary Report", to be used in conjunction with EEI Publication No. 75-50 (Ref. 1).

5. <u>Nuclear Safety</u>, September 1975 to August 1976.

Appendix I: Basic Definitions*

Availability: The fraction of time that a machine is actually capable of performing its function.

Reliability: The probability that a machine will function without failure over a specified period of time or amount of usage.

Base Loading: When a unit is generally run at or near rated output.

Peak Loading: When a unit is generally shutdown and is run only during high demand periods.

Load Following: Varying the output of a plant to supply a variable demand

Unit Year: This term is the common denominator used to normalize data from units of the same size with different lengths of service.

Forced Outage: The occurrence of a component failure or other conditions which require that the unit be removed from service immediately.

Maintenance Outages: The removal of a unit from service to perform work on specific components (this work is done to prevent a potential forced outage).

Planned Outage: The removal of a unit from service for inspection and/or general overhaul of one or more major equipment groups.

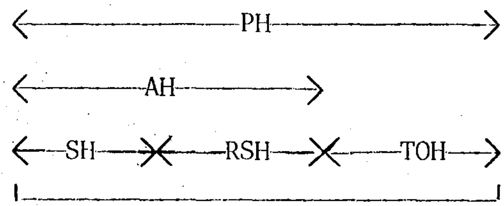
Partial Outage: Reduction in unit load caused by component failure or related conditions. (Note that forced, maintenance and planned outages are "full" coutages.)

Non-Curtailing Equipment Outages: The removal of a specific component from service for repair, which causes no reduction in unit load or a reduction of less than 2%.

Reserve Shutdown: Removal of a unit from service for economic or similar reasons.

*from reference 1

Appendix II: "Time Designations"



PH = Period Hours
AH = Available Hours
SH = Service Hours
RSH = Reserve Shut-down Hours
TOH = Total Outage Hours

Period Hours: (PH) The clock hours in the period under consideration (Generally one year, except the year during which a unit begins).

PH = SH + RSH + TOH

Available Hours: (AH) The time in hours during which a unit or major equipment is available.

AH = SH + RSH

Service Hours: (SH) The total number of hours the unit was actually operating with breakers closed to the station bus.

Reserve Shut-down Hours: (RSH) Reserve shut-down duration in hours.

Total Outage Hours: (TOH) The time in hours during which a unit is removed from service due to a forced, maintenance, or planned outage (or combination of these three).

TOH = FOH + MOH + POH

where FOH = Forced-Outage Hours
MOH = Maintenance-Outage Hours
POH = Planned-Outage Hours

Appendix III: Formulas for Outage and Availability

Forced Outage Rate = FOR = $\frac{FOH}{SH + FOH} \times 100$

Equiv. Forced Outage Rate = EFOR

(Note: Rates for EFOR are slightly higher than FOR since in EFOR partial outages are included)

Total Outage Rate = TOR = $\frac{TOH}{SH + TOH}$

Operating Availability = $\frac{AH}{PH} \times 100$

Capacity Factor = $\frac{\text{Total Gross Generation in MWe-Hr}}{\text{Period Hours} \times \text{MDC}} \times 100$

MDC = Maximum Dependable Capacity = the dependable main-unit capacity winter or summer, whichever is smaller.

Appendix IV - CATEGORIZATION OF COMPONENT OUTAGE CAUSES

FOSSIL-FUEL BOILER COMPONENT OUTAGE CAUSES

GENERAL

Boiler, General Code

TUBES

Water Walls
Generating Tubes
Superheater
Reheater - First
Reheater - Second
Economizer

AIR HANDLING

Air Preheater - Tubular
Air Preheater - Regenerative
Induced Draft Fans
Forced Draft Fans
Recirculating Fans
Desuperheaters and Attemperators
By-Pass Dampers
Furnace Refractory

VALVES AND PIPES

Safety Valves
Steam Valves and Piping
Valves and Piping - Feedwater and Blowdown
Gage Glasses

MISCELLANEOUS

Startup System (superheater or turbine by-pass system)
Light-Off System (ignitors, purging system, etc)
Headers
Inspection, License, Insurance
Auxiliary Boiler
Miscellaneous

FUEL AND WASTE SYSTEMS

Slag and Fly Ash System
Stack
Pulverizers
Cyclones
Fuel Handling Equipment (gas, oil, ocal, etc)
Fireside Cleaning
Acid Cleaning
Boiler Casing, Breeching and Ducts
Soot Blowers
Boiler Circulating Pumps
Air Compressors (sootblowing, control and station air)
Precipitator - Electrical
Precipitator - Mechanical
Burners
Explosion
Boiler Controls
Stack Emission

OPERATIONAL DIFFICULTIES

Furnace Slagging
Superheater Fouling
Reheater Fouling
Air Heater Fouling
Induced Draft Fan Fouling
Precipitator Fouling
Wet Coal
Poor Quality Coal (low Btu)
Drum, Steam Scrubbers and Separators, etc.
Pulverizer Capacity Limited (due to wear, but still in service)
Ashpit Trouble
Fly Ash Disposal Trouble

NUCLEAR REACTOR COMPONENT OUTAGE CAUSES

GENERAL

Reactor, General Code

PRIMARY COOLING SYSTEM (WITHOUT STEAM GENERATORS)

Reactor Vessel
Reactor Internals Including Core Support and Control Rod Guide Structures
Reactor Coolant System Valves and Piping
Reactor Coolant Recirculating Pumps and Drives
Pressurizer

STEAM GENERATORS

Steam Generator (Reactor Coolant System)

CONTROL RODS

Control Rods and Drives
Reactivity Limitation
Fuel Assembly Including Cladding, Burnable Poison Rods and Burnable Poison Shims

REFUELING

Refueling
Fuel Handling and Storage

MISCELLANEOUS

Miscellaneous

CONTAINMENT AND RELATED SYSTEMS

Reactor Containment
Reactor Containment Test
Reactor Containment Cooling and Ventilation - Normal
Reactor Containment Cooling and Gas Cleanup - Post Accident
Auxiliary Building Ventilation System

RADIOACTIVITY CONTROL

Plant Radiation Levels
Radioactivity Discharge Levels to Environment
Radioactive Waste Treatment System
Radioactive Waste Storage

INSTRUMENTATION AND CONTROL SYSTEM

Reactor Control (excluding protection) - Inst. and Control
Reactor Protection - Inst. and Control
Nuclear Instrumentation
Engineered Safeguards - Inst. and Control
Auxiliary Systems - Inst. and Control
Control and Instrument Power
Emergency Power System
Core Physics Test
Operator Training and License Testing

AUXILLIARY AND EMERGENCY COOLING SYSTEMS

Auxiliary or Standby Feedwater Supply System
Emergency Core Cooling System High Pressure
Emergency Core Cooling System Low Pressure
Core and Containment Cooling Long-term Post-Accident
Residual Heat Removal System

Component Cooling System
Chemical Addition System - Reactor Coolant Quality Control
Chemical Addition System - Reactor Coolant Reactivity Control

Auxiliary System Valves and Piping
Safety System Valves and Piping

STEAM TURBINE COMPONENT OUTAGE CAUSES

GENERAL

Turbine, General Code

NOZZLES, SHAFTS, BLADES, ETC

Turning Gear
Governors
Control, Turbine and
Reheat Stop Valves
Shaft Packing
Nozzles and Nozzle Blocks
Nozzle Bolting (first stage)
Diaphragms
Shaft
Wheels or Spindles
Buckets or Blades

TURBINE CONTROL

Vibration of Turbine
Generator Unit
Lube Oil System & Bearings
(except bearing vibration)
Turbine Control
Gland Steam Controller
Blade Fouling
Shell Leaks

Seal Leaks
Cylinder Outer
Cylinder Inner
Dummy Ring
Gland Rings
Diaphragm, Unit and Shroud Type

PIPING

Piping, Steam Drain and Gland
Piping, Steam Inlet and Reheat
Cross Over or Under Piping

MISCELLANEOUS

Moisture Removal Equipment
(nuclear plant)
Turbine Building Closed
Cooling Water System
(nuclear plant)
Steam Reheater (nuclear plant)
Inspection
Water Induction
Differential Expansion
Miscellaneous