AVAILABILITY PATTERNS IN FOSSIL-FIRED STEAM POWER PLANTS

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ABSTRACT

In an earlier report the main causes of outage in fossil-fired steam power plants over 600 MW were examined. This report compares the availability of units over 600 MW with that of units of 200-389 MW and 390-599 MW during the five years 1970 through 1974.

Baseload cyclic, coal, oil, mixed-fuel, once-through boiler, drum-type boiler, mature, and immature units are examined separately to show the effects of design and operating variables. The reasons for the observed differences are discussed. The conclusions lead to recommendations for collecting and utilizing outage data and for research to improve availability.

ACKNOWLEDGMENT

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SUMMARY

This report, based on data provided specially for EPRI by the Edison Electric Institute, examines the relative reliabilities of different categories of large fossil-fired electric power generating units. Each category is considered in three size ranges: 200-389 MW, 390-599 MW, and 600 MW and over. Comparisons are drawn between units with once-through and drum-type boilers, units burning different fuels, mature and immature units, cyclic and baseload units, units with steam temperatures below 537°C (1000°F), and units operating at 537°C and above. Historical trends in performance are analyzed for the years 1970 through 1974.

The results confirm that larger units have progressively lower availability than small ones. The effect is especially marked in the electric generator: generators below 390 MW show very high availability (99.9%). Forced outage rates in generators over 600 MW, although still low, are about 30 times higher than those in the 200-389 MW sizes. However, the overall availability of units over 600 MW is not lower than would be expected from the general trend observed with units between 200 MW and 600 MW. Taking into account the increasing technical sophistication of large modern plants, this must be regarded with some satisfaction. Moreover, there is clear evidence that the design and operation of the largest units continues to improve and availability is increasing in the process.

Units with once-through boilers (mainly units with supercritical steam conditions) have significantly lower availability than those with drum-type recirculating boilers. The lower availability is related to increases in both boiler and turbine outage rates and is probably due more to steam conditions than to the circulation system; once-through boilers are generally associated with steam pressures above 230 bar (3500 psi). The other comparisons made in the study did not reveal significant differences in reliability.

It is recommended that before considering any further commitment to large units a reliability analysis be made of the designs proposed. A vigorous research and development program is needed to reverse the downward trend in reliability with an increase in size by providing improved materials, designs, and operating procedures.

Section 1

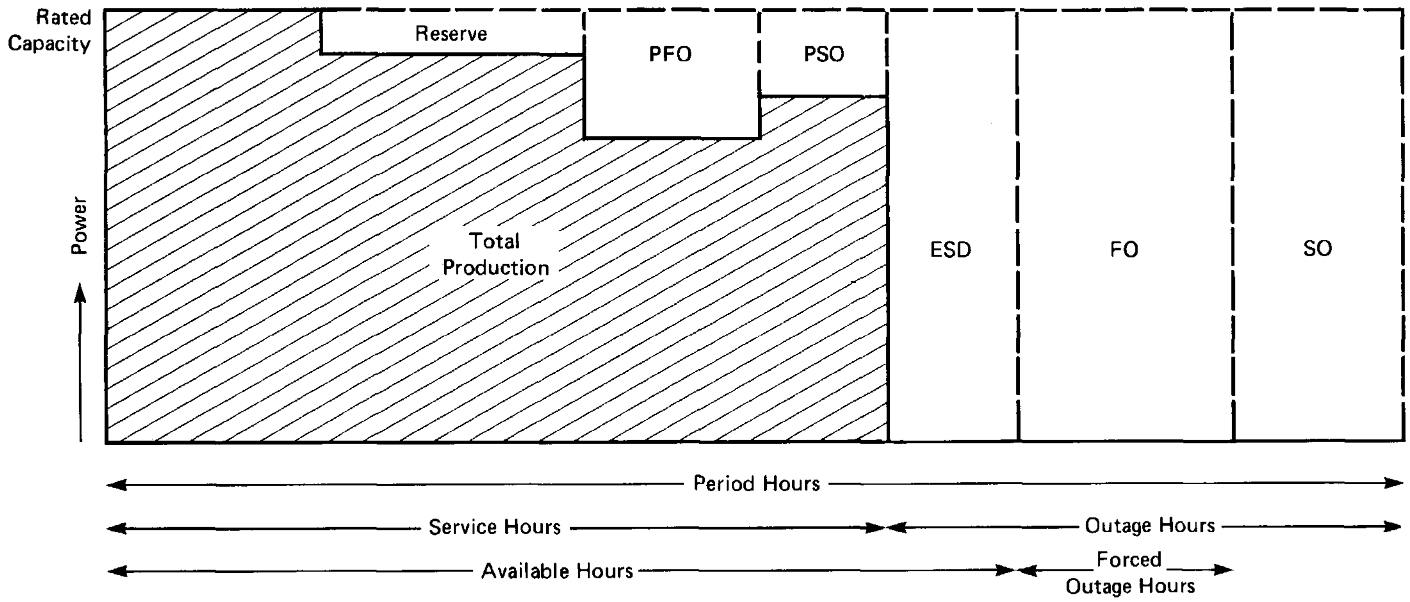
BASIS OF STUDY

BACKGROUND

A previous EPRI report (1) summarized recent data published by the Edison Electric Institute (EEI) and supplemented these data by reference to a series of informal meetings between EEI staff and utilities with operating power-generating units over 600 MW. When these data were analyzed, questions arose concerning the effects of several factors in design or operation, such as type of fuel, amount of cyclic loading imposed on the unit, plant maturity, boiler circulation system, and steam temperature.

In 1976 the Council for Economic Priorities (CEP) published a study of power plant performance, which emphasized the economic effects of availability (2); it was based on publicly available data sources, mainly Federal Power Commission (FPC) records (3, 4), and monthly status reports issued by the Nuclear Regulatory Commission (NRC) (5). These were supplemented by information on capacity factors obtained directly from utilities. The basis for comparing performance was a parameter called capacity performance. This was derived by adjusting the published capacity factors using a size-related multiplier to arrive at a measure of availability. Capacity factor is a valid measure of productivity but is a reasonable basis for comparing availability of units only when similar loading priorities apply. It is strongly influenced by local fuel cost and unit efficiency, factors that were ignored in the CEP study.

Figure 1 indicates the important factors that determine the capacity factor at which a given plant operates, and can be used to compare capacity



PFO – Partial Forced Outage (Operating problems force load reduction)
PSO – Partial Scheduled Outage (Load reduction to permit maintenance, and so on)
ESD – Economy Shutdown (Not economical to generate)
FO – Forced Outages (Equipment failures, accidents, environmental factors)
SO – Scheduled Outages (Routine or planned maintenance, inspection, and so on)

Figure 1 Factors affecting productivity of power plants factor with other reliability and productivity-related parameters. Utilities operate in such a way as to meet instantaneous load demands as economically as possible while providing a reserve of power that can be called on at very short notice to meet foreseeable load fluctuations. Since large steam power plants cannot be started rapidly (even alternative quick-start systems, such as gas turbines, require significant time to be brought on load), the reserve must be provided by underloading selected operating units; this is called the spinning reserve.

The operating cost of producing electric power on a particular unit depends on the local fuel cost and unit efficiency. The relative geographic locations of the power station and the load center may also affect choice of unit to meet a given demand. Economics dictate that more efficient fossil-fired units (usually larger, newer units) have priority over less efficient ones, and those burning cheaper fuels (coal, fuel oil) have priority over those burning more expensive fuels (distillate oils). For older units, economic dispatch practices rather than unit availability dominate the determination of capacity factor.

Capacity factor also has a feedback effect on the duration of scheduled outages. With finite maintenance resources, it is necessary to assign priorities to work in progress. This frequently means that repairs to the less important low-capacity factor plant require extended outage time. In such cases, the outage time statistics are not truly indicative of the extent of the repair or of the maintenance needed to restore the unit to service. In short, the capacity factor and its derivatives indicate the productivity of a unit but not the reasons for nonproductivity.

In its report, Improving the Productivity of Electric Power Plants (6), the Federal Energy Administration (FEA) concluded that capacity factor is a valid indicator of reliability for modern power plants, since much of the difference between availability and capacity factor for such plants is accounted for by inability to generate at full power (partial forced outage) rather than by deliberate underloading. This is largely fortuitous and is not true of plants, including modern ones, used for load following or cyclic duty.

Both FEA and CEP noted significant size-related trends in reliability of fossil-fired power generating units. The FEA study, which referred to EEI data (7), noted that as unit size had increased, so had the forced outage rate, while the availability factor had decreased. Over a wide range of unit sizes, capacity factor--as would be expected--was not consistent with these other indicators because of the effect of economic factors. Both FEA and CEP were inhibited in pursuing their analyses because of shortcomings in the data immediately available. FEA discussed the underlying factors affecting reliability, following its own investigations, in which a number of utilities were directly involved. CEP carried out a series of regression analyses of the data at its disposal, but these analyses have been widely criticized because of their weak factual foundation.

In October 1976 the Equipment Availability Task Force of the EEI Prime Movers Committee published some trends in reliability of large (over 390 MW) fossil-fired power plants (8). These trends were observed in plants that had been in commercial operation prior to January 1, 1971, and covered the operating years 1972, 1973, and 1974. On the whole, the trends are indefinite and the report is inconclusive.

For the present study, EPRI had access to data in the EEI records and was able to examine the performance of different types of fossil-fired generating units and judge performance on the basis of several criteria. Trends were studied over a five-year period. While the resulting analysis is still imperfect, it provides further insight into the reasons for reduced reliability of large fossil-fired power plants.

SCOPE OF STUDY

The present study covers the performance of fossil-fired steam power-generating units covered by EEI records in sizes above 200 MW for the five-year period from 1970 through 1974. The following categories were selected for examination and comparison:

- Baseload units
- Cyclic units
- Units burning coal only

Units burning oil only
Units burning other fuels or mixed fuels
Units with once-through boilers
Units with recirculation boilers
Immature units (1-3.99 years of service)
Mature units (4-9.99 years of service)
Units with steam temperatures below 537°C
Units with steam temperatures 537°C or higher

No distinction was made between subcritical and supercritical once-through systems. The majority of large once-through boilers are supercritical, and all recirculation, or drum-type, boilers are subcritical. No attempt was made to separate dry bottom pulverized-coal-fired units from those with slag tap furnaces, such as cyclones. While these categories are of some interest, it is doubtful whether they would have provided reliable data because of the small numbers in some of the samples. This problem was also encountered in some of the categories actually used. EEI has published separate summary reports, comparing drum-type and supercritical boilers over 390 MW (9) and giving data on maturity effects for coal-fired units (10).

RESULTS

Tables 1 through 5 present the principal findings by year of operation and size of unit. These tables give annual averages for availability, equivalent forced outage rate, and scheduled outage rate. The annual average times assigned to maintenance and planned outages are also given, as these are the principal components of scheduled outages. With the exception of Table 2, the forced outage hours are given for the plant as a whole and for boiler, turbine, and generator separately. Table 2 does not include the turbine and generator subcategories, since it is concerned essentially with fuels and boilers.

Tables 6 through 9 summarize and compare the major features of the earlier tables. Outages are expressed as rates or percentages rather than as times. The averages used in tables 6 through 9 are weighted averages of the five annual figures for each category, as given in tables 1 through 5.

Table 1
RELIABILITY DATA FOR BASELOAD AND CYCLIC UNITS

SIZE		200-389 MW					390-599 MW					>600 MW				
YEAR		1970	1971	1972	1973	1974	1970	1971	1972	1973	1974	1970	1971	1972	1973	1974
Cyclic Units																
Number		82	88	91	97	95	22	25	30	30	32	0	3	7	10	12
Availability	%	85.4	86.1	84.8	82.5	83.0	81.5	81.9	79.0	82.4	80.9		73.0	71.6	75.5	76.6
Equivalent Forced Outage Rate	%	6.3	6.7	8.2	10.1	10.2	7.9	11.6	9.8	9.8	12.3		21.5	15.3	22.1	14.3
Scheduled Outage Rate	%	10.3	9.6	9.4	10.8	11.3	14.4	10.4	15.2	11.3	11.6		11.2	19.4	11.0	16.4
Average Maintenance Outage	Hrs	216	265	277	215	358	288	209	273	251	276		563	439	206	212
Average Planned Outage	Hrs	664	555	543	726	607	927	683	991	695	683		308	841	714	1064
Average Forced Outage	Hrs	366	364	496	571	478	346	658	473	531	625		1230	588	1112	538
Average Boiler Forced Outage	Hrs/Inc	216/5	251/6	279/5	351/6	338/6	242/6	339/5	320/7	300/6	289/7		1082/11	306/7	650/11	279/9
Average Turbine Forced Outage	Hrs/Inc	92/1	71/1	183/1	134/1	99/1	55/1	255/1	111/2	133/1	225/2		85/2	63/3	109/3	172/2
Average Generator Forced Outage	Hrs/Inc	16/0	12/0	14/0	45/1	8/0	8/0	9/0	13/0	22/0	49/1		4/1	14/1	112/1	26/1
Baseload Units																
Number		84	89	97	98	114	36	40	47	55	62	23	27	36	45	56
Availability	%	84.0	84.2	82.3	83.9	80.5	80.3	78.5	76.1	77.3	75.4	68.9	73.0	72.7	74.0	74.6
Equivalent Forced Outage Rate	%	7.8	8.5	10.5	9.1	14.9	13.1	13.7	15.1	16.7	19.1	26.8	23.6	23.5	21.0	22.2
Scheduled Outage Rate	%	10.6	10.3	11.6	10.5	11.0	10.3	12.3	15.2	12.6	13.2	13.7	10.7	12.3	13.5	13.0
Average Maintenance Outage	Hrs	250	328	302	279	369	245	369	363	391	402	556	391	280	262	283
Average Planned Outage	Hrs	670	552	715	614	581	605	668	938	683	749	482	446	761	836	809
Average Forced Outage	Hrs	463	466	525	477	737	765	769	739	863	988	1313	1273	1262	1013	1037
Average Boiler Forced Outage	Hrs/Inc	353/6	356/7	390/7	317/6	406/7	519/10	499/9	402/7	460/7	578/8	662/8	493/10	531/10	527/10	738/11
Average Turbine Forced Outage	Hrs/Inc	50/1	48/1	65/1	94/1	89/1	139/2	201/2	188/2	234/2	220/2	327/3	379/3	236/3	104/3	182/2
Average Generator Forced Outage	Hrs/Inc	14/0	24/0	9/0	23/0	116/0	17/1	18/1	82/1	95/1	63/0	158/1	341/1	387/1	313/1	42/1

Table 2
BREAKDOWN OF AVAILABILITY DATA BY FUELS USED

SIZE		200-389 MW					390-599 MW					>600 MW				
YEAR		1970	1971	1972	1973	1974	1970	1971	1972	1973	1974	1970	1971	1972	1973	1974
Coal																
Number		86	87	87	66	53	29	36	38	29	30	19	20	25	25	27
Availability		84.8	84.9	82.3	81.0	84.0	80.5	79.4	74.6	75.8	73.3	70.1	73.6	72.4	71.0	73.6
Equivalent Forced Outage Rate	%	7.7	9.4	11.8	11.0	12.8	13.4	15.0	19.2	17.1	22.4	27.8	23.0	21.0	21.9	18.6
Scheduled Outage Rate	%	9.9	8.6	10.8	12.2	8.7	10.1	10.5	13.3	13.2	12.5	14.1	12.4	15.2	15.6	16.1
Average Maintenance Outage	Hrs	252	279	372	310	205	303	280	424	304	177	490	342	382	208	274
Average Planned Outage	Hrs	604	457	562	760	543	535	591	708	825	903	600	672	875	1052	1061
Average Forced Outage	Hrs	450	557	600	589	616	780	827	1023	941	1229	1222	1140	1023	1072	856
Average Boiler Forced Outage	Hrs/Inc	334/7	427/9	470/9	410/9	514/10	632/12	569/10	533/9	672/10	799/10	759/9	518/10	537/10	585/11	618/11
Oil																
Number		4	2	3	18	18	2	4	7	10	13	1	1	1	1	2
Availability		81.1	84.9	86.5	84.9	73.6	71.9	81.3	80.5	82.9	85.3	68.3	81.1	77.7	88.3	90.8
Equivalent Forced Outage Rate	%	12.4	6.7	9.2	9.0	20.5	24.6	8.4	11.7	7.0	15.3	18.2	8.3	9.4	17.3	18.5
Scheduled Outage Rate	%	9.5	11.6	10.6	10.4	12.6	10.7	12.4	12.7	13.6	7.8	24.2	13.6	15.3	2.9	3.9
Average Maintenance Outage	Hrs	258	239	96	166	343	177	153	205	528	289	736	251	0	112	269
Average Planned Outage	Hrs	577	780	832	717	691	759	930	733	662	349	1386	939	1348	140	0
Average Forced Outage	Hrs	818	302	254	400	1128	1517	550	496	301	557	648	462	611	765	354
Average Boiler Forced Outage	Hrs/Inc	427/7	184/7	212/7	184/5	454/10	130/2	393/5	242/8	203/5	263/8	169/4	339/12	156/10	146/8	22/2
Other Fuels																
Number		81	93	103	118	142	28	28	33	48	56	6	10	21	35	45
Availability		84.7	85.7	84.5	85.2	82.1	82.1	82.4	78.1	79.8	76.9	70.5	69.9	70.7	76.2	73.8
Equivalent Forced Outage Rate	%	6.2	5.1	7.2	8.6	11.4	6.3	10.0	8.6	13.7	15.3	21.6	25.8	23.6	21.0	22.5
Scheduled Outage Rate	%	11.1	11.5	10.5	9.1	12.1	14.5	10.7	17.0	12.1	13.8	13.3	10.0	13.3	11.1	13.5
Average Maintenance Outage	Hrs	208	311	221	220	400	255	221	219	318	448	713	413	372	259	251
Average Planned Outage	Hrs	747	663	696	558	653	968	713	1253	702	747	271	338	719	666	887
Average Forced Outage	Hrs	361	231	437	483	498	279	601	414	669	795	1192	1492	1302	1053	1064
Average Boiler Forced Outage	Hrs/Inc	231/4	159/4	221/4	303/5	326/6	170/5	287/4	236/5	308/6	391/7	181/3	659/11	513/10	558/11	728/11

Table 3
RELIABILITY DATA FOR ONCE-THROUGH AND RECIRCULATION UNITS

SIZE		200–389 MW					390–599 MW					>600 MW				
YEAR		1970	1971	1972	1973	1974	1970	1971	1972	1973	1974	1970	1971	1972	1973	1974
Once-Through																
Number		20	20	20	22	23	34	38	43	45	49	21	27	39	48	53
Availability	%	73.6	78.7	76.8	72.8	74.1	78.3	77.5	75.5	78.8	75.7	69.0	73.2	72.7	73.0	73.5
Equivalent Forced Outage Rate	%	16.0	13.9	13.8	18.5	18.1	12.9	17.1	13.1	13.5	17.9	27.3	22.3	21.1	21.1	23.0
Scheduled Outage Rate	%	15.3	11.3	14.8	14.9	15.1	13.5	10.5	15.1	11.3	12.9	14.9	12.2	13.8	13.9	13.5
Average Maintenance Outage	Hrs	364	228	406	299	529	323	352	325	226	398	595	424	345	210	324
Average Planned Outage	Hrs	973	763	896	1004	746	761	530	976	750	710	562	535	807	934	804
Average Forced Outage	Hrs	973	870	735	1078	903	654	1008	798	851	966	1252	1144	1126	1074	1081
Average Boiler Forced Outage	Hrs/Inc	488/8	688/10	659/8	676/9	671/10	423/7	566/7	416/5	477/6	571/8	835/10	623/10	602/11	600/11	728/11
Average Turbine Forced Outage	Hrs/Inc	177/1	92/1	16/1	294/2	100/1	159/2	358/2	212/1	184/1	200/2	232/3	369/2	240/3	97/3	231/2
Average Generator Forced Outage	Hrs/Inc	10/0	10/0	25/1	6/0	23/0	11/1	20/0	131/1	110/0	88/1	56/1	95/1	171/1	277/1	41/1
Recirculation																
Number		151	164	172	181	194	27	32	37	45	50	6	7	9	13	21
Availability	%	86.1	85.8	83.9	84.7	82.1	83.4	82.9	77.7	78.9	77.9	73.5	74.0	68.4	79.1	75.5
Equivalent Forced Outage Rate	%	6.1	7.0	9.1	8.8	12.4	9.0	8.1	15.0	14.9	17.0	23.7	23.9	25.2	21.9	15.8
Scheduled Outage Rate	%	9.7	10.0	10.4	9.9	11.0	10.2	12.2	15.0	13.5	12.4	10.2	8.9	16.3	8.7	16.1
Average Maintenance Outage	Hrs	213	302	284	243	340	196	231	319	438	292	338	251	434	330	97
Average Planned Outage	Hrs	622	542	618	609	608	687	817	930	694	774	433	473	762	377	1236
Average Forced Outage	Hrs	354	358	490	458.	591	554	423	605	632	825	1227	1396	1118	990	687
Average Boiler Forced Outage	Hrs/Inc	272/6	250/6	302/6	296/6	350/7	430/10	354/8	330/9	339/8	427/9	106/3	313/10	148/3	420/11	519/11
Average Turbine Forced Outage	Hrs/Inc	55/1	63/1	133/1	89/1	89/1	31/1	26/1	152/3	198/3	240/3	516/4	75/2	48/2	131/3	100/1
Average Generator Forced Outage	Hrs/Inc	16/0	19/0	11/0	37/0	72/0	15/0	9/1	59/1	30/1	37/1	411/3	954/2	819/1	359/2	29/1

Table 4
AVAILABILITY DATA FOR NEW AND MATURE UNITS

SIZE		200-389 MW					390-599 MW					>600 MW				
YEAR		1970	1971	1972	1973	1974	1970	1971	1972	1973	1974	1970	1971	1972	1973	1974
1-3.99 Years Old																
Number		23	16	20	19	19	26	29	25	24	21	17	21	29	28	38
Availability	%	80.6	79.4	78.0	84.1	79.9	78.9	75.1	76.4	78.3	76.2	66.8	73.9	73.1	75.0	74.4
Equivalent Forced Outage Rate	%	8.3	9.3	13.2	8.0	9.0	12.5	14.1	11.7	14.9	19.7	27.1	21.0	21.6	20.7	22.1
Scheduled Outage Rate	%	13.0	16.3	14.7	10.7	15.1	13.5	14.3	15.7	11.3	10.4	15.3	12.5	13.3	12.0	13.5
Average Maintenance Outage	Hrs	259	330	241	213	671	237	420	391	469	364	737	444	287	254	275
Average Planned Outage	Hrs	876	1097	1050	721	652	947	829	988	520	548	602	649	881	798	911
Average Forced Outage	Hrs	563	377	642	456	436	656	929	686	908	1168	1569	1192	1186	1137	1053
Average Boiler Forced Outage	Hrs/Inc	360/6	229/5	165/5	197/6	190/5	396/9	395/7	221/6	318/7	427/9	915/10	657/10	578/12	451/10	705/11
Average Turbine Forced Outage	Hrs/Inc	123/2	97/2	327/2	201/1	199/2	199/2	465/2	322/3	365/3	380/3	397/4	361/2	150/3	152/3	187/2
Average Generator Forced Outage	Hrs/Inc	8/0	9/0	7/0	23/1	16/1	15/1	14/1	64/1	181/1	159/1	69/1	106/1	333/1	397/1	55/1
4-9.99 Years Old																
Number		66	63	62	61	53	24	34	43	51	60	4	6	12	20	26
Availability	%	83.0	84.5	81.4	81.9	82.2	82.0	83.6	78.5	79.3	78.0	73.8	72.7	68.9	77.5	73.0
Equivalent Forced Outage Rate	%	7.9	7.5	9.7	10.8	13.4	9.7	12.4	11.0	11.2	15.8	28.7	22.8	24.6	19.3	20.4
Scheduled Outage Rate	%	11.7	11.1	12.1	11.4	11.0	11.2	9.1	15.1	13.1	12.5	13.4	12.8	15.4	11.1	15.3
Average Maintenance Outage	Hrs	217	362	308	257	253	331	224	272	259	350	348	433	341	336	313
Average Planned Outage	Hrs	813	608	759	737	715	650	576	1058	885	749	829	687	1015	639	1028
Average Forced Outage	Hrs	453	385	562	591	591	592	632	553	668	835	1113	1264	1372	988	1021
Average Boiler Forced Outage	Hrs/Inc	263/5	296/7	362/6	408/6	402/7	475/9	551/8	417/6	443/6	525/7	391/9	405/8	563/10	739/12	719/11
Average Turbine Forced Outage	Hrs/Inc	100/1	32/1	157/0	120/1	128/1	32/1	19/1	80/1	118/1	176/2	101/1	226/1	378/2	81/2	250/2
Average Generator Forced Outage	Hrs/Inc	20/0	6/0	17/0	13/0	8/0	14/0	12/0	18/0	26/0	29/0	599/2	611/1	362/0	116/1	24/1

Table 5
AVAILABILITY DATA BY STEAM TEMPERATURE

SIZE		200–389 MW					390–599 MW					>600 MW				
YEAR		1970	1971	1972	1973	1974	1970	1971	1972	1973	1974	1970	1971	1972	1973	1974
Units Below 537°C																
Number		7	10	12	14	15	2	2	4	4	6	0	0	0	0	0
Availability	%	80.9	82.0	77.1	81.1	73.5	77.8	93.1	75.0	73.8	80.1					
Equivalent Forced Outage Rate	%	5.3	5.7	6.0	9.1	12.0	5.3	9.3	25.2	14.9	27.2					
Scheduled Outage Rate	%	16.5	16.4	19.6	14.7	19.9	19.5	2.5	12.2	17.6	7.1					
Average Maintenance Outage	Hrs	435	178	227	192	426	134	199	416	889	296					
Average Planned Outage	Hrs	1305	1027	1439	1017	1190	1574	194	480	649	227					
Average Forced Outage	Hrs	144	114	273	339	528	232	383	935	753	948					
Average Boiler Forced Outage	Hrs/Inc	125/3	81/3	196/3	268/6	448/8	169/8	374/6	520/12	236/9	438/13					
Average Turbine Forced Outage	Hrs/Inc	75/1	6/1	25/1	7/1	27/1	57/4	5/0	26/3	232/3	289/1					
Average Generator Forced Outage	Hrs/Inc	0/0	0/0	8/0	16/0	12/0	6/1	0/0	0/0	23/1	3/0					
Units Over 537°C																
Number		167	177	184	192	205	59	68	76	86	93	27	34	48	61	74
Availability	%	84.8	85.2	83.8	83.5	81.9	80.8	79.6	76.6	79.1	76.7	70.0	73.4	72.0	74.3	74.1
Equivalent Forced Outage Rate	%	7.3	7.7	9.5	9.7	12.9	11.3	13.0	13.4	14.2	16.9	26.6	22.7	21.8	21.3	21.0
Scheduled Outage Rate	%	10.2	9.8	10.2	10.3	10.8	11.7	11.5	15.2	12.1	13.0	13.8	11.5	14.2	12.8	14.2
Average Maintenance Outage	Hrs	235	298	295	250	354	271	300	317	306	348	538	388	362	236	260
Average Planned Outage	Hrs	643	545	591	638	578	699	680	980	726	775	534	522	798	815	926
Average Forced Outage	Hrs	431	425	523	535	625	622	751	697	741	892	1246	1196	1125	1056	969
Average Boiler Forced Outage	Hrs/Inc	302/6	306/7	344/6	341/6	375/7	435/8	472/8	369/7	416/7	502/8	673/9	559/10	517/10	562/11	669/11
Average Turbine Forced Outage	Hrs/Inc	68/1	68/1	125/1	117/1	94/1	104/1	212/2	192/2	189/2	216/2	295/3	309/2	204/3	104/3	194/2
Average Generator Forced Outage	Hrs/Inc	16/0	19/0	12/0	35/1	71/0	13/0	15/1	103/1	73/1	66/1	135/1	272/1	292/1	294/1	37/1

Table 6

SUMMARY OF DATA: CYCLIC AND BASELOAD UNITS

(Weighted averages: 1970 through 1974)

SIZE		200-389 MW		390-599 MW		>600 MW	
TYPE OF DUTY		CYC	BL	CYC	BL	CYC	BL
Unit Availability	%	84.2	82.8	81.0	77.2	74.8	73.1
Equivalent Forced Outage Rate	%	8.4	10.4	10.4	16.0	17.6	22.9
Scheduled Outage Rate	%	10.3	10.8	12.5	12.9	14.9	12.7
Forced Outage Rate	%	6.0	7.0	7.3	11.4	12.6	16.5
Boiler Forced Outage Rate	%	3.9	4.8	4.2	7.0	7.9	9.4
Turbine Forced Outage Rate	%	1.6	0.9	2.3	3.0	2.0	3.7
Generator Forced Outage Rate	%	0.2	0.5	0.3	0.9	0.8	5.7
Capacity Factor/Availability	%	73.6	82.2	72.4	80.6	66.3	78.1
Unit Years in Sample		453	482	139	240	32	187

Table 7

SUMMARY OF DATA: COAL (C), OIL (O), AND OTHER FUELS (M)

(Weighted averages: 1970 through 1974)

SIZE		200-389 MW			390-599 MW			>600 MW		
FUEL		C	O	M	C	O	M	C	O	M
Unit Availability	%	83.4	80.1	84.2	77.3	82.5	79.8	72.2	82.8	73.5
Equivalent Forced Outage Rate	%	10.3	13.8	8.1	17.5	12.0	11.7	22.1	15.0	22.5
Scheduled Outage Rate	%	10.0	11.3	10.9	11.9	11.0	13.6	14.8	6.4	12.4
Forced Outage Rate	%	7.2	9.9	5.5	13.1	7.3	8.0	15.4	8.3	16.5
Boiler Forced Outage Rate	%	5.6	4.7	3.4	9.0	3.6	4.2	9.4	2.1	9.3
Unit Years in Sample		379	45	537	162	36	193	116	6	117

Table 8

SUMMARY OF DATA: ONCE-THROUGH AND RECIRCULATION BOILERS

(Weighted averages: 1970 through 1974)

SIZE		200-389 MW		390-599 MW		>600 MW	
BOILER CIRCULATION		OT	R	OT	R	OT	R
Unit Availability	%	75.8	84.4	77.0	79.7	72.6	74.8
Equivalent Forced Outage Rate	%	16.0	8.7	14.9	12.8	23.0	22.1
Scheduled Outage Rate	%	14.3	10.2	12.7	15.1	16.2	15.0
Forced Outage Rate	%	12.5	5.6	11.9	8.5	16.2	14.6
Boiler Forced Outage Rate	%	9.1	3.9	7.3	5.2	10.3	5.8
Turbine Forced Outage Rate	%	2.0	1.2	3.3	2.1	3.6	2.5
Generator Forced Outage Rate	%	0.2	0.4	1.1	0.4	2.2	7.6
Unit Years in Sample		105	862	209	191	188	56

Table 9

SUMMARY OF DATA: NEW AND MATURE UNITS

(Weighted averages: 1970 through 1974)

SIZE		200-389 MW		390-599 MW		>600 MW	
AGE (YEARS)		1-3.99	4-9.99	1-3.99	4-9.99	1-3.99	4-9.99
Unit Availability	%	80.4	82.6	76.9	79.7	72.1	73.6
Equivalent Forced Outage Rate	%	9.6	9.7	14.4	12.5	20.5	21.6
Scheduled Outage Rate	%	13.8	11.5	13.2	12.5	13.2	13.8
Forced Outage Rate	%	6.9	6.6	11.3	9.0	16.0	14.7
Boiler Forced Outage Rate	%	3.3	4.5	4.9	6.5	9.3	9.2
Turbine Forced Outage Rate	%	2.7	1.4	4.9	1.4	3.4	3.2
Generator Forced Outage Rate	%	0.1	0.1	1.2	0.3	3.0	2.9
Unit Years in Sample		97	305	125	212	133	68

Weighting has been applied to account for the different numbers of units included in each year of operation.

The terms used in the tables are listed and defined at the end of this report. Figure 1 illustrates the factors used. In general, the definitions are obvious, but the concept of equivalent forced outage is not immediately clear. Equivalent forced outage is a way of recognizing load reductions forced by shortcomings in performance in terms of equivalent loss of production at rated power. Referring to Figure 1, the loss of production due to partial forced outages is represented by the area marked PFO. This is equivalent to a complete loss of production for a shorter period; a 20% reduction in power for five hours would be equivalent to a full outage for one hour. Note, too, that scheduled and forced outage rates are based on the sum of in-service hours and outage hours in the relevant category. This sum is less than the total period hours. This has two important effects: the outage rates are greater than they would be if based on period hours, and the sum of availability, forced outage, and scheduled outage rates exceeds 100%. These effects will be clarified by reference to the definitions on page 3-3. The definitions provide a realistic measure of the relevant outage causes, since a unit already out for one cause cannot be subject to another.

Section 2

FACTORS IN EXAMINATION AND COMPARISON

EFFECT OF CYCLIC DUTY

Table 6 shows that baseload units generally incurred slightly more forced outage time than cyclic units. This trend is reflected almost throughout the table, but the differences for the largest plant sizes are not significant. There is some concern today that the need to cycle large, modern units will impose thermal stress cycles, which will cause low-cycle fatigue failures and other problems. Historically, it would appear that such effects have been more than offset by the lower average loadings on all parts of cyclic units.

Unfortunately, the cyclic plant sample for units over 600 MW was small and, in fact, nonexistent before 1971. Low-cycle fatigue failures and creep distortion effects are unlikely to show until there is much more operating experience, so the figures in Table 6 should not be viewed with complacency. It is known that even in the unit size range around 200 MW, many turbine rotors have experienced sufficient thermal stress cycles to require regular inspection for critical flaw propagation. The well-documented failure of the Gallatin rotor (11) has demonstrated the importance of this problem. The consequence of rotor failure would inevitably be serious, and at present there is no reliable way of assessing rotor serviceability.

The ratio of capacity factor to availability decreases with plant size for both cyclic and baseload plants, presumably due to decreasing operational flexibility. Larger units are more prone to partial outage, as well as full outage. Partial outage decreases capacity factor but not availability. Comparison of the equivalent forced outage rates with the forced outage rates shows the impact of partial outages. The ratio of capacity factor to availability is surprisingly small (around 80%) for baseload units of all sizes.

EFFECT OF FUEL TYPE

In tables 2 and 7, the Other Fuels category includes units that burn a variety of fuels and is not representative of gas-fired units, as might be deduced. In many cases, a significant amount of coal would have been burned, so the distinction between fuel types is less clear than might be desired.

For plants in the 200-389 MW and 390-599 MW ranges, Table 7 indicates that coal-fired units have forced, equivalent forced, and boiler forced outage rates higher than those burning other fuels. The boiler forced outage hours and incident rates are also consistently higher (Table 2). The reverse trend in the scheduled outage rates is partly due to the fact that in coal-fired units, some schedule maintenance may be accommodated in forced outage periods. The difference in availability is greatest in the 350-599 MW units, but in all size categories the availability of coal-fired units is less than that of units burning other fuels. The penalty is small, considering the significant increase in complexity introduced by coal- and ash-handling equipment and the arduous operating conditions to which it is subjected.

In units over 600 MW, the figures for availability and outage rates are remarkably consistent between coal-fired units and those fired by fuels other than coal or oil alone. This is surprising in view of the frequently stated opinion that coal-fired boiler problems, such as slagging and fouling, have been compounded in large units. If this opinion is valid, it appears that units burning other fuels (which admittedly include mixed or alternative fuels) have experienced a parallel increase in fuel-related problems. Where mixed fuels are used, coal has probably formed a larger proportion of the total in recent years.

The data for oil-fired units in Table 2 show considerable irregularities, and the sample of purely oil-fired units in the largest sizes is too small to provide a reliable average. With this qualification, the figures show oil-fired units above 390 MW to have appreciably better availability than units burning coal or other fuels. All size groups include units that were switched at short notice from coal burning to oil burning to meet new environmental standards. These units might have been expected to have some shakedown problems following conversion.

EFFECT OF BOILER CIRCULATION SYSTEM

Table 8 indicates that units with once-through boilers have higher forced outage rates than those with recirculation boilers. Turbines associated with once-through boilers show the same trend. These outage rates are probably due to the fact that most units with once-through boilers are supercritical pressure units and not due to the circulation system per se. There are also significant differences in boiler design and operation between once-through boiler units and recirculation units, which are not pressure-dependent.

In the case of units over 600 MW, the availability of once-through boilers is significantly lower than that of recirculation units. The latter have an unusually high generator forced outage rate, which cannot be related logically to the boiler circulation system. The sample in this class is rather small (Table 3), and it appears likely that the high generator forced outage rate was the result of a few incidents of exceptionally long duration, which have distorted the average. If the effect of this anomaly were considered, the availability of large units with once-through boilers would be lower by a considerable margin than that for units with recirculation boilers.

The EEI summary-comparisons of drum-type and supercritical coal-fired boilers in the 390-599 MW and the over 600 MW ranges (9) shows a similar trend. This confirms that classification by circulation system, rather than by pressure, has segregated essentially the same units in these sizes. In a later report (10) EEI has categorized boilers by circulation system.

The most important differences between once-through and recirculation boiler units are apparent in the 200-389 MW range. The once-through boilers in this size range include both subcritical and early supercritical units in which innovative ideas were tested, whereas recirculation boilers of similar size represent a mature design class. This needs to be considered when judging the inherent characteristics of the two classes of boiler.

EFFECT OF MATURITY

In the data presented in tables 4 and 9, immature plants are defined as those aged 1 to 3.99 years. This definition avoids the initial period of erratic operation and therefore assures uniformity of data. Mature plants are defined as those in the 4 to 9.99 year age bracket. This grouping excludes units experiencing wearout phenomena and should be representative of units at or about the peak of their reliability.

For all three size ranges, there is a distinct improvement in availability with maturity. In contrast to this trend, there is a slight increase in boiler forced outage rate for the smaller-unit categories, but turbine forced outage rates decrease significantly and useful reductions occur in scheduled outage rates. It is difficult to be sure whether the increase in boiler forced outage rate with maturity is significant, but it might be the result of corrosion processes that contribute increasingly to tube failures with age.

In the case of the largest units (over 600 MW), the effect of maturity is less clear. There is a slight improvement in availability with corresponding decreases in generator, boiler, and turbine forced outage rates, as well as in unit forced outage rate. Only in the case of unit forced outage rate, however, is the improvement significant. The information in Figure 2, based on the results of another EPRI study (12), suggests that the effect of maturity might have been underestimated in the present work; however, the information is based on subcritical units only.

The data given in a recent EEI summary of coal-fired units availability (10) is confusing in regard to maturity effects. The samples tend to be small and the scatter is large. For units with drum-type boilers, those over six years old generally show better availability than newer units, but the reverse is true for units with once-through boilers in the 390-599 MW and over 600 MW sizes.

HISTORICAL EFFECTS

Since nearly all the units covered by this survey were found to have steam inlet temperatures of 537^{o}C or higher (Table 5), this sample was used as the basis for a comparison of unit performance for the years 1970 through 1974 (figures 3 through 6).

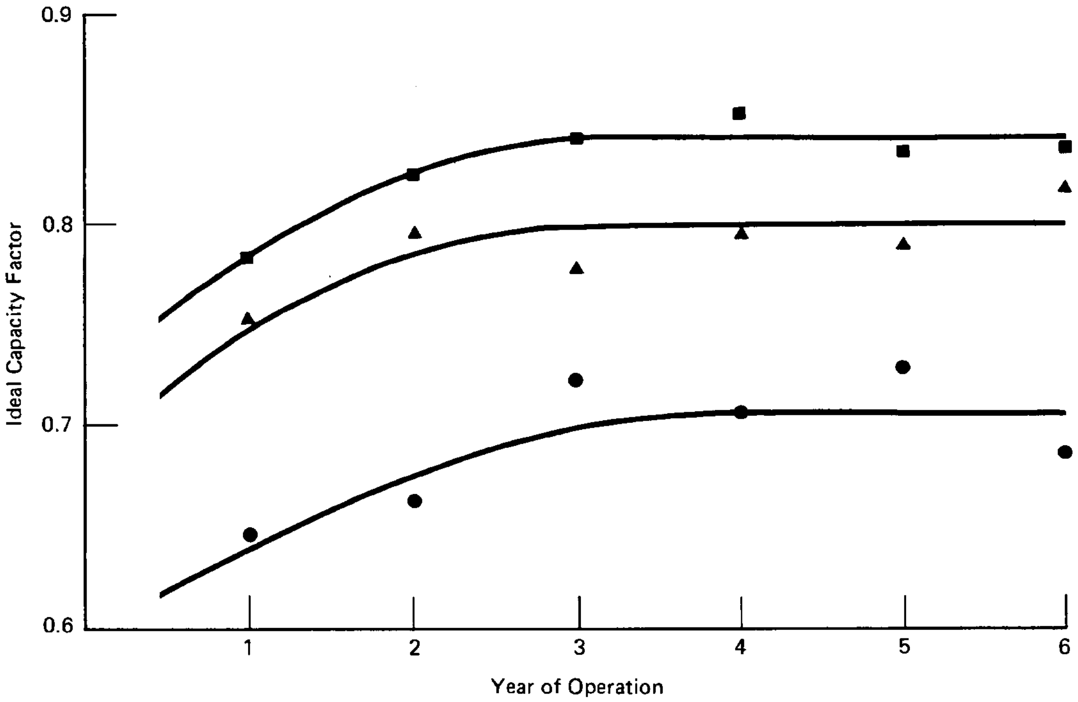


Figure 2 Maturation of subcritical fossil generating plant (after Fisher [12])

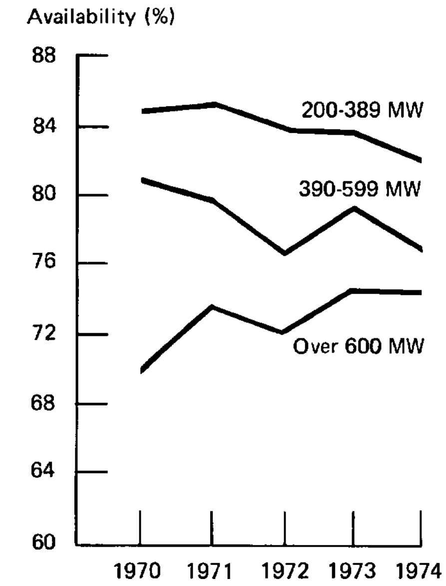


Figure 3 Annual availability

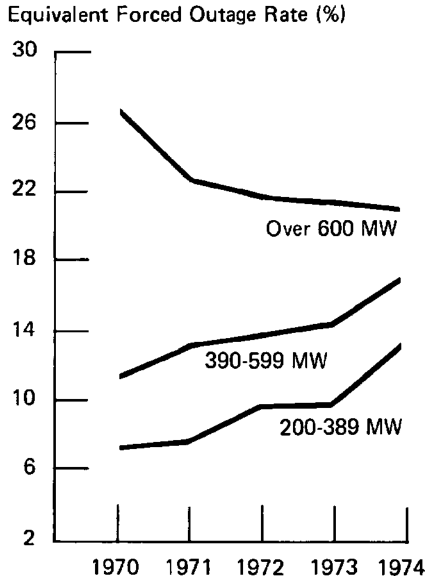


Figure 4 Annual equivalent forced outage

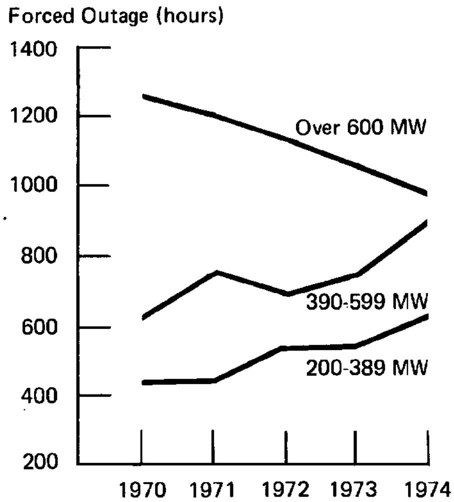


Figure 5 Annual forced outage

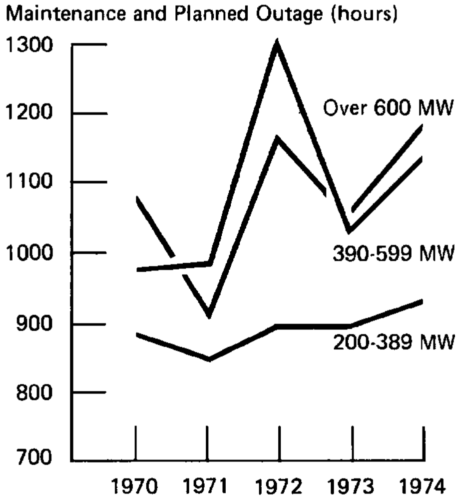


Figure 6 Annual maintenance plus planned outage

NOTE: Figures 3 through 6 refer to all units with steam inlet temperatures of 537 °C or higher

Although there has been a fairly steady decline in availability of the smaller units, with increased forced and planned outage rates, the large units (over 600 MW) show a marked improvement in availability and forced outage rates in the years 1970 through 1974. In this period, the number of units in the over 600 MW sample increased from 27 to 74, indicating that about 12 new units were being introduced each year. Considering the relative immaturity of units of this size, the trend indicates that utilities and their suppliers are steadily overcoming many of the problems experienced initially with large units.

The explanation for this continuing improvement would appear to be in the relative immaturity of design of the larger units and the aging of the smaller ones. While the design of the larger plant is still evolving toward more reliability, some of the smaller units are approaching the limit of their useful life. Table 4 shows that the trend toward increased availability is more evident in immature plants than in mature plants. This again suggests that the trend is due more to design maturation than to plant maturation.

Labor priorities have probably also had an adverse effect on availability of the smaller units. Table 8 shows that nearly half the units are on cycling duty, and these would get lower repair priority than the large units, most of which are baseload units. There is no reliable means of assessing the importance of priorities on availability.

Reference to any of tables 1 through 5 shows that whereas the number of units in the over 600 MW range has increased rapidly, the number of units in the 200-389 MW range is almost static, while the 390-599 MW range has grown relatively slowly.

Reference 10 provides separate historical data for coal-fired, once-through, and drum-type boiler units for the ten years 1966 through 1975. The declining availability for 200-389 MW units, noted above, is evident throughout this period. For 390-599 MW units there appears to have been a drop in availability roughly between 1969 and 1972, with no clear trend since then. Because of the small sample, trends indicated for units above 600 MW prior to 1970 are not considered reliable. High availabilities were achieved in these early years, probably because of special attention by both vendors and owners. The improvement in reliability since 1970 was sustained through 1975.

EFFECT OF SIZE

There have been many comments on the unreliability of large generating units (1, 2, 6, 12). Fisher (12) used a concept of ideal capacity factor, which corresponds closely to the EEI equivalent availability. His work suggested that appropriate values for the plant sizes considered here would be 85%, 80%, and about 70% (corresponding to median plant sizes of 300, 500, and 800 MW, respectively). Since his analysis excluded the effect of economy load curtailments, it should give higher values than equivalent availability figures, which averaged 80.8, 74.5, and 67.2 for the years covered in the present study.

A striking feature of the largest units is the relatively high rate of forced outage due to generator problems. Units of 200-389 MW enjoy very high generator reliability, whereas the largest units have had, on average, one or two outages per year, accounting for average availability losses on the order of 100-200 hours. As has been observed in an earlier EPRI report (FP-422-SR), generator outages are occasionally very lengthy and the average outage figure is not typical of any common kind of outage.

The reason for lower generator reliability probably lies in the greater power density of the largest units, which has, in turn, necessitated greater complexity. In particular, the need for hydrogen or water-cooled stators and hydrogen-cooled rotors has introduced new components (heat exchangers, seals, fluid circuits) that contribute to unreliability in the larger sizes. Failure of either a stator or a rotor cooling system can lead quickly to major damage.

The great majority of units covered by this survey are 3600-rpm machines. With 1800-rpm machines, which are commonly used on nuclear units and on some of the largest fossil-fired units, the power density is lower and the design problems are less acute. Nuclear unit generators enjoy very high reliability.

For mature units over 600 MW, Table 4 suggests that generator reliability is improving.

In the case of both boiler and turbine, higher forced outage rates are to be expected with the larger units. In the boiler, the most frequent cause of outage is failure of tubes. The total length of tubing is roughly proportional to the boiler steaming capacity, so that the risk of tube failure is also proportional to steaming capacity.

In the turbine, increased capacity is also achieved by increasing the number of low-pressure units, typically from two in the the smallest units considered in this report, to six in the largest units. Thus, the risk of low-pressure blade failure, a major cause of turbine outage, is also proportional to unit size. Large units also have more bearings, another major problem area, and generally more serious expansion and distortion problems.

Reference to tables 1 through 5 shows that both the number of forced outages and the forced outage hours due to boiler and turbine problems increase with size more or less, as would be expected. Large turbines require, in general, more scheduled outages than smaller machines. It is common to stagger major overhauls between different parts of a large machine, overhauling one or two sections at a time, so that a large machine with, typically, five cylinders requires more frequent downtime than a machine with only three cylinders.

Another factor affecting both forced and scheduled outage time is accessibility. With the largest units, the time to cool the turbine before it can be opened, and the task of unbolting the flanges in proper sequence to avoid distortion, take three to six days. Reassembly requires similar care and involves considerable labor. Whereas low-pressure cylinders are duplicated or triplicated in large machines, high-pressure and intermediate cylinders are scaled up in size and section so that accessibility for repair becomes increasingly restricted.

Large boilers also have problems of accessibility. Tube repairs usually require the erection of considerable scaffold structures inside the furnace and their removal after repair and test. Furnace height has tended to increase more rapidly than lateral dimensions in order to provide adequate radiant evaporative surface, so that total heights on the order of 45 m (150 ft) are reached on the largest units. However, although the boiler forced outage time is greater than the turbine or generator forced outage time for all sizes, it has proved to be relatively less sensitive to size. The ratio of boiler to turbine to generator forced outage times changes progressively with size (Table 10).

Table 10

DURATION AND FREQUENCY OF FORCED OUTAGES RELATED TO UNIT SIZE

SIZE	200–389 MW	390–599 MW	>600 MW
Ratio of Turbine Forced Outage Rate to Boiler Forced Outage Rate	0.28	0.42	0.37
Ratio of Generator Forced Outage Rate to Boiler Forced Outage Rate	0.09	0.12	0.34
Ratio of Turbine Forced Outage Incidents to Boiler Forced Outage Incidents	0.17	0.25	0.27
Ratio of Generator Forced Outage Incidents to Boiler Forced Outage Incidents	0.02	0.10	0.10

Section 3

CONCLUSIONS AND RECOMMENDATIONS

By using material from EEI records, this study has been able to add useful insights into reliability patterns in large steam power plants, with particular relevance to units entering service in the decade prior to 1974. The trends noted are believed to have continued since then, but this should be verified as more data become available. Strict statistical analyses of the data were not attempted because of limited samples and known variability of utility reporting procedures. However, the conclusions listed below are considered more reliable than those previously published because of the better data base used.

CONCLUSIONS

1. The present analysis confirms that the reliability of large fossil-fired power plants has declined with increase in unit size and the adoption of once-through boilers with supercritical steam conditions. The fall in reliability is not necessarily associated with an overall economic penalty, since there are clear efficiency gains to be had with larger and higher-pressure units.

2. The trend to lower availability of large units is logical and might have been predictable, at least qualitatively, from a reliability analysis. Factors contributing to the trend are the increased complication introduced by such factors as the adoption of water- and hydrogen-cooled generators, the increased number of vital components inherent in larger boilers and in multiple-exhaust low-pressure turbines, the increased size of high- and intermediate-pressure turbines, and increases in operating pressure.

3. In the largest units (over 600 MW), the trend from 1970 through 1974 shows a steady improvement in reliability as design and operating problems in this new class were overcome and as experience was gained. The major factor appears to be design maturation rather than plant maturation.

4. There is little evidence that during the period from 1970 through 1974 reliability was adversely affected by changing fuel quality, although there were major increases in scheduled outages in 1972, possibly related to conversions and modifications following environmental regulations. The evidence is obscured by the use of mixed or alternate fuels in many units.

5. The analysis shows no adverse effect of cyclic duty, but this does not justify a conclusion that such effects will not be found with the larger, higher-pressure units. The effect of cyclic loading may not appear immediately and, in the short term, the beneficial effect of lower average loading may outweigh the adverse effects of cycling.

RECOMMENDATIONS

1. Before a commitment is made to build any large power-generating unit, reliability and maintainability analyses should be made. These should take into account both inherent, size-related penalties, such as high thermal inertia, and penalties arising from increased design complexity. The results of this analysis should be factored into the economic judgment of the best unit size.

2. The lower availability of supercritical pressure units with once-through boilers should be evaluated against their thermodynamic advantages and lower initial cost. The best choice of steam conditions will depend on local fuel prices, load demand variability, and system makeup.

3. Vigorous efforts should be made in research and development to identify and overcome the current obstacles to high reliability and maintainability of large steam-generating units. Such R&D should be undertaken in the fields of materials science, design, operation, and maintenance.

4. The compilation of reliability and performance data should be improved to provide a more quantitative basis for future reliability analysis.

DEFINITION OF TERMS

<u>Capacity Factor</u>

$$\text{Capacity Factor} = \frac{\text{Power Produced}}{(\text{Hours in Period}) \times (\text{Rated Capacity})}$$

<u>Equivalent Forced Outage Rate</u> (EFOR):

For each forced partial outage, an equivalent full load outage duration is calculated to include the effect of partial as well as full forced outages on the forced outage rate.

EFOR is calculated as follows:

TE = FPOH (CR/CF),

where

TE is equivalent forced outage time;

CR is size of reduction or derating from full load;

CF is rated capacity;

then

EFOR = 100 [(TF + TES)/(TO + TF + TAS + TPS)],

where

TF is total full forced outage time;

TO is total operation time at 100% capability;

TAS is sum of actual forced partial outage times;

TES is sum of equivalent forced outage times;

TPS is sum of equivalent scheduled partial operating times.

Forced Outage Rate [FOH / (SH + FOH) 100]

Scheduled Outage Rate [SOH / (SH + SOH) 100]

SH = Hours in service

FOH = Forced outage hours

SOH = Scheduled outage hours

Operating Availability [AH/PH 100]

Equivalent Availability [AH - (EPFOH + EPSOH) /PH]

AH = Available hours

PH = Hours in period (8760 for 1 year)

EPFOH = Equivalent partial forced outage hours

EPSOH = Equivalent partial scheduled outage hours

Equivalent Outage Time is the full outage time, which would produce a loss of production equivalent to an actual load reduction.

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