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BASIS FOR PG AND E RELIABILITY CALCULATIONS

The concept of reliability can be applied to many aspects of the electric power industry. For this presentation we will be concerned with the reliability of planned system generating resources for meeting projected loads. System transmission reliability is not included; although, interconnections with other systems are. Generation reliability calculations require the use of probability theory to determine the chances or probabilities of certain events occurring or not occurring.

There are two basic types of events for which probabilities are calculated. The first type can be classified as capacity outage. The second, loss of load. Today, most utilities using a reliability criteria for planning system generation carry their calculations through the loss of load stage. This requires that capacity forced outage probabilities be determined first, and then loss of load probabilities can be calculated.

The technique used to determine the probabilities of capacity forced outages depends upon the principle of independence and upon the mutual exclusiveness of events. Here mutually exclusive means that the system being analyzed can exist in only one outage state at any point in time.

To abbreviate some descriptions we can introduce some notation which is commonly used in texts on probability theory. "X" will be a random variable which will represent the capacity on forced outage at any point in time. The mathematical statement for the probability that the capacity on forced outage "X" is greater than or equal to any chosen amount "x" is the function: $P(X \geq x)$. If $P(X \geq x)$ is plotted versus "x", the qualitative result is as shown in the following graph.

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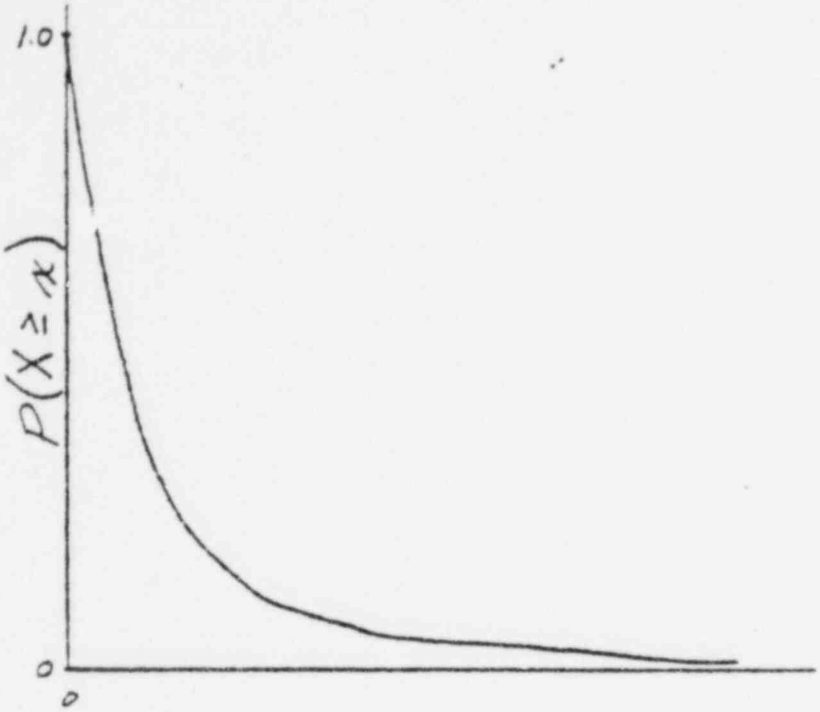

The graph shows that the possibility of having a force outage equal to or greater than a chosen value of "x" becomes smaller as "x" is increased. Stated in another way, for any scheduled reserve capacity "x", the graph indicates the probability that forced outages will equal or exceed that capacity.

To develop a plot similar to that illustrated above requires some data for the system being analyzed. For small systems with relatively few units the resulting plot is usually quite stepped, whereas for large systems with many different unit sizes it is fairly smooth.

Assume the hypothetical system outlined below:

Hypothetical System

PLANT	No. Units	Capacity	q	p= 1-q
A	1	100 MW	.10	.90
B	1	50 MW	.03	.97
C	1	60 MW	.07	.93

p is the probability that, if a unit is observed, it will be running.

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q is the probability that, if the unit is observed, it will be shut down on forced outage.

In this example the unit can be either on line or out on forced outage. Therefore, the probability of either of these two mutually exclusive events occurring is $p + q = 1$.

By applying probability theory to this problem, the probability of the occurrance of each possible forced capacity outage can be obtained.

For example, the probability that there are zero megawatts on forced outage for the hypothetical system with three units is merely the product of the probabilities that each unit is on line or $p_A \times p_B \times p_C$. To find the probability that exactly 50 megawatts are on forced outage, we see that this would mean unit B would be on forced outage and units A and C on line. This is represented by $p_A \times p_C \times q_B$.

The sum of the probabilities for each possible outage must equal one, if all possible outages have been considered for the system.

Forced Outage in MW	Probability $P(X = x)$	Units on Forced Outage
0	$p_A p_B p_C$ = .81189	0
50	$p_A p_C q_B$ = .02511	1
60	$p_A p_B q_C$ = .06111	1
100	$p_C p_B q_A$ = .09021	1
110	$p_A q_B q_C$ = .00189	2
150	$p_C q_A q_B$ = .00279	2
160	$p_B q_A q_C$ = .00679	2
210	$q_A q_B q_C$ = .00021	3
	1.00000	

This column lists all possible capacity outages. Note this does not include forced deratings.

This column shows the probability of having exactly the listed amount of forced outage.

To determine $P(X \geq x)$, the probabilities of all possible outages greater than the given outage must be summed including the probability of having exactly that outage. For example, if it is desired to find the probability of the occurrance of a forced outage equal to or greater than 150 megawatts, $P(X \geq 150)$, the exact forced outage probabilities of 150, 160 and 210 must be summed:

$$P(X \geq 150) = P(X = 150) + P(X = 160) + P(X = 210).$$
$$.00979 = .00279 + .00679 + .00021$$

The individual probabilities may be summed because they are for <u>mutually exclusive events</u>. The $P(X \geq x)$ is determined for each value of "x" (0, 50, 60, 100, 110, 150, 160, 210) by cumulative adding of $P(X=x)$ values starting at the highest x value (i.e., 210).

Forced Outage in MW	$P(X=x)$	$P(X \geq x)$
0	.81189	1.00000
50	.02511	.18811
60	.06111	.16300
100	.09021	.10189
110	.00189	.01168
150	.00279	.00979
160	.00679	.00700
210	.00021	.00021
	1.00000	

The plot of $P(X \geq x)$ shown on the following page (Chart 1) indicates the stepped appearance generally found in small systems with relatively large unit sizes, and therefore, a limited number of possible outage states. Chart 2 follows Chart 1 and represents a large system having a relatively much smaller maximum unit size and many units. This results in a smoother $P(X \geq x)$ curve which yields a more uniform response to changes in reserve capacity in reliability calculations.

CHART 1

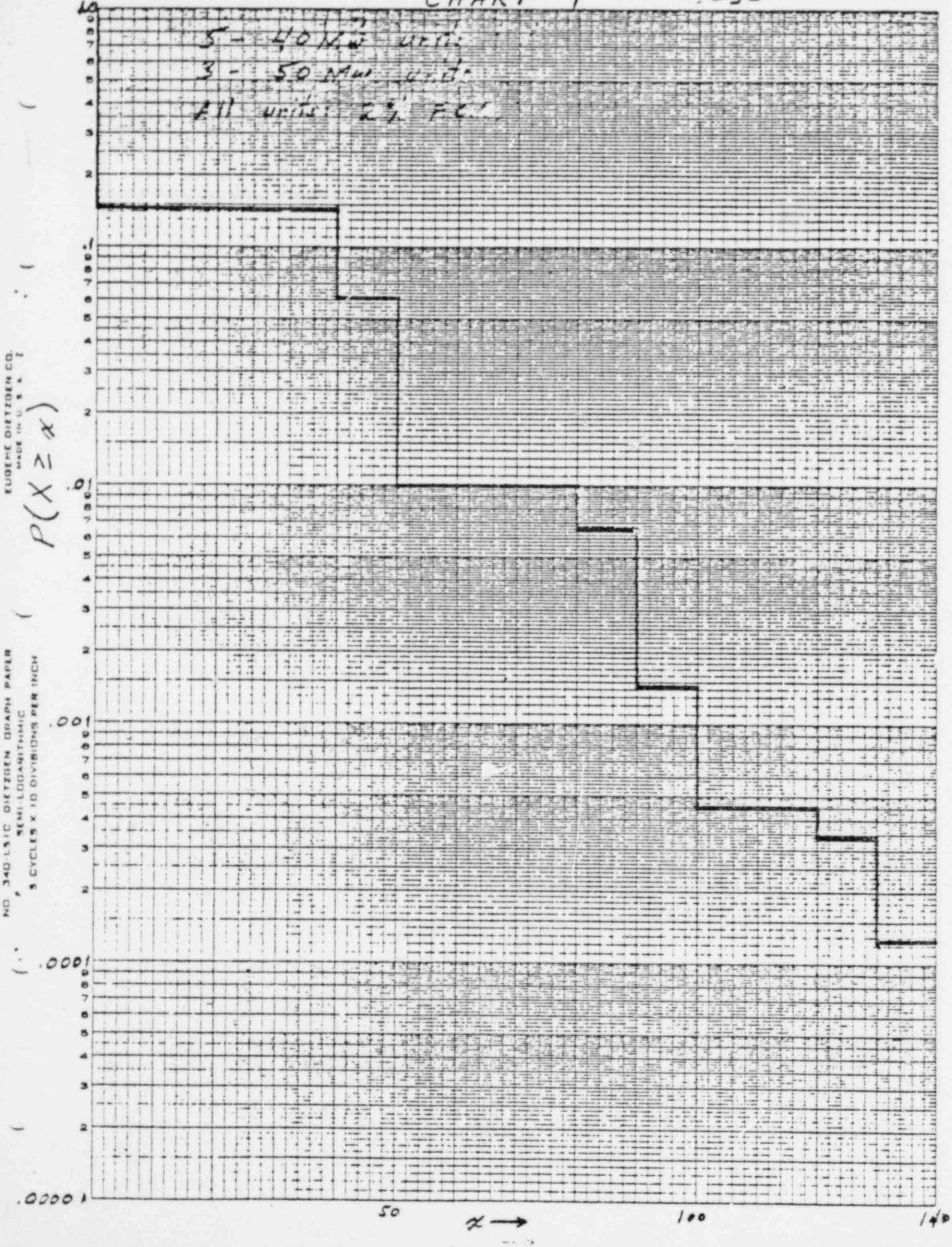
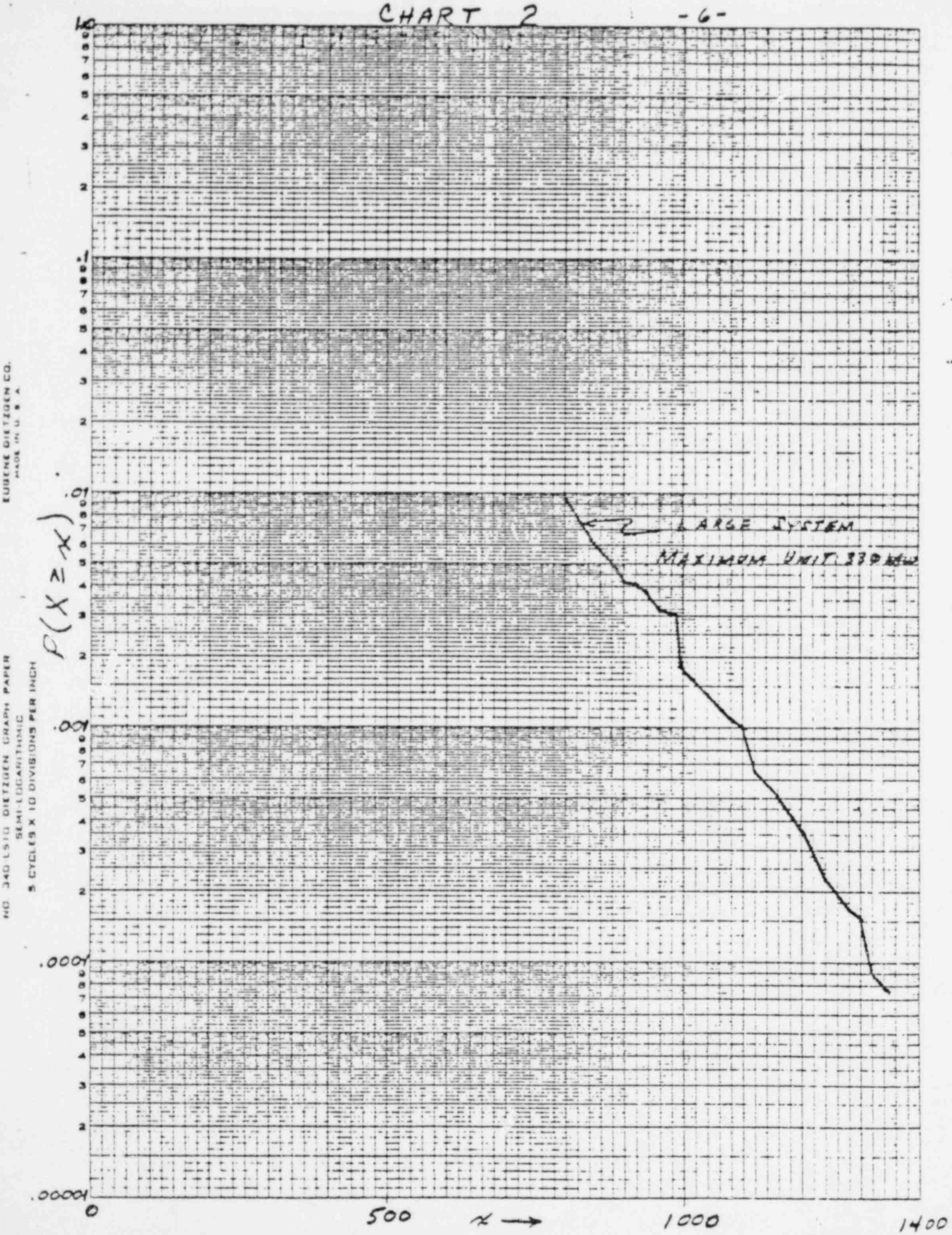

5 - 40 Mw units
3 - 50 Mw units
All units 2% F.C.
$P(X \geq x)$
$x \rightarrow$
50
100
140
.1
.01
.001
.0001
.00001
EUGENE DIETZGEN CO.
MADE IN U.S.A.
NO. 340-L510 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
5 CYCLES X 10 DIVISIONS PER INCH

CHART 2


LARGE SYSTEM
MAXIMUM UNIT: 339 MW
$P(X \geq x)$
$x \rightarrow$
0
500
1000
1400
1.0
.1
.01
.001
.0001
.00001
EUGENE DIETZGEN CO.
MADE IN U.S.A.
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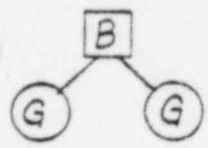
For reliability calculations, accurate answers can be obtained only if the P(X=x) function is calculated after removing from consideration any units that are scheduled out of service for overhaul.

The three unit system analyzed above is of the simplest form. Complications usually occur and some of these can be dealt with. Suppose that a fourth plant is added to the base system and that it is a common-feed type unit.

New Unit:

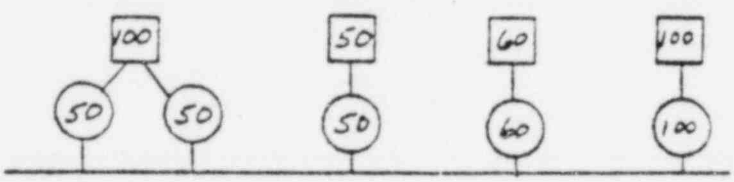


Boiler: $p = .98$, $q = .02$

Generators: $p = .97$, $q = .03$

The new system can be schematically represented as follows:

New System:



The probability function $P(X = x)$ for the common feed plant is as follows:

Forced Outage (MW)	Probability $P(X = x)$
0	$p_B \times p_G \times p_G = .98 \times .97 \times .97 = \underline{.922082}$
50	$2(p_B \times p_G \times q_G) = 2(.98 \times .97 \times .03) = \underline{.057036}$
100	$p_B \times q_G \times q_G + p_G \times p_G \times q_B + 2(q_B \times p_G \times q_G) + q_B \times q_G \times q_G = .98 \times .03 \times .03 + .97 \times .97 \times .02 + 2\,(.02 \times .97 \times .03) + .02 \times .03 \times .03 = \underline{.020882}$

Shown on the following page are the possible forced outages for the common feed unit and all states yielding that forced outage.

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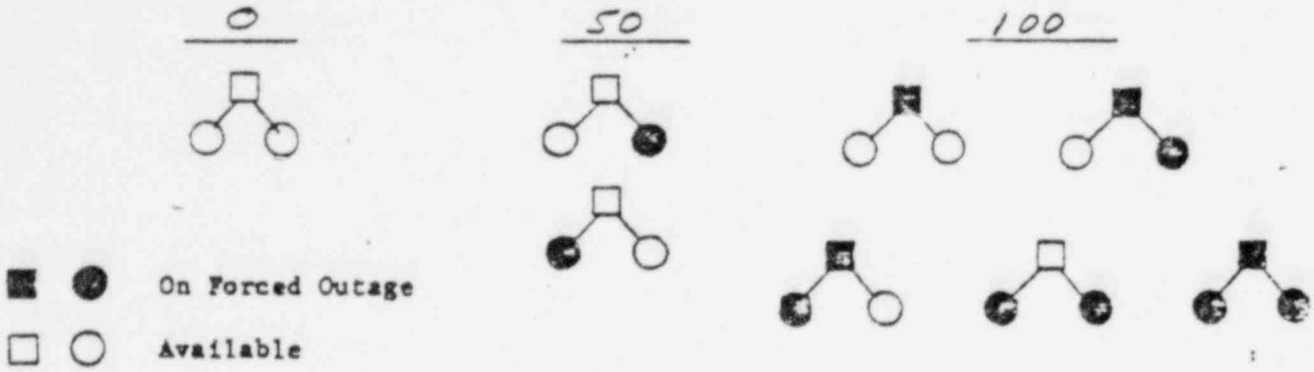
MW ON FORCED OUTAGE



Once the probabilities of all possible outage cases for the common feed units are known, the units can be combined with the other units in the system using the independence principle. The probability of each possible outage can then be determined. In this case several possible (mutually exclusive) situations may result in the same amount of forced outage. For example, it is possible to have a 50 MW outage, if the common feed units are on line, but the 50 MW unit in Plant B is off line. It would also be possible if one of the generators of the common feed unit were off line and all other units were on line. Using the independence principle and multiplying probabilities together, the probability of each event that will result in exactly "x" MW of forced outage can be obtained. Summing probabilities for events which result in the same forced outage, "x", the probability of that outage occurring within the whole system is obtained. $P(X \geq x)$ is then determined as explained in the first example. The detail of calculations is shown on Table I.

Units which have partial outage states are treated the same as common-feed type units. Quite often it is desirable to represent a unit by three or more forced outage states (two of which are on and off) particularly if a unit repeatedly suffers the same forced curtailment.

(Common Feed Plant Combined With the Three Plants of Example 1)

Table I

LINE	COMMON FEED UNITS MW CAPACITY	OUTAGE PROBABILITY	COLUMN 1	2	3	4	5	6	7	8
	MW CAPACITY		0	50	60	100	110	150	160	210
		OUTAGE PROBABILITY	.81189	.02511	.06111	.09021	.00189	.00279	.00679	.00021
A	0	.922082	0 .7486292	50 .0231535	60 .0563484	100 .0831810	110 .0017427	150 .0025726	160 .0062609	210 .0001936
B	50	.057036	50 .0463070	100 .0014322	110 .0034855	150 .0051452	160 .0001078	200 .0001591	210 .0003873	260 .0000120
C	100	.020882	100 .0169539	150 .0005243	160 .0012761	200 .0018837	210 .0000395	250 .0000583	260 .0001418	310 .0000044

Foreced Outage For System (MW)		Probability P(X = x)	P(X ≥ x)
0		.7486292	1.000000
50	A,2 + B,1 =	.0694605	.2513708
60	A,3 =	.0563484	.1819103
100	B,2 + C,1 + A,4 =	.1015671	.1255619
110	B,3 + A,5 =	.0052282	.0239948
150	A,6 + B,4 =	.0082421	.0187666
160	A,7 + B,5 + C,3 =	.0076448	.0105245
200		.0020428	.0028797
210		.0006204	.0008369
250		.0000583	.0002165
260		.0001538	.0001582
310		.0000044	.0000044
		1.0000000	

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Computer programs have been developed to carry out the calculation described. Several of these programs require a complete recomputation of the probability functions every time a change is made in unit schedules or capacities. These changes usually can be associated with overhaul schedules and hydro plants capabilities where affected by head variations from month to month. Because the computational process is quite time consuming especially for large systems it is very desirable to find a short cut.

A short cut exists which gives accurate results provided care is taken in writing the computer program. The array containing the $P(X = x)$ must not be cumulated into a $P(X \geq x)$ array. $P(X \geq x)$ values should be stored in a separate array for use in reliability calculations. This is because any changes that occur are incorporated into the $P(X = x)$ array. If an attempt is made to reduce the $P(X \geq x)$ array to a discrete $P(X = x)$ array, problems arise because of significant figure rounding inside the computer. On an IBM 360-65 double precision is required for accurate results in probability calculations.

This next example illustrates how the forced outage effect of a unit with three outage states can be removed from capacity outage probability tables. The logic can be extended to any number of outage states desired. In order to verify the removal procedure, we can add this three outage state unit to the system and then remove it.

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Initial System

3 40 MW units q = .10

2 10 MW units q = .10

Unit to be added - 40 MW's with a 10 MW partial outage state. Number of outage states = 3

	Added Unit			
	0	10	40	
$P_0(X = x)$	.80	.10	.10	$P_A(X = x)$
0 .59049	0 .472392	10 .059049	40 .059049	0 .472392
10 .13122	10 .104976	20 .013122	50 .013122	10 .164025
20 .00729	20 .005832	30 .000729	60 .000729	20 .018954
40 .19683	40 .157464	50 .019683	80 .019683	30 .000729
50 .04374	50 .034992	60 .004374	90 .004374	40 .216513
60 .00243	60 .001944	70 .000243	100 .000243	50 .067797
80 .02187	80 .017496	90 .002187	120 .002187	60 .007047
90 .00486	90 .003888	100 .000486	130 .000486	70 .000243
100 .00027	100 .000216	110 .000027	140 .000027	80 .037179
120 .00081	120 .000648	130 .000081	160 .000081	90 .010449
130 .00018	130 .000144	140 .000018	170 .000018	100 .000945
140 .00001	140 .000008	150 .000001	180 .000001	110 .000027
1.00000				120 .002835

etc.

Z A Y 1 2 5 1 0 0 12 6

Suppose now that we schedule this added unit to be out of service for overhaul at some point in time. We subtract this resource from the total resources and we also need to change our capacity outage probability table because this unit cannot contribute to forced outage probabilities while it's on the floor.

Unit to be removed from service

$P_A(X=x)$	0 .80	10 .1	40 .1	$P_O(X=x)$
0 .472392 → ÷ .80 =	0 .59049	10 .059049	40 .059049	0 .59049
10 .164025	10 .104976/.8	20 .013122	50 .013122	10 .13122
20 .018954	20 .005832/.8	30 .000729	60 .000729	20 .00729
30 .000729	30 0	40 0	70 0	30 0
40 .216513	40 .157464/.8	50 .019683	80 .019683	40 .19683
50 .067797	50 .034992/.8	60 .004374	90 .004374	50 .04374
60 .007047	60 .001944/.8	70 .000243	100 .000243	60 .00243
70 .000243	70 0	80 0	110 0	70 0
80 .037179	80 .017496/.8	90 .002187	120 .002187	80 .02187
90 .010449	90 .003888/.8	100 .000486	130 .000486	90 .00486
100 .000945				etc.
110 .000027				
120 .002835				
130 .000711				
etc.				

The logic diagram for computer solution to this procedure is on the following page. It should be noted that the discrete probability array uses the outage states as indices and all outage states are increased by 1 so that the 0 outage state is stored in the first position.

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LOGIC DIAGRAM FOR

MAKING CHANGES IN CAPACITY

OUTAGE PROBABILITY TABLES

N = Unit Number

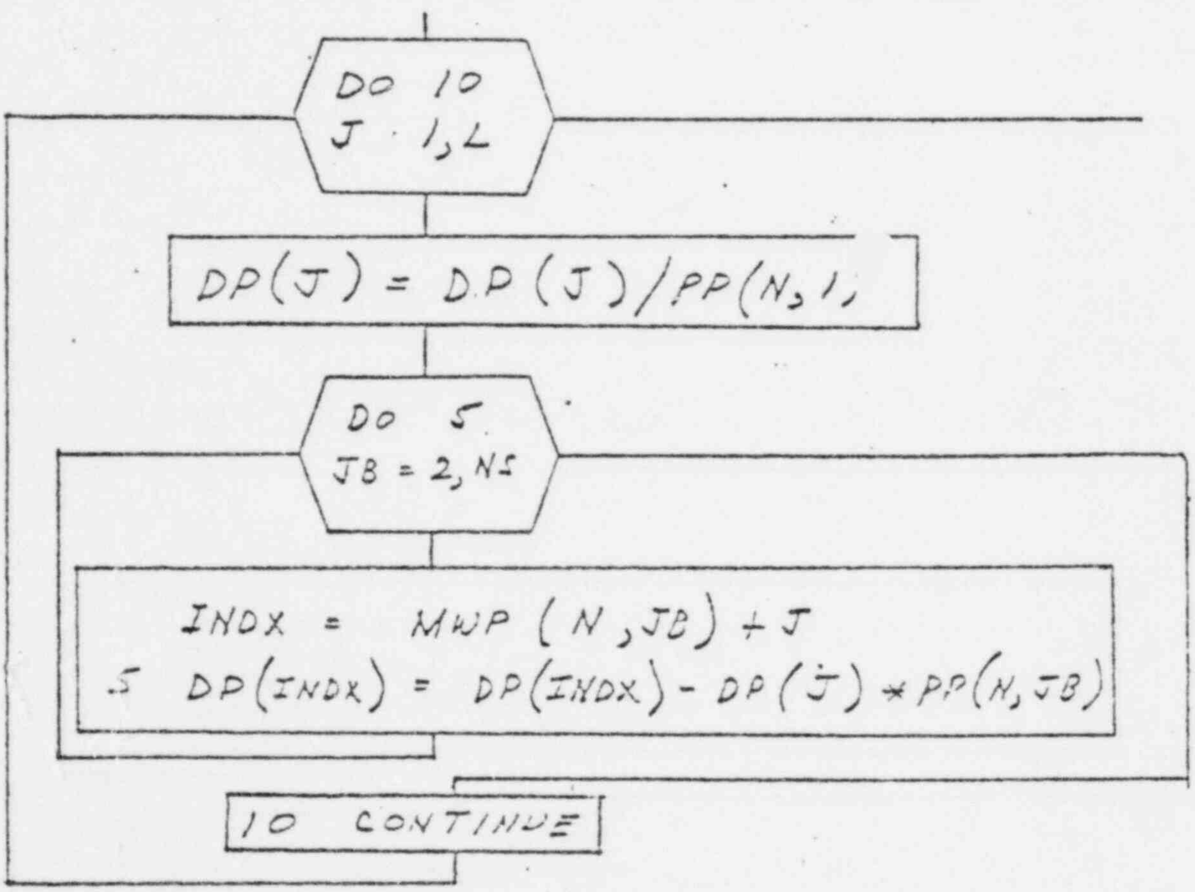
NS = Number of outage states for unit or plant

DP = Discrete probability array   P(X = x)

L = Length of outage table

PP = Probability of unit outage state

MWP = Megawatt outage associated with outage state



For the previous example the system had six units in service before Unit No. 6 was scheduled out for overhaul. Unit No. 6 is the 3 state unit that was added to the initial 5 unit system. The following data would be stored by a computer for Unit No. 6: PP(6,1) = .80, PP(6,2) = .10, PP(6,3) = .10, NS = 3, MWP(6,1) = 0, MWP(6,2) = 10, MWP(6,3) = 40

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Peliability Calculations

Reliability calculations require that expected loads be incorporated into the analysis in some manner. There are many different approaches used to develop what can be called a load model. They vary from those which employ a normal distribution to an estimate of the monthly or annual peak load. The reliability index obtained from any reliability study depends upon the type of load model and the method used to calculate system reliability.

Reliability indicies are obtained from calculations which begin by determining the probabilities not meeting projected loads. Whether the reliability index is a pure probability or an expected value depends upon what is done with the probabilities of not meeting the projected loads.

Expected Value Method of Loss of Load Reliability Calculations

PG and E uses the years/day of expected load loss as its reliability index. This index is often stated as the loss of load probability is one day in N years, where N is the reliability index. The reliability index for this method of expressing generation reliability is obtained by first determining for a given study period the expected number of days that the projected loads cannot be met with the planned resources. Because study periods can vary in length the reliability index is determined by calculating the number of years that could be composed of the same study period repeated over and over before the expected number of days of load loss would equal 1.0. For example, if during a one year study period the expected number of days lost were computed to equal 0.1, then it is calculated that you would expect to lose load 1 day for every 10 years that were identical to the year studied. The load model used

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is a daily peak one because it is assumed that calculating the chance of not meeting the daily peak provides an appropriate test of reliability.

The following charts on pages 17 and 18 show how the reliability index for a 10 day study period is determined for an example system with twelve 100 mw units each having a 10% F.O.R. First a capacity forced outage probability table is calculated by the procedure previously detailed (resulting capacity forced outage probability table is on page 17). The chart on page 18 shows how the load model is subjected to a reliability test. Given a load model, the reserve capacity on each day can be determined. The probabilities of exceeding the reserves is obtained by a table lookup procedure in the capacity forced outage probability tables. In computer core, the capacity forced outage probability table, an array of $P(X \geq x)$, is stored, so that the array index is equal to the reserve + 1 mw [0 mw occupies the first position in the $P(X \geq x)$ array].

The expected number of days of load loss is determined by summing the daily probabilities of not meeting the load. The expected number of days lost per year would be calculated from:

$$\frac{.147 \text{ days}}{10 \text{ days}} = \frac{D}{365 \text{ days}}$$

$$D = 5.37$$

D is the expected number of days per year that generation would not be sufficient to meet the load. The reliability index, N, would be less than one year in this case:

$$N = \frac{1.0}{5.37 \text{ days/year}} = .186 \text{ years/day}$$

The N value is then checked against a reliability criteria to determine whether or not system reliability is sufficient. If the reliability criterion was something like 1 day in 0.1 years, this system would pass. PGandE's reliability criterion is 1 day in 10 years and this example system would fail miserably.

Aids to Revising Resources

Because reliability testing is a trial and error process of resource adjustment, it is most advantageous to know about how much the reliability index will change if resources are changed. This can be most easily accomplished in a computer program by internal modification of the load model so that say six different load models are tested at the same time and reliability indicies for all six are determined. This requires very little extra computer time because the capacity forced outage probability tables remain the same. The chart on page 19 shows the resulting reliability index curve verses increases or decreases in projected loads. By inspection of this graph, it is possible to make a good estimate of how much to change resources by, to obtain the desired reliability index on the next try. Because changing the load represents effective or perfect megawatt changes, some knowledge of the effective load carrying capability of various types and sizes of units is required. For example, a 1000 mw unit might only have 600 mw of effective load carrying capability if it was the largest unit on the system and had a high forced outage rate. If the reliability index curve showed that the system was over designed by 600 mw in a particular month, it might be possible to delay the 1000 mw unit.

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SYSTEM RELIABILITY TESTING

NON-UNIFORM LOAD

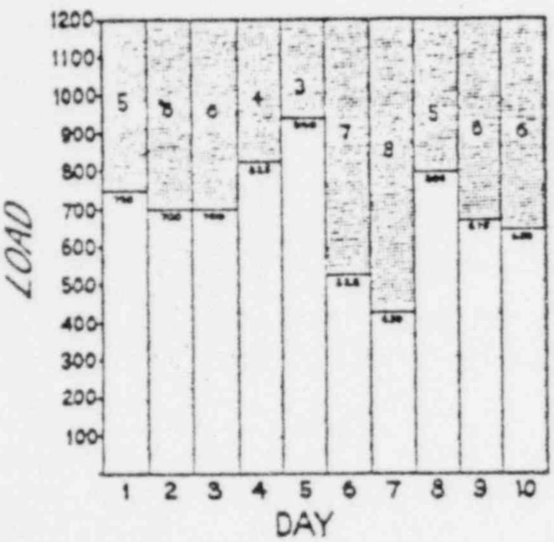
12 - 100 MW UNITS
10 % FORCED OUTAGE RATE

Capacity Outage Probabilities

POSSIBLE OUTAGE STATES	PROBABILITY OF EXACT OUTAGE STATE OCCURRING	PROBABILITY OF EQUAL OR GREATER OUTAGE
0	.28243	1.0
100	.37657	.71757
200	.23013	.34100
300	.085233	.11087
400	.0213077	.025637
500	.00378807	.0043293
600	.00049105	.00054123
700	.0000467665	.00005018
800	.00000324767	.0000034135
900	.000000160375	.00000016583
1000	.000000005346	.000000005455
1100	.000000000108	.000000000109
1200	.000000000001	.000000000001
SUM	1.000000000000	

Z A Y 1 2 5 1 0 -18- 1 2

SYSTEM RELIABILITY TESTING
1200 MW INSTALLED CAPACITY



UNITS OUT OF SERVICE	PROBABILITY OF EQUAL OR GREATER NUMBER OF UNITS OUT OF SERVICE
1	.71757
2	.34100
3	.11087
4	.025637
5	.0043293
6	.00054123
7	.00005018
8	.0000034135

DAY	LOAD	RESERVE	UNITS OUT TO REQUIRE LOAD CURTAILMENT	PROBABILITY OF EXCEEDING RESERVE
1	750	450	5 or more	.0043293
2	700	500	6 " "	.0005412
3	700	500	6 " "	.0005412
4	825	375	4 " "	.0256370
5	940	260	3 " "	.1108700
6	525	675	7 " "	.0000502
7	430	770	8 " "	.0000034
8	800	400	5 " "	.0043293
9	675	525	6 " "	.0005412
10	650	550	6 " "	.0005412
				.1473840

.1473840 EXPECTED NUMBER OF DAYS WITH SOME AMOUNT OF LOST LOAD FOR THE TEN DAY PERIOD

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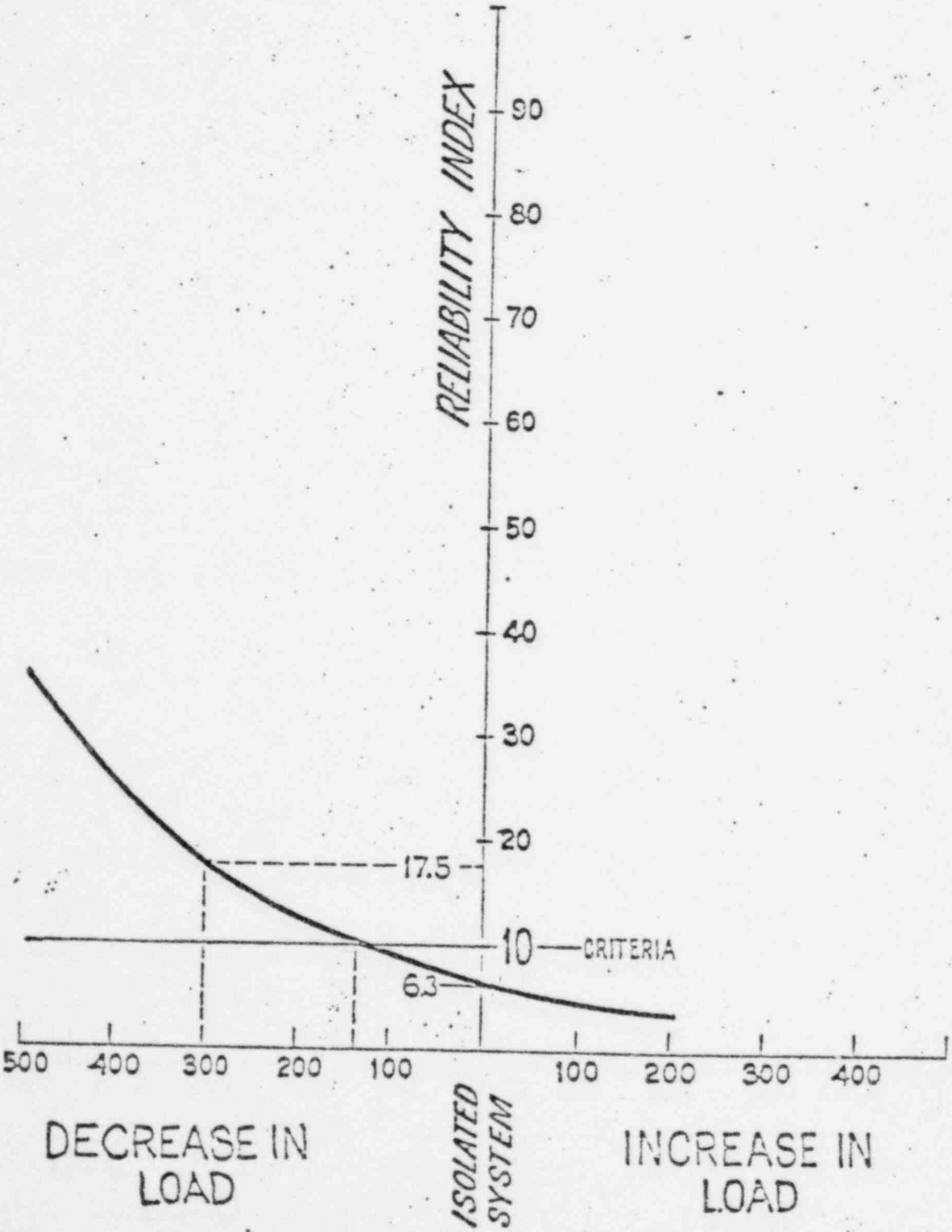
RESERVE REQUIREMENTS



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RESERVE POOLING

Case of Infinite Capability Interconnection

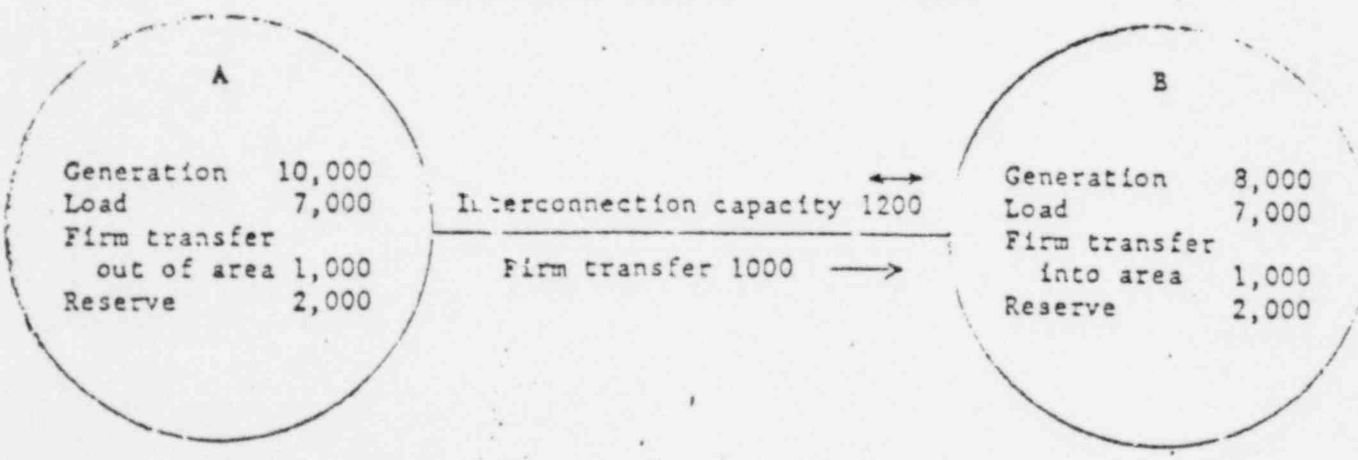
This case is the easiest to handle because the transmission system is capable of transferring the entire reserve capacity of each pooled utility to any other pooled utility at any time. For reliability studies all of the pooled units can be put into the capacity outage tables directly. This is what we assume when analyzing our PG&E area.

Case of Limited Capability Interconnection

If two systems are interconnected as shown on the diagram below and firm power flows in the indicated direction, a limited intertie situation exists.

A ⟶ B

Interconnection capacity	1200
Firm transfer	-1000
Reserve transfer capability	200
Inaccessible reserve	1800



Non-delivery of firm transfer	1000
Remaining reserve in area B	1000
Reserve transfer capability	2000

A ⟵ B

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For reliability studies, each area can consider the reserve capacity in the other area as a source of generation with an infinite number of partial outage states. The maximum capacity of this source of generation is, of course, limited by available reserves or intertie capacity whichever is least. To represent this external source of generation, a tie model is developed for each system from its "isolated" capacity outage table. The diagram on page 22 shows how a 1000 mw tie model was developed for a particular week from a capacity outage table for the PG&E system. Five outage states were chosen to represent the availability of the reserve capacity. For each partial outage state of the tie model, the probability is obtained by determining the probability of forced outages on the system occurring anywhere within the interval represented by the partial outage state. For the 200 mw partial outage state, the outage rate is $P(X \geq 1000) - P(X \geq 1200)$ or $.0285 - .0110 = .0175$. Probabilities for other partial outage states are similarly obtained except that the 1000 mw outage state must include the probability of any outage over 1800 mw - not just those between 1800 and 2000 mw.

Intertie Model

0	200	500	800	1000
.9715	.0175	.0082	.0022	.0006

Intertie Model Including Outage
Rate of Interconnection (.002)

$P(X = 0) = (1.0 - .002)(.9715) = .9695570$

$P(X = 200) = .998 \times .0175 = .0174650$

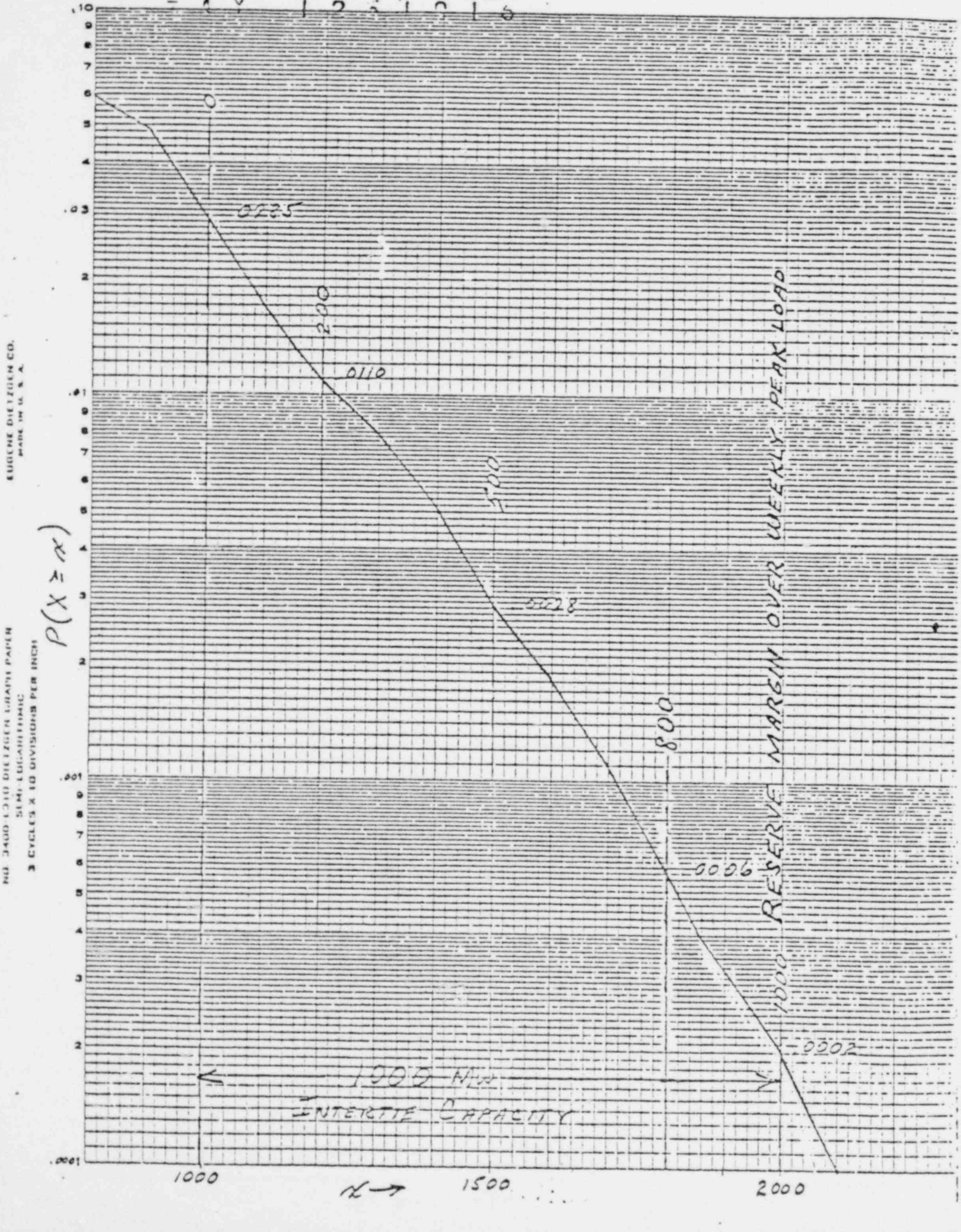
$P(X = 500) = .998 \times .0082 = .0081836$

$P(X = 800) = .998 \times .0022 = .0021956$

$P(X = 1000) = .0006 + .002 - .0006 \times .002 = .0025988$

1.0000000

0	200	500	800	1000
.969557	.0174650	.0081836	.0021956	.0025988



P(X ≥ x)
RESERVE MARGIN OVER WEEKLY PEAK LOAD
0
200
500
800
1000
.0235
.0110
.0028
.0006
.0002
1000 MW
INTERTIE CAPACITY
1000
1500
2000
x →
.10
.01
.001
.0001
NO. 3400-L310 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
3 CYCLES X 10 DIVISIONS PER INCH
EUGENE DIETZGEN CO.
MADE IN U.S.A.

This intertie model is incorporated into the receiving area's capacity outage tables and resources. The number of outage states used and the frequency of intertie model computation (weekly, daily, monthly, annually) are variable. Increasing both will result in higher reliability indicies.

The process of reserve reduction in both areas is by trial and error. New generation is postponed and intertie models are redeveloped and exchanged. Intertie models must be redeveloped because their outage probabilities increase as reserves are reduced. With the two area pool, closure on the desired reliability index can be reached by the third round.

PACIFIC GAS AND ELECTRIC COMPANY

PG&E · 77 BEALE STREET, 31ST FLOOR · SAN FRANCISCO, CALIFORNIA 94106 · (415) 781-4211

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June 16, 1980

DOCKETED
USNRC
JUN 2 0 1980
Office of the Secretary
Docketing & Service
Branch

Honorable Samuel Chilk
Secretary
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

Attention: Docketing and Service Section

Re: Pacific Gas and Electric Company
Stanislaus Nuclear Project Unit No. 1
NRC Docket No. P-564A

Dear Mr. Chilk:

It has been brought to our attention that some pages of a document which were to be a part of an exhibit to Pacific Gas and Electric Company's Answers to the Fourth Set of Interrogatories Propounded by the California Department of Water Resources served on July 16, 1979, were not copied correctly.

I have enclosed for filing with the Answers a complete copy of Exhibit I to the Answers. The superceded Exhibit should be discarded and the replacement copy substituted in its place. This day I served copies of the Exhibit on those persons who were served the Answers.

I regret any inconvenience occasioned by our mistake.

Sincerely,

Richard L. Meiss

Richard L. Meiss

RLM:ll
encl.

cc: All Parties on Service List

Z A Y 1 2 5 0

BASIS FOR PG AND E RELIABILITY CALCULATIONS

The concept of reliability can be applied to many aspects of the electric power industry. For this presentation we will be concerned with the reliability of planned system generating resources for meeting projected loads. System transmission reliability is not included; although, interconnections with other systems are. Generation reliability calculations require the use of probability theory to determine the chances or probabilities of certain events occurring or not occurring.

There are two basic types of events for which probabilities are calculated. The first type can be classified as capacity outage. The second, loss of load. Today, most utilities using a reliability criteria for planning system generation carry their calculations through the loss of load stage. This requires that capacity forced outage probabilities be determined first, and then loss of load probabilities can be calculated.

The technique used to determine the probabilities of capacity forced outages depends upon the principle of independence and upon the mutual exclusiveness of events. Here mutually exclusive means that the system being analyzed can exist in only one outage state at any point in time.

To abbreviate some descriptions we can introduce some notation which is commonly used in texts on probability theory. "X" will be a random variable which will represent the capacity on forced outage at any point in time. The mathematical statement for the probability that the capacity on forced outage "X" is greater than or equal to any chosen amount "x" is the function: $P(X \geq x)$. If $P(X \geq x)$ is plotted versus "x", the qualitative result is as shown in the following graph.

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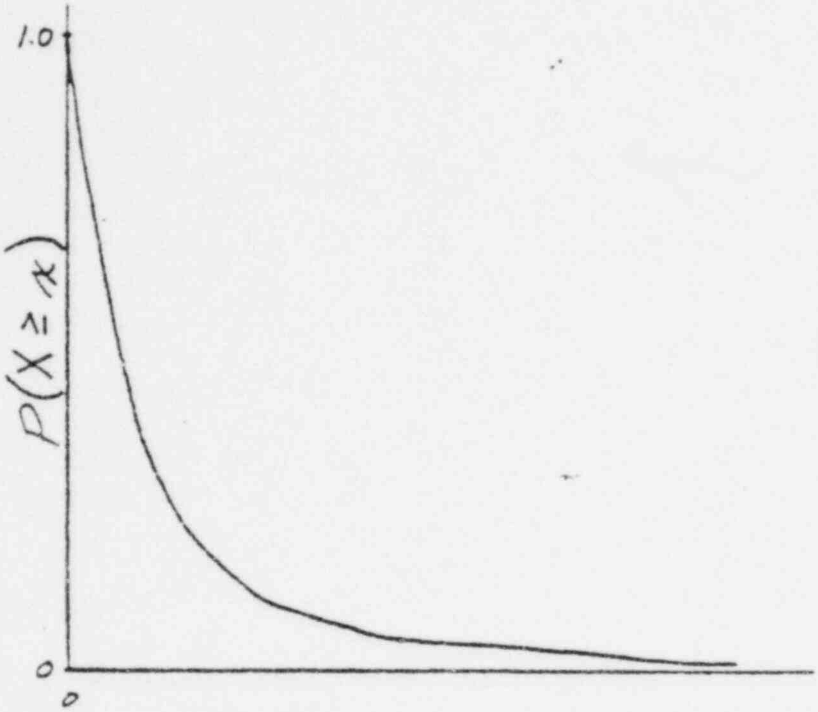


The graph shows that the possibility of having a force outage equal to or greater than a chosen value of "x" becomes smaller as "x" is increased. Stated in another way, for any scheduled reserve capacity "x", the graph indicates the probability that forced outages will equal or exceed that capacity.

To develop a plot similar to that illustrated above requires some data for the system being analyzed. For small systems with relatively few units the resulting plot is usually quite stepped, whereas for large systems with many different unit sizes it is fairly smooth.

Assume the hypothetical system outlined below:

Hypothetical System

PLANT	No. Units	Capacity	q	p= 1-q
A	1	100 MW	.10	.90
B	1	50 MW	.03	.97
C	1	60 MW	.07	.93

p is the probability that, if a unit is observed, it will be running.

7 A Y 1 2 5 0 9 9 3 Z

q is the probability that, if the unit is observed, it will be shut down on forced outage.

In this example the unit can be either on line or out on forced outage. Therefore, the probability of either of these two mutually exclusive events occurring is $p + q = 1$.

By applying probability theory to this problem, the probability of the occurrance of each possible forced capacity outage can be obtained.

For example, the probability that there are zero megawatts on forced outage for the hypothetical system with three units is merely the product of the probabilities that each unit is on line or $p_A \times p_B \times p_C$. To find the probability that exactly 50 megawatts are on forced outage, we see that this would mean unit B would be on forced outage and units A and C on line. This is represented by $p_A \times p_C \times q_B$.

The sum of the probabilities for each possible outage must equal one, if all possible outages have been considered for the system.

Forced Outage in MW	Probability $P(X = x)$	Units on Forced Outage
0	$p_A p_B p_C$ = .81189	0
50	$p_A p_C q_B$ = .02511	1
60	$p_A p_B q_C$ = .06111	1
100	$p_C p_B q_A$ = .09021	1
110	$p_A q_B q_C$ = .00189	2
150	$p_C q_A q_B$ = .00279	2
160	$p_B q_A q_C$ = .00679	2
210	$q_A q_B q_C$ = .00021	3
	1.00000	

This column lists all possible capacity outages. Note this does not include forced deratings.

This column shows the probability of having exactly the listed amount of forced outage.

To determine $P(X \geq x)$, the probabilities of all possible outages greater than the given outage must be summed including the probability of having exactly that outage. For example, if it is desired to find the probability of the occurrance of a forced outage equal to or greater than 150 megawatts, $P(X \geq 150)$, the exact forced outage probabilities of 150, 160 and 210 must be summed:

$$P(X \geq 150) = P(X = 150) + P(X = 160) + P(X = 210).$$

$$.00979 = .00279 + .00679 + .00021$$

The individual probabilities may be summed because they are for mutually exclusive events. The $P(X \geq x)$ is determined for each value of "x" (0, 50, 60, 100, 110, 150, 160, 210) by cumulative adding of $P(X=x)$ values starting at the highest x value (i.e., 210).

Forced Outage in MW	$P(X=x)$	$P(X \geq x)$
0	.81189	1.00000
50	.02511	.18811
60	.06111	.16300
100	.09021	.10189
110	.00189	.01168
150	.00279	.00979
160	.00679	.00700
210	.00021	.00021
	1.00000	

The plot of $P(X \geq x)$ shown on the following page (Chart 1) indicates the stepped appearance generally found in small systems with relatively large unit sizes, and therefore, a limited number of possible outage states. Chart 2 follows Chart 1 and represents a large system having a relatively much smaller maximum unit size and many units. This results in a smoother $P(X \geq x)$ curve which yields a more uniform response to changes in reserve capacity in reliability calculations.

CHART 1

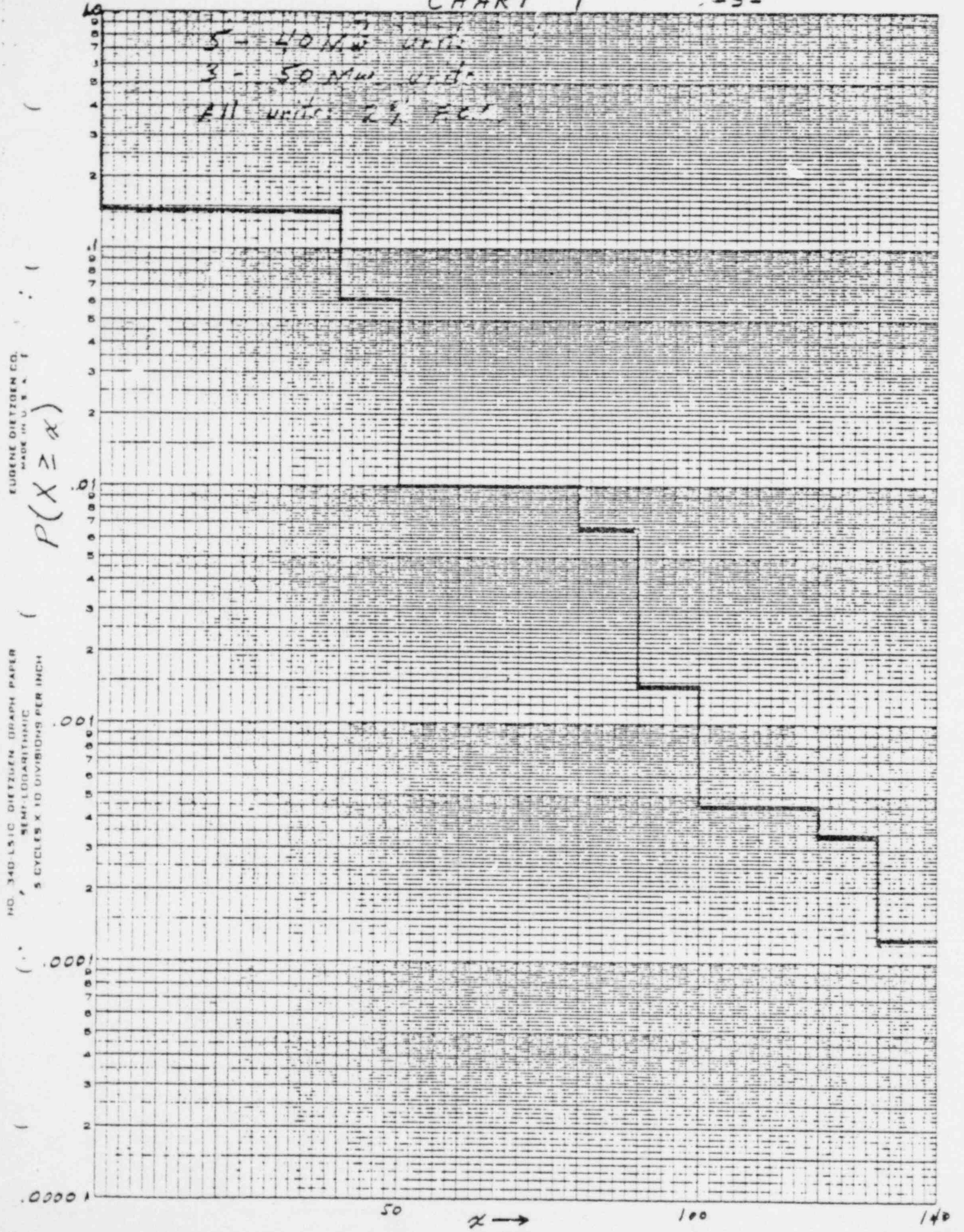
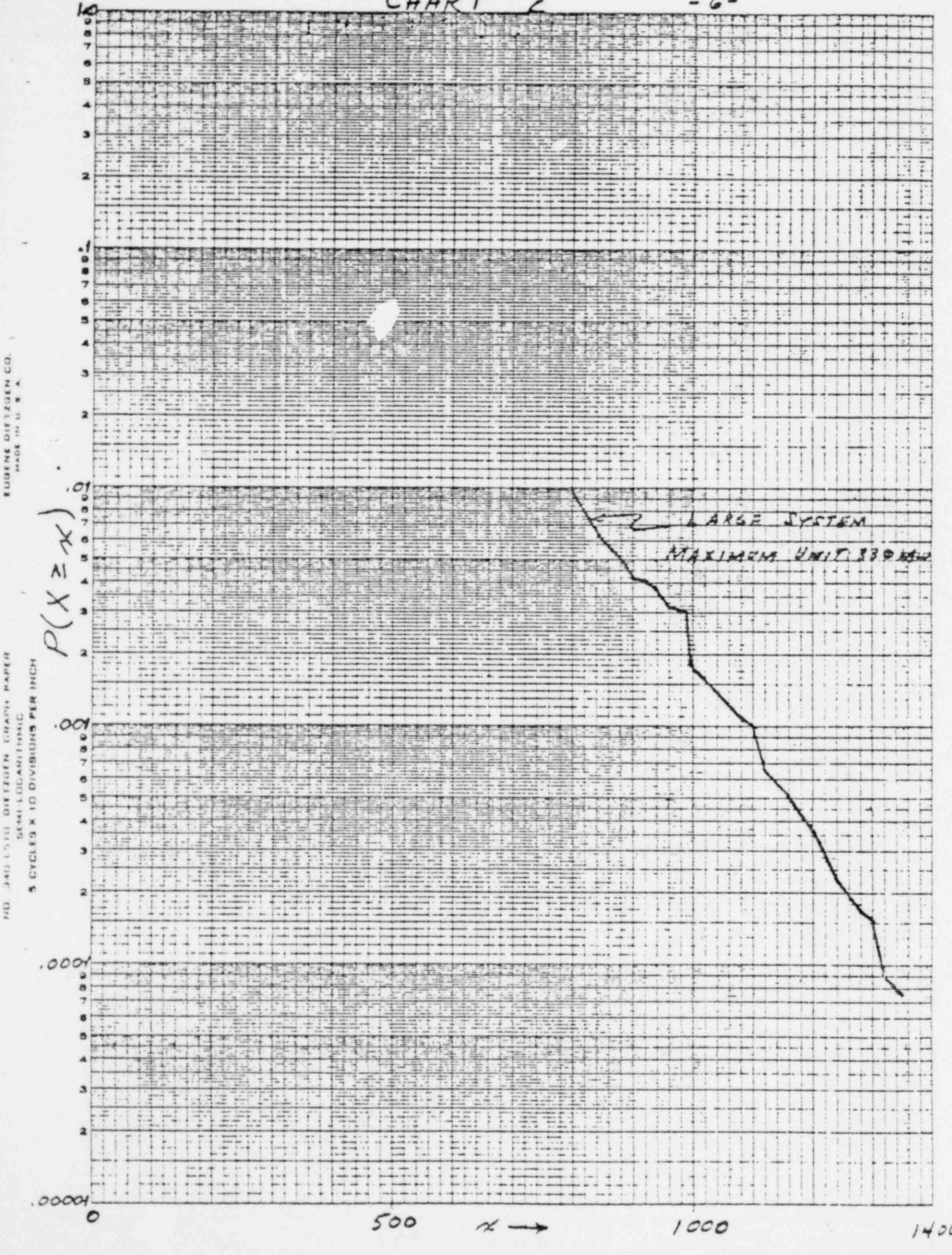

5 - 40 Mw units
3 - 50 Mw units
All units: 2% F.C.
$P(X \geq x)$
1.0
.1
.01
.001
.0001
.00001
50
100
140
$x \longrightarrow$
EUGENE DIETZGEN CO.
MADE IN U.S.A.
NO. 340-L510 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
5 CYCLES X 10 DIVISIONS PER INCH

CHART 2


P(X ≥ x)
1.0
.1
.01
.001
.0001
.00001
0
500
1000
1400
x →
LARGE SYSTEM
MAXIMUM UNIT 330 MW
NO. 340-L510 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
5 CYCLES X 10 DIVISIONS PER INCH
EUGENE DIETZGEN CO.
MADE IN U. S. A.

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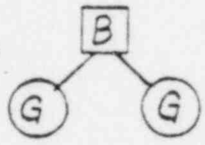
For reliability calculations, accurate answers can be obtained only if the P(X=x) function is calculated after removing from consideration any units that are scheduled out of service for overhaul.

The three unit system analyzed above is of the simplest form. Complications usually occur and some of these can be dealt with. Suppose that a fourth plant is added to the base system and that it is a common-feed type unit.

New Unit:

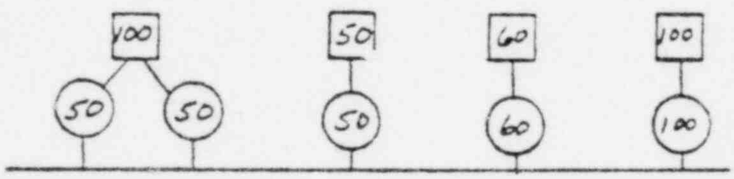


Boiler: $p = .98,\ q = .02$

Generators: $p = .97,\ q = .03$

The new system can be schematically represented as follows:

New System:



The probability function $P(X = x)$ for the common feed plant is as follows:

Forced Outage (MW)	Probability $P(X = x)$
0	$p_B \times p_G \times p_G = .98 \times .97 \times .97 = \underline{.922082}$
50	$2(p_B \times p_G \times q_G) = 2(.98 \times .97 \times .03) = \underline{.057036}$
100	$p_B \times q_G \times q_G + p_G \times p_G \times q_B + 2(q_B \times p_G \times q_G) + q_B \times q_G \times q_G = .98 \times .03 \times .03 + .97 \times .97 \times .02 + 2(.02 \times .97 \times .03) + .02 \times .03 \times .03 = \underline{.020882}$

Shown on the following page are the possible forced outages for the common feed unit and all states yielding that forced outage.

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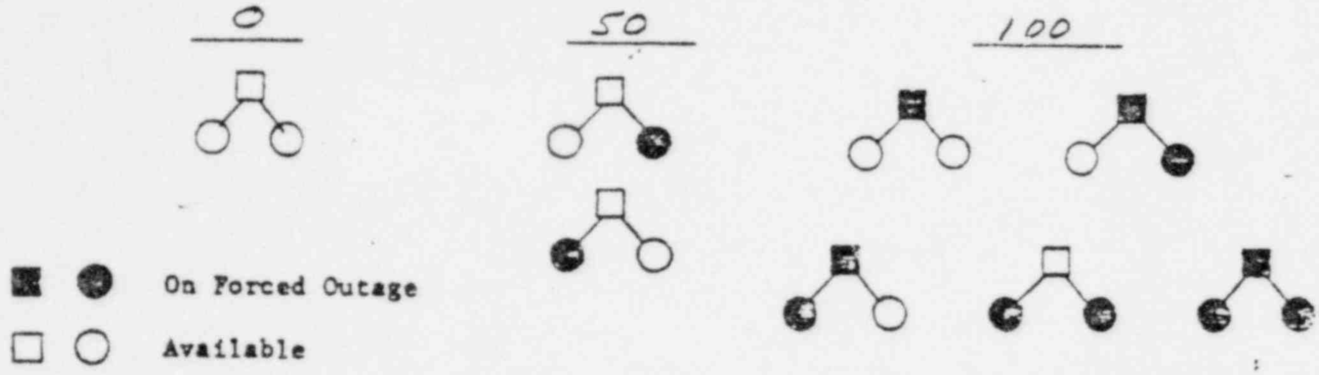
MW ON FORCED OUTAGE



Once the probabilities of all possible outage cases for the common feed units are known, the units can be combined with the other units in the system using the independence principle. The probability of each possible outage can then be determined. In this case several possible (mutually exclusive) situations may result in the same amount of forced outage. For example, it is possible to have a 50 MW outage, if the common feed units are on line, but the 50 MW unit in Plant B is off line. It would also be possible if one of the generators of the common feed unit were off line and all other units were on line. Using the independence principle and multiplying probabilities together, the probability of each event that will result in exactly "x" MW of forced outage can be obtained. Summing probabilities for events which result in the same forced outage, "x", the probability of that outage occurring within the whole system is obtained. $P(X \geq x)$ is then determined as explained in the first example. The detail of calculations is shown on Table I.

Units which have partial outage states are treated the same as common-feed type units. Quite often it is desirable to represent a unit by three or more forced outage states (two of which are on and off) particularly if a unit repeatedly suffers the same forced curtailment.

(Common Feed Plant Combined With the Three Plants of Example 1)

Table I

COMMON FEED UNITS										
	COLUMN		1	2	3	4	5	6	7	8
	MW CAPACITY		0	50	60	100	110	150	160	210
LINE		OUTAGE PROBABILITY	.81189	.02511	.06111	.09021	.00189	.00279	.00679	.00021
A	0	.922082	0 .7486292	50 .0231535	60 .0563484	100 .0831810	110 .0017427	150 .0025726	160 .0062609	210 .0001936
B	50	.057036	50 .0463070	100 .0014322	110 .0034855	150 .0051452	160 .0001078	200 .0001591	210 .0003873	260 .0000120
C	100	.020882	100 .0169539	150 .0005243	160 .0012761	200 .0018837	210 .0000395	250 .0000583	260 .0001418	310 .0000044

Foreced Outage For System (MW)		Probability P(X = x)	P(X ≥ x)
0		.7486292	1.000000
50	A,2 + B,1 =	.0694605	.2513708
60	A,3 =	.0563484	.1819103
100	B,2 + C,1 + A,4 =	.1015671	.1255619
110	B,3 + A,5 =	.0052282	.0239948
150	A,6 + B,4 =	.0082421	.0187666
160	A,7 + B,5 + C,3 =	.0076448	.0105245
200		.0020428	.0028797
210		.0006204	.0008369
250		.0000583	.0002165
260		.0001538	.0001582
310		.0000044	.0000044
		1.0000000	

Computer programs have been developed to carry out the calculation described. Several of these programs require a complete recomputation of the probability functions every time a change is made in unit schedules or capacities. These changes usually can be associated with overhaul schedules and hydro plants capabilities where affected by head variations from month to month. Because the computational process is quite time consuming especially for large systems it is very desirable to find a short cut.

A short cut exists which gives accurate results provided care is taken in writing the computer program. The array containing the $P(X = x)$ must not be cumulated into a $P(X \geq x)$ array. $P(X \geq x)$ values should be stored in a separate array for use in reliability calculations. This is because any changes that occur are incorporated into the $P(X = x)$ array. If an attempt is made to reduce the $P(X \geq x)$ array to a discrete $P(X = x)$ array, problems arise because of significant figure rounding inside the computer. On an IBM 360-65 double precision is required for accurate results in probability calculations.

This next example illustrates how the forced outage effect of a unit with three outage states can be removed from capacity outage probability tables. The logic can be extended to any number of outage states desired. In order to verify the removal procedure, we can add this three outage state unit to the system and then remove it.

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Initial System

3 40 MW units q = .10

2 10 MW units q = .10

Unit to be added - 40 MW's with a 10 MW partial outage state. Number of outage states = 3

$P_0(X = x)$	Added Unit 0 .80	 10 .10	 40 .10	$P_A(X = x)$
0 .59049	0 .472392	10 .059049	40 .059049	0 .472392
10 .13122	10 .104976	20 .013122	50 .013122	10 .164025
20 .00729	20 .005832	30 .000729	60 .000729	20 .018954
40 .19683	40 .157464	50 .019683	80 .019683	30 .000729
50 .0 .374	50 .034992	60 .004374	90 .004374	40 .216513
60 .00243	60 .001944	70 .000243	100 .000243	50 .067797
80 .02187	80 .017496	90 .002187	120 .002187	60 .007047
90 .00486	90 .003888	100 .000486	130 .000486	70 .000243
100 .00027	100 .000216	110 .000027	140 .000027	80 .037179
120 .00081	120 .000648	130 .000081	160 .000081	90 .010449
130 .00018	130 .000144	140 .000018	170 .000018	100 .000945
140 .00001	140 .000008	150 .000001	180 .000001	110 .000027
1.00000				120 .002835
				etc.

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Suppose now that we schedule this added unit to be out of service for overhaul at some point in time. We subtract this resource from the total resources and we also need to change our capacity outage probability table because this unit cannot contribute to forced outage probabilities while it's on the floor.

Unit to be removed from service

$P_A(X=x)$	0 .80	10 .1	40 .1	$P_O(X = x)$
0 .472392 → ÷ .80 =	0 .59049	10 .059049	40 .059049	0 .59049
10 .164025	10 .104976/.8	20 .01312[illegible]	50 .013122	10 .13122
20 .018954	20 .005832/.8	30 .000729	60 .000729	20 .00729
30 .000729	30 0	40 0	70 0	30 0
40 .216513	40 .157464/.8	50 .019683	80 .019683	40 .19683
50 .067797	50 .034992/.8	60 .004374	90 .004374	50 .04374
60 .007047	60 .001944/.8	70 .000243	100 .000243	60 .00243
70 .000243	70 0	80 0	110 0	70 0
80 .037179	80 .017496/.8	90 .002187	120 .002187	80 .02187
90 .010449	90 .003888/.8	100 .000486	130 .000486	90 .00486
100 .000945				etc.
110 .000027				
120 .002835				
130 .000711				
etc.				

The logic diagram for computer solution to this procedure is on the following page. It should be noted that the discrete probability array uses the outage states as indices and all outage states are increased by 1 so that the 0 outage state is stored in the first position.

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Reliability Calculations

Reliability calculations require that expected loads be incorporated into the analysis in some manner. There are many different approaches used to develop what can be called a load model. They vary from those which employ a normal distribution to an estimate of the monthly or annual peak load. The reliability index obtained from any reliability study depends upon the type of load model and the method used to calculate system reliability.

Reliability indicies are obtained from calculations which begin by determining the probabilities not meeting projected loads. Whether the reliability index is a pure probability or an expected value depends upon what is done with the probabilities of not meeting the projected loads.

Expected Value Method of Loss of Load Reliability Calculations

PG and E uses the years/day of expected load loss as its reliability index. This index is often stated as the loss of load probability is one day in N years, where N is the reliability index. The reliability index for this method of expressing generation reliability is obtained by first determining for a given study period the expected number of days that the projected loads cannot be met with the planned resources. Because study periods can vary in length the reliability index is determined by calculating the number of years that could be composed of the same study period repeated over and over before the expected number of days of load loss would equal 1.0. For example, if during a one year study period the expected number of days lost were computed to equal 0.1, then it is calculated that you would expect to lose load 1 day for every 10 years that were identical to the year studied. The load model used

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is a daily peak one because it is assumed that calculating the chance of not meeting the daily peak provides an appropriate test of reliability.

The following charts on pages 17 and 18 show how the reliability index for a 10 day study period is determined for an example system with twelve 100 mw units each having a 10% F.O.R. First a capacity forced outage probability table is calculated by the procedure previously detailed (resulting capacity forced outage probability table is on page 17). The chart on page 18 shows how the load model is subjected to a reliability test. Given a load model, the reserve capacity on each day can be determined. The probabilities of exceeding the reserves is obtained by a table lookup procedure in the capacity forced outage probability tables. In computer core, the capacity forced outage probability table, an array of $P(X \geq x)$, is stored, so that the array index is equal to the reserve + 1 mw [0 mw occupies the first position in the $P(X \geq x)$ array].

The expected number of days of load loss is determined by summing the daily probabilities of not meeting the load. The expected number of days lost per year would be calculated from:

$$\frac{.147 \text{ days}}{10 \text{ days}} = \frac{D}{365 \text{ days}}$$

$$D = 5.37$$

D is the expected number of days per year that generation would not be sufficient to meet the load. The reliability index, N, would be less than one year in this case:

$$N = \frac{1.0}{5.37 \text{ days/year}} = .186 \text{ years/day}$$

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LOGIC DIAGRAM FOR

MAKING CHANGES IN CAPACITY

OUTAGE PROBABILITY TABLES

N = Unit Number

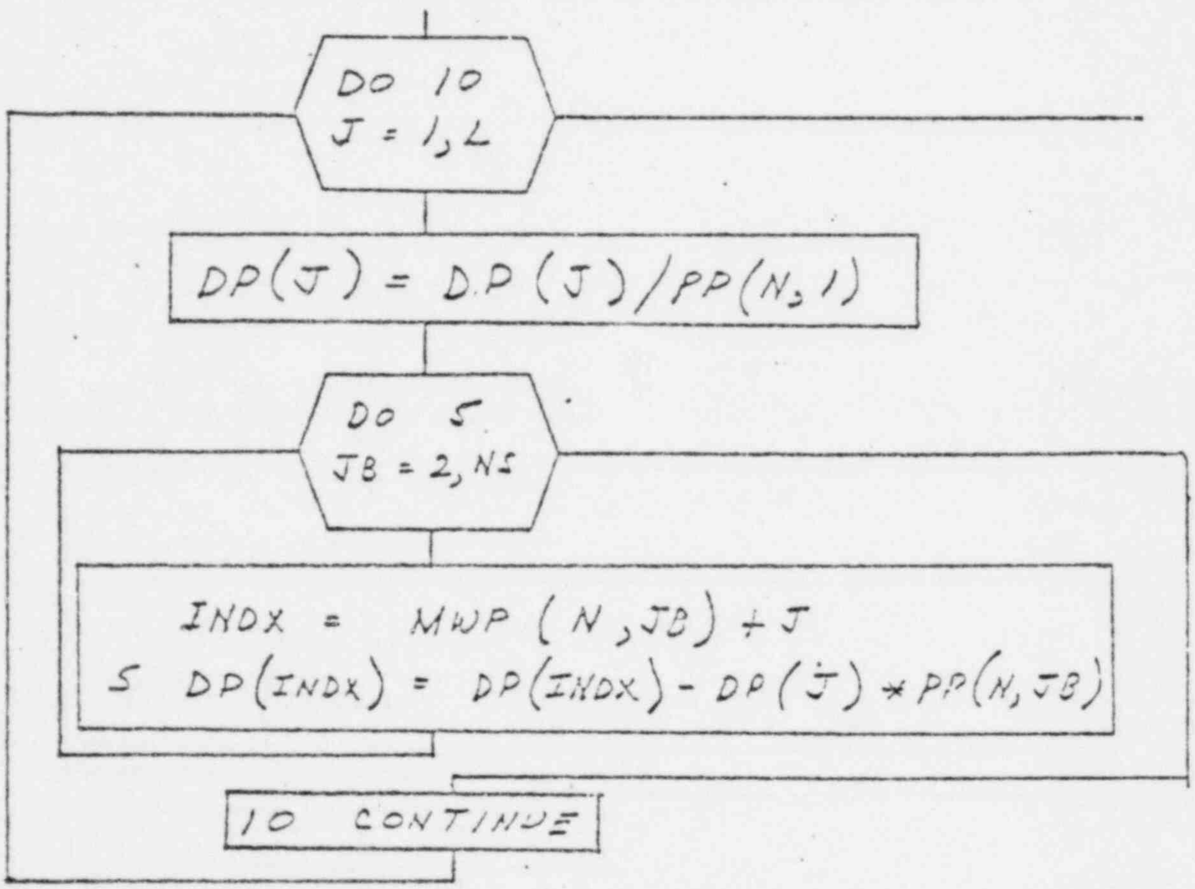
NS = Number of outage states for unit or plant

DP = Discrete probability array P(X = x)

L = Length of outage table

PP = Probability of unit outage state

MWP = Megawatt outage associated with outage state



For the previous example the system had six units in service before Unit No. 6 was scheduled out for overhaul. Unit No. 6 is the 3 state unit that was added to the initial 5 unit system. The following data would be stored by a computer for Unit No. 6: PP(6,1) = .80, PP(6,2) = .10, PP(6,3) = .10, NS = 3, MWP(6,1) = 0, MWP(6,2) = 10, MWP(6,3) = 40

The N value is then checked against a reliability criteria to determine whether or not system reliability is sufficient. If the reliability criterion was something like 1 day in 0.1 years, this system would pass. PGandE's reliability criterion is 1 day in 10 years and this example system would fail miserably.

Aids to Revising Resources

Because reliability testing is a trial and error process of resource adjustment, it is most advantageous to know about how much the reliability index will change if resources are changed. This can be most easily accomplished in a computer program by internal modification of the load model so that say six different load models are tested at the same time and reliability indicies for all six are determined. This requires very little extra computer time because the capacity forced outage probability tables remain the same. The chart on page 19 shows the resulting reliability index curve verses increases or decreases in projected loads. By inspection of this graph, it is possible to make a good estimate of how much to change resources by, to obtain the desired reliability index on the next try. Because changing the load represents effective or perfect megawatt changes, some knowledge of the effective load carrying capability of various types and sizes of units is required. For example, a 1000 mw unit might only have 600 mw of effective load carrying capability if it was the largest unit on the system and had a high forced outage rate. If the reliability index curve showed that the system was over designed by 600 mw in a particular month, it might be possible to delay the 1000 mw unit.

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SYSTEM RELIABILITY TESTING

NON-UNIFORM LOAD

12 - 100 MW UNITS
10 % FORCED OUTAGE RATE

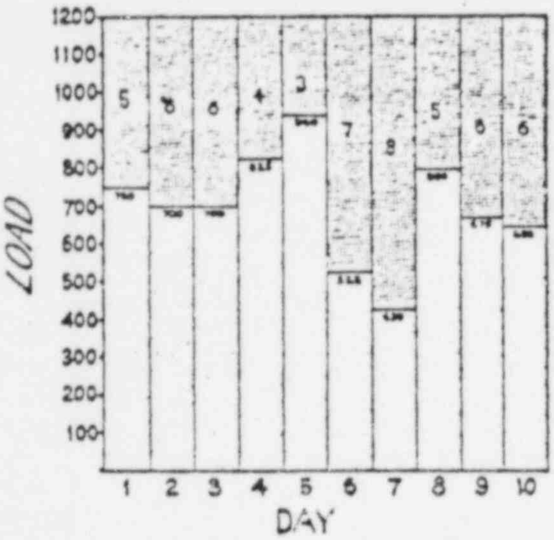
Capacity Outage Probabilities

POSSIBLE OUTAGE STATES	PROBABILITY OF EXACT OUTAGE STATE OCCURRING	PROBABILITY OF EQUAL OR GREATER OUTAGE
0	.28243	1.0
100	.37657	.71757
200	.23013	.34100
300	.085233	.11087
400	.0213077	.025637
500	.00378807	.0043293
600	.00049105	.00054123
700	.0000467665	.00005018
800	.00000324767	.0000034135
900	.000000160375	.00000016583
1000	.000000005346	.000000005455
1100	.000000000108	.000000000109
1200	.000000000001	.000000000001
SUM	1.000000000000	

Z A Y 1 2 5 1 0 18 T 2

SYSTEM RELIABILITY TESTING

1200 MW INSTALLED CAPACITY



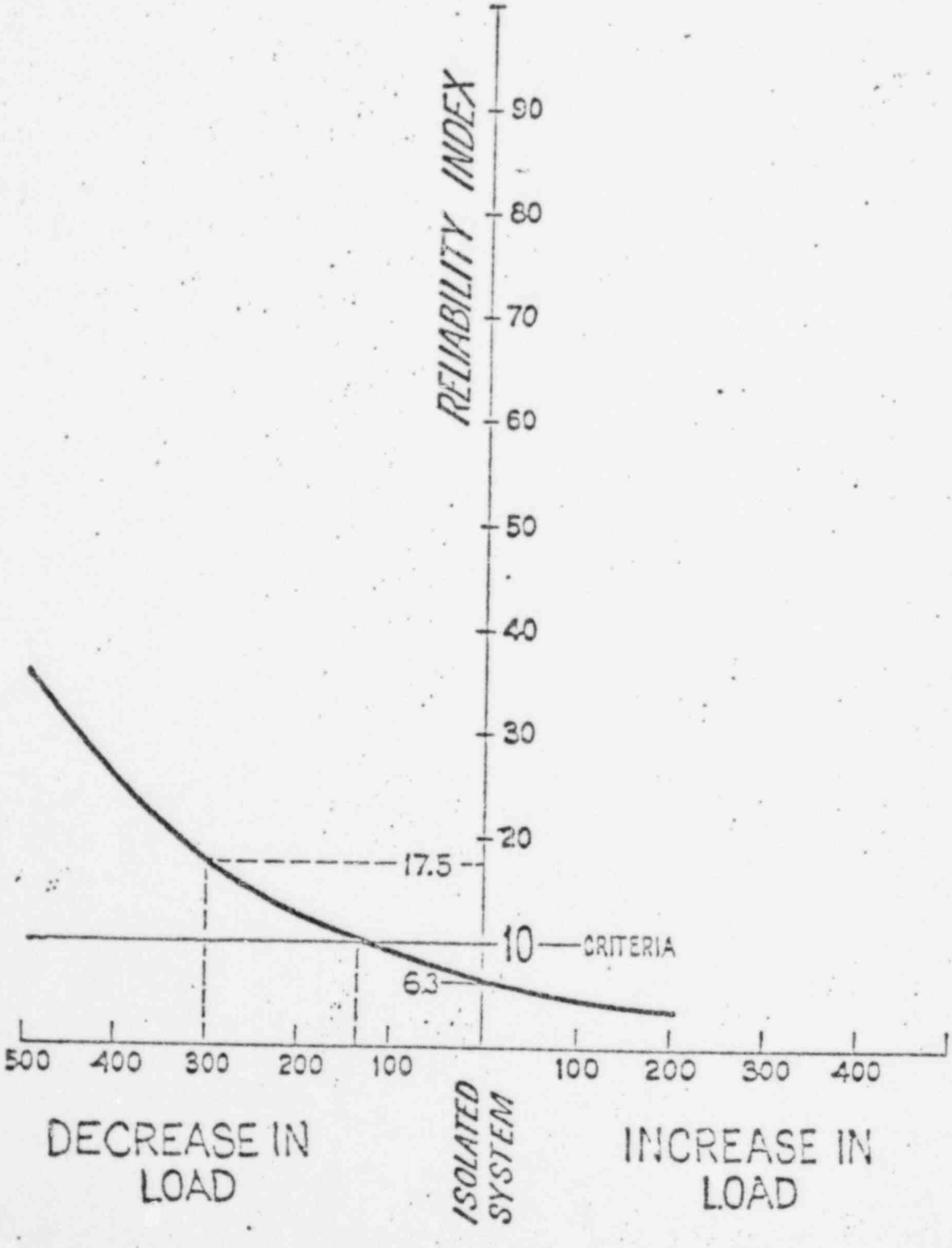
UNITS OUT OF SERVICE	PROBABILITY OF EQUAL OR GREATER NUMBER OF UNITS OUT OF SERVICE
1	.71757
2	.34100
3	.11087
4	.025637
5	.0043293
6	.00054123
7	.00005018
8	.0000034135

DAY	LOAD	RESERVE	UNITS OUT TO REQUIRE LOAD CURTAILMENT	PROBABILITY OF EXCEEDING RESERVE
1	750	450	5 or more	.0043293
2	700	500	6 " "	.0005412
3	700	500	6 " "	.0005412
4	825	375	4 " "	.0256370
5	940	260	3 " "	.1108700
6	525	675	7 " "	.0000502
7	430	770	8 " "	.0000034
8	800	400	5 " "	.0043293
9	675	525	6 " "	.0005412
10	650	550	6 " "	.0005412
				.1473840

.1473840 EXPECTED NUMBER OF DAYS WITH SOME AMOUNT OF LOST LOAD FOR THE TEN DAY PERIOD

ZAY 1251013

RESERVE REQUIREMENTS



ZAY 1251014

RESERVE POOLING

Case of Infinite Capability Interconnection

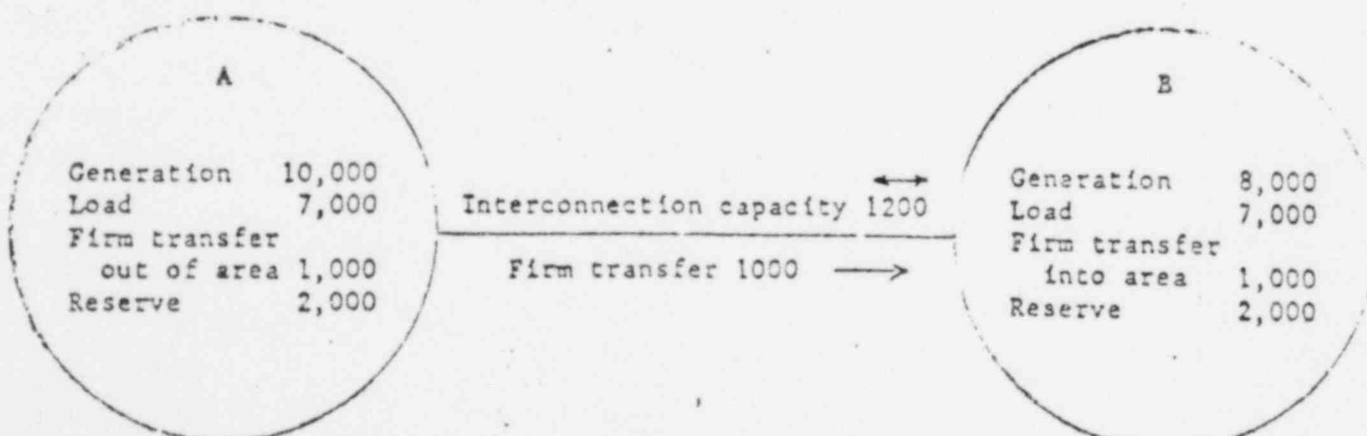
This case is the easiest to handle because the transmission system is capable of transferring the entire reserve capacity of each pooled utility to any other pooled utility at any time. For reliability studies all of the pooled units can be put into the capacity outage tables directly. This is what we assume when analyzing our PG&E area.

Case of Limited Capability Interconnection

If two systems are interconnected as shown on the diagram below and firm power flows in the indicated direction, a limited intertie situation exists.

A ⟶ B

Interconnection capacity	1200
Firm transfer	-1000
Reserve transfer capability	200
Inaccessible reserve	1800



Non-delivery of firm transfer	1000
Remaining reserve in area B	1000
Reserve transfer capability	2000

A ⟵ B

ZAY 1251015

For reliability studies, each area can consider the reserve capacity in the other area as a source of generation with an infinite number of partial outage states. The maximum capacity of this source of generation is, of course, limited by available reserves or intertie capacity whichever is least. To represent this external source of generation, a tie model is developed for each system from its "isolated" capacity outage table. The diagram on page 22 shows how a 1000 mw tie model was developed for a particular week from a capacity outage table for the PG&E system. Five outage states were chosen to represent the availability of the reserve capacity. For each partial outage state of the tie model, the probability is obtained by determining the probability of forced outages on the system occurring anywhere within the interval represented by the partial outage state. For the 200 mw partial outage state, the outage rate is $P(X \geq 1000) - P(X \geq 1200)$ or .0285 - .0110 = .0175. Probabilities for other partial outage states are similarly obtained except that the 1000 mw outage state must include the probability of any outage over 1800 mw - not just those between 1800 and 2000 mw.

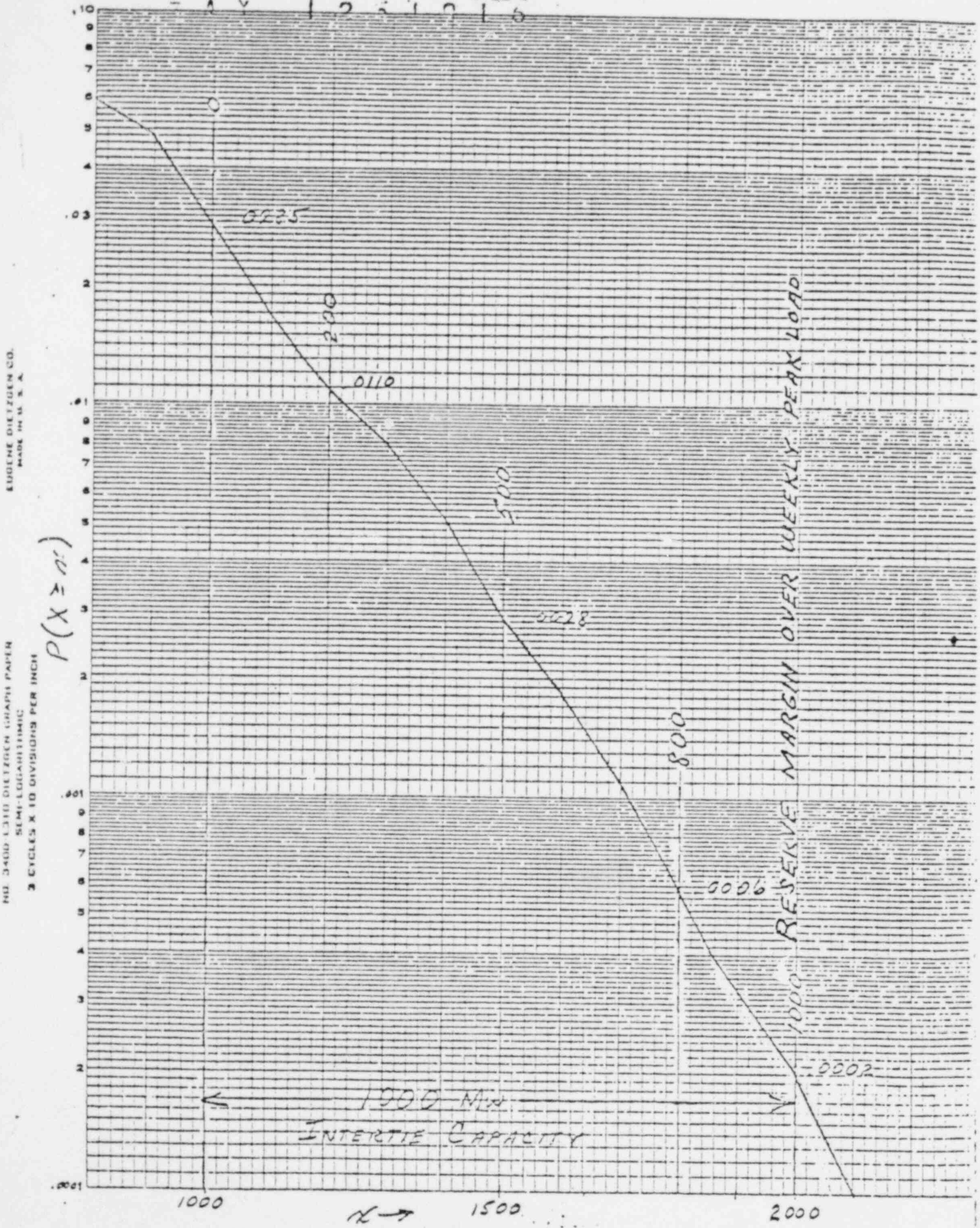
Intertie Model

0	200	500	800	1000
.9715	.0175	.0082	.0022	.0006

Intertie Model Including Outage Rate of Interconnection (.002)

P(X = 0)	= (1.0 - .002) (.9715)	=	.9695570
P(X = 200)	= .998 x .0175	=	.0174650
P(X = 500)	= .998 x .0082	=	.0081836
P(X = 800)	= .998 x .0022	=	.0021956
P(X = 1000)	= .0006 + .002 - .0006 x .002	=	.0025988
			1.0000000

0	200	500	800	1000
.969557	.0174650	.0081836	.0021956	.0025988



P(X ≥ x)
RESERVE MARGIN OVER WEEKLY PEAK LOAD
1000 MW
INTERTIE CAPACITY
.0225
200
.0110
500
.0028
800
.0006
1000
.0002
1000
1500
2000
x →
.10
.03
.01
.001
.0001
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This intertie model is incorporated into the receiving area's capacity outage tables and resources. The number of outage states used and the frequency of intertie model computation (weekly, daily, monthly, annually) are variable. Increasing both will result in higher reliability indicies.

The process of reserve reduction in both areas is by trial and error. New generation is postponed and intertie models are redeveloped and exchanged. Intertie models must be redeveloped because their outage probabilities increase as reserves are reduced. With the two area pool, closure on the desired reliability index can be reached by the third round.