POWER GENERATION

FOR

HIGH-RELIABILITY QUADRUPLE-DIVERSITY COMMUNICATIONS SYSTEMS

JANUARY 1963

[redacted]

JACKSON & MORELAND, INC.

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Boston, January 25, 1963

Mr. J. J. Gano
J. J. Gano & Associates
2225 Massachusetts Avenue
Cambridge, Massachusetts

Dear Mr. Gano:

We submit herewith the report "Power Generation for High-reliability Quadruple-diversity Communications Systems."

This report reflects the revisions and redrafting called for by the client's representative. Before reproducing it, however, we have made additional minor editorial changes and have rechecked the validity of the indicated conclusions.

Very truly yours,

JACKSON & MORELAND, INC.

By A E Fitzgerald
A. E. Fitzgerald

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1.0 PURPOSE

A study has been made with the purpose of developing a design philosophy for determining the number and size of diesel generators to supply primary power at stations which are a part of a high-reliability quadruple-diversity communication system.

2.0 SCOPE OF STUDY

The study for evolving the design philosophy for primary power generation plants, presented herein, applies basically to a high-reliability quadruple-diversity communication system. More specifically, this communication load is considered of utmost importance, but other loads, of secondary importance, do exist and must be accommodated. Descriptions of all load types, together with their arrangement and requirements, were developed at meetings with personnel from ESD and MITRE.

The design philosophy is concerned with the effect of forced outages and scheduled maintenance on diesel-generator-unit availability and hence on the number of units required in a plant. It is not concerned with detailed specifications of the generators or their equipment. A "no-break" power supply is considered outside of the scope of this study.

3.0 SUMMARY OF CONCLUSIONS

As a result of these studies, the following recommendations or conclusions are in order:

(1) There should be six diesel-engine-generators per plant.

(2) Four of these diesel-engine-generators should carry the full load, two supplying power to each of two separate busses.

The two remaining generator units are to be used as standby or spare units.

(3) The diesel-generator units should be sized so that each can carry half the technical load or half the total interruptible load, whichever is greater.

(4) A conservative estimate of availability for such a power plant to carry the complete and full load is 99.97 per cent.

> This represents an unavailability of the power plant to carry the full load on an average of 2.5 hours per year; or, on a 20 year plant life basis, it is equivalent to an unavailability of 50 hours. In a particular plant, this 50 hours may occur over zero, one, two or more instances with unpredictable durations at unpredictable moments anytime from the first to the last year.

(5) The power plant availability in reference to supplying only the technical load portion of the full load is essentially 100 per cent.

(6) The number of spare diesel-engine-generator units for the power plant is basically determined by attaining satisfactory availability of the power supply to accommodate the short-term interruptible electronic and utility loads.

4.0 LOADS

4.1 LOAD TYPES

The total load at each station within a high-reliability quadruple-diversity communication system is divided into three classes:

4.1.1 NON-INTERRUPTIBLE OR TECHNICAL LOAD

The high-reliability quadruple-diversity communication system, for purposes of this report, is to be considered as a combination of two dual-diversity tropospheric-scatter communication units. Each unit operating individually is assumed to be capable of providing some degree of communication. However, normal operation is such that two dual-diversity units will operate, in an approximate parallel arrangement, to form quadruple-diversity communication capable of providing an even greater degree of communication capability. Thus sufficient power should be available at all times to energize both dual-diversity communication units at a given station. Even if one of the two dual-diversity units should fail, power should still be available for the failed unit so that maintenance may proceed as rapidly as is practical.

A great deal of attention has been invited to the importance of this communication load and the importance of providing the highest priority, over other loads, for continuous operation. A power supply outage resulting in insufficient power to a dual-diversity communication unit (in some actual cases 0.75 second and more) may cause a shutdown of the dual-diversity communications from which it may require fifteen minutes or longer to recover. Because of such a shutdown, the dual-diversity communications unit must be re-energized, a process which may necessitate cycling and sequencing of power to several sections. Some additional time may also be required for full operational efficiency because of initial difficulties often encountered when electronics within the communication system are re-energized after an unexpected shutdown. Thus a continuous supply of power is most desirable even at the expense of shedding or disconnecting other loads of less importance.

Consequently the above communication system load will be treated as a Non-interruptible load; it will also be referred to as the "Technical" load. All auxiliary equipment necessary for the proper operation of the communication system (such as equipment for cooling) must be considered as part of this Technical load.

4.1.2 SHORT-TERM-INTERRUPTIBLE ELECTRONICS LOAD

At many of the stations within the quadruple-diversity communication system, there may be additional electronic equipment such as radars, navigational guidance devices, and other radio equipment. The reliability requirement for this equipment is not as critical, and interrupted operation for a fraction of an hour a few times a year may be tolerable. This load type is of second priority in the sense of being supplied with primary power. Because of the lower priority, this type of load will have provision for automatic shedding or disconnection in the event of certain curtailments in the primary power capacity.

4.1.3 UTILITY LOAD

The remaining loads at the communication stations are classified as utility, and include lighting, heating, appliances, etc. In general, the Utility load is considered third priority from the viewpoint of being supplied with primary power. As for the case of the Short-Term-Interruptible Electronic load, provision for automatic shedding or disconnection from the primary power source must also be considered for the Utility load. For stations located in cold-climate areas, much of the Utility load must be considered essential on a long-term basis so that power outages for more than an hour are undesirable if not intolerable.

4.2 LOAD ARRANGEMENT

The nature of a communications center employing two independent dual-diversity units leads to a double-bus configuration as a logical consequence. In effect, this arrangement provides two independent primary power sources, one to supply each dual-diversity unit. The selection of number and arrangement of generating units on the two busses is given in 6.0. The basis of design will be to consider the Short-Term-Interruptible Electronic and the Utility loads equally divided so that half is connected to each bus. Thus, in the event of any capacity curtailment at the primary power supply, the Short-Term Interruptible Electronic and Utility loads on the associated bus will be automatically dropped in order to maintain a continuous supply of power to the appropriate dual-diversity communication unit. In the meantime a standby generating unit can be started, brought up to speed, synchronized and then put onto the bus, after which the interrupted loads may be reconnected. This procedure or arrangement eliminates the undesirable alternatives of: (a) carrying spinning reserve, or (b) attempting to start and synchronize a standby unit under pressure of imminent loss of communications.

The necessity of load shedding is a function of both the output required (demand) and the available capacity of the plant at any given moment. In general, demand varies with time, but, for the load types presented herein, the demand may be assumed constant.

5.0 AVAILABILITY

5.1 USE OF THE TERM AVAILABILITY

The term "Availability" will hereafter be used instead of the more popular expression of reliability.

Reliability, in general, is a term which implies time dependency starting at some time datum such as the time at which the switch is turned on. On the other hand, "Availability" is not associated with a time reference, but it is associated with an average period of time in which equipment may be operable over some long time span. This can be any long time span having no particular starting point in the time scale within the lifetime of the equipment. Thus the concept of availability is applicable for the case of a station's communication and primary power equipments in the quadruple-diversity communications system. Lifetimes of these equipments may be expected to be of the order of 20 years.

Availability is expressed as a fraction or percentage of some sufficiently long time interval in which an equipment or system in question is capable of operation.

Availability may be calculated by the following formula where the time interval basis is taken as the mean time between failures plus the mean outage time:

$$A = \frac{T}{T + t} \qquad (5.1)$$

where T = mean operable time between failures

t = mean outage time

Availability may also be expressed as: "1" minus the unavailability fraction for the equipment, unit, or system in question, since availability plus unavailability must equal unity. For a power plant, availability may be expressed as "1" minus expectation of power plant capacity curtailment. The term capacity curtailment is to mean the inability of the power plant to provide the total load demand, where total load includes the combined Technical, Short-Term-Interruptible Electronic, and Utility load types. The expression Expectation of Power Plant Capacity Curtailment will be employed for the quantitative discussion that follows and for labeling the abscissa of figures 1, 2 and 3.

5.2 STATISTICAL NATURE OF THE TERM AVAILABILITY

The terms Availability or Expectation must be interpreted as measures of statistical probability. Being statistical in nature, a value of expectation of power plant capacity curtailment should not be interpreted as an absolute or specific number applicable to a single plant in an overall communications system, but rather as an indication of the average behavior that may be expected in the lifetimes of many plants. In actuality, some plants may have a far greater incidence of power capacity curtailment whereas others may experience very little capacity curtailment or none at all. Furthermore, at any individual plant, a capacity curtailment might occur on zero, one, two or more separate occasions in the lifetime of the plant. The occurrence of any one of these capacity curtailments may be experienced at any time from the first to the last year of the plant's lifetime. The duration of any one of these capacity curtailments is also a variable, with a possible range from a few seconds up to approximately 50 hours.

5.3 GENERATOR UNIT AVAILABILITY

When equation (5.1) is applied to single generator units of a power plant, the mean outage time, t, will include all downtime due to scheduled outage for maintenance and/or enforced outages such as may result from failures or accidents. Outage time may be considered as that time in which a generator unit is not available to carry its share of the required load.

Diesel engine generating units are highly developed, dependable machines but, due to the wide variety of designs, load schedules, fuels burned, and operating and maintenance practices, it has been impossible to establish comprehensive and generally applicable availability data. Nevertheless, we believe sufficient data exist to give a reasonable basis for establishing a design philosophy for selecting the number of units required. The collected data, summarized in Appendix A, indicate that it is conservative to take unit availability on the basis of 5 per cent scheduled outage and 1 per cent forced outage. A reasonable range of outage, as a basis for predicting unit availability, is considered to extend from 1 to 5 per cent for scheduled outage and 0.5 to 1 per cent for forced outage. The design philosophy herein developed, however, will accommodate outage values outside this range.

5.4 POWER PLANT AVAILABILITY

The availability of a multi-unit power plant in terms of availability of the individual units is a function of the number of units installed and the actual number of units required to carry the full load. The quantitative relationship is developed in Appendix B. Appendix B also develops an approximate analysis which is sufficiently accurate for graphical presentation as in figures 1, 2 and 3. The results of this power plant availability analysis are expressed in terms of unavailability or expectation of power plant capacity curtailment. Figures 1 and 2 on pages 12 and 13 are intended to bring out the general relationships for multi-unit power plants with one or two spare generating units respectively, while figure 3, page 18, is intended to apply directly as an aid for determining the required number of diesel engine generators for a type of communication system under consideration in this report.

5.4.1 <u>DISCUSSION OF FIGURES 1 AND 2</u>

Where one extra engine is installed as a spare generator unit, figure 1 shows the effect upon power plant capacity curtailment or unavailability as a function of generator unit outage probabilities for a family of curves whose parameter is the actual number of generating units chosen to carry the full load demand of the station. For example, in figure 1, if a 5 engine plant is considered (i.e., 4 engines have been chosen to carry the full load) then capacity curtailment will occur when the pl … erating units.

… e 1 is the product of scheduled unit outage rate (value between 0 and 1) times the forced unit outage rate (also a value between 0 and 1). The two ordinate scales on the left are intended to aid in locating typical combinations of forced and scheduled outage probabilities that will form the product on the right hand ordinate scale. Some of these typical outage combinations were employed in constructing the graph on the basis of the approximation discussed in Appendix B. Other combinations of outage probabilities may be applied so long as their product appears on the right-hand scale.

Figure 2 shows data similar to that in figure 1 but instead of one spare unit there are two spares. (One should note in figure 2 that the right-hand ordinate takes into account the square of forced outage rate whereas only the unit exponent is used for figure 1.)

From these figures, the following general conclusions may be made:

(a) Power availability increases (or expectation of power plant capacity curtailment decreases) when the number of units chosen to carry full load is decreased. For example, when the number of units chosen is decreased from 4 to 1, the expectation of power plant capacity curtailment decreases by approximately one order of magnitude.

(b) Power availability also increases when two spare generating units are provided (figure 2) instead of one spare (figure 1). In fact, the expectation of power plant capacity curtailment decreases by at least two orders of magnitude when two spares are used instead of one.

(c) A power plant with an allowance for only one spare generator unit will not be suitable to supply the total load under consideration in this study since the order of magnitude (based on the needs of the least critical part of the load) requires an expectation of power plant capacity curtailment of 10^{-5} to 10^{-4}. These values of expectation are equivalent on an average yearly basis to 5 to 50 minutes per year respectively. The conclusion assumes the "reasonable range for unit outage rates" shown in figure 1.

(d) A power plant with an allowance for two spare generator units may be sufficient to supply the total load under consideration in this study. This assumes the "reasonable range for unit outage rates" shown in figure 2 and the "range of interest for expectation". Any number of generators chosen (up to 4) to carry the total load will give an expectation of capacity curtailment of 10^{-4} or less for unit outages of, for example, 5 per cent scheduled and 0.6 per cent enforced. Hence, an allowance for at least two spare generators must be made in the design of a power plant for the combination of load types under consideration in this study and for the range of unit outage rates assumed to be reasonable.

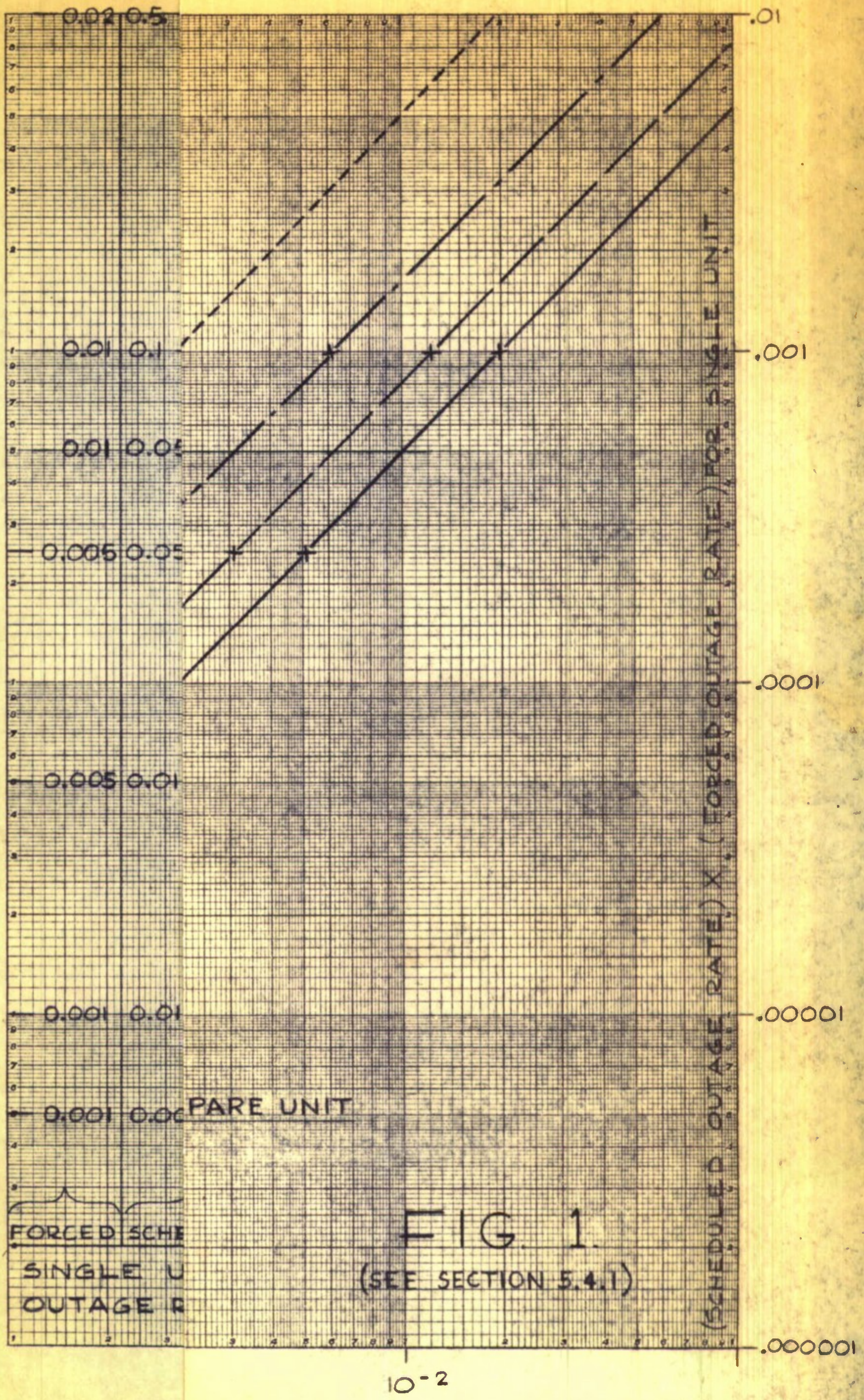

FIG. 1
(SEE SECTION 5.4.1)

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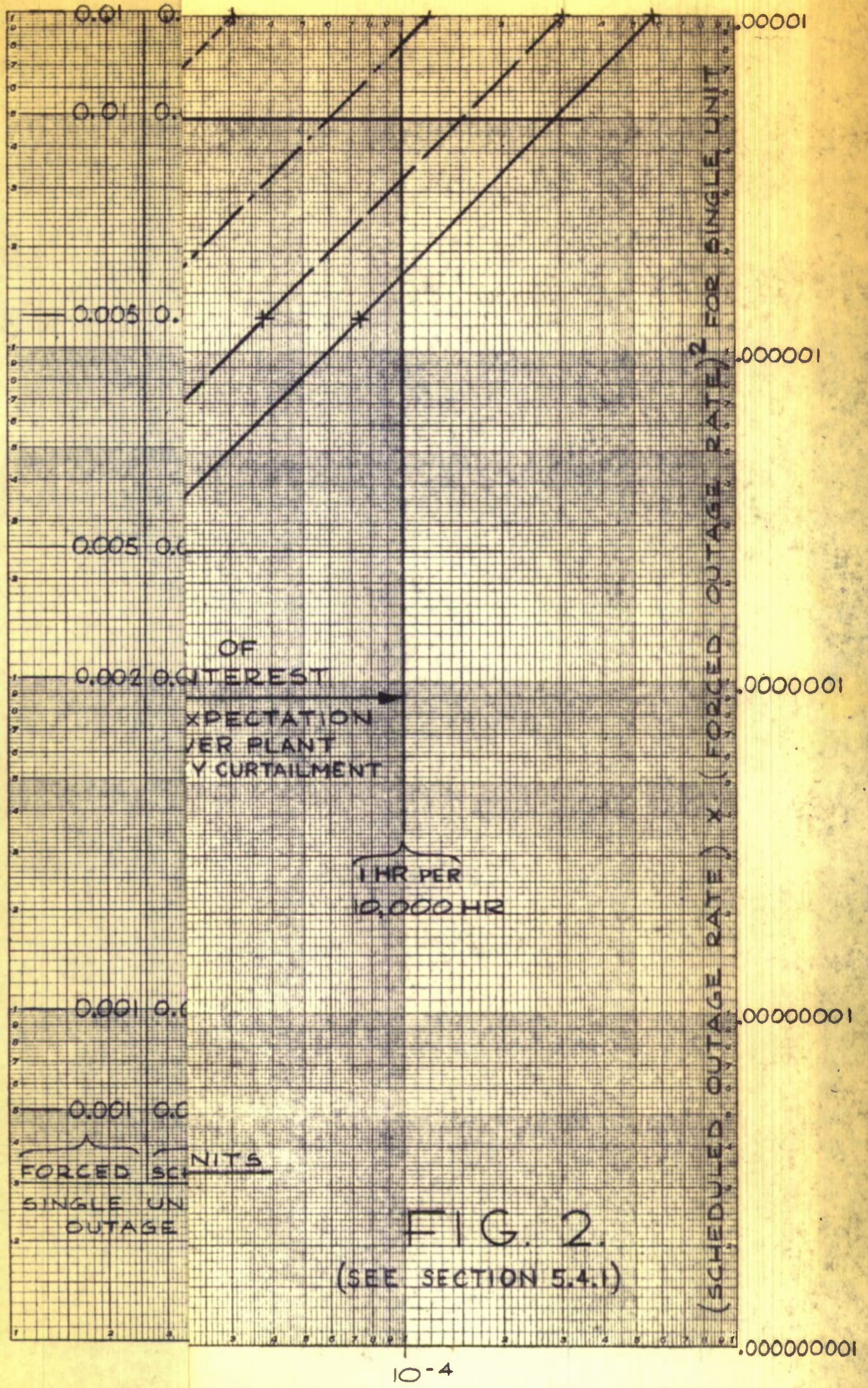

FIG. 2.
(SEE SECTION 5.4.1)

E TIME

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6.0 CHOOSING NUMBER OF GENERATOR UNITS TO CARRY FULL LOAD

Section 5.4.1 (a) shows that the greatest power plant availability is obtained when a single generator is employed to carry the load, if the number of spare units is fixed. However, if a failure occurred in that single unit, the consequent power shutdown to the Technical load would be unacceptable. The logic of load subdivision previously described lends itself to the selection of more than one unit to supply the full load. From an economic viewpoint, it can also be seen that, with a fixed number of spares, the choice of a smaller number of units to carry full load results in a larger installed capacity. For example, one unit plus two spares requires a 300 per cent plant rating to be installed, while four units plus two spares requires only a 150 per cent plant rating to be installed. The larger number of smaller units will take more space and cost more per KW, but the smaller plant capacity and more units will probably result in an over-all cost no greater, and possibly less, than for the larger capacity plant with fewer units. Smaller units also have advantages of less stringent foundation requirements, adaptability to higher speeds, ease of transportation to remote sites, and ease of maintenance. On the other hand, the upper limit to the number of units chosen must be dictated basically by the sacrifice, to be tolerated, in power availability.

The fact that the plants under consideration are designed to serve quadruple-diversity systems composed of a pair of redundant dual-diversity communication units makes it logical to employ an even number of generator units on two separate busses for normal operation. The basic electrical design concept which divides the load on each bus into approximately equal parts, one non-interruptible and the other short-term interruptible, demands, as a logical consequence, that each bus be served by two generating units, so one unit can continue to carry non-interruptible loads after the other has failed. Therefore, the total load is logically carried by four generator units, two for each bus.

7.0 SPECIFIC APPLICATION OF AVAILABILITY DATA

Figure 3 represents a re-arrangement of the data from figures 1 and 2. As previously, the expectation of power plant capacity curtailment is presented along the abscissa. The power plant availability figure is obtained by subtracting the expectation of capacity curtailment from unity. The total number of generating units, including spares, that will be required for the power plant may be determined from a reading along the ordinate of the graph. To accommodate other independent variables in the design, a family of curves is presented whose parameters are the number of generators chosen to carry the full load demand and various combinations of generator unit outage rates.

Figure 3 may be employed for plants using 2, 3, or 4 generator units to supply the total required load and requiring a total of 4, 5, 6, or 7 engines (including the spares) to achieve a desired power plant availability. As in the previous figures, a quantitative understanding may be obtained of the effect on power plant availability by varying the number of generator units to carry the total load as well as varying the number of spares.

For the load combination considered in this study, figure 3 shows that with 4 generator units to carry the full load and with reasonable ranges of generator unit outage rates, then at least 6 and possibly 7 units should be installed in the plant to attain the range of expectation of power plant capacity curtailment desired (10^{-4} to 10^{-5}). There are, however, several factors which tend to make the data of figure 3 conservative. First, the actual unit operating time* is less than plant operating time so power plant availability should be greater than obtained from the graph in proportion to some function of the ratio of total units installed to the number of units required to carry the full load. Second, the margins or safety factors built into the predicted load magnitudes, combined with the fact that standard generator ratings are generally selected larger than the predicted load demand, result in an actual capacity for the four generator units greater than the nominal full load demand. Third, part of the interruptible load is housekeeping load, some or all of which might be shed much longer than the average of 5 to 50 minutes per year discussed previously. Fourth, the interruptible load will not be, in general, equal to the technical load, and, since generator unit sizes are based on the larger of these two load types, an excess of capacity will occur. The combination of these four factors, makes it appear, in many cases, that a plant, selected with a nominal number of four generator units to carry full load, may in fact carry the essential loads with only three generator units although it would normally be operating with four. Thus, figure 3 shows that, if three generator units are capable of carrying the full load, the expectation of power plant capacity curtailment will be reduced by two orders of magnitude.

Therefore, six generator units (including the two spares) are considered, in general, to have ample availability for the combination of loads under discussion in this study. For some special or critical cases where some of the above four factors of conservatism are not applicable, a total of seven units might be justifiable after sufficient investigation of details.

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* Normal rotational use of units in a six engine plant results in an actual unit operating time which is approximately two-thirds of the plant operating time when four units are operated to supply full load.

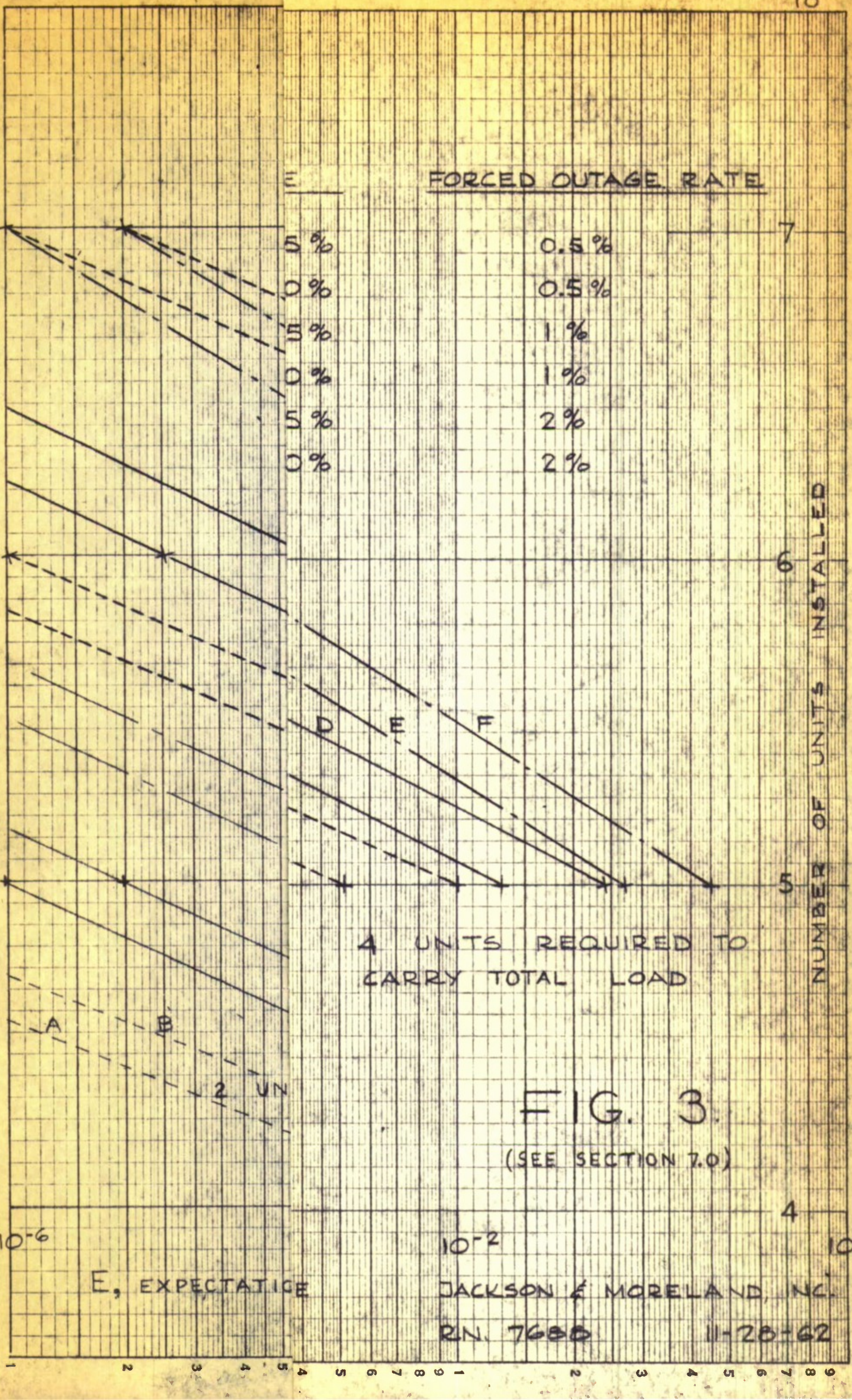

FIG. 3
(SEE SECTION 7.0)

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APPENDIX A

TABULATION OF AVAILABILITY DATA ON DIESEL ENGINE GENERATING UNITS

Inquiries to various government agencies including NASA, Army Engineers, Navy Bureau of Ships, Air Force Office of Civil Engineering, Rural Electrification Administration, and National Academy of Sciences revealed that the problem of obtaining diesel engine availability data is recognized but, in the time allowed for this study, no compilation of such data was found. Nevertheless, supporting data from other sources have been obtained.

A-1 Data from ASME reports

Pertinent information used in estimating unit availabilities came primarily from the ASME annual "Oil and Gas Power Cost" Reports for the years from 1951 through 1960 and is tabulated in Table A-1 on page 21.

A-2 Data from the General Motors Corporation

Supplementary information, which follows, was obtained from GMC on the performance of 162 engines in the DEWline communications system and 1252 engines in refrigerator car service.

(a) Copy of a letter from Federal Electric Corporation from which the following is extracted:

"Per request in your letter of May 5, 1961, we are submitting information on the General Motors 60 KW prime power diesel generator sets installed on the DEWline.

"The units, totaling 162, averaged 17,800 operating hours between major overhauls which consists of complete disassembly of the engine, rebuild, and/or replacement of all components. The crankcase drain interval is 400 hours and lube oil filters are replaced every 200 hours."

(b) Extract from a letter by Fruit Growers Express:

"......concerning the number and performance of Detroit Diesel Model 2-71 1200 RPM engines in service in our mechanically equipped refrigerator cars:

'The first engine of this type was placed in operation March 17, 1950, and we now have 1,252 refrigerator cars in service equipped with the 2-71 engine.

"As of January 1, 1958, the 1,252 mechanically equipped cars with an average age of 2 years and 8 months had accumulated an average of 8,995 engine hours each - 799 with less than 9,999 engine hours, 306 with 10,000 to 18,999 engine hours, 145 with 19,000 to 25,999 engine hours and 1 having over 26,000 engine hours without requiring a major or general overhaul. Based on our experience and the excellent performance of these engines to date, we have not reached a conclusion as to when the engines will require general overhaul.

"Many of these engines have been in continuous operation for as long as 20 days without any attention beyond fuel oil and lubricating oil. The 1,252 mechanically equipped cars have accumulated a total of 11,261,740 engine hours of operation through 1957 and have successfully completed a total of 50,646 trips in loaded movement to every state in the United States and to Canada."

(Note: These engines are rated 34 hp - generators 20 KW)

Operating Year	Kw of	No. of Units	Scheduled Maintenance: Average Operating Hours Per Unit	Average Maintenance Hours Per Unit	Average % of Operating Time
1960***		47	4139	354	8.55
1958		48	4505	221	4.90
1957		33	4904	157	3.20
1956		55	4279	2[illegible]3	6.15
1955		55	4365	215	4.92
1954		92	4017	253	6.30
1953 *		71	3993	209	5.24
1952 *		99	4330	192	4.43
1951 *		92	4113	141	3.43
Average		592 Unit Years	4294	223	5.20

* Taken f

** Only se

*** No outa

A-3 Summary of Data from Sections A-1 and A-2

From the ten-year average of the ASME report, the average time under scheduled maintenance is approximately 5.0 per cent of unit operating time. The data on the DEWline engines indicate an average of 17,800 hours between major overhauls, intervals of 400 hours for crankcase drain and 200 hours for oil filter changes. This is estimated to be equivalent to scheduled outage of between 2 per cent and 3 per cent of operating time. The experience with the refrigerator car engines and other miscellaneous items of data fall in the same general range.

APPENDIX B

POWER PLANT AVAILABILITY ANALYSIS

Availability of power plant generating capacity is a function of the number of engine-generator sets required to carry full load, the number of spare sets, and the scheduled-maintenance and forced-outage probabilities of each set. These data are handled by probability analysis to obtain a numerical measure of average availability.

A unit with a forced-outage probability (or unavailability) of Q has an availability of $P = 1-Q$. Then Q is the probability that no capacity is available from the unit, and P is the probability that rated capacity is available. Evidently $P + Q = 1$, which, of course, means that it is certain that either no capacity or full capacity is available. For a two-unit station, the probabilities are as follows:

Both units 1 and 2 available	P_1P_2
Unit 1 available and not unit 2	P_1Q_2
Unit 2 available and not unit 1	P_2Q_1
Either one of the two units available and not the other	$P_1Q_2 + P_2Q_1$
Both units 1 and 2 not available	Q_1Q_2

The complete probability distribution for a two-unit installation with identical units is

$$P^2 + 2PQ + Q^2 = (P + Q)^2 = 1.0$$

The corresponding expression for a station with *n* identical units is given by the familiar binomial expansion

$$(P + Q)^n = 1$$

The following example for a six-unit installation will serve to illustrate the process used in the report to determine station reliability. The binomial expansion is

$$(P + Q)^6 = 1$$

or $$P^6 + 6P^5Q + 15P^4Q^2 + 20P^3Q^3 + 15P^2Q^4 + 6PQ^5 + Q^6 = 1$$

The first term is the probability that all six units are available; the last term is the probability that all six units are not available. The second term is the probability that any combination of five units are available and the remaining one unit is not available. The coefficient 6 before this second term indicates that there are six possible ways to have any one generator out of six unavailable. The third term is the probability that any two of the six generators are unavailable. Similar interpretations can be made for the remaining terms.

If four units are required to carry the load, then the probability that there are less than four units available is the probability of power plant capacity curtailment. This is the sum of the probabilities that only three, two, one and no units are available or

$$20P^3Q^3 + 15P^2Q^4 + 6PQ^5 + Q^6$$

Now scheduled maintenance must be considered. The basic assumption is that there will never be more than one unit out for scheduled maintenance at any time. For a plant of six engines, each having a scheduled-maintenance rate of 0.05 (5 per cent), there are only five engines available (6 x 0.05) = 0.30, or 30 per cent of the time. In this case, we would consider a five-unit plant to be available 30 per cent of the time.

For the sample six-unit plant with each unit having a 5 per cent maintenance rate and a forced-outage rate of Q, and with four units required to carry the load, the probability or expectation of power plant capacity curtailment is:

$$0.70(20P^3Q^3 + 15P^2Q^4 + 6PQ^5 + Q^6) \quad + \quad 0.30\ (10P^3Q^2 + 10P^2Q^3 + 5PQ^4 + Q^5)$$

representing 70 per cent of the time and the probability that less than 4 units out of 6 are available

representing 30 per cent of the time and the probability that less than 4 units out of 5 are available

With a forced-outage rate of one per cent (Q = 0.01), the resulting probability or expectation of power plant capacity curtailment is 0.000308. The corresponding power plant availability is 1.0 - 0.000308 = 0.999692 or 99.97 per cent.

For outage rates in the range considered in this report, the term having the smallest exponent of Q contributes all but a few per cent of the probability of outage, and that term alone can be used for quick calculations. In the sample case (Q = 0.01):

$$0.30\ (10P^3Q^2) = 0.30\ (10)\ (.99)^3(.01)^2 = 0.000291$$

which is within 5-1/2 per cent of the 0.000308 obtained rigorously.