FSED-NSG-217-73/18

DISCUSSION OF RTG POWER PREDICTION TECHNIQUES AND RECOMMENDED INTERIM APPROACH

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May 30, 1973

1. Introduction

This report forms part of Task 020 of our contract, which calls for review and recommendations on RTG performance prediction methods in current use. These predict the EOM power distribution of generators which have not experienced any catastrophic failures, such as loss of cover gas. In a recent report[1] we examined the prediction methods used for the Viking generators, and concluded that the Monte Carlo method used in that program is a very useful technique when adequate input data are available; but that the existing data base for these generators is much too small to justify the use of such a sophisticated technique.

Two principal weaknesses in present methods of predicting EOM performance were identified. The first is that no scatter is allowed for the converter's thermoelectric degradation rate, which - we feel - is really the most important input variable required for the Monte Carlo calculation. Without a scatter assigned to this variable, computed distributions of EOM power are relatively meaningless; nor can meaningful confidence levels be assigned to them.

The second major weakness of the currently used method is that it is based on a correlation of degradation with hot junction temperature which is of questionable validity. The correlation is questionable because it is based on tests of three different generators, each operating at a different test temperature. With this kind of a data base, it is impossible to tell how much of the observed performance differences are due to the systematic effects of varying hot junction temperature, and how much they are due to random variation of the three generators (e.g., due to differences in materials, fabrication, dimensional variation, and processing techniques). The method as applied by Teledyne implicitly assumes that the three test generators would have exhibited identical performance had they been tested at the same temperature. The basis for this assumption is not obvious. If incorrect, it could lead to serious errors in predicting the effect of temperature on degradation.

Recent test data, presented at the Thermoelectric Working Group Meeting in March 1973, illustrates that random performance scatter between RTG's can, in fact, exceed the systematic effect of temperature on degradation. In a paper presented by F. A. Russo, he described the performance history of SNAP-19 generators S/N 38 and 40. Even though their respective operating temperatures differed by 60°F (1020°F/360°F versus 960°F/300°F), Russo reported no significant differences in their degradation rates during the first year of testing. Subsequent least-square analysis of this early data did reveal a discernible difference, 0.21 versus 0.25 watts/month, but opposite to the direction perdicted by Teledyne's carpet plots. The hotter generator (S/N 38) exhibited less degradation. Presumably, scatter between generators outweighed the normal temperature dependence. Clearly, several data points at each temperature would be needed to quantify the temperature dependence of degradation with reasonable confidence.

The two weaknesses discussed above are really related, in that they both stem from the scarcity of experimental data and from the attempt to squeeze out too many significant conclusions from too little data. There is a point beyond which mathematical artistry cannot compensate for the lack of experimental data.

2. Alternative Approach

The tests presently under way will not, in our opinion, generate enough data to justify the use of the Monte Carlo method as presently applied. As suggested in a recent report[2], we believe it possible to devise such tests; but their implementation would take too long to yield data in time for the Viking launch schedule. We therefore advocate temporarily abandoning the present approach and reverting to an admittedly cruder method. It is better to employ a crude method with known shortcomings than to use a sophisticated approach which rests on shaky foundation because of inadequate input data.

The simpler approach referred to above is to regard the RTG as simply a black box for converting thermal power into electrical power, without concerning ourselves with its internal details. We assume that the data base represents a sampling of a normally distributed population of identically manufactured converters, and that variations between RTG's are due to random (uncontrolled) variations, without our seeking to define their causes. In this approach it is assumed that all RTG tests were carried out at temperatures close enough to the Viking design temperatures to justify lumping together all of the test results. For purposes of this report, it is assumed that operation for 20,000 hours at temperatures between 980 and 1060°F results in degradation equivalent to the Viking flight profile. In the case of generators tested for less than 20,000 hours, the EOM power was predicted by linearly extrapolating the measurements made after the initial burn-in and high-degradation period. This is admittedly far from perfect, but it is all that can justifiably be done with presently available data.

By lumping all data together, we can establish a big enough data base to assign a lower confidence limit to our computed predictions. This makes the EOM predictions much more meaningful, because it takes account of the actual number of data points on which they are based.

3. Summary

To illustrate the above approach, we first apply it to predicting the probabilistic distribution of RTG degradation at various levels of confidence. This is a relatively straightforward and easy-to-follow application, since it uses the existing test data with only minimal adjustments or corrections. As shown in Section 5, the results derived can be used for two principal purposes: to predict the EOM performance distributions (at various confidence levels) of a specific RTG which has already been built and whose BOL performance has been measured; and to specify what minimum BOL power a generator must have in order to yield a given EOM power with a specified probability (i.e. performance reliability) and level of confidence.

The results computed in Section 5 indicate that, for a confidence level of 75%, a generator with a BOL power at the present minimum acceptance level of 41 watts will fall far short of the Viking RTG objective of 99.12% performance reliability at 35 watts EOM. Typically, a generator producing 41 watts BOL would have a performance reliability of only 46% in achieving 35 watts EOM; and would have an EOM power output of only 32.0 watts at the assigned performance reliability of 99.12 %.

Next, in Section 6, we describe the application of the method to the case of a generic RTG, i.e. a converter that has been designed like the previous test generators, but not yet built. All we know about it is the probabilistic distributions of its fuel loading and BOL electrical power. As will be seen, this case is somewhat less straightforward, since the experimental data must first be corrected for variations in thermal power and cover gas composition. The results computed lead to the prediction (at 75% confidence) that a Viking generator of present design only has a 72% probability of producing 35 watts EOM; and will only produce 32.5 watts EOM at the assigned 99.12% performance reliability.

The reasons for the discrepancy between our and Teledyne's predictions are examined in Section 7. For a typical case, it is shown that 25% of the discrepancy is due to our imposition of a 75% confidence level correction; 33% of the discrepancy is due to their basing degradation predictions and BOL power predictions on two different generator populations; and the remaining 42% of the discrepancy is due to the omission of scatter from their degradation rate predictions.

The effect of basing all predictions only on data from Pioneer generators is presented in Section 8. Use of that data base is very good for predicting BOL power, but very questionable for predicting degradation, because of uncertainties about in-flight power measurements. Even if this more optimistic but questionable data base is used, however, our predictions are still more pessimistic than those of Teledyne. First, our results suggest that the minimum

BOL acceptance power should be raised from 41 watts to 43 watts, to meet the EOM goal of 35 watts at 99.12% performance reliability. Second, our analysis based on Pioneer generator data predicts that the Viking generators will just meet their design goal, but without the 1.5-watt margin predicted by Teledyne.

Finally, Section 9 presents an epilogue necessitated by some very recent changes in the Viking RTG design, including the replacement of impervious diffusion bonds by permeable Viton O-rings, venting of helium into the generator rather than directly overboard, and the possibile addition of a gas reservoir initially filled with argon. These changes make it much more important to account for changes of gas composition in the generator. It would therefore be very desirable to retain the power and versatility of the Monte Carlo method, while avoiding the shortcomings in its present method of application, elucidated in this report. Recommendations for doing this, by introducing degradation scatter and confidence level corrections into the Monte Carlo analysis, are presented in Section 9.

4. Data Base

In selecting which experimental data to use in a given prediction analysis, the following three factors must be maximized: the accuracy of the measurements used; the consistency of the test specimens and test conditions with the actual equipment operation to be predicted; and the number of data points, to minimize confidence level corrections. The first two of these objectives are frequently in conflict with the third. In that case, beyond a certain point the data base can only be expanded by including more questionable data.

To minimize arguments about which data to include, the present report presents results derived from three different data bases: the smallest and least questionable data base includes only four generators. Three of these, S/N 26, 29, and 31, had been used in the Teledyne analysis. These three were electrically heated and operated at constant thermal input throughout the test. The last unit, S/N 42, was an RTG, and its measurements had to be corrected for isotopic decay.

Even in this small population, there are some significant differences between the four generators, either in construction, processing or operating history. For predicting the distribution of BOL power in Section 6, the test results are all corrected to a common initial thermal power (682 watts) and a common gas composition (75/25 helium/argon). These corrections are not used in Section 5, where we are only interested in the ratio of final to initial power.

The second data base used in this report was derived from six generator tests: the same four listed above, plus S/N 38 and 40. Inclusion of these last two generators provides more data points, which reduces the correction for confidence limits. On the other hand, it may be objected that these two generators are not really part of the same population, because they did not contain any getters. However, some of the generators used in the Teledyne analysis also did not have any getters during the early part of the tests.

The third data base employed in the present analysis is derived from ten generator tests: the six listed above, plus the four Pioneer-10 flight generators: S/N 44, 45, 46, and 48. In spite of their obvious benefit in broadening the data base, there are some legitimate objections to the inclusion of data from these four generators: There is a 0.8-watt uncertainty in the power output per generator, because of telemetry limitations. Some of the test parameters, such as cold junction temperature, were not as constant as in a well-controlled laboratory experiment, and the power conditioner aboard the Pioneer 10 does not maintain the RTG output at either constant voltage or maximum power.

To summarize, the analyses reported below were carried out for the same narrow data base used by Teledyne, and also for two others which were broader but also contained more questionable data. Results for all three data bases are presented, to maximize the information available to the reader, and to illustrate the effect of the various assumptions on the resultant conclusions. As shown in Section 5, these three data bases yielded similar results. The basic conclusions differ quantitatively, but not qualitatively.

Before proceeding with the analysis in Sections 5 and 6, it is of interest to plot the computed degradation rates of the ten generators against the corresponding hot junction temperatures. This is done in Figure 1, which actually contains eleven points since one of the ten generators (S/N 26) was operated for extended periods at two different temperatures (1020 and 1060°F). Figure 1 also shows a curve representing the temperature-degradation correlation used in Teledyne's Monte Carlo analysis. The curve, which was extracted from the TI carpet plot[3], is a curve fit to the data from generator S/N 26, 29, and 31. The figure illustrates our contention about the shaky foundation of such a temperature correlation, and the actual extent of data scatter.

It should also be noted that the inspection procedures used in the Viking program require rejection of any generator producing less than 41 watts BOL. The corrected data for the ten generators were checked against this condition. After corrections to 679-watt fuel inventory and a 75/25 helium/argon mixture, all generators met the 41-watt minimum BOL power output specification for Viking.

5. Predicted Degradation

This section deals with prediction techniques for generators which have already been built, and whose BOL power has been measured. The same techniques can also be used to specify the minimum BOL acceptance power for generators required to meet specified values of EOM power, performance reliability, and confidence level.

The test data used in Sections 5 and 6 are listed in Table I, before and after corrections. Standard statistical analysis was applied to the three data bases, to compute the mean values and standard deviations of the power degradation ratio and the BOL power. These results are also presented in Table I.

The probabilistic distributions computed from these results are most clearly displayed on probability graph paper. Figure 2 shows the probability that the EOM/BOL power ratio will exceed a given value, for each of the three data bases. These plots represent the distributions of the measured data, before any confidence level corrections have been applied. By themselves, these distributions are not very meaningful, since they do not take account of how few data points each distribution is based on. It is worth noting, however, that the three distributions of the generator data have very similar mean values; but in the region of high probabilities, in which we are most interested, the ten-generator data base predicts appreciably less degradation, even before applying the confidence level corrections.

The effect of applying those corrections to the test data distributions is shown in Figures 3, 4, and 5 for the three data bases. Each figure shows the distribution of probability that the EOM/BOL power ratio will exceed a given value. The curves presented are for the original data, and for confidence levels of 75, 90, and 95%.

As can be seen, for this range of confidence level the distribution curves deviate quite markedly from the test data distribution. This is particularly true for high probabilities, which is the region of greatest interest since the Viking program calls for an assigned performance reliability of 99.12%. This value combines with an assigned operational reliability (against catastrophic failure) of 99.88% to yield the prescribed overall reliability of 99%.

As would be expected, the confidence level corrections are greatest for the smallest data base (4 generators), and diminish for larger data bases. This is seen by comparison of Figures 3, 4, and 5. Figure 6 combines the 90%-confidence curves for the three data bases. At the assigned 99.12% performance reliability, the 4-generator data base leads to significantly poorer results, because the scarcity of data requires much larger confidence corrections.

The EOM/BOL power ratios plotted in Figures 3, 4, and 5 are for generator degradation in 20,000 hours at constant thermal input, i.e. without fuel decay. The goal of the Viking program is to produce 35 watts EOM, after fuel decay. Applying the AEC-prescribed correction of 1.2 watts(e) for fuel decay, we require a generator which would produce 36.2 watts after 20,000 hours without fuel decay. Thus, the BOL power required to meet the Viking EOM power goal is obtained by dividing 36.2 watts by the EOM/BOL power ratios. Doing this results in the upper scales shown in Figures 3, 4, and 5. These scales can be used to determine what BOL power is required to produce 35 watts EOM, at a given performance reliability and level of confidence.

Perhaps a clear way of displaying this information is illustrated in Figures 7, 8, and 9, again for the three data bases analyzed. The three figures are all for a 75% confidence level. For this level of confidence, each curve shows the EOM power distribution for a specific BOL power. The Viking program goal of 35-watt EOM power and 99.12% performance reliability is also displayed in each figure. Let us examine Figure 8, for the six-generator data base. Meeting the above-defined EOM goal for Viking is shown to require a BOL power of approximately 44.7 watts, which is considerably above the minimum acceptance limit of 41 watts. In fact, a generator producing 41 watts BOL would have a performance reliability of only 46% in achieving 35 watts EOM power; and would have an EOM power output of only about 32.0 watts at the assigned performance reliability of 99.12%.

6. EOM Power Prediction During Design

The power prediction techniques described in the previous section are useful for two purposes: to predict the probabilistic distribution of EOM power of a generator which has already been built and whose BOL power has been measured; and to specify the minimum BOL power acceptance level for generators which must meet specified values of EOM power, performance reliability, and confidence level.

The present section of the report extends these prediction techniques, so they may be used for two other purposes: to predict the probabilistic distribution of EOM power of a generator which has been designed but not yet built; and to select the design parameters for a new generator having specified values of EOM power, performance reliability, and confidence level.

The latter two objectives are more difficult to satisfy than the former two. The former only require knowledge of the RTG degradation rate and its scatter. The latter objectives require additional information about the expected distribution of the fuel loading around its nominal design value; and also information about the probabilistic BOL power distribution of a generator with a given design and fuel loading. These two distributions, fuel loading and BOL power, are then combined with the degradation distribution to predict the EOM power distribution for a given generator design. Since the methods for doing this are not as standard as those used earlier in Section 5, they will be described in some detail.

The EOM power P_E of a specific Viking generator is given by

$$P_E = P_B + 0.1 (q - 682) \gamma - 1.2, \tag{1}$$

where P_B is its BOL power for the fuel loading design value of 682 watts(t), q is the actual value of the initial thermal power, and γ represents the EOM/BOL power ratio resulting from degradation in the absence of fuel decay. The numerical factors 0.1 and 1.2 are specified in the Viking RTG contract. The factor 0.1 may be interpreted as a differential efficiency: every 1-watt increase in initial thermal power is assumed to raise the BOL electrical output by 0.1 watt. The latter factor, 1.2 watts, represents the contract-specified electrical power loss due to fuel decay. There is, of course, some uncertainty about the proper values for these correction factors. Nevertheless, the contract values were used in our analysis, since these uncertainties are not expected to have a significant effect on the results.

From Eq. (1), we can readily express the mean EOM power $\overline{P}_E$ as a function of the mean BOL power $\overline{P}_B$ and the mean degradation ratio $\overline{\gamma}$:

$$\overline{P}_E = \overline{P}_B \overline{\gamma} - 1.2 . \tag{2}$$

Before deriving the probabilistic distribution of P_E about its mean $\overline{P}_E$, let us first discuss the general problem of combining variables with individual distributions. For a variable which is the sum of other variables, e.g.

$$z = x + y, \tag{3}$$

the standard deviation σ of the sum is related to those of its parts by the simple expression:

$$\sigma_z = (\sigma_x^{\,2} + \sigma_y^{\,2})^{1/2}. \tag{4}$$

In the case of a variable which is the product of others, e.g.

$$z = xy, \tag{5}$$

there is no generally valid, simple expression for σ_z. However, in the special case where $\sigma_x << \bar{x}$ and $\sigma_y << \bar{y}$, an expression analogous to Eq. (4) can be derived. In that case, for the range of variable values of significant interest, we conclude that

$$x - \bar{x} << \bar{x}, \tag{6}$$

$$y - \bar{y} << \bar{y}. \tag{7}$$

Equation (5) can be rewritten in the form

$$z = \left[\bar{x} + (x - \bar{x})\right] \left[\bar{y} + (y - \bar{y})\right]. \tag{8}$$

Cross-multiplying and dropping the negligible last term on the basis of Eqs. (6) and (7), we obtain

$$z = \bar{x}\bar{y} + \bar{y}\,(x-\bar{x}) + \bar{x}\,(y-\bar{y})\ , \tag{9}$$

which can be divided by $\bar{z} = \bar{x}\bar{y}$ to yield

$$z/\bar{z} = x/\bar{x} + y/\bar{y} - 1 \tag{10}$$

Since the variables in Eq. (10) are additive, similar to Eq. (3), we can write a simple expression relating their standard deviations, similar to Eq. (4):

$$\sigma_z/\bar{z} = \left[\,(\sigma_x/\bar{x})^2 + (\sigma_y/\bar{y})^2\,\right]^{1/2} \tag{11}$$

Applying an analogous approach to Eq. (1), we obtain the following expression relating the standard deviations of the EOM power (σ_E), of the BOL power (σ_B), of the initial thermal power (σ_q), and of the EOM/BOL degradation ratio (σ_γ);

$$\sigma_E = \left[\,\sigma_B{}^2 + (0.1\,\sigma_q)^2 + (\bar{P}_B\,\sigma_\gamma)^2\,\right]^{1/2}. \tag{12}$$

The above expression does not contain any confidence-level corrections; i.e., it would only be valid if σ_B, σ_q, and σ_γ were each based on a very large number of measurements. To predict a probabilistic distribution based on a limited number of measurements, tolerance factors (K) must be applied. This was done, using the equation :

$$K_E\,\sigma_E = \left[(K_B\,\sigma_B)^2 + (0.1\,K_q\,\sigma_q)^2 + (\bar{P}_B\,K_\gamma\,\sigma_\gamma)^2\right]^{1/2}. \tag{13}$$

The values of the tolerance factors K_B, K_q, and K_γ can be obtained from appropriate tables. For example, Table II from Reference 4 gives the values of tolerance factors as a function of the number of data points n, the performance reliability R, and the confidence level C.

Once the value of $K_E \sigma_E$ for a given performance reliability R has been computed by means of Eq. (13), the corresponding EOM power is given by

$$P_E = \bar{P}_E - K_E \sigma_E . \tag{14}$$

This process is repeated for different values of R, to generate the probabilistic distribution of the EOM power at the desired confidence level.

In applying the above equations to the Viking data base, we are hampered by the same scarcity of data mentioned previously. In addition, the use of the data in this section raises a new problem. In Section 5 we were primarily interested in the ratio of the EOM and BOL powers, not in their absolute magnitudes. In the present section, we are interested in the absolute value of P_B at the normal design point. The measured BOL power must therefore be corrected for off-design values of fuel loading and gas composition of the test generators. These corrections are presented in Table I, which also lists the computed values of $\bar{\gamma}$, σ_γ, $\bar{P}_B$, and σ_B for the 4-, 6-, and 10-generator data bases. The scatter of the fuel loading q about its 682-watt mean value was represented by an assumed standard deviation σ_q of 2 watts (t).

The results of the above analysis for the six-generator data base are illustrated in Figure 10, which also presents Teledyne's prediction of the EOM power distribution. The reasons for the discrepancy between the two predictions are examined in Section 7. Figure 10 shows that our prediction falls far short of the Viking EOM goal, i.e. 99.12% probability of achieving 35 watts. As can be seen, for a 75% confidence level we predict a 72% probability of achieving 35 watts EOM; or conversely, 32.5 watts at 99.12% probability.

One other point about the above EOM curve is worth noting. This is illustrated in Figure 11, where the predicted power distribution for the unbuilt generator is superimposed on corresponding curves for generators which have already been built and had their BOL power measured. The former distribution is represented by the solid curve; the four dotted curves, which were presented earlier in Figure 8, are for generators with BOL power of 41, 43, 45, and 47 watts; and the dashed curve is for a BOL power of 41.98 watts, which is the predicted mean BOL power of the Viking-design generator, as shown in Table I. The difference between the dshed and solid curves represents the effect of the uncertainty in fuel loading (σ_q) and BOL power (σ_B). As can be seen, that effect is quite small. In other words, the degradation term (σ_γ) in Eq. (13) has the dominant effect.

7. Discussion

The principal aim of this report is to describe performance prediction techniques for use during the present interim period, until adequate data are available to justify the use of the more accurate Monte Carlo technique. Its aim is not to dissect or critique the Viking RTG performance prediction techniques used by Teledyne. That was the subject of an earlier report[1]. Nevertheless, it is of at least academic interest to inquire why the results of our prediction analysis are so much more pessimistic than those derived by Teledyne.

To facilitate this inquiry, Figure 12 compares the Teledyne prediction (dashed curve) with our six-generator data base predictions (solid curves) for various assumptions. To be consistent, none of the curves includes a correction for possible creep failure of the Pt - Rh fuel capsule. The lowest solid curve depicts the results of our analysis for a 75% confidence level. As can be seen, at the assigned 99.12% performance reliability, the EOM power is predicted as 36.6 watts by Teledyne and as 32.5 watts by our analysis, a very substantial discrepancy of 4.1 watts. What differences in our prediction techniques contribute most to this discrepancy?

The first factor to examine is the contribution of the confidence level correction, which was not applied in the Teledyne analysis. Omitting this correction ignores the scarcity of data on which the prediction is based. The middle one of the three solid curves shows what our analysis would have predicted without confidence level corrections. As can be seen, at the assigned 99.12% performance reliability, imposition of the 75% confidence requirement lowers the EOM power prediction by 1.0 watts, or about 25% of the total 4.1 watt difference. Thus, while the confidence level correction is certainly not negligible, it is not the major contributor to the discrepancy.

The second factor to examine is the effect of the mean BOL power. As shown in Table I, the six-generator data base yielded a value of 41.98 watts for $\overline{P}_B$. By contrast, Teledyne predicts a mean BOL power of 43.63 watts[5], based on measurements of the Pioneer flight generators corrected to the Viking fuel loading. The upper solid curve in Figure 12 shows what our analysis would predict, without confidence level correction, and with an assumed mean BOL power of 43.63 watts. As can be seen, at the assigned performance reliability of 99.12%, the use of Teledyne's more optimistic value of $\overline{P}_B$ would raise our EOM prediction by 1.35 watts, or about 33% of the total 4.1 watt difference.

Clearly, Teledyne's higher value of mean BOL power is a major contributor to the difference between our predictions. It will probably be argued that the use of this value is justified because it is more representative of the latest crop of SNAP-19 generators. However, these are not the generators on which the degradation measurements used by Teledyne were made. Predicting EOM power by combining BOL measurements from one generator population with degradation measurements on a different population appears to be highly questionable.

An additional objection is that the high BOL powers used by Teledyne have, to our knowledge, never been actually measured; they were obtained by using the assumed 10% differential efficiency to correct the measured BOL output of generators with lower fuel loadings to the higher 682-watt loading used on Viking. The magnitude of that correction was typically around 3 watts (e), not a minor amount.

While Viking generators now under construction may very well bear out the validity of the high BOL power predictions for high fuel loadings, this raises another question. Because of their higher fuel loadings, the Viking generators will spend a good part of their life at substantially higher hot junction temperatures than those experienced by the Pioneer generators. Since only very limited degradation measurements have been made in this temperature range, the predicted degradation rates could be in serious error.

Returning to our inquiry into the causes of the 4.1 watt EOM power prediction difference between Teledyne's and our analyses, we have thus far identified two factors contributing 25% and 33% of that difference. What accounts for the remaining 42% of this discrepancy?

Comparison of the dashed curve and upper solid curve in Figure shows that the two have almost identical mean values, 37.6 and 37.5 watts. Thus, the difference between the two curves does not appear to be the result of a difference in mean degradation rates between the two analyses. This seems to indicate that our lumping together all of the degradation measurements, without applying a temperature correlation, does not account for the difference in predicted EOM power.

The dashed and upper solid curves in Figure 12 differ only in slope, which is indicative of scatter. We therefore conclude that the last 42% of the 4.1 watt discrepancy results from the fact that we applied a standard deviation to the degradation ratio γ , while Teledyne did not.

To summarize, for the assigned performance reliability of 99.12% our analysis predicts an EOM power which is a substantial 4.1 watts lower than that predicted by Teledyne. Of that difference, roughly 25% is due to our imposition of a 75% confidence requirement, 33% results from Teledyne's use of degradation and BOL power predictions from two different generator populations, and 42% is due to the omission of degradation rate scatter from Teledyne's Monte Carlo analysis.

Finally, we note that the Viking lander carries two RTGs. If the EOM minimum power goal were really 70 watts out of the two generators rather than 35 watts out of each, the probability of achieving that goal would of course be greater than our earlier prediction. While the combined mean power rises by a factor of 2, the combined standard deviation is only $\sqrt{2}$ as large as that of the single generator. This is because a below-normal power from one generator may be compensated by above-normal power from the other. Simultaneous occurrence of very low powers from both generators is much less likely.

Figure 13 illustrates how much benefit this averaging process offers in meeting the EOM goals. For the six-generator data base and a 75% confidence level, the dashed curve shows our previous prediction for one generator (left scale), and the solid curve shows the predicted distribution of the combined output of both generators (right scale). Since the curves were plotted with the right power scale having exactly twice the value of the left scale, it follows that the difference between the two curves represents the improvement due to the averaging effect. As can be seen, the probability of producing at least 70 watts in two generators (81%) is ten percentage points higher than the probability of producing at least 35 watts in one generator.

8. EOM Power Prediction Based on Pioneer Flight Generators

As discussed earlier, we have a very poor base for making any predictions. The generators on which we have the most reliable degradation measurements are somewhat obsolescent and probably not representative of current production. On the other hand, for the generators which best represent the current product only very approximate degradation measurements are available, because of limitations in telemetry and power conditioner control. Teledyne's stratagem of combining the BOL power measurements on Pioneer RTGs with degradation measurements on early ETGs seems to us of questionable validity. All measurements used in a prediction analysis should be based on samples of the same population, e.g. the Pioneer flight generators.

The present section describes the predictions obtained by ignoring the inadequacies of the Pioneer in-flight measurements, basing degradation predictions on data from the four Pioneer-10 flight generators, and basing BOL power predictions on data from eleven Pioneer generators (S/N 43 through 53). The resultant predictions are summarized in Figures 14 and 15. As can be seen, these predictions are considerably more optimistic than those reported earlier. However, even for this data base Figure 14 indicates that the present minimum acceptance limit of 41 watts BOL is too low and should be raised to 43 watts. According to the eleven-generator BOL distribution, there is only a 9% probability of having less than 43 watts BOL.

Finally, Figure 15 shows the predicted EOM power distribution of the generic Viking generator (i.e., before BOL measurement), for a 75% confidence level. As shown, at the assigned 99.12% performance reliability the curve just intersects the 35-watt EOM goal. But it is still 1.5 watts below the corresponding Teledyne prediction (dashed curve). Since the two curves are based on the same BOL distribution and show the same mean EOM power, the discrepancy between them is not due to our overestimating the mean degradation rate. In fact, without the 75% confidence correction we show a higher mean EOM power, as illustrated by the dotted curve. Therefore, we again conclude that a major part of the discrepancy is due to the omission of degradation scatter in the Teledyne analysis.

9. Epilogue

At the time the preceding sections were written, the Viking design called for a hermetically sealed generator housing, with the helium from the fuel capsule vented either directly overboard or into a separate reservoir, not into the converter. That design has recently undergone major changes, because of concern about the reliability of the diffusion bond joining the electrical receptacle to the generator housing.

The questionable diffusion bond has now been replaced by a Viton O-ring, which is more reliable but which is known to have a significant permeability. In the new design, the helium from the fuel capsule will be vented into the converter, and the converter volume will be connected, to the gas reservoir by another permeable O-ring. Present plans are to initially load the converter with mostly helium, and the gas reservoir with mostly argon.

The performance of SNAP-19 generators is sensitive to gas composition, because gas conductivity affects the thermal resistance of gaps and parasitic heat losses through the thermal insulation. While generators of the previous design would have had a constant gas inventory throughout the mission, with the new design significant changes in gas composition and pressure will occur in the generator.

Both helium and argon diffuse through Viton O-rings. The two gases have different diffusion rates, which are strongly influenced by temperature. Thus, careful analysis is required to predict the gas composition history of the generator. The transient analysis must take account of the variation of O-ring temperatures with time. It should also take account of uncertainty and variability of Viton permeabilities.

Because of the complexity of the analysis required for this design, it would be highly desirable to be able to use the more powerful Monte Carlo analysis in place of the simpler methods discussed earlier, while avoiding the shortcomings of the prediction approach in current use.

As described earlier, those shortcomings mostly concern the failure to account for scatter in degradation rates, and to apply confidence level corrections to all input data (including Viton permeability) which are based on a limited number of measurements. The importance of these correction terms, and their influence on the predicted EOM performance, was demonstrated in the preceding sections.

Ultimately, of course, more and better data are needed to overcome these shortcomings. Meanwhile, however, there is no reason why the type of degradation scatter and confidence level corrections described in the preceding sections should not be applied to the Monte Carlo analysis right now. Admittedly, this would still be far from perfect, because of the scarcity of data, the uncertainty about which data validly belong in the data base, and the inaccuracy of some of the key measurements. But even with these considerations, predictions which included these two correction terms would still be much more believable than those which ignored them.

References

1) "Comments on the RTG Reliability and Performance Prediction Methods Used in the Viking Program". FSED-NSG-217-73/14, February 12, 1973.

2) "Recommended Test Changes to Expand Data Base on Thermoelectric Degradation". FSED-NSG-217-73/17, April 2, 1973.

3) "SNAP 19 Viking ETG/Prototype RTG Proof Design Review", December 18-19, 1972. ESD 2960-71, Figure IV-21.

4) Lloyd, David K. and Myron Lipow, Reliability: Management, Methods and Mathematics, Prentice-Hall, Inc. 1962.

5) "SNAP-19 Viking ETG/Prototype RTG Proof Design Review", December 18-19, 1972. Table for Population 4.

Table I:
SUMMARY OF DATA BASE, CORRECTIONS, AND DERIVED DISTRIBUTIONS

	Generator Type	ETG's				RTG's					
	Serial Number	26	29	31	42	38[f]	40[f]	44[g]	45[g]	46[g]	48[g]
Data for Section 4	BOL Power (watts)[b]	40.5[a]	38.4	43.4	38.0	40.1	39.2	41.1	40.2	40.4	40.6
	EOM Power (20,000 hours)	34.2	35.0	38.7	33.1[a]	34.0[a]	33.6[a]	35.7[a]	35.2[a]	35.8[a]	34.2[a]
	Corrected for fuel decay[c]	34.2	35.0	38.7	34.3	35.2	34.8	36.9	36.4	37.0	35.4
	EOM/BOL Power Ratio	.845	.912	.893	.903	.878	.889	.895	.905	.916	.871
	Degradation Rate (%/month)	.558	.317	.385	.349	.439	.400	.378	.342	.302	.464
Data for Section 5	BOL Thermal Power (watts)	640	675	675	644	647	646	649	646	647	649
	% Helium (BOL)[h]	0	100	0	75	75	75	75	75	75	75
	BOL Power (watts)										
	Corrected to 682 watts (t)[d]	44.4	38.8	43.8	41.5	43.6	42.8	44.5	43.9	44.0	44.0
	Corrected to 75/25 He/A[e]	41.7	41.3	41.3	41.5	43.6	42.8	44.5	43.9	44.0	44.0
Distribution for Data Bases	Generators in Data Base	4				6		10			
	Mean BOL Power (corrected)	41.37				41.98		42.91			
	Std. Deviation (watts)	0.275				0.367		1.411			
	Mean EOM/BOL Ratio	.888				.887		.891			
	Std. Deviation	.0299				.0235		.0214			

[a] By extrapolation of data

[b] Corrected to 330°F fin root.

[c] $\Delta P = 1.2$ watts

[d] $\Delta P = 0.1\ \Delta q$

[e] ESD-2960-71 Figure IV-14

[f] No getter

[g] Flight data subject to 0.8 watt(e) uncertainty. Curve fitted through low points of toggle. Data furnished by R. Du Val, but TI cable correction use

[h] Balance is argon

Table II.

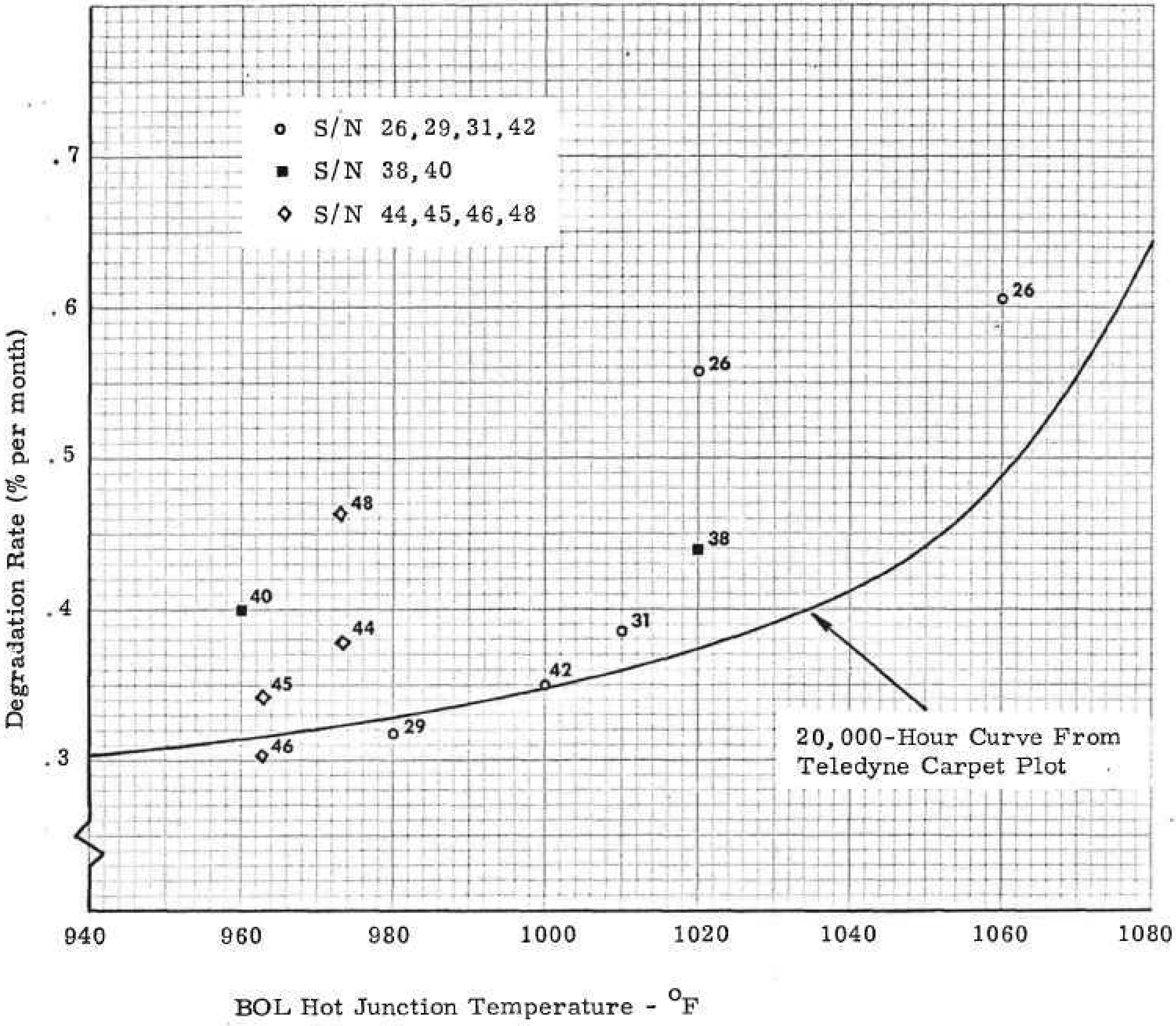
Tolerance Factors for Normal Distributions

Factors K such that the probability is C that at least a proportion R of the distribution will be less than $\bar{x} + Ks'$ (or greater than $\bar{x} - Ks'$), where $\bar{x}$ and s' are estimates of the mean and the standard deviation* computed from a sample of size n

R / n	C= 0.75					C= 0.90					C= 0.95					C= 0.99				
	.75	.90	.95	.99	.999	.75	.90	.95	.99	.999	.75	.90	.95	.99	.999	.75	.90	.95	.99	.999
3	1.464	2.501	3.152	4.396	5.805	2.602	4.258	5.310	7.340	9.651	3.804	6.158	7.655	10.552	13.857					
4	1.256	2.134	2.680	3.726	4.910	1.972	3.187	3.957	5.437	7.128	2.619	4.163	5.145	7.042	9.215					
5	1.152	1.961	2.463	3.421	4.507	1.698	2.742	3.400	4.666	6.112	2.149	3.407	4.202	5.741	7.501					
6	1.087	1.860	2.336	3.243	4.273	1.540	2.494	3.091	4.242	5.556	1.895	3.006	3.707	5.062	6.612	2.849	4.408	5.409	7.334	9.540
7	1.043	1.791	2.250	3.126	4.118	1.435	2.333	2.894	3.972	5.201	1.732	2.755	3.399	4.641	6.061	2.490	3.856	4.730	6.411	8.348
8	1.010	1.740	2.190	3.042	4.008	1.360	2.219	2.755	3.783	4.955	1.617	2.582	3.188	4.353	5.686	2.252	3.496	4.287	5.811	7.566
9	0.984	1.702	2.141	2.977	3.924	1.302	2.133	2.649	3.641	4.772	1.532	2.454	3.031	4.143	5.414	2.085	3.242	3.971	5.389	7.014
10	0.964	1.671	2.103	2.927	3.858	1.257	2.065	2.568	3.532	4.629	1.465	2.355	2.911	3.981	5.203	1.954	3.048	3.739	5.075	6.603
11	0.947	1.646	2.073	2.885	3.804	1.219	2.012	2.503	3.444	4.515	1.411	2.275	2.815	3.852	5.036	1.854	2.897	3.557	4.828	6.284
12	0.933	1.624	2.048	2.851	3.760	1.188	1.966	2.448	3.371	4.420	1.366	2.210	2.736	3.747	4.900	1.771	2.773	3.410	4.633	6.032
13	0.919	1.606	2.026	2.822	3.722	1.162	1.928	2.403	3.310	4.341	1.329	2.155	2.670	3.659	4.787	1.702	2.677	3.290	4.472	5.826
14	0.909	1.591	2.007	2.796	3.690	1.139	1.895	2.363	3.257	4.274	1.296	2.108	2.614	3.585	4.690	1.645	2.592	3.189	4.336	5.651
15	0.899	1.577	1.991	2.776	3.661	1.119	1.866	2.329	3.212	4.215	1.268	2.068	2.566	3.520	4.607	1.596	2.521	3.102	4.224	5.507
16	0.891	1.566	1.977	2.756	3.637	1.101	1.842	2.299	3.172	4.164	1.242	2.032	2.523	3.463	4.534	1.553	2.458	3.028	4.124	5.374
17	0.883	1.554	1.964	2.739	3.615	1.085	1.820	2.272	3.136	4.118	1.220	2.001	2.486	3.415	4.471	1.514	2.405	2.962	4.038	5.268
18	0.876	1.544	1.951	2.723	3.595	1.071	1.800	2.249	3.106	4.078	1.200	1.974	2.453	3.370	4.415	1.481	2.357	2.906	3.961	5.167
19	0.870	1.536	1.942	2.710	3.577	1.058	1.781	2.228	3.078	4.041	1.183	1.949	2.423	3.331	4.364	1.450	2.315	2.855	3.893	5.078
20	0.865	1.528	1.933	2.697	3.561	1.046	1.765	2.208	3.052	4.009	1.167	1.926	2.396	3.295	4.319	1.424	2.275	2.807	3.832	5.003

$$* \quad s' = \left[\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right]^{1/2}$$

Figure 1:
CORRELATION OF DEGRADATION RATE WITH BOL HOT JUNCTION TEMPERATURE



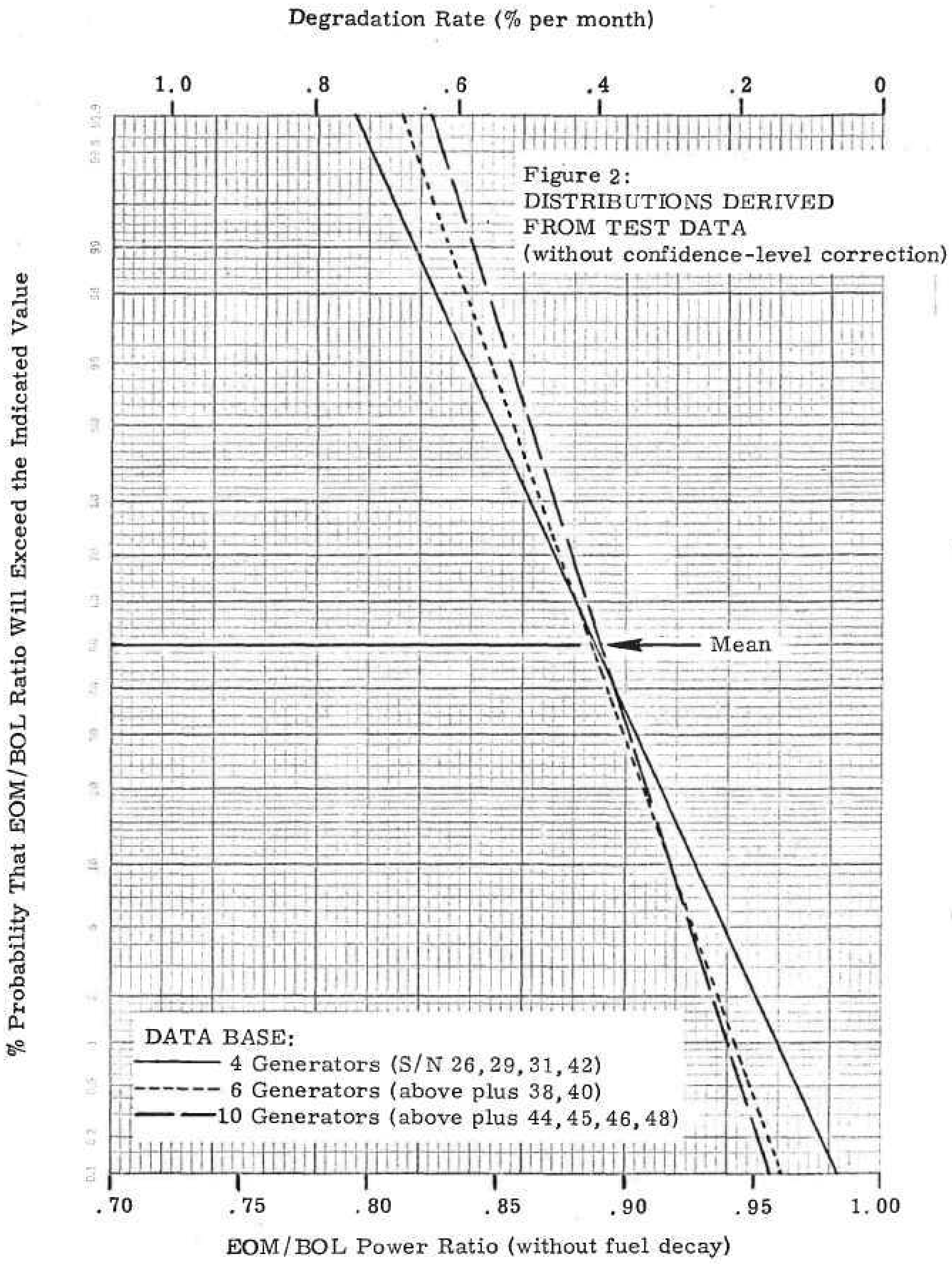


Figure 2:
DISTRIBUTIONS DERIVED
FROM TEST DATA
(without confidence-level correction)

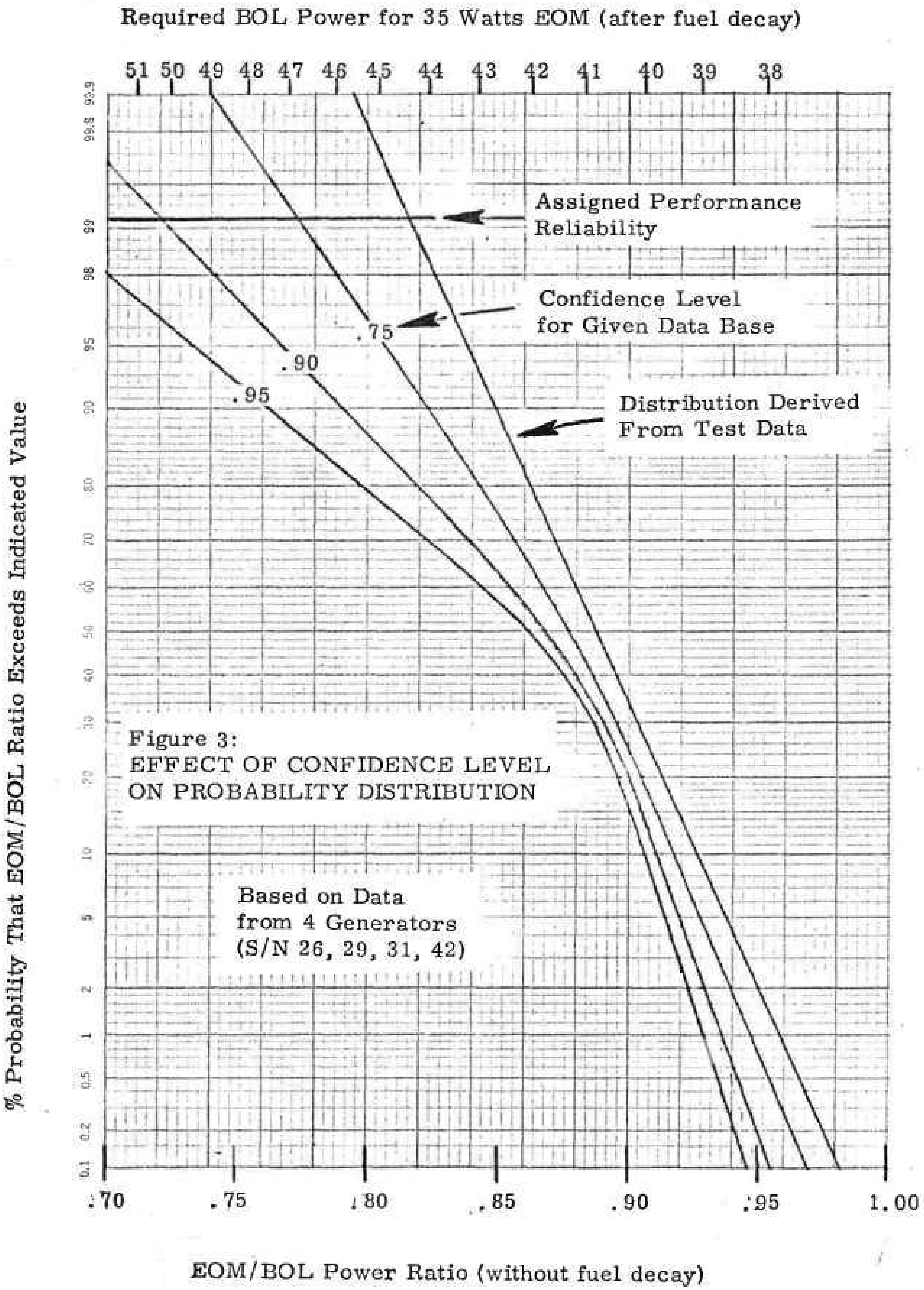
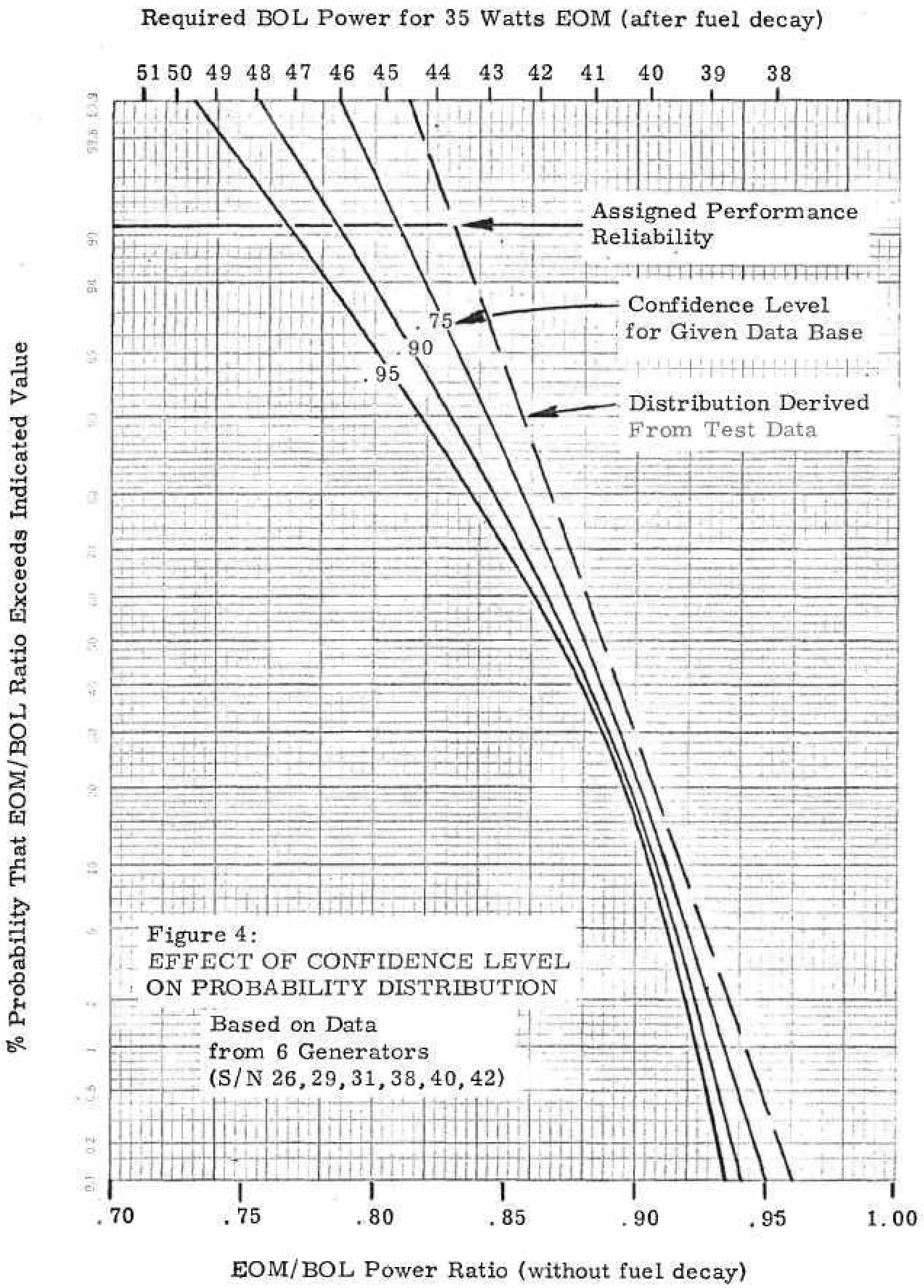


Figure 3:
EFFECT OF CONFIDENCE LEVEL ON PROBABILITY DISTRIBUTION



Assigned Performance Reliability

Confidence Level for Given Data Base

Distribution Derived From Test Data

Figure 4:
EFFECT OF CONFIDENCE LEVEL ON PROBABILITY DISTRIBUTION

Based on Data
from 6 Generators
(S/N 26, 29, 31, 38, 40, 42)

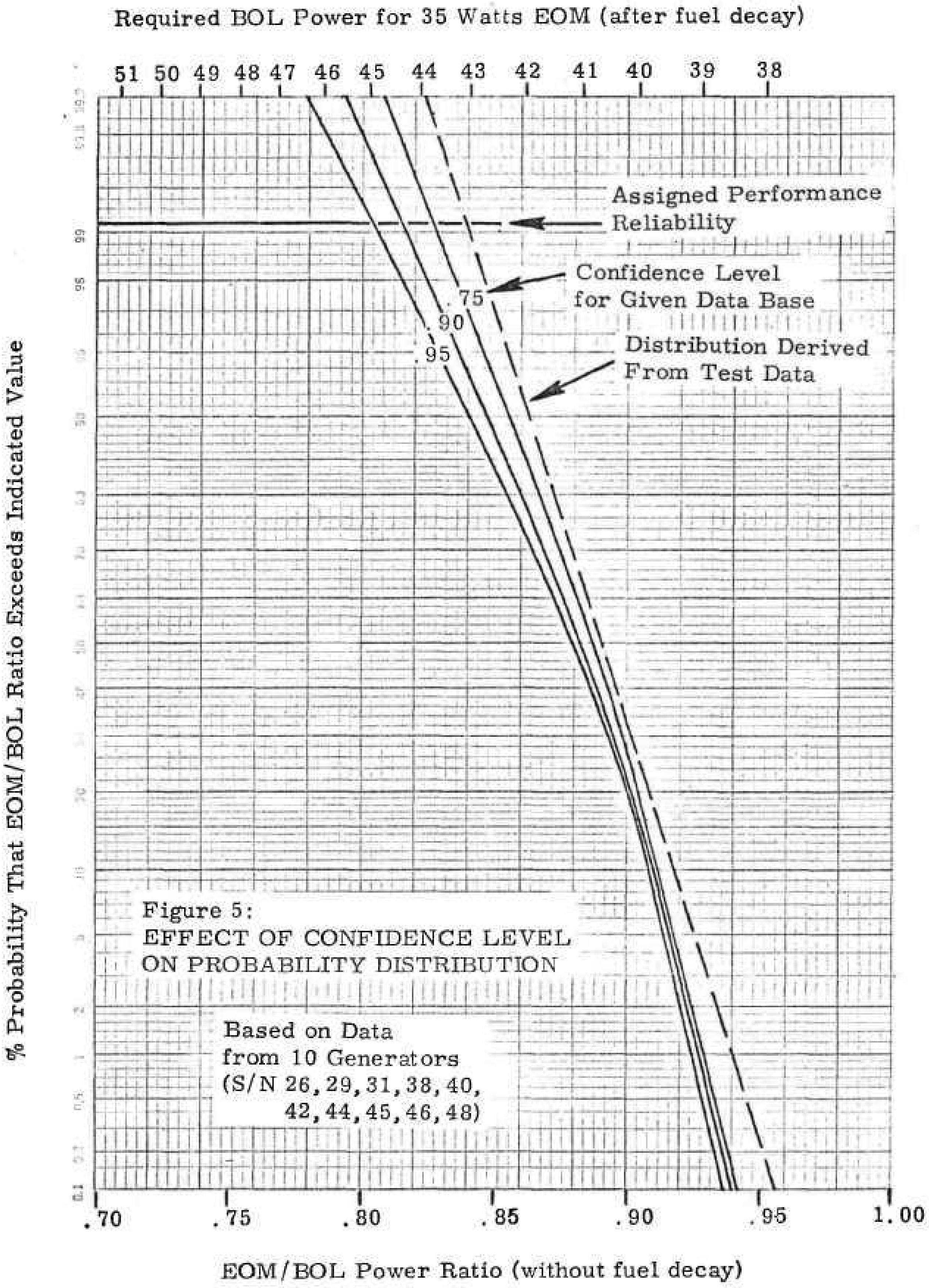


Figure 5:
EFFECT OF CONFIDENCE LEVEL ON PROBABILITY DISTRIBUTION

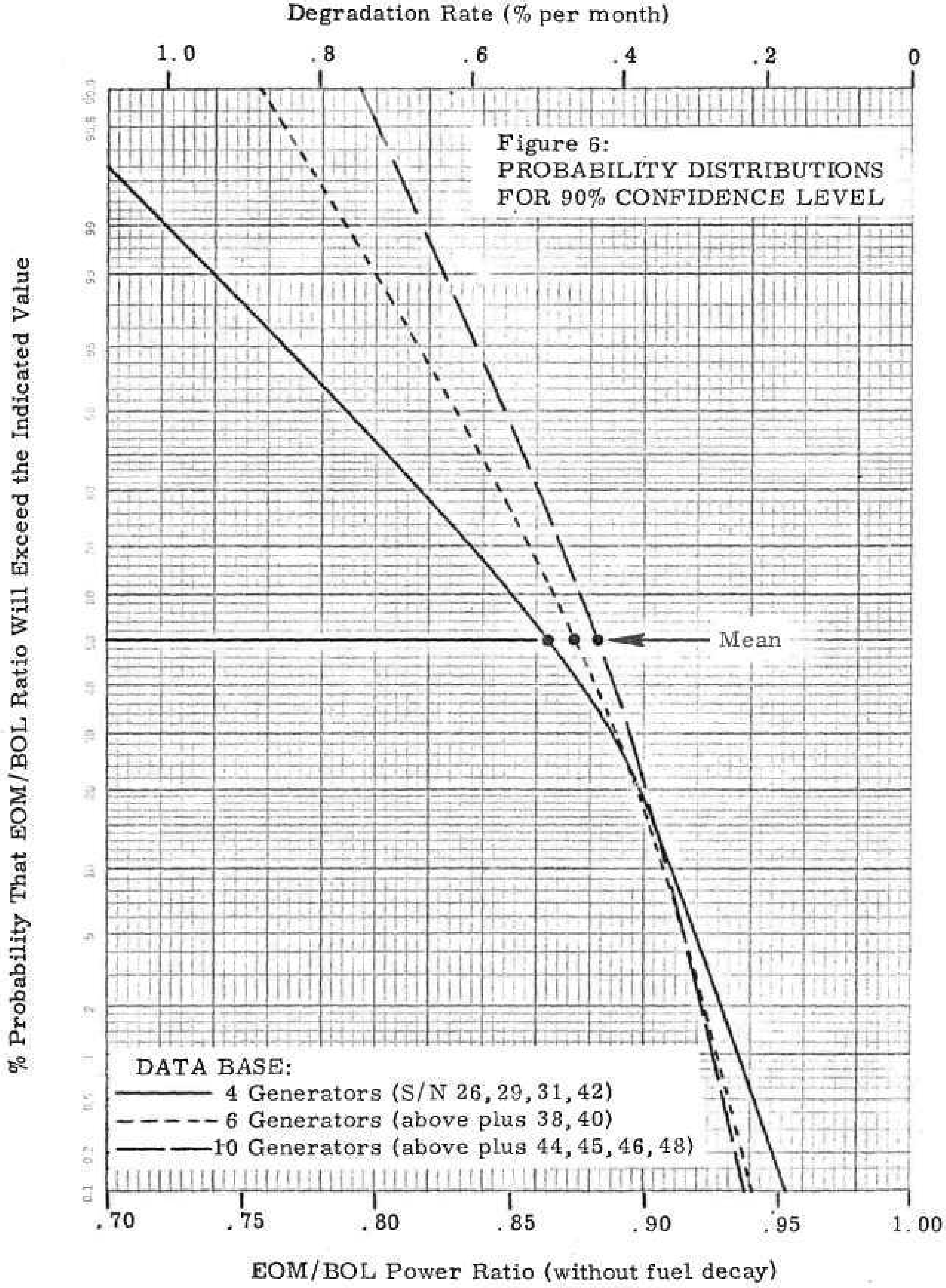


Figure 6:
PROBABILITY DISTRIBUTIONS
FOR 90% CONFIDENCE LEVEL

Figure 7:
PERFORMANCE PREDICTIONS FOR VARIOUS BOL POWERS BASED ON DATA FROM 4 GENERATORS (S/N 26, 29, 31, 42)

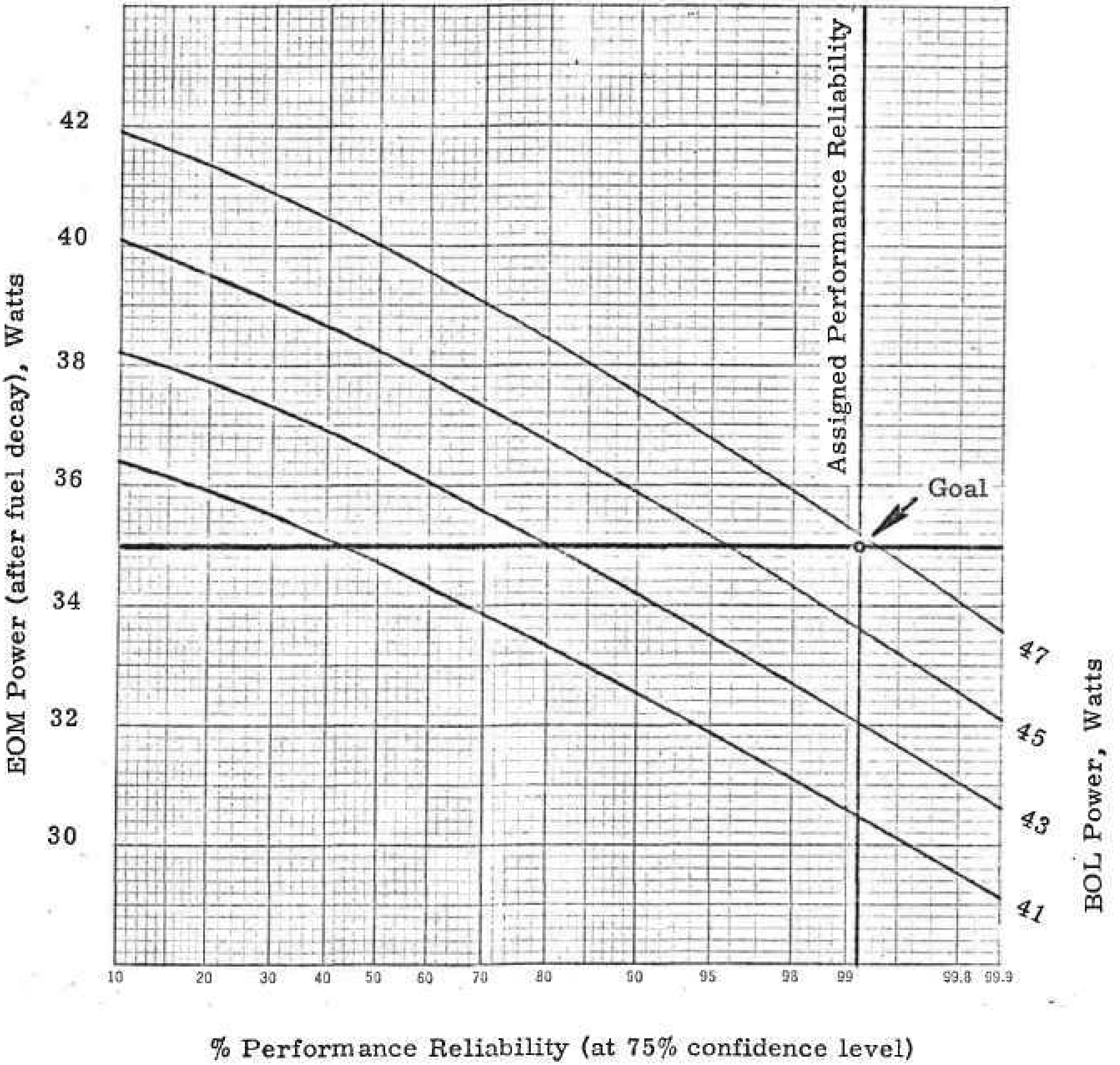


Figure 8:
PREFORMANCE PREDICTIONS FOR VARIOUS BOL POWERS
BASED ON DATA FROM 6 GENERATORS (S/N 26, 29, 31, 38, 40, 42)

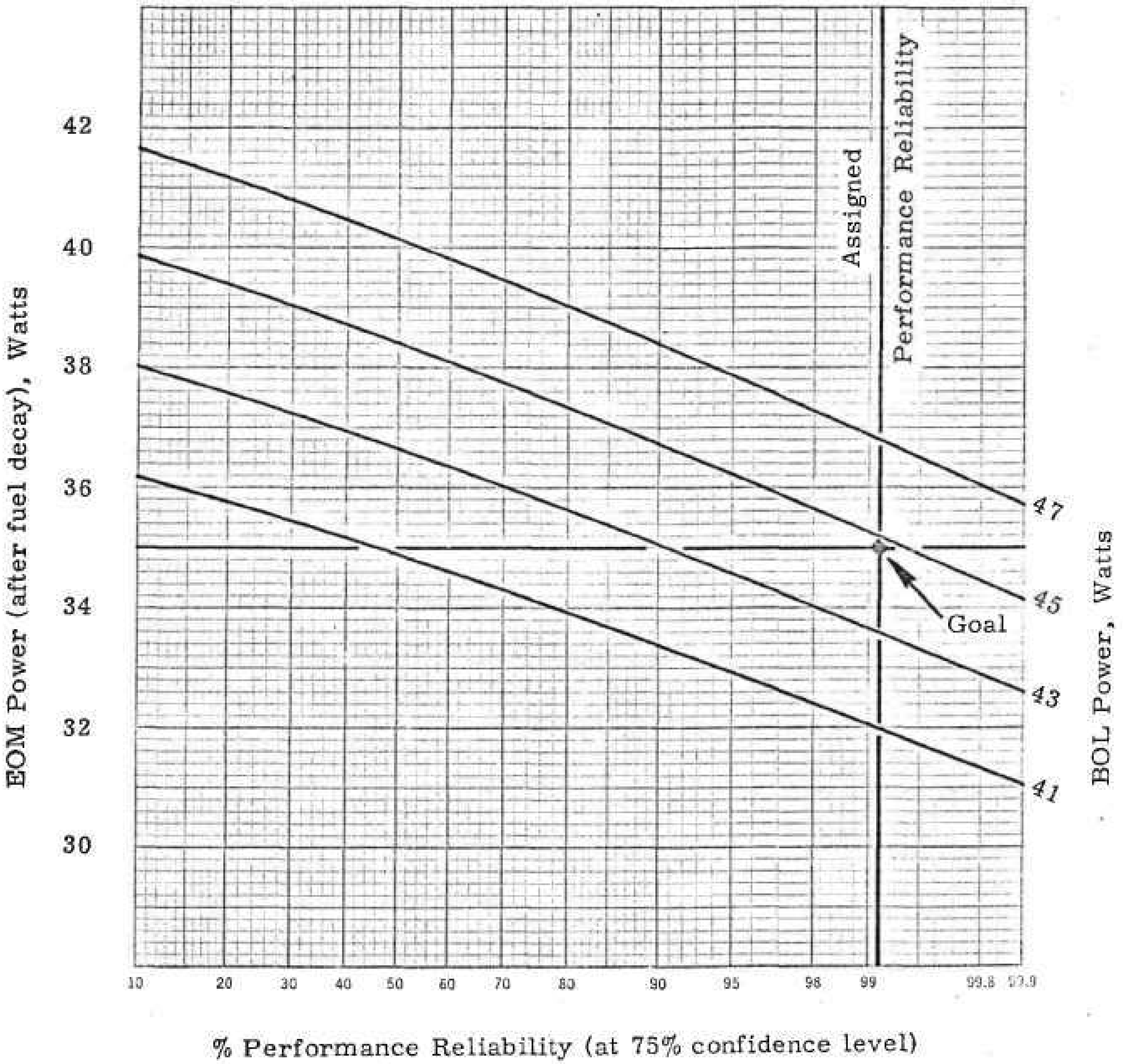


Figure 9:
PERFORMANCE PREDICTIONS FOR VARIOUS BOL POWERS
BASED ON DATA FROM 10 GENERATORS (S/N 26, 29, 31, 38, 40, 42, 44, 45, 46, 48)

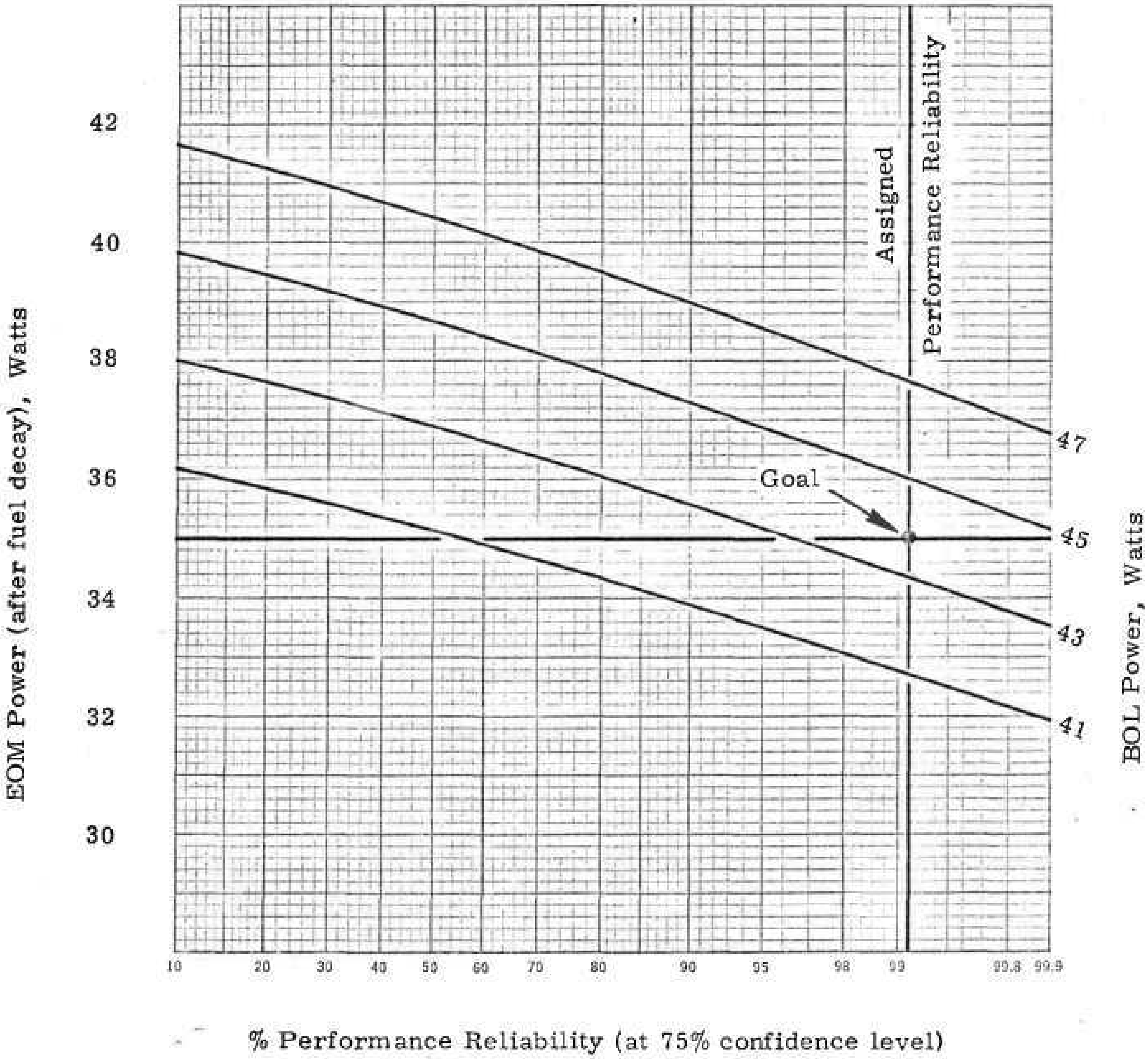


Figure 10:
PREDICTED EOM POWER DISTRIBUTION OF
VIKING-DESIGN GENERATOR (For Six-Generator Data Base)

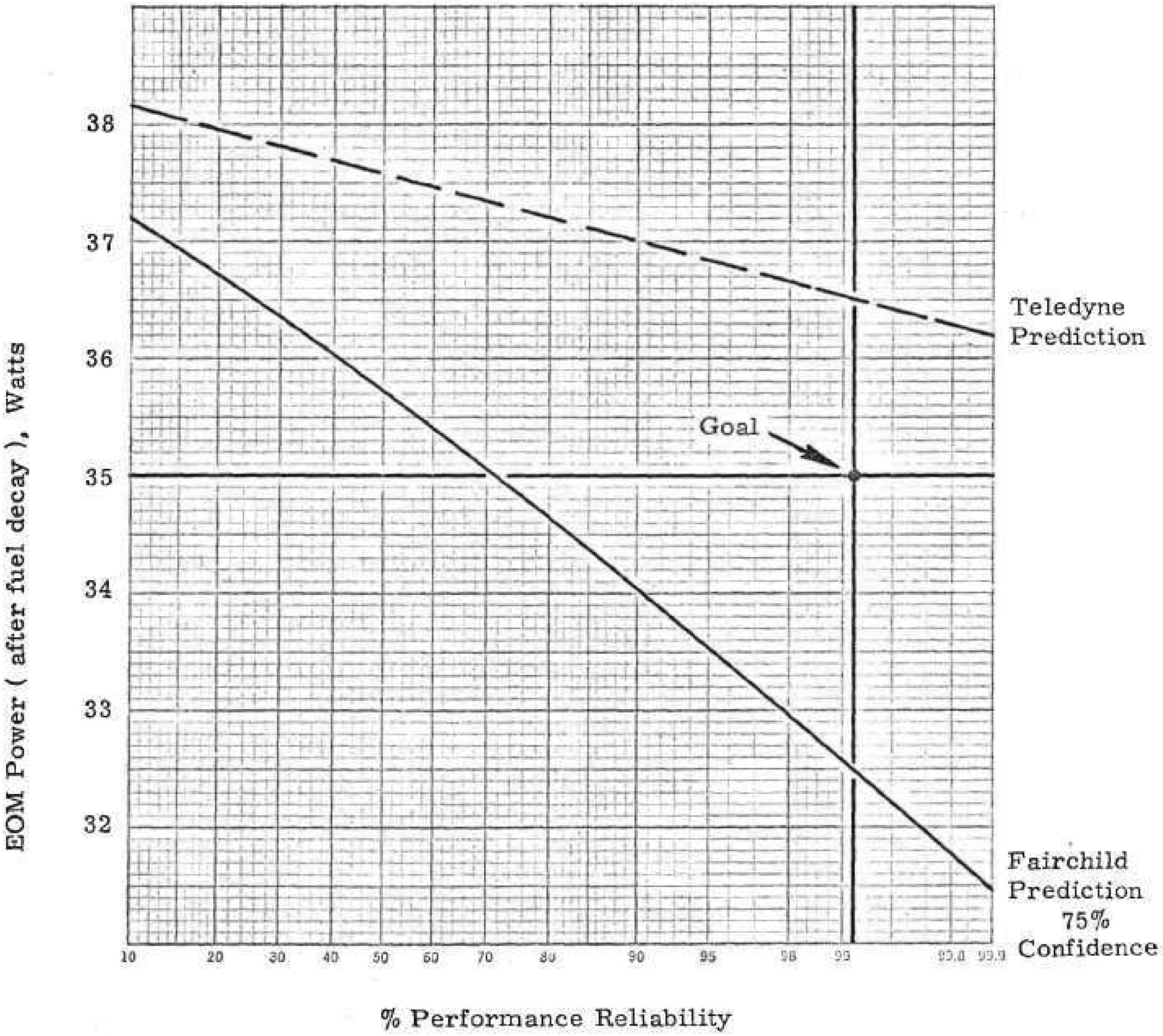


Figure 11:
EFFECT OF SCATTER IN FUEL LOADING
BOL POWER, AND DEGRADATION

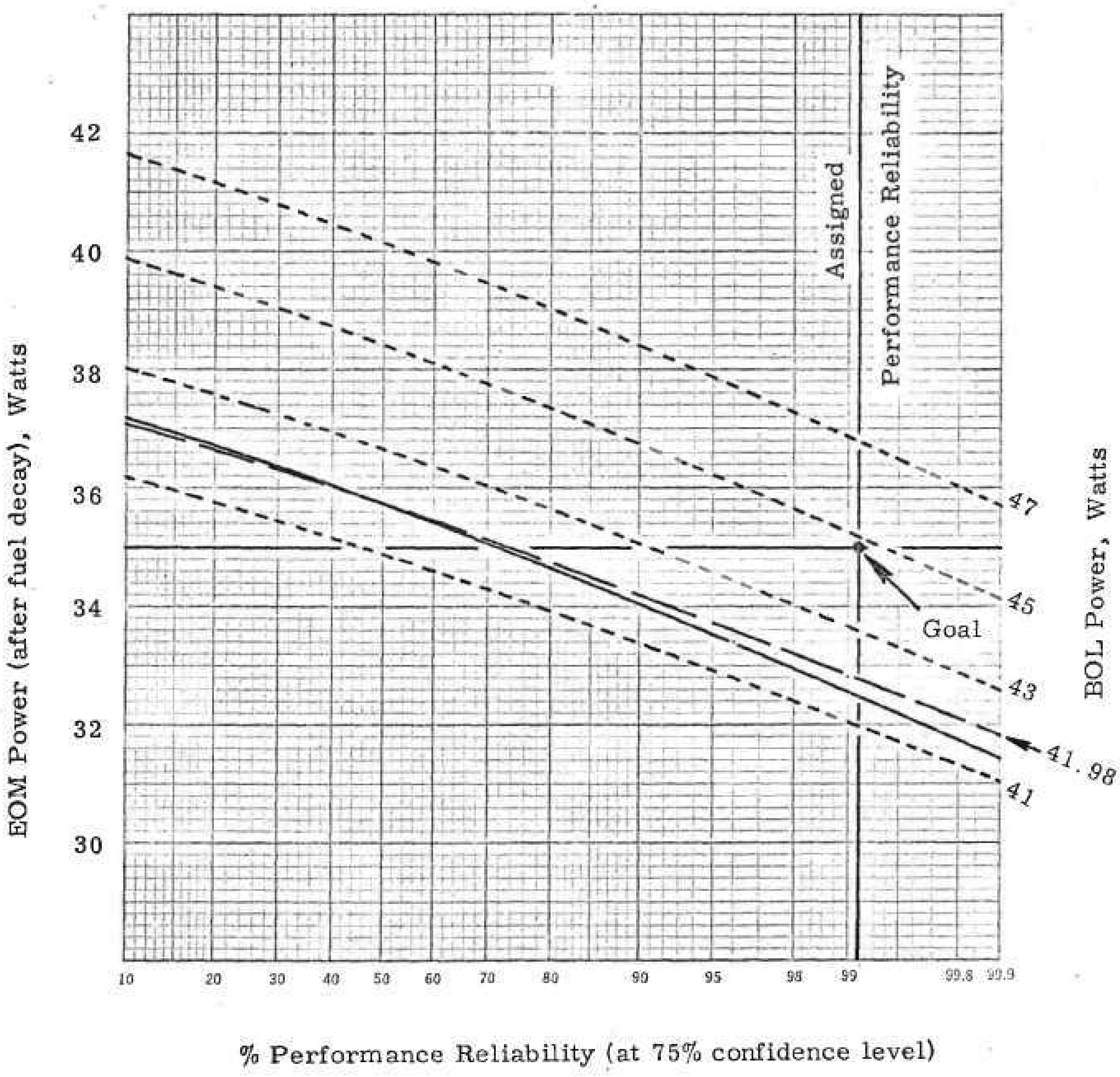


Figure 12:
COMPARISON OF EOM POWER PREDICTIONS
(For Six-Generator Data Base)

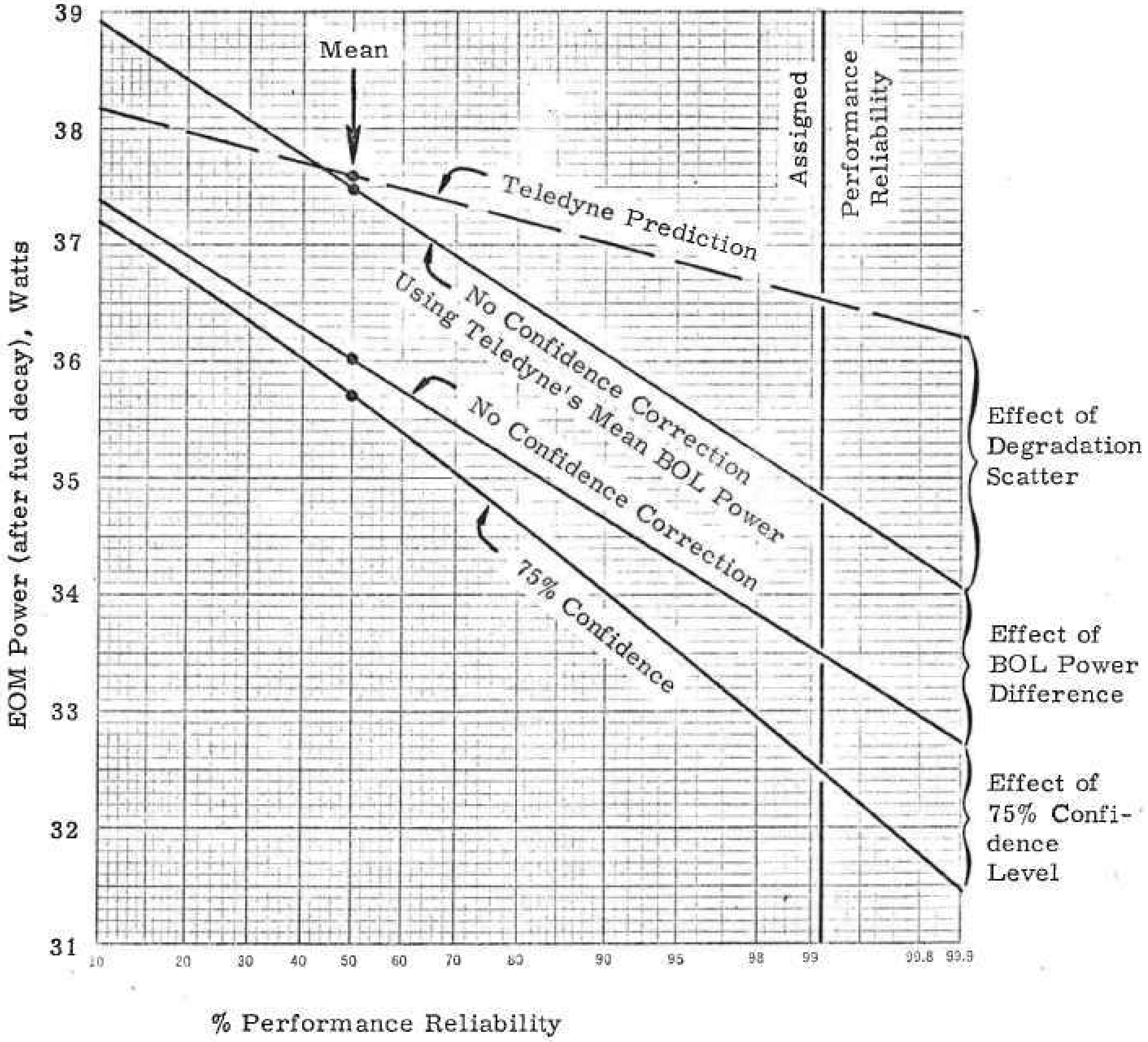


Figure 13:
EFFECT OF AVERAGING THE POWER FROM TWO GENERATORS
(For Six-Generator Data Base)

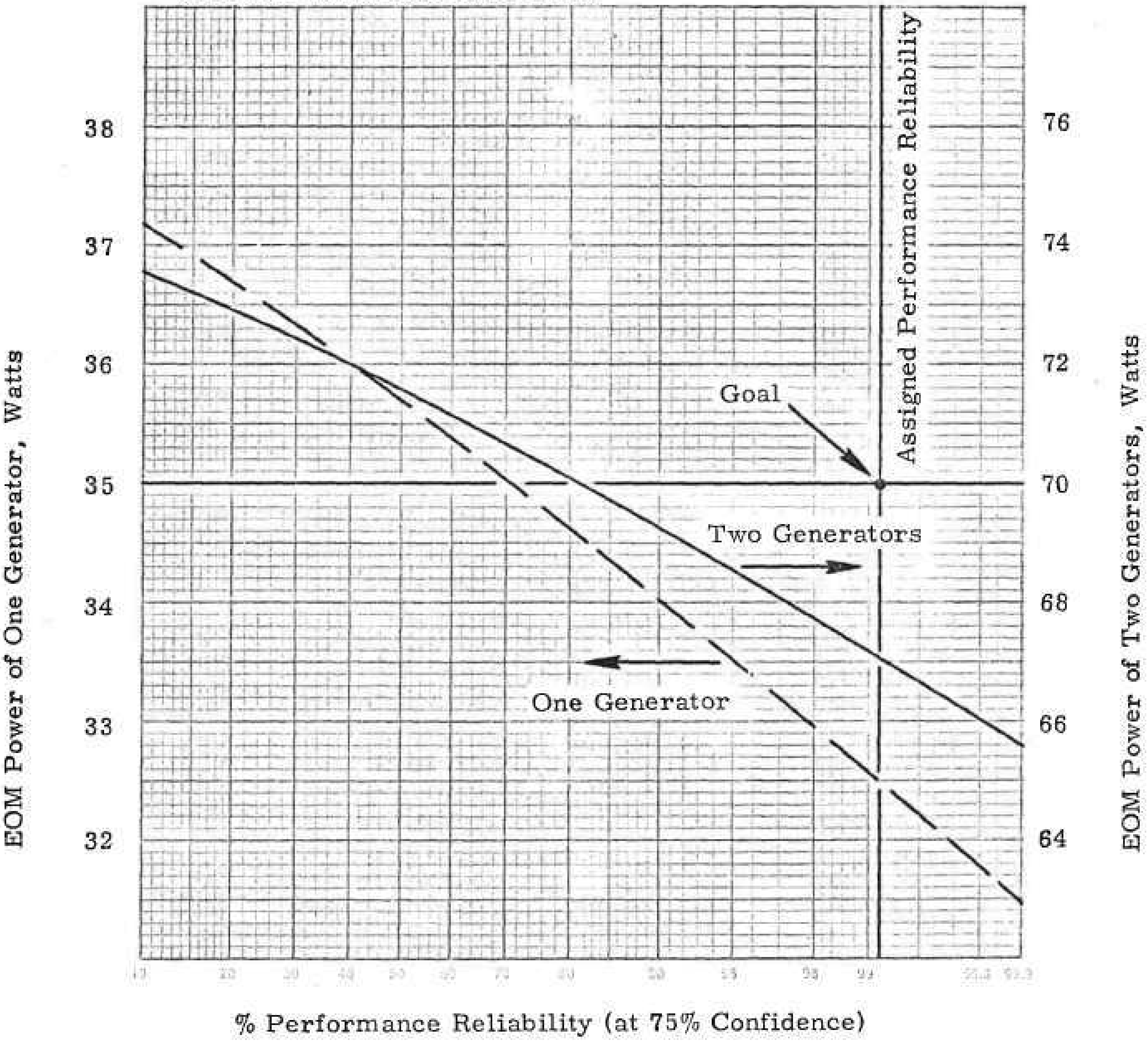


Figure 14:
PERFORMANCE PREDICTIONS FOR VARIOUS BOL POWERS BASED ON PIONEER-10 FLIGHT GENERATOR DATA

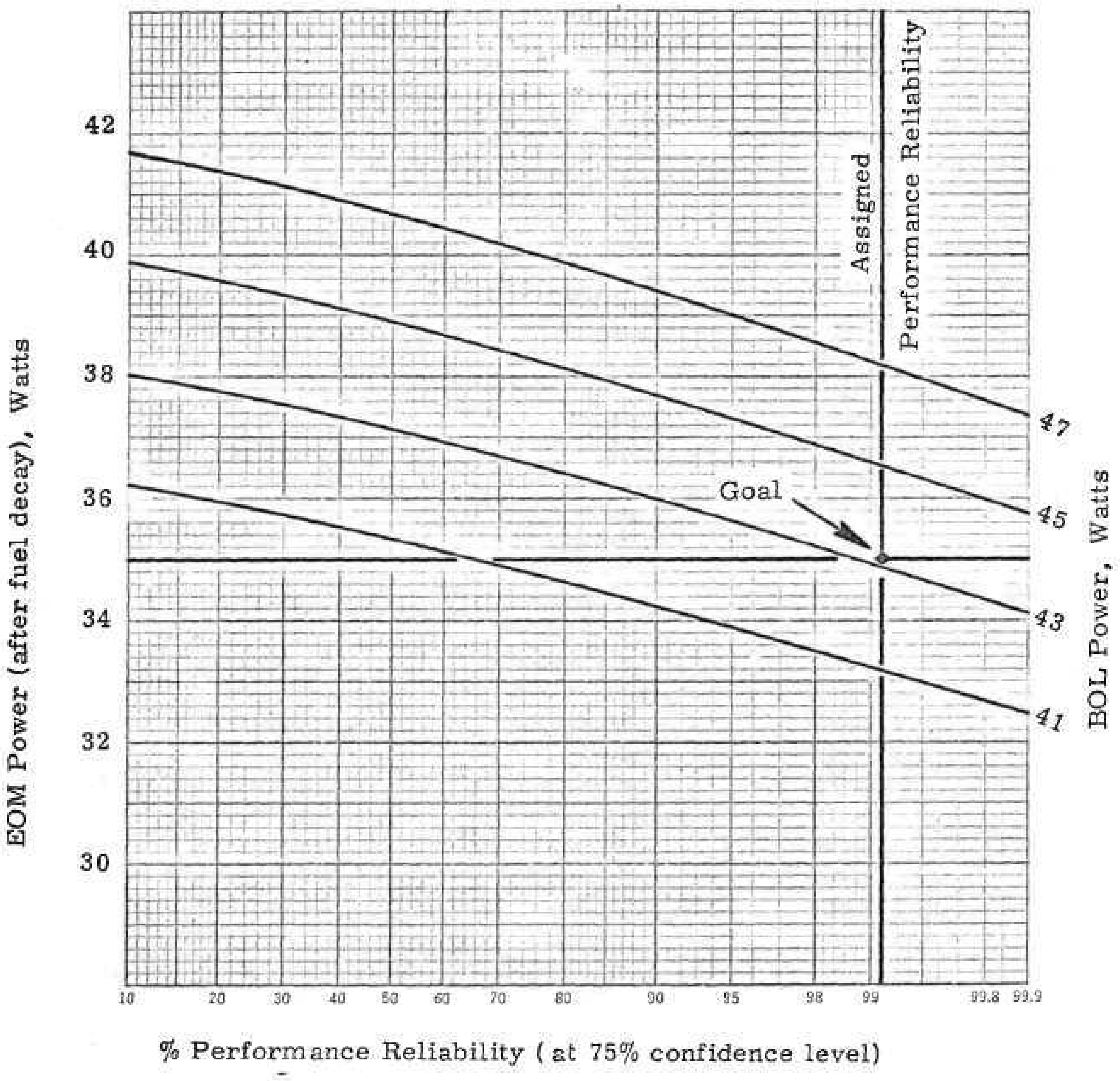


Figure 15: PREDICTED EOM POWER DISTRIBUTION BASED ON PIONEER FLIGHT GENERATOR DATA