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THERMIONIC REACTOR RELIABILITY

by

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[redacted]
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THERMIONIC REACTOR NETWORK RELIABILITY*

J. W. Holland

ABSTRACT. Thermionic converter network reliability is determined as a function of the network electrical configuration and the converter reliability. The study shows that the most reliable configuration is the matrix type of network, with series-connected converters cross-connected in parallel between converters so that an alternate path for electrical current is provided in the event of an open-circuit failure. It was found that with an optimized cross-connector, the most reliable matrix has about three times as many cells in series as in parallel, which conveniently coincides with the advantage of high voltage production. By supplying a small amount of redundant power to the network at the beginning of operation, matrix reliabilities can be orders of magnitude higher than the reliability of the converters.

INTRODUCTION. Evaluation of thermionic network power capabilities over the life of the system must include consideration of the effects that malfunctioning thermionic converters have upon the output of the system. The ultimate goal of such a study is to determine the minimum power redundancy required to maintain the design power output throughout the system lifetime, given the converter reliability and the minimum acceptable system reliability. Conversely, the converter test program may be guided within practical limits of quality control to provide the desired reliability and empirical confidence consistent with the reactor life expectancy, system reliability, and limitations on power redundancy.

Because of the low thermionic generator voltage, it is desirable to connect cells in series in a thermionic power system. This practice is in conflict with a requirement for high reliability and low power redundancy if a single open-circuit failure results in the loss of an entire series. It has been suggested that if series strings of converters are cross-connected in parallel, as illustrated in Figure 1, an alternate path would be provided for the current from the series of cells that contain the open-circuit failure. In the present analysis, this method of connection was evaluated with the goal of improving system reliability.

A mathematical synthesis of the network allows an evaluation of the effects of malfunctioning converters in a cross-connected matrix. The reliability of the matrix may then be determined by combining the results of the matrix analysis with a statistical analysis of failure combinations. This analysis was initially performed on a square, 25-converter reference matrix in which the cross-connectors, failure propagation, and systematical effects of converter failures on a matrix were investigated. Matrices of other sizes and shapes were then compared with the 5 x 5 reference matrix.

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ANALYTICAL METHOD AND ASSUMPTIONS. Matrix reliability, R_m, is defined for this study as the probability that the matrix electrical output at the end of operating life will exceed a given fraction of the initial output. This fraction of the initial output is termed relative power, P_r. The matrix reliability calculations are performed in the following way. Probabilities are computed by means of the binominal distribution function for random failure combinations corresponding to a matrix size and converter reliability. The power losses resulting from these failure combinations yield the desired information: the matrix reliability as a function of the relative matrix power, with converter reliability as a parameter.

A digital computer program was developed[1] to solve the matrix equations governing the converter network. The code calculates the voltage-current response of the network and the network components to various changes in the operating variables. These variables include: converter operating characteristics such as the I-V relationship and emitter temperature; load characteristics; cross-connector resistances; and two types of converter malfunctions, short- and open-circuit failures. The short-circuit mode is a simple case of electrode shorting where the converter produces no power and the internal resistance assumes a value equal to the resistance of the emitter stem and electrodes. The open-circuit condition assumes cesium loss from the electrode space, either from a cell envelope failure or by loss of cesium pressure control, with a resultant high interelectrode resistance and zero emf. In the absence of adequate failure data, it is assumed that open-circuit and short-circuit failures occur with equal probability. Both open- and short-circuit failures have occurred in the current thermionic converter technology program, but this information does not bear directly on an eventual application, since the testing environment and the mechanical-thermal design were not duplicated.

A type of failure not included in this study is the shorting of two or more of the converters to the network support structure and cooling loop. It is assumed that the probability of this type of failure is small compared to that of open- and short-circuit cell failures, and therefore will not affect the results of this network reliability analysis. If necessary, this type of failure might be made insignificant by the use of multiple isolated coolant loops.

Values of the converter characteristics used in the input of the matrix code are derived from the experimental data of a Mark VI out-of-pile thermionic converter.[2] The converter has a cylindrical emitter of vapor-deposited tungsten with an effective emitting area of 28 cm^2 spaced at 0.008 in. from a molybdenum collector. The maximum power derived from the cell is 10 watts/cm^2 at an average emitter temperature of 1800°C with the emitter lead geometry optimized for maximum efficiency.

In a network of thermionic converters, a failure in some cases causes a decrease in cell current in nearby converters with a resulting increase in emitter temperature. The emitter temperature that can be sustained without causing failure of the cell depends primarily on materials compatibility and the mechanical and thermal design of the cell. In this study, it is assumed that if an emitter temperature exceeds 2000°C, the converter will eventually fail. This event will have occurred due to a redistribution of electrical currents within the matrix and is termed failure propagation. Probably, it is more likely that partial power degradation will accompany high emitter temperatures. However, for the purpose of investigating the worst effects of long-term operation at high emitter temperatures, complete cell failure, either open- or short-circuit, is assumed where propagation is investigated.

MATRIX POWER LOSSES DUE TO CONVERTER FAILURES

5 x 5 Reference Matrix. The 5 x 5 square matrix of 25 cross-connected converters was selected for the reference matrix of the basic studies because it is large enough to yield results generally applicable to large-size matrices and yet small enough that the cost of calculating many cases is not prohibitive. A square matrix was selected for its symmetry.

The selection of the optimum cross-connector resistance is made on the basis of 1 or 2 failures, since for the interesting range of converter reliabilities, 1 and 2 failures are most probable.(1) Figure 2 shows the relative power output of the network as a function of cross-connection resistance for single failures. The intersection of the open-circuit failure curve with the short-circuit failure curve at 1-mohm indicates that a minimum power loss would be obtained using a 1-mohm cross-connector if single open- and short-circuit failures occur with equal probability. A sample check was made with two failure combinations, with the same results indicated. It is noted in Figure 2 that with the optimum 1-mohm cross-connector, the relative power varied between 91% and 93%.

Twenty-four cases each of 2 through 8 failure combinations were selected at random with respect to both location and failure mode. In Figure 3a, the maximum, minimum, and average relative powers are shown as a function of the number of failures. It is seen that 90% of the data fell within a relatively narrow band. Also shown is the fraction of the cases studied in which secondary failures may be propagated under the assumption that perturbed converters with emitter temperatures exceeding 2000°C will fail. It is noted that for more than 3 failures a significant fraction of the cases did have converters with emitters hotter than 2000°C. However, it is relatively improbable for the main cases of interest that greater than 3 failures will occur and, besides, it will be seen that employment of matrix shapes other than the 5 x 5 reduces failure propagation to a negligible importance.

To determine the relative worth of cross-connectors, the same cases that were computed in the previous study were recomputed without cross-connectors. In the results shown in Figure 3b, the scatter of values is very much wider than that previously obtained with cross-connectors and the 90% band is almost as wide as the envelope formed by the maximum and minimum. Comparing these results with the optimum cross-connector results, it is noted that for a single failure, the average power loss was 8% for the optimized situation as compared to 15% for no cross-connector.

Effect of Matrix Size on Power Loss. Power losses due to converter failures are computed for 2 x 2, 3 x 3, and 4 x 4 square matrices, both with and without optimized cross-connectors to determine the effects of matrix size. The cross-connectors for these matrices are optimized similarly to the optimization for the 5 x 5 matrix, i.e., on the basis of single failures and for equal probabilities of open- and short-circuit failures. In Figure 4, the points of intersection for the open- and short-circuit curves give the optimum values that are used in the power loss calculations. It is noted in Figure 4 that the 2 x 2 matrix open- and short-circuit curves approach each other asymptotically and below 10^{-4} ohm are rather insensitive to changes in cross-connector resistance. A resistance of 8×10^{-5} was arbitrarily selected for the 2 x 2 matrix studies, which is justifiable because of the lack of sensitivity in the power loss. The loci of the optima for square matrices asymptotically approach 1×10^{-3} ohm for matrices larger than 5 x 5.

It is shown in Figure 5a that with an optimized cross-connector, the same power loss is obtained for a given fraction of the converters failing at random, regardless of the matrix size. It is further shown that the maximum to minimum range is also equal. The power loss results of matrices with no cross-connectors are shown in Figure 5b. Contrary to the optimum cross-connector results, the power losses vary systematically according to matrix size, with the 5 x 5 matrix having the largest power losses and the 2 x 2 matrix the smallest. This result is expected since a single open-circuit failure in a series of cells causes the loss of power from the entire series. It is noted in Figure 5b that the optimized matrix always has a higher relative power, but the gain over the 2 x 2 matrix power is almost negligible. Although little relative power is to be gained by the employment of cross-connectors in the smaller matrices, it will be seen there are important reliability considerations in the selection of matrix size.

Effect of Matrix Shape on Power Loss. Power losses are computed for the 12 x 2, 8 x 3, 6 x 4, 5 x 5, 4 x 6 and 3 x 8 matrix shapes illustrated in Figure 6. The first number indicates the number of converters in series and the second, the number in parallel. All of these matrices have 24 converters to permit comparison with the 5 x 5 reference matrix so the effects of a matrix shape can be investigated without perturbation from size effects.

Optimum cross-connector resistances are shown in Figure 7. The resistance optima for all possible configurations from 12 x 2 to 2 x 12 fell within the range from 1.5×10^{-4} to 1.5×10^{-3} ohms. It is noted that the optimum resistance asymptotically approaches 1.5×10^{-3} ohms for matrices with more cells in parallel than in series.

Results of the power loss calculations for the variably shaped optimum cross-connected matrices are plotted in Figure 8a as a function of the fractional number of random failures. The range of values for each failure fraction (maximum to minimum) is not plotted to prevent confusion, but is close to the range shown in Figure 5a. Similar to the results of the previous matrix size study, the results in Figure 8a show that with an optimized cross-connector the relative power is essentially independent of matrix shape. This result is useful in subsequent calculations because the power loss for a single shape can be computed and then the results can be applied to other matrix shapes. It was shown in this study that two additional points are of interest. First, failure propagation is predominant in short matrices and relatively rare in long matrices. This is an important result, since long matrices are desirable for high voltage. The second point is that zero power for the 12 x 2 matrix is relatively probable, and thus gives a matrix reliability with less confidence. This zero minimum did not occur in the 160 cases studied for the 8 x 3 and 6 x 4 matrices because of the low probability of 3 or 4 converters failing in parallel.

Failure propagation rarely occurs in the 6 x 4 and 8 x 3 matrices for the following reasons. In a failed cell, the current terminates in an open-circuit failure case and either terminates, or reverses, owing to a short-circuit failure. The emitter temperatures of cells immediately in series with the failed cell will increase in temperature, depending on the value for the cross-connector resistance. In the long matrices, the optimum cross-connector resistance is low and provides an adequate alternate path for the cells in series with the failed converter. In short wide matrices, however, the cross-connector resistance is larger, and thus the current decreases in cells in series with the failed cell, causing failure propagation.

From these results it appears that the best matrix shape is the 8 x 3 from several standpoints: (1) good voltage production, (2) small range from maximum to minimum, and (3) no failure propagation. The power loss results for the variably shaped matrices with no cross-connectors are shown in Figure 8b as a function of the fraction of failed converters. It is seen that the power losses vary according to the matrix shape, with failures in the 12 x 2 matrix giving the largest losses. This result is exactly what one would expect, since open-circuit failures cause the loss of a whole series of cells. It is also shown that the optimized cross-connected matrix always has a higher power. Little is to be gained, however, from using cross-connectors in a 3 x 8 or a 2 x 12 matrix.

<u>MATRIX RELIABILITY</u>. The matrix shape study showed that the power loss for matrices with optimum cross-connectors and no propagated failures was independent of matrix shape. Since the probability for a given number of initial failures is a unique function of cell reliability and the total number of converters, it is clear that matrix reliability is also independent of matrix shape under the aforementioned conditions. As previously indicated, propagation rarely occurs in 6 x 4 matrices and not at all in 8 x 3 matrices, which makes the latter matrices the most reliable. This result is important to the systems designer, since matrices with more cells in parallel, in addition to being the most reliable, also produce a more useful voltage than shorter matrices.

The matrix reliability is plotted as a function of relative power in Figure 9 for the 24 converter matrices with optimized cross-connectors and no failure propagation. A number of points are of interest in examining these results. It is noted that for a 70% relative power, a matrix reliability of 0.9 is obtained for the matrix containing converters with a reliability of 0.9. At the same relative power, however, converters with a reliability of 0.95 give a 0.994 matrix reliability, and converters with a reliability of 0.99 yield a matrix reliability of 0.99999. This raises several extremely important points: (1) a tremendous advantage is gained from using high reliability converters, and (2) through applying the principle of power redundancy, there is an increase in matrix reliability by three orders of magnitude over that of the converters for 70% relative power and 0.99 cell reliability. If all of the 24 converters with 0.9 reliability had been in a series connection, the maximum network reliability would have been only 0.08. The same series connection with converters with a reliability of 0.99 gives a matrix reliability of 0.79, which is still probably inadequate for most applications.

Results from the matrix size study combined with the probability of occurrence give the matrix reliability as a function of the relative power as shown in Figure 10. It is noted that the curves for a given cell reliability cross each other; the $P_s = 0.9$ curves cross at a relative power of 0.75 while the $P_s = 0.99$ curves cross at 0.92. To the left of the crossover points, large matrices have higher reliabilities than small matrices. For instance, in the set of $P_s = 0.95$ curves at a relative power of 0.70, the 5 x 5 matrix has a reliability of 0.994, while the 2 x 2 matrix has only a 0.955 reliability, a substantially lesser value. For high reliability converters ($P_s = 0.99$), the crossover points occur at higher relative powers. Thus, it is apparent that if large high voltage matrices are desired, high reliability converters give proportionally higher matrix reliabilities for less power redundancy.

From the data of Figure 10, a cross-plot is constructed in Figure 11 in the form of matrix reliability versus matrix size for a 70% relative power. This plot is valid for optimum cross-connected matrices of all shapes as long as converter propagation is negligible, which is true for 8 x 3 matrices. The graph shows that by extrapolation, a 50-cell matrix with converters having a reliability of 0.95 would have a reliability of 0.9994, which is 100 times more reliable than the converter itself. Figure 11 shows a significant advantage to large matrices and high converter reliability. A general conclusion for this part of the reliability study is that a matrix should be large, with an 8 x 3 shape (with optimum cross-connectors) if relative powers less than the crossover point are tolerable from a systems standpoint.

In Figure 12, the worth of the optimized cross-connector in an 8 x 3 matrix is illustrated. At a 70% relative power, the cross-connector increases matrix reliability by three orders of magnitude from 0.99 to 0.99999 for a matrix with 0.99 reliable cells. With 0.95 reliable cells, the matrix reliability increases from 0.78 to 0.994, a very significant difference.

TESTING REQUIRED TO ESTABLISH CONVERTER RELIABILITY. Before a complex power system of thermionic converters is constructed, an empirical confidence in the reliability of the individual converters should be established by a life test program. If, for example, in a first thermionic reactor experiment a 0.9 converter reliability is selected, 22 converters will have to be operated without a random failure for the expected length of the reactor operation if a confidence of 90% is desired. If one failure occurs and the source of the failure cannot be eliminated from future converters, then 37 life tests must be performed. For a 0.95 reliable converter with 90% confidence, 44 tests would be required without a failure.

SUMMARY AND CONCLUSIONS. Employment of optimized cross-connectors in a matrix of converters supplemented with power redundancy in the system can boost the reliability of a thermionic network significantly. A matrix reliability of 0.994 at a relative power of 70% was shown in the example of the optimum cross-connected 8 x 3 matrix with converters having a reliability of 0.95 and an equal probability for open- and short-circuit failures. In this matrix configuration, no failure propagation was observed in the 80 cases studied. If no cross-connector had been employed, the matrix reliability would have been only 0.78, or 50 times less than the optimized cross-connected matrix. The use of high reliability converters ($\geq .95$) was shown to offer considerable advantage over the use of a lower reliability converter (0.9).

The shape-size study indicated that matrices with roughly twice as many cells in series as in parallel are the most reliable matrices. It was shown in a study of 24-cell matrices that the 8 series by 3 parallel configuration gave the highest reliability and among the cases studied produced a higher than average voltage. Recommendation for the most reliable size matrix depends on converter reliability and system power redundancy. It was shown that large matrices are most reliable for 0.95 reliable converters and a matrix relative power of less than 82%. An example using the 0.95 reliable converter showed that at a 70% relative power, a 24-cell matrix gave a matrix reliability of 0.994, while a 4-cell matrix yielded a 0.95 reliability. Extrapolation to a 50-cell matrix indicated a reliability of 0.9994, which is 100 times greater than the cell reliability.

As was observed in the matrix reliability analysis, increased reliability may be obtained at the sacrifice of matrix relative power. The amount of power redundancy the system may employ depends on the trade-off between the system reliability and the system weight, size, and cost. Evaluation of these trade-offs is beyond the scope of this study but is of ultimate importance in the design of a thermionic system.

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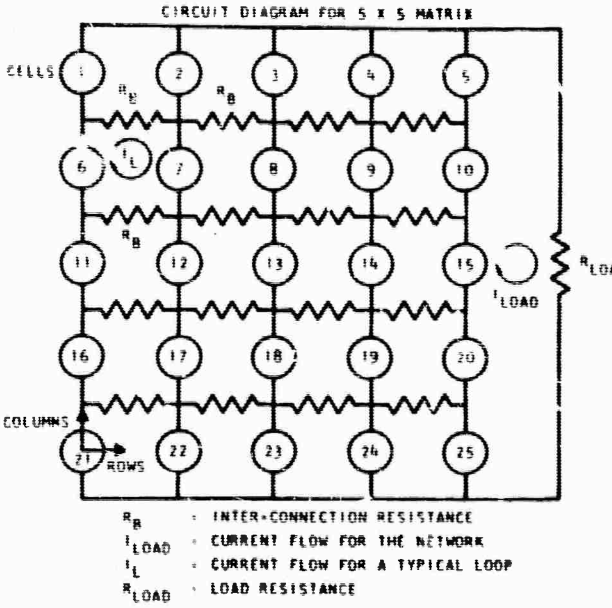

FIGURE 1 SCHEMATIC OF A 5 X 5 MATRIX OF THERMIONIC CONVERTERS SHOWING CROSS-CONNECTORS

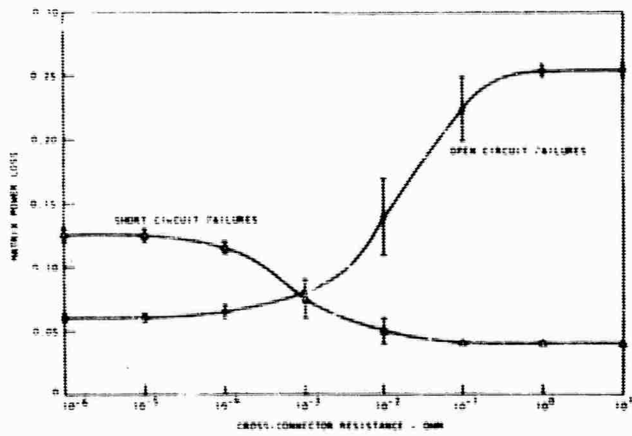

FIGURE 2 SINGLE FAILURE DEGRADATION VS CROSS-CONNECTOR RESISTANCE

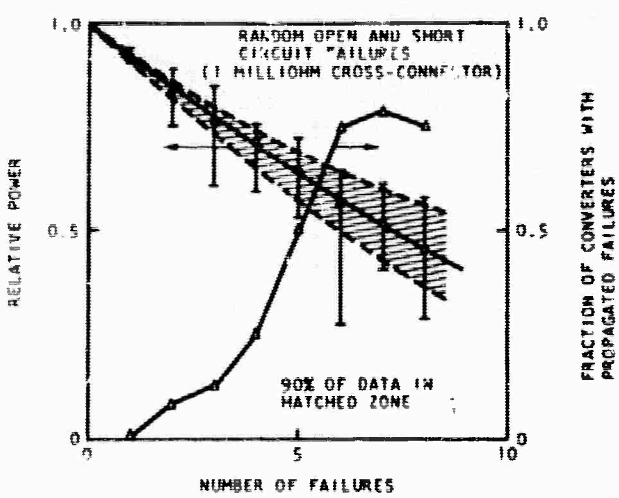

FIGURE 3a RELATIVE POWER VS RANDOM FAILURES FOR MATRIX WITH A MILLIOHM CROSS-CONNECTOR

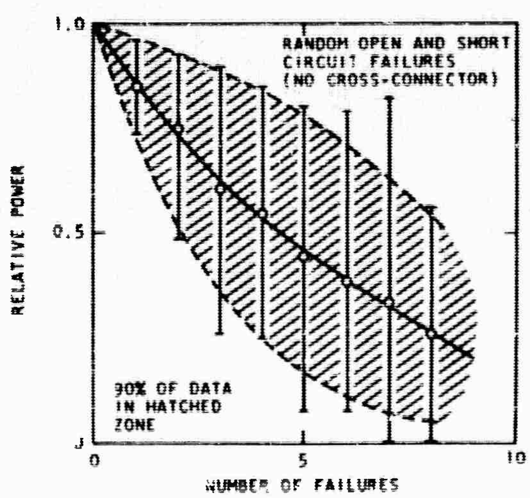

FIGURE 3b RELATIVE POWER VS RANDOM FAILURES FOR A MATRIX WITH NO CROSS-CONNECTOR

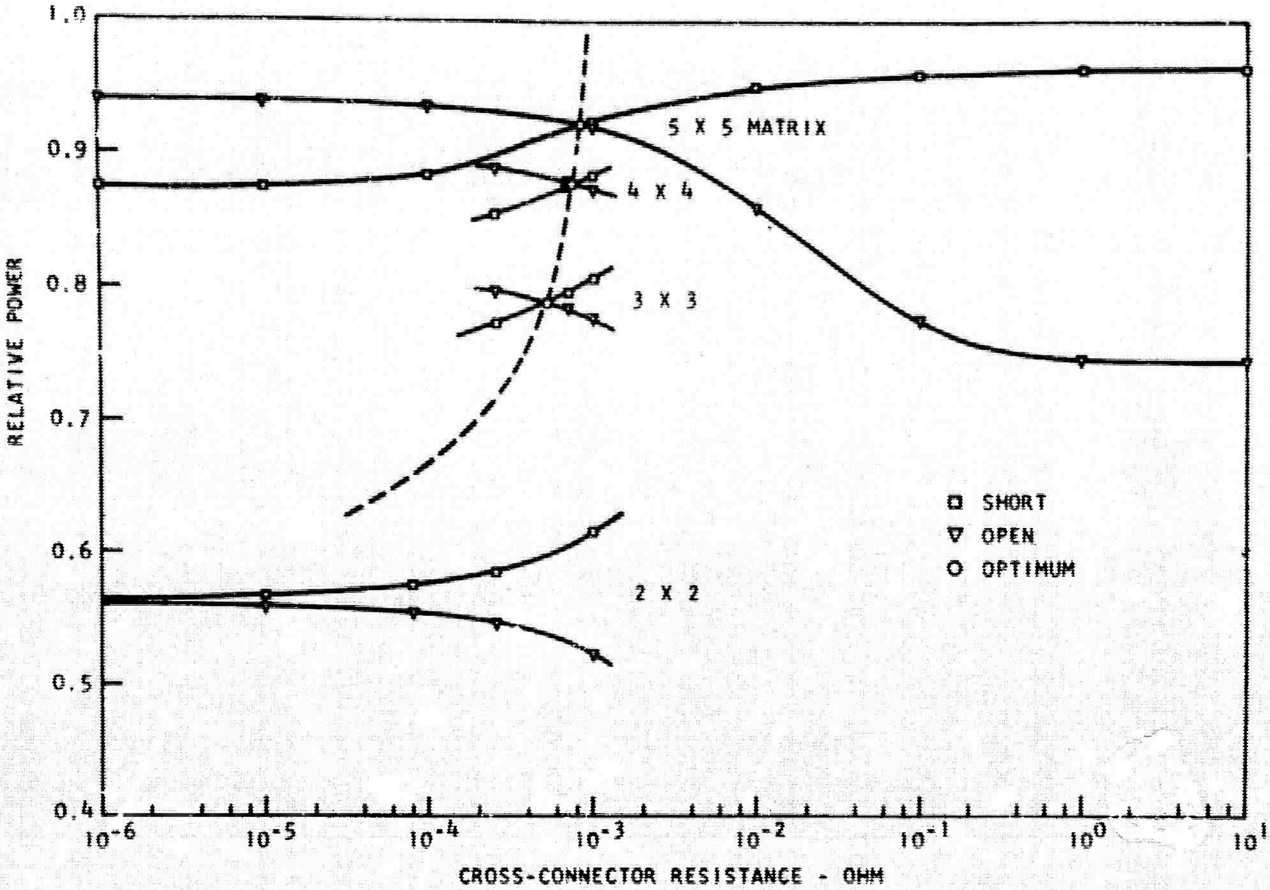

FIGURE 4 DETERMINATION OF OPTIMUM CROSS-CONNECTOR RESISTANCE FOR VARIABLE SIZED SQUARE MATRICES

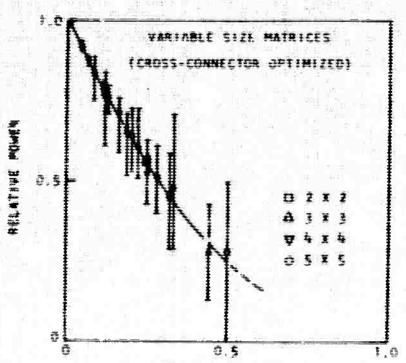

FIGURE 5a RELATIVE POWER VS FRACTION OF RANDOM FAILURES FOR VARIABLE SIZED MATRICES WITH OPTIMUM CROSS-CONNECTORS

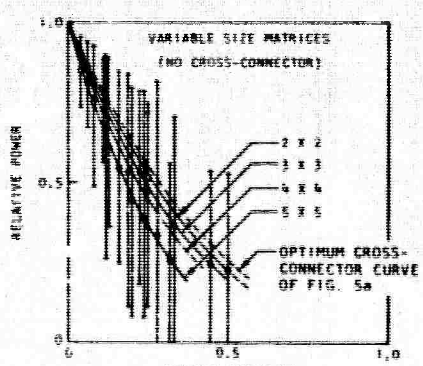

FIGURE 5b RELATIVE POWER VS FRACTION OF RANDOM FAILURES FOR VARIABLE SIZED MATRICES WITH NO CROSS-CONNECTORS

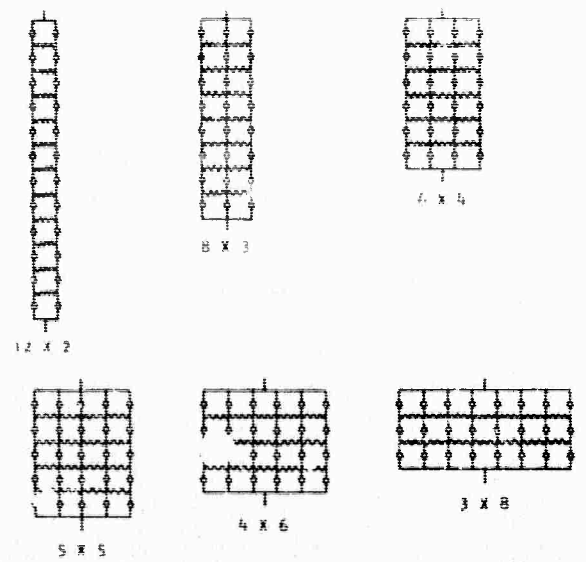

FIGURE 6 MATRICES COMPARED IN THE SHAPE STUDY

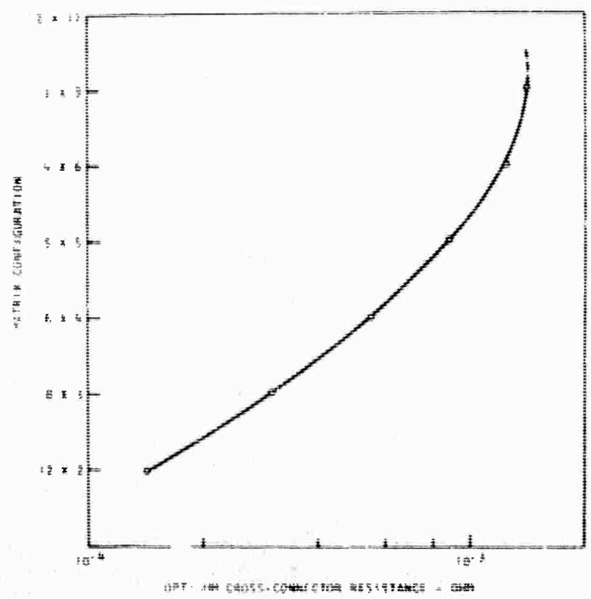

FIGURE 7 OPTIMUM CROSS-CONNECTOR RESISTANCE FOR VARIABLE SHAPED MATRICES

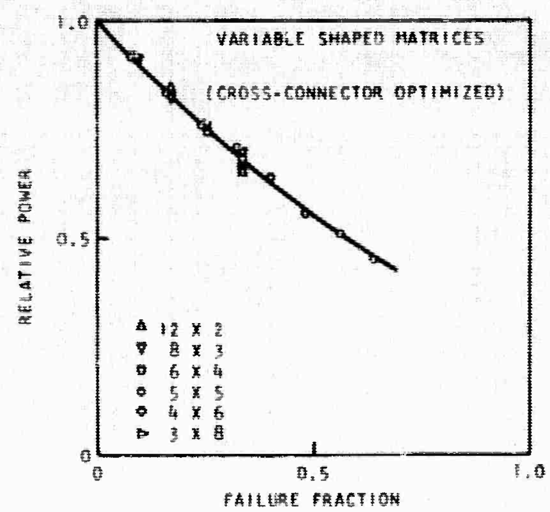

FIGURE 8a RELATIVE POWER VS FRACTION OF RANDOM FAILURES FOR VARIABLE SHAPED MATRICES WITH NO CROSS-CONNECTORS

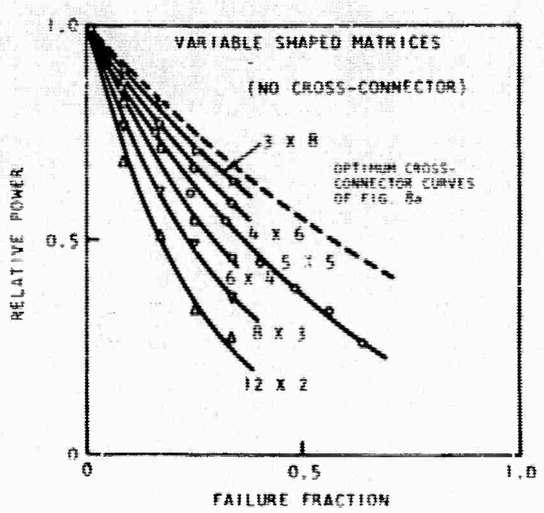

FIGURE 8b RELATIVE POWER VS FRACTION OF RANDOM FAILURES FOR VARIABLE SHAPED MATRICES WITH NO CROSS-CONNECTORS

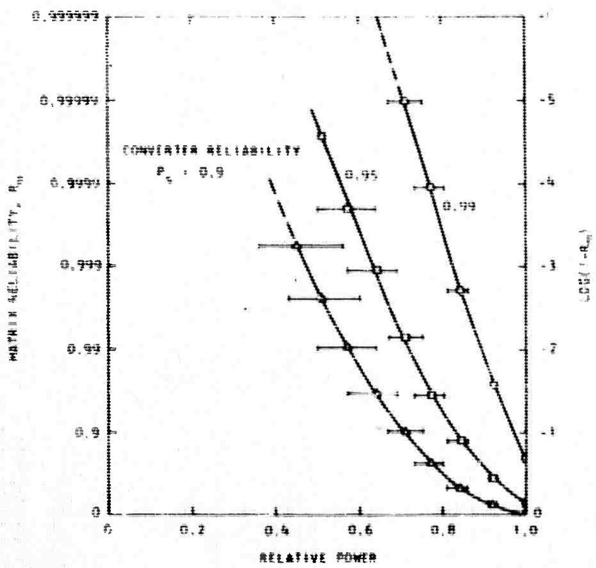

FIGURE 9 MATRIX RELIABILITY VS RELATIVE POWER FOR A 24 CONVERTER MATRIX WITH OPTIMIZED CROSS-CONNECTORS

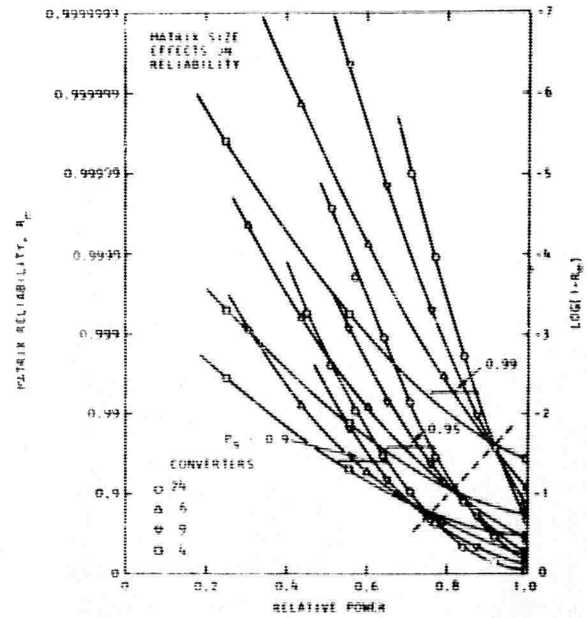

FIGURE 10 MATRIX RELIABILITY FOR VARIABLE SIZED MATRICES WITH OPTIMUM CROSS-CONNECTORS AND NO FAILURE PROPAGATION

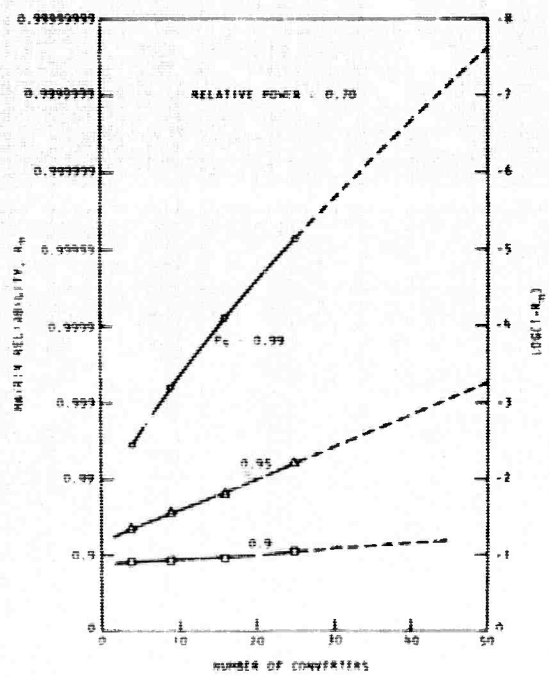

FIGURE 11 MATRIX RELIABILITY VS MATRIX SIZE FOR 0.70 RELATIVE POWER

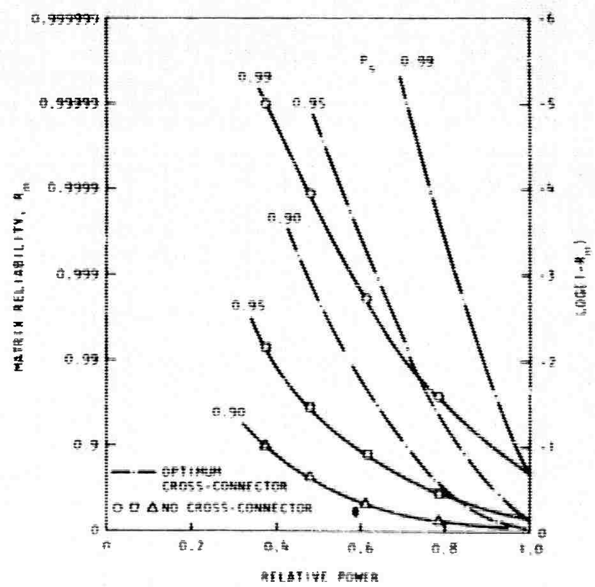

FIGURE 12 COMPARISON OF 8 X 3 MATRIX RELIABILITIES WITH AND WITHOUT CROSS-CONNECTORS