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INTEGRATED MODELING AND ANALYSIS OF FAULT-TOLERANT SYSTEMS WITH--ETC(U)
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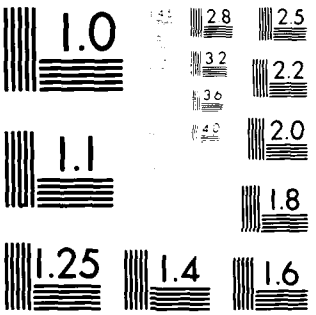

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INTEGRATED MODELING AND ANALYSIS OF FAULT-TOLERANT SYSTEMS WITH FAULT-TOLERANT SOFTWARE

AFOSR-80-0117

Final Report for
Project No. 2304D9, P.O. No. 80-00721

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Submitted to:

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Bolling AFB, D.C. 20332

1980

Submitted by:

Aaron S. Collins, Ph.D
Principal Investigator
Tennessee Technological University
Cookeville, Tennessee 38501

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A. D. BLOSE
Technical Information Officer

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Introduction

Research aimed at improving the reliability of computer systems has been performed almost independently by a number of disciplines in the past. As a result, different modeling methods, nomenclature, and perspectives have evolved within the various sub-disciplines. More significantly, optimum tradeoffs are not achieved during the design process. This research effort pulls together results and methodology from fault-tolerant architecture and fault-tolerant software to determine the effect of including software realities in system structural design decisions for reliability enhancement purposes. Specifically, projected software error rate data is incorporated in an analysis of fault-tolerant computer architectures assuming that multiple version software is available. Petri net-like models are investigated as a tool for performing integrated hardware/software system reliability and performance studies.

Objectives

Since software does not fail in the same manner as hardware, it is difficult to make reasonable tradeoffs between hardware fault tolerance and software reliability. Since software faults are due to design and implementation errors, and not to equipment breakdown, an accepted measure of software reliability has not evolved [1, 2, 3]. A considerable

amount of empirical data is available [2, 4, 5, 6], however, which quantifies error rates which have been recorded in existing systems. Based on this data, it is possible to make some reasonable error rate predictions for software developed under known conditions. A range for the expected value of error rate, therefore, can be determined prior to the development of a software system.

A number of fault tolerant computer architectures claim very high reliability figures with failure probabilities as low as 10^{-9} per hour [7, 8]. Such figures are clearly out of line with those obtained for software error rates and therefore, represent a false measure of overall system reliability.

Robert Bernhard (9) identifies software as the key problem in achieving a 'no-downtime' avionic computer which does not reduce the overall reliability of the aircraft. Up to 100,000 lines of code are needed for avionics, and the Fault-Tolerant Multiprocessor, Software Implemented Fault Tolerance, and other ultrareliable avionic computer designs assume that no bugs are present in the software. A close analysis of the level of software quality which is achievable is warranted.

Integrated Hardware/Software Reliability Model

Several ultrareliable avionic computer architectures are currently under development. Of special interest are the FTMP (8), SIFT (7), and FTSC (12). A careful look at these computer architectures shows that each is designed to prevent hardware failures from causing a system failure, but neither

directly provides for software redundancy (13). Since either a system hardware failure or a system software failure results in a system failure, it is apparent that from a total system reliability analysis viewpoint, the hardware and software are in series for these systems. Either a hardware or a software failure will cause a system failure. The design specifications for these systems provide a hardware failure rate of 10^{-9} per hour and assumes perfect software. Accordingly, the corresponding system reliability graph is shown below.

System Hardware Reliability	System Software Reliability
$R(t) = 1-10^{-9}$	$R(t) = 1$

The question which is immediately raised here is: "Is $R(t) = 1$ achievable for approximately 100,000 lines of avionic system software, and if not, what is achievable?"

Although software does not "fail" in the sense of hardware breakage or malfunction, it does run in real-time so that the rate of occurrence of system malfunctions due to software "bugs" or imbedded design and implementation errors can be determined over an operational time period if sufficient data is gathered. It is possible therefore, to speak of software-caused system malfunctions in terms of equivalent hardware failures. The term "Software Reliability" is used in this work in this manner ... as the reliability figure which would have been arrived at had the failures been caused by hardware malfunction. This hardware/software failure

equivalence is not recognized by many researchers, but is valid from the total system performance viewpoint being investigated here. In fact, it is necessary to consider software when determining total system reliability. Assumptions and approximations which allow computation of hardware and software reliability using the same measure of reliability for both are necessary for achieving an optimal total system design.

Proposed methods of determining a numerical value for software reliability have fallen into two general categories (2), time domain and data domain approaches. The data domain approaches. The data domain is quite important from the software analysis and testing viewpoint in that testing of various combinations of inputs and tracing through different paths through a program are our most effective software debugging and validation processes. The time domain analysis of software failure data is a form of system quality assurance which is independent of the system structure and of the programmer's judgement, therefore, it provides a form of independent review of the software quality. From that standpoint alone, time domain software quality measures are important, but they also have the advantage of being in a form similar to hardware reliability. This allows a reasonable, if not esthetically pleasing, approach to projecting the overall system failure rate.

It is necessary to make some assumptions in order to have a basis for calculating a 'reliability' figure for software.

For the purpose of this analysis, it will be assumed that each line of code is a unit and that each unit is equally likely to fail in a given time period. Obviously, certain segments of a software system will be better designed, more thoroughly tested, less complicated, and less failure prone than other segments. From an overall system viewpoint, however, the assumption of equally reliable lines of code all operating in series from a reliability analysis viewpoint, is both workable and reasonable. The mathematics of hardware reliability may be directly applied to software if this assumption is made, and statistics from existing software indicates that longer programs tend to have more errors.

Perhaps the most troublesome issue involved in treating hardware and software failures as equivalent events is the fact that software errors do not recur once they are repaired. Hardware failures are related to wearout and tend to repeat themselves on identical units. It is not necessary to become involved in failure modes to count failures, however, The fact that software failures are unique and could theoretically be reduced to zero additional failures after all problems have been corrected, whereas, hardware problems recur, may be ignored during any finite period of the system's life simply by putting the two failure phenomena on an equivalent basis, namely failures per hour during a portion of the steady-state working life of the system.

Some definitions follow which allow software failure probability to be modeled in a manner similar to hardware reliability modeling.

$F(t)$ = Probability Distribution Function

= Probability that a given line of code will have failed by time 't'

$$= \frac{\text{Number of failed lines* prior to time t}}{\text{Total number of lines}}$$

$R(t)$ = Reliability or Probability of success

= Probability that a given line of code will <u>not</u> have failed by time 't'.

$$= \frac{\text{Number of non-failed lines* prior to time t.}}{\text{Total number of lines}}$$

$$= \frac{n(t)}{N}$$

$$f(t) = \frac{d\,F(t)}{dt} = \text{Failure Density Function}$$

$$= \frac{\text{Number of failed lines/Number of hours}}{\text{Total number of lines}}$$

$n(t)$ = Number of never failed lines (number of survivors)

= Total number of lines - Number of failures

N = Total number of lines

The failure density function will be assumed to be exponential. This corresponds to the decrease in the failure rate experienced as errors are removed from new software. Also, an equivalent hazard rate, $z(t) = \lambda$, is chosen and set equal to a constant, λ. The following equations which were derived for hardware reliability (Shooman) result:

$$z(t) = \lambda$$

$$f(t) = \lambda e^{-\lambda t}$$

---

*A line which fails, is repaired, then fails again would count as two failed lines, so that the F(t) numerator is simply the total number of failures prior to time, t.

$$R(t) = e^{-\lambda t}$$

Although it may be argued that the hazard rate has no physical meaning for software since the number of surviving lines remains constant after repair, it is quite useful as a psuedo-hazard rate which serves as a parameter to establish the time constant for f(t). Note that for $R(t) \cong 1$, $z(t) \cong f(t)$. This will be the case for good software during the operations phase of its life.

Since:

$$\int_0^\infty f(t)dt = \int_0^\infty \lambda e^{-\lambda t} dt = 1$$

it is clear that this model implies that every line of code is expected to eventually fail, just as every hardware component is expected to eventually fail. Data from several sources (2, 4, 5) indicate that the total number of failures expected over the life of a software system is only a small fraction of the total number of lines of code in the system. Accordingly, an appropriate form for the failure density function is:

$$f(t) = K_i \int_0^t \lambda e^{-\lambda t} \, dT + K_2 \cdot \delta(\infty)$$

where: $0 < K_1 \leq 1$

$0 \leq K_2 < 1$

$\delta(t)$ = dirac delta function

$\delta(\infty)$ = impulse at $t = \infty$

This form for the failure density function incorporates the idea that many lines will never fail, that is, they will fail at time = ∞. Schick and Wolverton (2) recorded approximately 1200 errors in 65,000 lines of code. This suggests a value of K_1 of .018 and a value of K_2 of .982. The software studied by Schick and Wolverton did not have such a simple form for its failure density curve, but this approach suggests a failure density curve of the form shown in Figure 1.

A range of values for z(t) which corresponds to good to extremely high quality software is needed. Schick and Wolverton (2) report an error rate during the operations phase of a large software system of .025 errors per 1000 lines of code per week. This corresponds to $.1488 \times 10^{-6}$ errors/line/hour. The Bell Telephone System's Electronic Switching System has proved to have one of the most reliable software packages for which recorded data is available. It was designed to have only one and one-half hours of downtime in forty years. Assuming that this represents a single failure in forty years for 65,000 lines of code, we get a rough upper bound on software quality based on previous data of:

$$\text{Failure Rate} = \frac{1 \text{ failure}}{(40 \text{ years})(365 \text{ days/year})(24 \text{ hours/day})(65{,}000 \text{ lines})}$$

$$= 4 \times 10^{-11} \text{ failures/line/hour}$$

Note that the upper bound on system failure rate for the ESS

system under these assumptions is:

$$\text{Failure Rate} = \frac{1 \text{ Failure}}{(40 \text{ years})(365 \text{ days/year})(24 \text{ hrs/day})}$$

$$= \frac{2.8 \times 10^{-6} \text{ failures}}{\text{hr./65000 lines.}}$$

This does not approach 10^{-9} failures/hour.

Integrated Hardware/Software Functional Model

An investigation into the role of Petri net-like models as tools to aid in design and analysis of high reliability systems (14) indicated that a great deal of information can be obtained by using such graphs for modeling and simulation of hardware/software systems. The ability of such models to reflect the performance of both hardware and softward make them a prime candidate for use as a common language between hardware and software professionals. It was clearly determined that co-ordination of parallel events such as must occur when multiple processors and systems incorporating redundant hardware or software are simulated or analyzed can be handled by Petri net-like models.

A Graphic Model of Behavior (14) simulation model of a microprocessor was developed early in this project. This model simulates the timing and functions of the hardware during the execution of assembly language instructions, and as such represents a subgraph of the software model. This model includes the information present on a hardware timing diagram and incorporates a data graph which represents the data on the microprocessor pins. A similar model could be obtained for any

computer system.

The results in this study are based on the time domain software reliability model developed in the previous section, but a few conclusions regarding Petri net-like models may be drawn. Such graphs are more useful for simulation and performance analysis than for the reliability analysis of existing hardware/software systems. They could also be useful in optimizing the reliability of a system being designed if introduced prior to the choice of the hardware/software boundary. Their application to complete system modeling (hardware and software) is quite feasible, but results in a very detailed simulation. Levels of abstraction are needed.

Effects of Incorporating Software Redundancy

Assuming that extremely high reliability is required for a system, two alternatives present themselves:

1. Use modern software design, development, and validation procedures to improve the per line failure rate of software (15)

2. Incorporate redundancy in the software system then improve the overall system reliability.

Since additional experience is required to quantify the effects of making maximum use of modern software development tools, the effects of software redundancy are investigated here. Obviously, such an alternative is cost effective only if the penalty for a single software failure is extremely high.

To evaluate the general range of software reliability which could be expected from a non-redundant and from a triple-modular-redundant software avionic system, a hypothetical 100,000 line system was broken into modules which ranged in

length from one line per module to 10,000 lines per module. The psuedo-hazard rate for each line was varied from 9.52 x 10^{-6} failures/line/hour to 1.16 x 10^{-12} failures/line/hour, and the reliability of each module was calculated by assuming that all lines are in series from a reliability analysis standpoint. For an N line module which has hazard rate of Z errors/line per hour, the hazard rate for the module is $N \cdot Z$, and the reliability of the module is $R(t) = e^{-N \cdot Zt}$. If three software modules are designed and developed for the same software specification, then connected to a 2-out-of-3 voter, the reliability (10) of the TMR module is $R^2(3-2R)$. The overall system reliability is obtained by treating all modules as if they were in series from a reliability analysis viewpoint. The system reliability is therefore the reliability of one module, whether redundant or not, raised to an integer power equal to the number of modules. These equations appear in the Fortran programs in Figures 7 and 8. The variables in the program are defined in Table 19.

Figure 2 shows the probability of failure as a function of the failure rate per line for a hypothetical system which consists of 100,000 lines of non-redundant code. The non-redundant curve shows that even with per line reliability equivalent to the ESS system ($\cong 10^{-11}$ failures/line/hour), the system reliability is only approximately 10^{-6} failures per hour. This, of course, is far below the quality of ultra-reliable avionic computer hardware (10^{-9} failures/hour). Clearly, either improved software quality on a per line basis or software redundancy is required to achieve software system proba-

bility of failure in the neighborhood of 10^{-9}/hour.

The other three curves represent total software system reliability assuming that each module is triple redundant. Various module lengths are used, but the 100 line/module curve is near the appropriate length for most software modules. It would probably prove more practical to design redundancy into software on the basis of much larger system subsets, however. The range of per line reliability required to achieve a total software system reliability in the neighborhood of 10^{-9} failures/hour is seen to be from approximately 10^{-9} to 10^{-8} failures/line/hour. This level of software quality has already been achieved, therefore, one conclusion which can be drawn from this graph is that an overall software system reliability of 10^{-9} failures/hour can be achieved if the cost of developing triple modular redundant software can be accepted, and if the design specification from which all three independent software teams work can be assumed to be perfect. This last assumption is a little difficult to defend.

It may also be observed from Figure 2 that the triple-modular-redundant system reliability improves as the length of each module is decreased. This result is analogous to the higher system reliability (Shooman) achieved by component redundancy versus system redundancy for hardware systems. It is certainly absurd to consider software redundancy on a per line basis, however, even though this appears to be the optimum strategy according to Figure 2. The reasonable conclusion is that if redundancy is employed for software, the length of the code in a redundant unit should be as short as possible

consistent with retaining the independence of the software design and development teams. Redundant units with lengths between 100 lines and 10,000 lines, depending on the system, appear useful.

Figures 3 and 4 show the reliability of a single module with no software redundancy and with TMR respectively. The obvious information here is that module reliability improves as module length decreases. The quantitative information shows that, for instance, a 10,000 line module (or complete program) with a failure/line/hour of 10^{-9} will result in 10^{-5} failures per line per hour for the module with no redundancy. For an equivalent TMR system with the same failure/line/hour, a 10,000 line TMR module is seen to exhibit better than a 10^{-9} system reliability. For a 10,000 line system with system, not module, redundancy, this would meet the avionic hardware reliability standards. Figure 5 also shows that module length does not affect system reliability for non-redundant code under the assumptions of this study. That it is impossible to achieve high quality software with excessively long or excessively short modules has been amply documented elsewhere. Figure 6 shows that even for non-redundant software, a long module is less reliable than a short module, simply because each line of code adds another component which may fail.

Figures 5 and 6 repeat the information in Figures 2, 3, and 4 in a different form. The independent variable here is module length and the various curves represent various per line failure rates. Once again, it is seen that ignoring the very real problem of maintaining program team independence

when redundant code segments become short, many short TMR modules result in higher system reliability than a few long TMR modules.

Conclusions

1. Hardware and software are in series for reliability analysis purposes.

2. Software has been assumed to have R=1 for ultra reliable digital system design.

3. Time domain software measures are independent of the programmer's judgement, therefore are a form of independent review and are valid as a software quality measure.

4. Although time domain software measures are difficult to apply as predictors of reliability for a particular system, they are quite useful for an assessment of what has been achieved and what can be achieved when we look back at data gathered over the life span of existing systems.

5. The assumption that each line of code in a software system is equally likely to fail has some reliability modeling validity from both the evidence of empirical data and from the viewpoint of abstraction of stochastic events.

6. Hardware and software failures may be treated as equivalent from a reliability viewpoint if the basis for computing reliability is a simple count of all system failures.

7. A credible failure density function for a single line of software is a weighted exponential with a weighted impulse at $t=\infty$. The impulse at infinity will carry most of the failure probability.

8. The range of failures/line/hour for previous software includes at least the range of 10^{-7} to 10^{-11}.

9. The upper limit of software reliability which can be achieved using modern software design and development methodology remains to be determined.

10. Even the best software previously developed, may not measure up to the 10^{-9} failures/hour needed for avionic systems.

11. Triple Modular Redundant software, though more expensive, can yield system reliability in the 10^{-9} range with software which is no better on a per-line basis than that

which has been previously documented.

12. Redundancy involving many small software modules yields higher reliability than redundancy involving a few large modules. This effect is limited by the inability to retain design independence for various software teams when the size of redundant modules becomes small.

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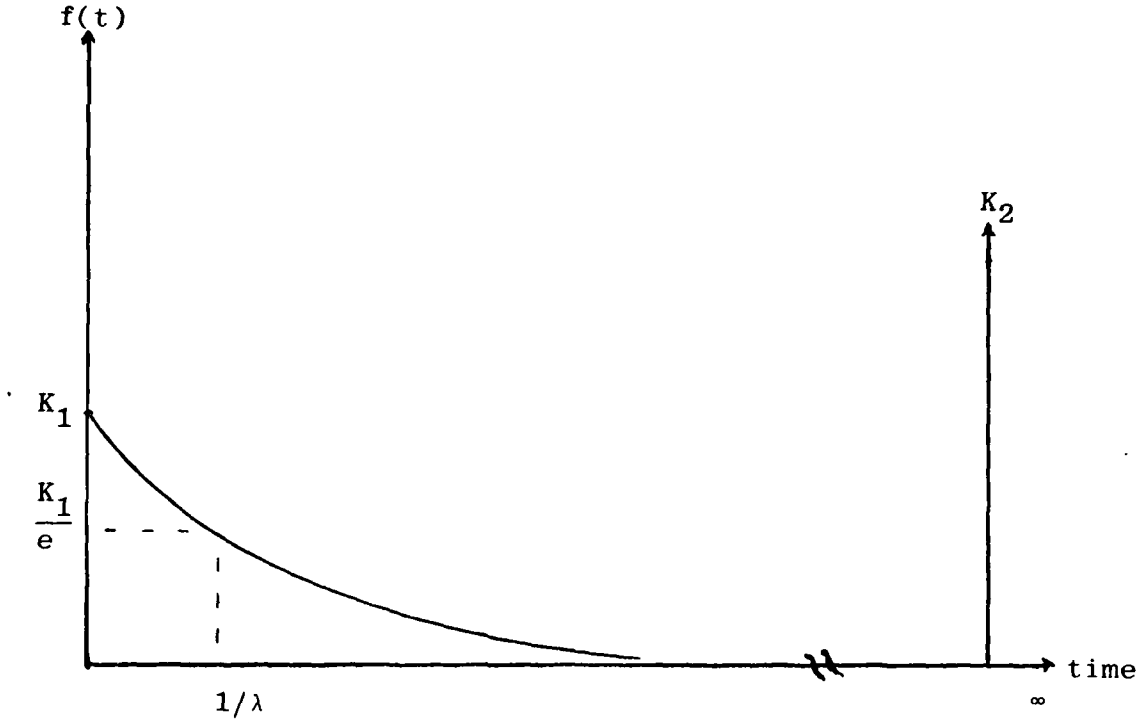

Figure 1. Failure Density Function for a Single Line of Computer Code

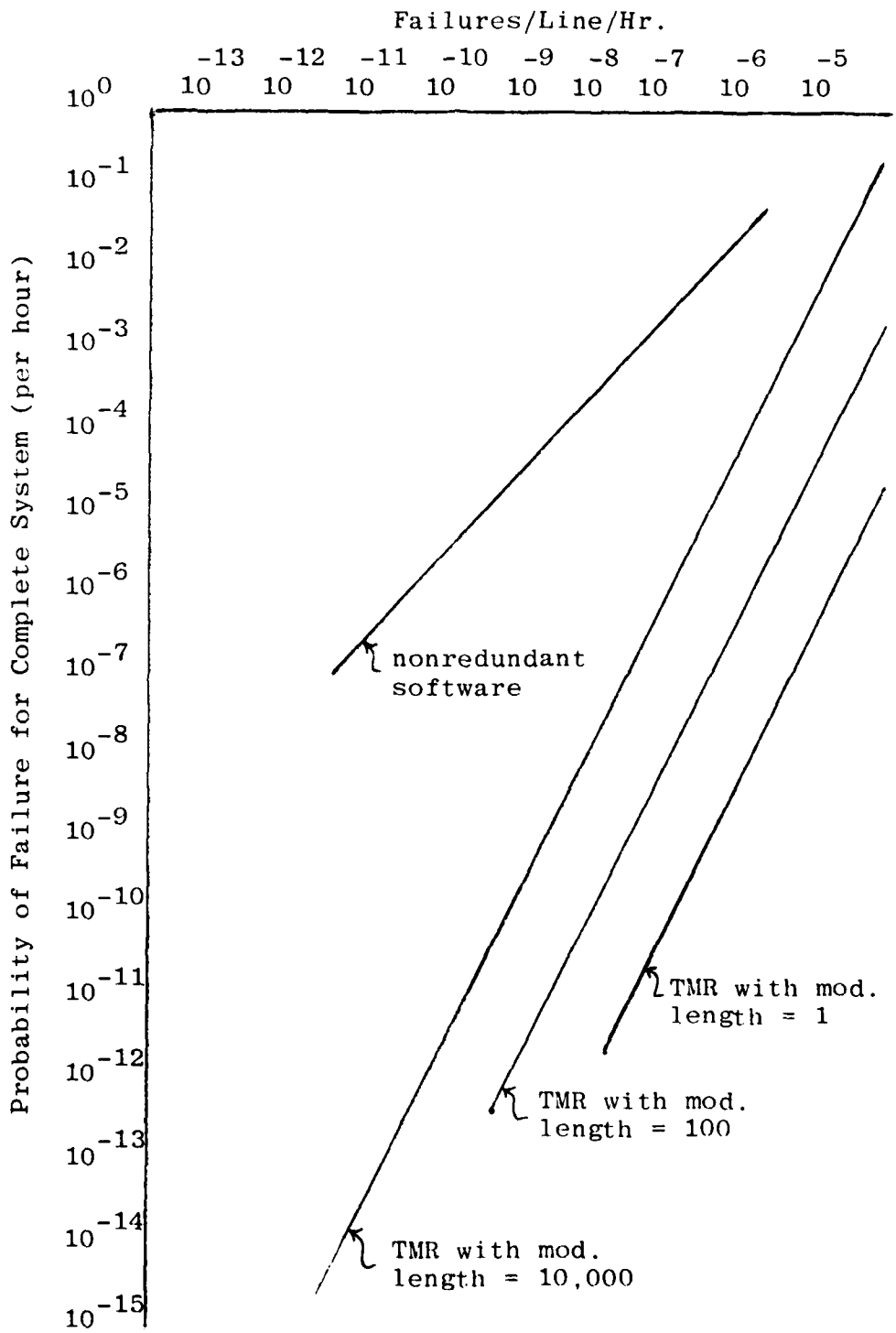

Figure 2. Probability of Failure for Complete System versus Failures/Line/Hour

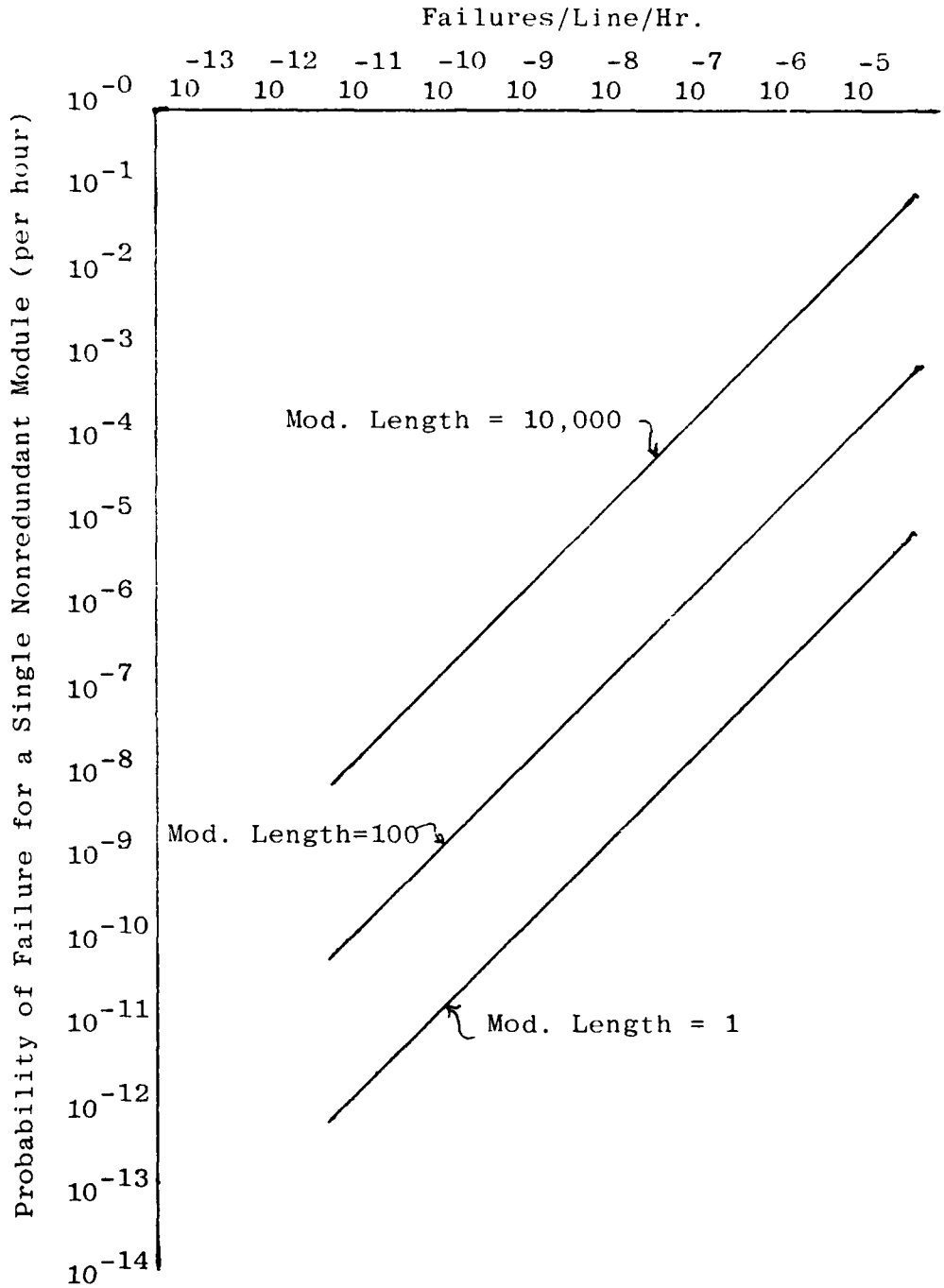

Figure 3. Probability of Failure for a Single Non-redundant Module versus Failures/Line/Hour

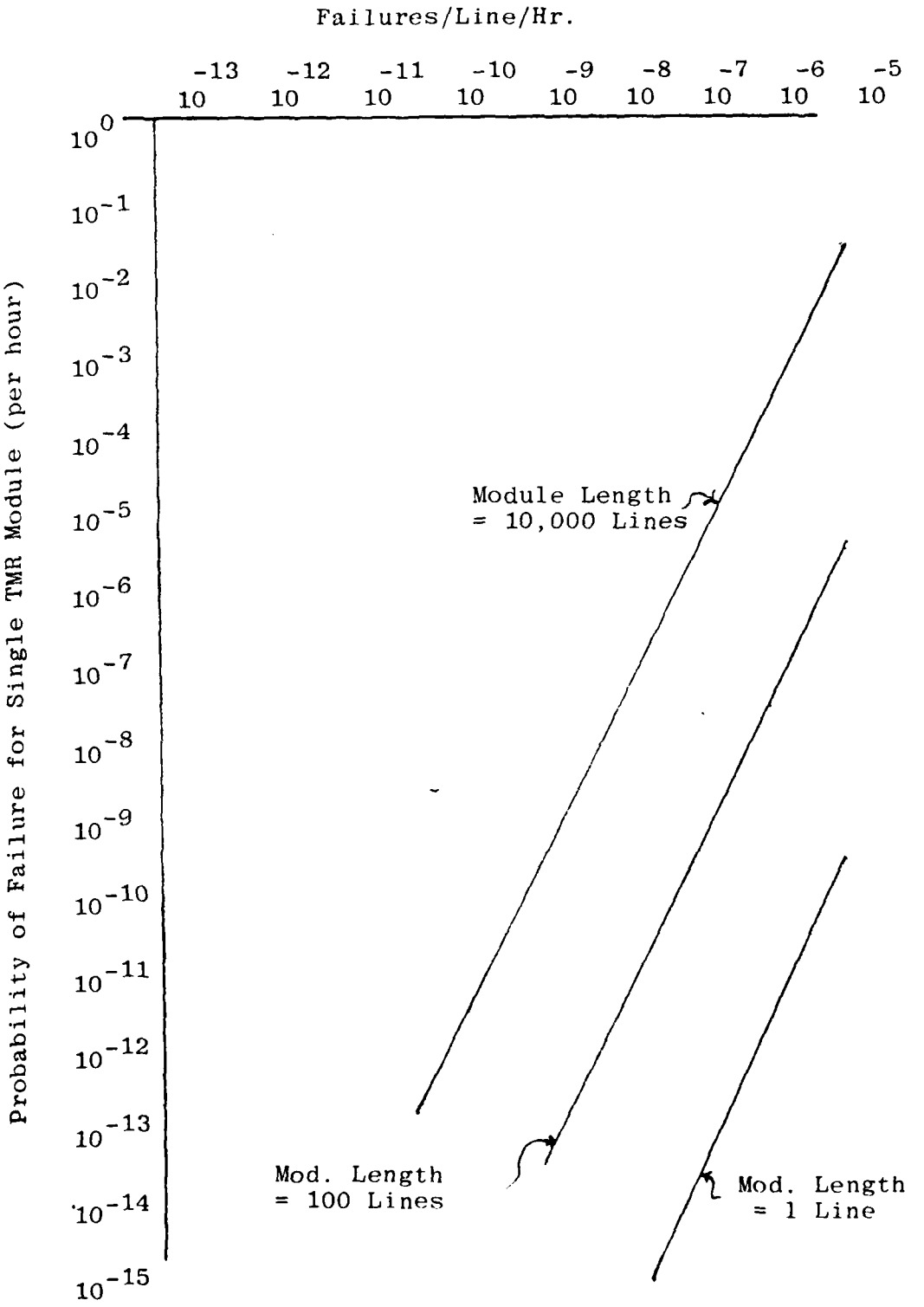

Figure 4. Probability of Failure for Single TMR Module versus Failures/Line/Hour

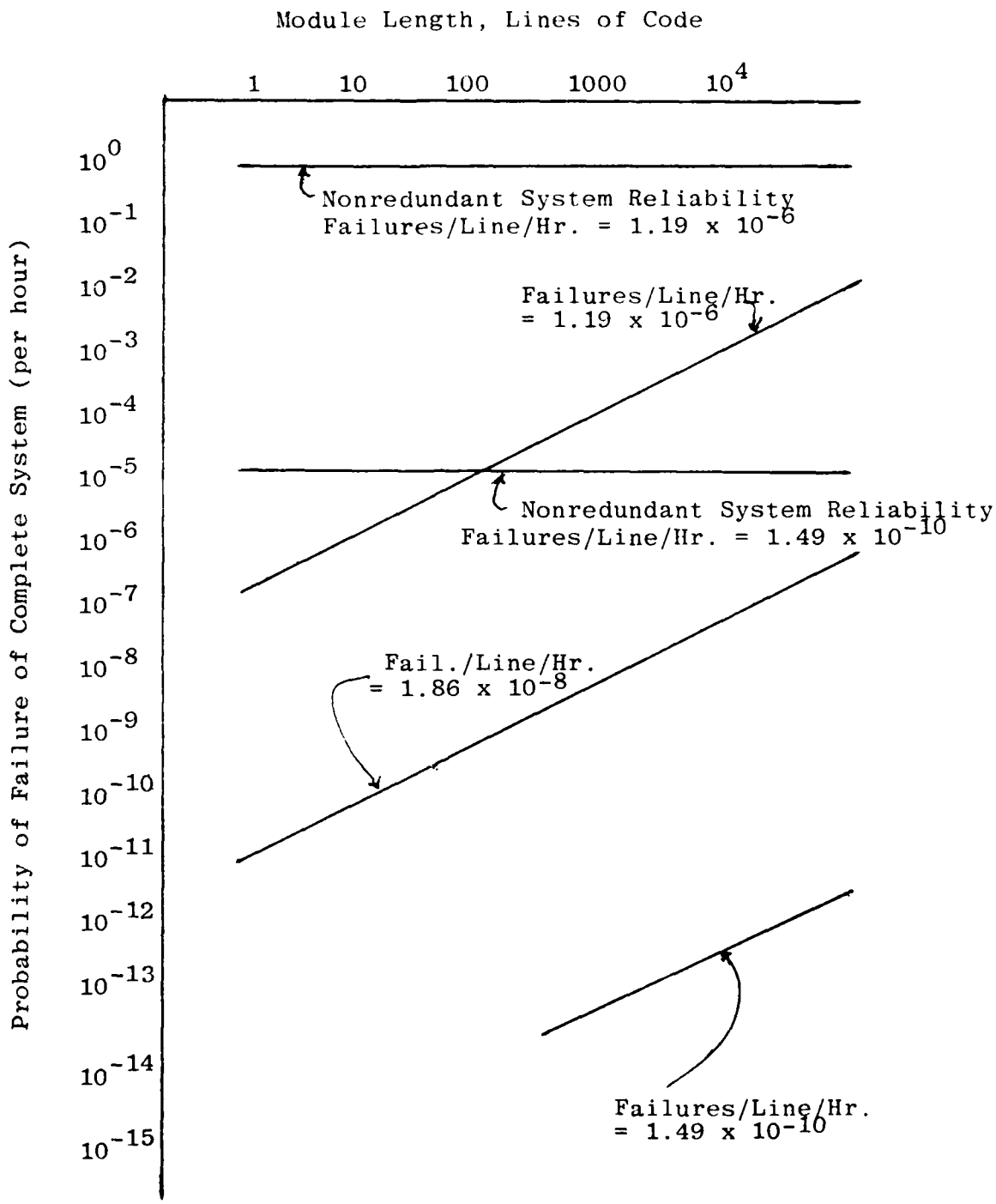

Figure 5. Probability of Failure of Complete System versus Module Length

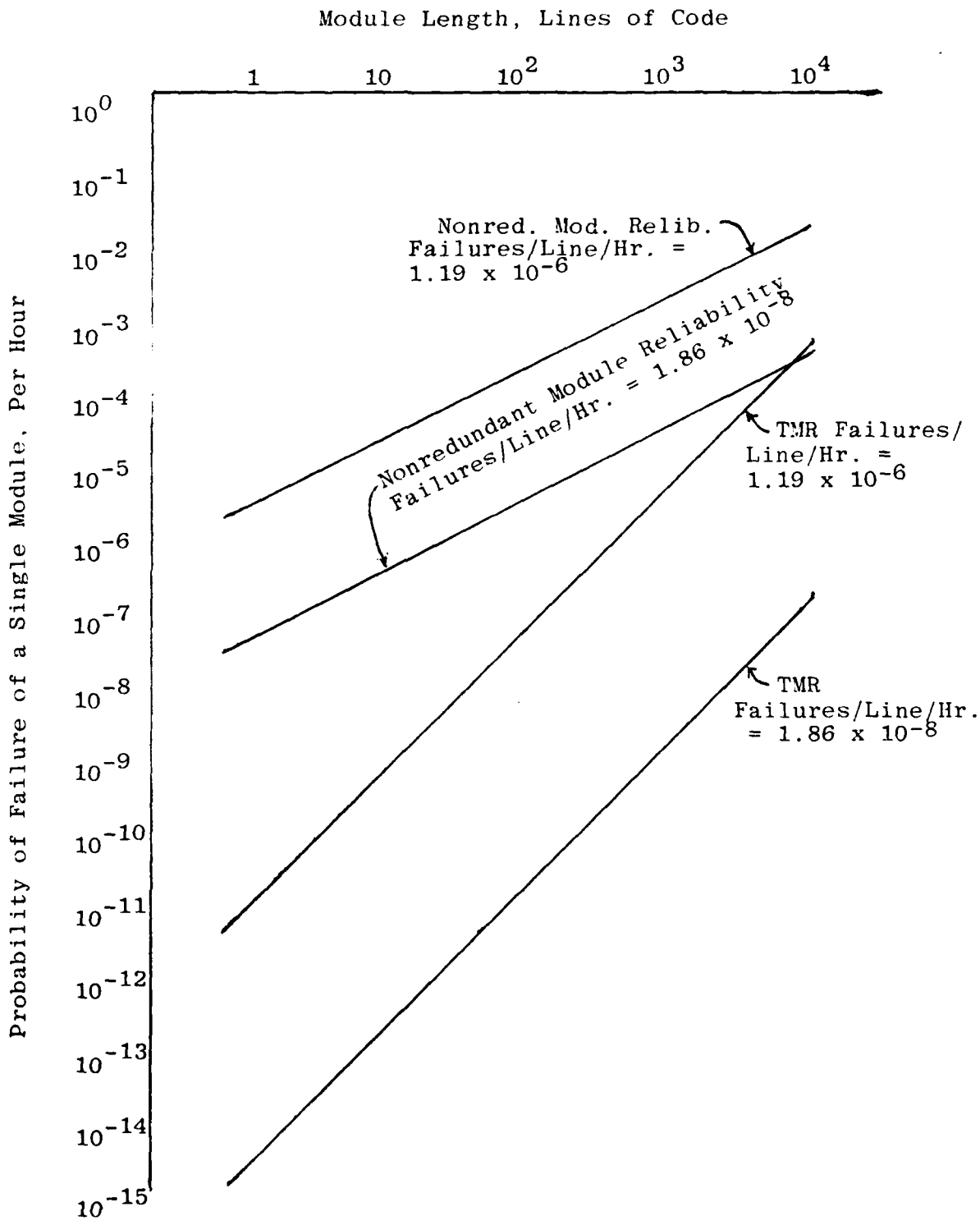

Figure 6. Probability of Failure of a Single Module versus Module Length

```
      DO 2 J=1,9
      ELAM1=3.72D-6/2.5D1
      ELAM1=ELAM1/1.28D2
      GO TO (10,20,30,40,50,60,70,80,90),J
10    ALINES=1
      GO TO 200
20    ALINES=10
      GO TO 200
30    ALINES=25
      GO TO 200
40    ALINES=50
      GO TO 200
50    ALINES=100
      GO TO 200
60    ALINES=500
      GO TO 200
70    ALINES=1000
      GO TO 200
80    ALINES=5000
      GO TO 200
90    ALINES=10000
      GO TO 200
200   WRITE(7,101)
101   FORMAT(1X,///,'   FAIL/LINE/HR    ','  NONRED RELIB/MOD  ',
     1 '   THR RELIB/MOD    ','    SYSTEM RELIB    ',
     1 '  NONREDUN SYS RELIB  ','ER/100K/MO','  NUMMOD  ',/)
      DO 1 I=1,14
      ELAMDA=ELAM1*ALINES
      PROB=DEXP(-ELAMDA)
      R1MOD=PROB*PROB*(.3D1-.2D1*PROB)
      ANUMMD=1.0D5/ALINES
      RNONRD=PROB**ANUMMD
      RSYS=R1MOD**ANUMMD
      SERRMO= (ELAMDA/ALINES) *1.0D5*2.4D1*3.0D1
      P1=.1D1-PROB
      R1=.1D1-R1MOD
      RS=.1D1-RSYS
      RN=.1D1-RNONRD
      WRITE(7,100)ELAM1,P1,R1,RS,RN,SERRMO,ANUMMD
100   FORMAT(1X,5D21.14,2D10.2)
      ELAM1=ELAM1*.20D1
1     CONTINUE
2     CONTINUE
      STOP
      END
```

Figure 7. Fortran Program for Calculating Failure Rates in Tables 1 through 9.

```
      DOUBLE PRECISION ELAMDA, PROB,R1MOD,RSYS,ANUMMD,SERRMO,ALINES,RNONRD
      DOUBLE PRECISION P1,R1,RS,RN
      DO 2 J=1,9
      ELAM1=3.72D-6/2.5D1
      ELAM1=ELAM1/1.28D5
      GO TO (10,20,30,40,50,60,70,80,90),J
10    ALINES=1
      GO TO 200
20    ALINES=10
      GO TO 200
30    ALINES=25
      GO TO 200
40    ALINES=50
      GO TO 200
50    ALINES=100
      GO TO 200
60    ALINES=500
      GO TO 200
70    ALINES=1000
      GO TO 200
80    ALINES=5000
      GO TO 200
90    ALINES=10000
      GO TO 200
200   WRITE(7,101)
101   FORMAT(1X,///,'    FAIL/LINE/HR    ','  NONRED RELIB/MOD  ',
     1 '   THR RELIB/MOD    ','    SYSTEM RELIB    ',
     1 '  NONREDUN SYS RELIB  ','ER/100K/MO','  NUMMOD  ',/)
      DO 1 I=1,14
      ELAMDA=ELAM1*ALINES
      PROB=DEXP(-ELAMDA)
      R1MOD=PROB*PROB*(.3D1-.2D1*PROB)
      ANUMMD=1.0D5/ALINES
      RNONRD=PROB**ANUMMD
      RSYS=R1MOD**ANUMMD
      SERRMO= (ELAMDA/ALINES) *1.0D5*2.4D1*3.0D1
      P1=.1D1-PROB
      R1=.1D1-R1MOD
      RS=.1D1-RSYS
      RN=.1D1-RNONRD
      WRITE(7,100)ELAM1,P1,R1,RS,RN,SERRMO,ANUMMD
100   FORMAT(1X,5D21.14,2D10.2)
      ELAM1=ELAM1*.20D1
1     CONTINUE
2     CONTINUE
      STOP
      END
```

Figure 8. Fortran Program for Calculating Failure Rates for Tables 10 through 18.

Table 1. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 100,000 modules of 1 line each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116249998516340D-08	.116249998186299D-08	.000000000000000D+01	.138758449175210D-11	.116229057312010D-03	.84D-01	.10D+06
.232499997032360D-08	.232499998037933D-08	.000000000000000D+01	.138758449175210D-11	.232315811462402D-03	.17D+00	.10D+06
.464999994065350D-08	.464999997412010D-08	.932667268468870D-16	.111021331017370D-10	.464916229248050D-03	.33D+00	.10D+06
.929999988130700D-08	.929999963150690D-08	.249800180540660D-15	.374698883032210D-10	.929554039916990D-03	.67D+00	.10D+06
.185999997626140D-07	.185999994017920D-07	.106658966120170D-14	.100246620000860D-09	.185829401016240D-02	.13D+01	.10D+06
.371999995252280D-07	.371999986643050D-07	.416333634234430D-14	.426047933044240D-09	.371307134628330D-02	.27D+01	.10D+06
.743999990509560D-07	.743999961222430D-07	.165423230669150D-13	.166741603857550D-08	.741237401962260D-02	.54D+01	.10D+06
.148799995100910D-06	.148799986873780D-06	.663635812969690D-13	.664052129950580D-08	.147698052161407D-01	.11D+02	.10D+06
.297599996201820D-06	.297599951737390D-06	.265704125368420D-12	.265815142397320D-07	.293215513229370D-01	.21D+02	.10D+06
.595199992403650D-06	.595199815114910D-06	.106273323474680D-11	.106279562664400D-06	.577333056449890D-01	.43D+02	.10D+06
.119039998480730D-05	.119039927612420D-05	.425114686138000D-11	.425125816175260D-06	.112227737903590D+00	.86D+02	.10D+06
.238079996961460D-05	.238079713535400D-05	.170045783010050D-10	.170046679250080D-05	.211860358715060D+00	.17D+03	.10D+06
.476159993922920D-05	.476158860268640D-05	.680179940149020D-10	.680177765689790D-05	.378835916519170D+00	.34D+03	.10D+06
.952319987845840D-05	.952315453275900D-05	.272069713980190D-09	.272066089241210D-04	.614155173301700D+00	.69D+03	.10D+06

Table 2. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 10,000 modules of 10 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116249998516340D-08	.116249996018340D-07	.416333634234430D-15	.457950344312510D-11	.116229057312010D-03	.84D-01	.10D+05
.232499997032680D-08	.232499993008120D-07	.155431223447520D-14	.159593310789860D-10	.232458114624020D-03	.17D+00	.10D+05
.464999994065350D-08	.464999981714120D-07	.645317133063370D-14	.646009495897100D-10	.464916229248050D-03	.33D+00	.10D+05
.929999988130700D-08	.929999943166670D-07	.259653409884210D-13	.260555299558260D-09	.929594039916990D-03	.67D+00	.10D+05
.185999997626140D-07	.185999920167880D-06	.103819730590260D-12	.103889102875950D-08	.185829401016240D-02	.13D+01	.10D+05
.371999995252280D-07	.371999925932730D-06	.415126268695150D-12	.415209518156430D-08	.371307139628300D-02	.27D+01	.10D+05
.743999990504560D-07	.743999713628820D-06	.166057445571970D-11	.166059524325800D-07	.741237401962280D-02	.54D+01	.10D+05
.148799998100910D-06	.148799587332530D-05	.664235333402980D-11	.664246412179770D-07	.147698521614070D-01	.11D+02	.10D+05
.297599996201820D-06	.297599553358840D-05	.265696076251490D-10	.265697012266660D-06	.293215513229370D-01	.21D+02	.10D+05
.595199992403650D-06	.595198221074730D-05	.106277792122360D-09	.106277798082870D-05	.577833056449890D-01	.43D+02	.10D+05
.119039998480730D-05	.119039289955550D-04	.425107199442110D-09	.425106406867770D-05	.112227737903590D+00	.86D+02	.10D+05
.238079996961460D-05	.238077162877940D-04	.170039507474410D-08	.170038072911660D-04	.211860358715060D+00	.17D+03	.10D+05
.476159993922920D-05	.476148657684030D-04	.680131043151460D-08	.680107930027120D-04	.378835916519170D+00	.34D+03	.10D+05
.952319987345840D-05	.952274643615520D-04	.272030828144120D-07	.271993835272380D-03	.614155173301700D+00	.69D+03	.10D+05

Table 3. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 4000 modules of 25 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116249998516340D-08	.290624990878510D-07	.247024622979100D-14	.100473518394040D-10	.116229057312010D-03	.840D-01	.400D+04
.232499997032680D-08	.581249974540570D-07	.101446628875120D-13	.408283139527120D-10	.232458114624020D-03	.170D+00	.400D+04
.464999994065350D-08	.116249991619080D-06	.405092626110100D-13	.162203431242070D-09	.464916229248050D-03	.330D+00	.400D+04
.929999988130700D-08	.232499969873850D-06	.162120317170390D-12	.648592166085930D-09	.929594037916990D-03	.670D+00	.400D+04
.185999997626140D-07	.464999885790850D-06	.648717191076290D-12	.259517392298130D-08	.125829401016240D-02	.130D+01	.400D+04
.371999995252280D-07	.929999555546180D-06	.259466059748800D-11	.103787809874190D-07	.371307134628300D-02	.270D+01	.400D+04
.743999990504560D-07	.185999824629800D-05	.103786979011030D-10	.415149571525440D-07	.741237401962280D-02	.540D+01	.400D+04
.148799998100910D-06	.371999360321050D-05	.415149026267160D-10	.166059985123870D-06	.147698521614070D-01	.110D+02	.400D+04
.297599996201820D-06	.743997222817090D-05	.166058708450660D-09	.664235001626710D-06	.293215513229370D-01	.210D+02	.400D+04
.595199992403650D-06	.148798891032860D-04	.664226701418970D-09	.265690366449410D-05	.577833056449890D-01	.430D+02	.400D+04
.119039998480730D-05	.297595567956690D-04	.265684088618380D-08	.106273074906570D-04	.112277737903590D+00	.860D+02	.400D+04
.238079996961460D-05	.595182279601870D-04	.106268366883990D-07	.425064440505860D-04	.211560355715060D+00	.170D+03	.400D+04
.476159993922920D-05	.119032913501100D-03	.425031303763480D-07	.169998074080590D-03	.378835916519170D+00	.340D+03	.400D+04
.952319987845840D-05	.238051658167860D-03	.169978795719340D-06	.679684151006750D-03	.614155173301760D+00	.670D+03	.400D+04

Table 4. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 2000 modules of 50 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116249999851634D-08	.581249974540570D-07	.101446628875120D-13	.204140870874170D-10	.116229057312010D-03	.84D-01	.20D+04
.232499997032680D-08	.116249991619080D-06	.405092626110100D-13	.811016392932020D-10	.232458114624020D-03	.17D+00	.20D+04
.464999994065350D-08	.232499969873850D-06	.162120317170890D-12	.324295951203780D-09	.464916229248050D-03	.33D+00	.20D+04
.929999988130700D-08	.464999385790850D-06	.648717191076290D-12	.129758684352940D-08	.929594039916990D-03	.67D+00	.20D+04
.185999997626140D-07	.929999555546180D-06	.259466059748800D-11	.518939043125940D-08	.185829401016240D-02	.13D+01	.20D+04
.371999995252280D-07	.185999824627800D-05	.103786979011030D-10	.207574787081110D-07	.371307134628300D-02	.27D+01	.20D+04
.743999990504560D-07	.371999303321050D-05	.415149026267160D-10	.830299959481140D-07	.741237401962280D-02	.54D+01	.20D+04
.148799998100910D-06	.743997222817090D-05	.166058708450660D-09	.332117555845720D-06	.147698521614070D-01	.11D+02	.20D+04
.297599996201820D-06	.148798891032860D-04	.664226701418970D-09	.132845271459680D-05	.292215513229370D-01	.21D+02	.20D+04
.595199992403650D-06	.297595567956690D-04	.265684083618330D-08	.531366786277190D-05	.577633056449690D-01	.43D+02	.20D+04
.119039998807300D-05	.595182279601870D-04	.106268366883990D-07	.212534478797040D-04	.112227737903590D+00	.86D+02	.20D+04
.238079996241460D-05	.119032913501100D-03	.425031303763480D-07	.850026497654780D-04	.211860358715060D+00	.17D+03	.20D+04
.476159993522920D-05	.238051658167860D-03	.169978795719340D-06	.339899891454410D-03	.378835916519170D+00	.34D+03	.20D+04
.952319987845840D-05	.476046647743890D-03	.679645463709690D-06	.135836798135750D-02	.614155173301700D+00	.69D+03	.20D+04

Table 5. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 1000 modules of 100 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116249999516340D-08	.116249991619030D-06	.405092626110100D-13	.405507433187680D-10	.116229957312010D-03	.84D-01	.10D+04
.232499997032680D-08	.232499969873850D-06	.162120317170890D-12	.162147906213050D-09	.232458114624020D-03	.17D+00	.10D+04
.464999994065350D-08	.464999885790850D-06	.648717191076290D-12	.648793352375780D-09	.464916229248050D-03	.33D+00	.10D+04
.929999998130700D-08	.929999555546180D-06	.259466059748800D-11	.259469509766850D-08	.929594039916990D-03	.67D+00	.10D+04
.185999997626140D-07	.185999824629800D-05	.103786979011030D-10	.103787393818110D-07	.185829401016240D-02	.13D+01	.10D+04
.371999995252280D-07	.371999303321050D-05	.415149026267160D-10	.415149998772030D-07	.371307134628300D-02	.27D+01	.10D+04
.743999990504560D-07	.743997222817090D-05	.166058708450660D-09	.166058791675750D-06	.741237401962280D-02	.54D+01	.10D+04
.148799998100910D-06	.148798891032860D-04	.664226701418970D-09	.664226577809510D-06	.147698521614070D-01	.11D+02	.10D+04
.297599996201820D-06	.297595567956690D-04	.265684088618380D-08	.265683748070170D-05	.293215513229370D-01	.21D+02	.10D+04
.595199992403650D-06	.595182279601870D-04	.106268366883990D-07	.106267604040190D-04	.577833056449890D-01	.43D+02	.10D+04
.119037998480730D-05	.119032913501100D-03	.425031303763480D-07	.425022231023420D-04	.112227737902590D+00	.86D+02	.10D+04
.238079996961460D-05	.238051658167850D-03	.169978795719340D-06	.169964364669730D-03	.211860358715060D+00	.17D+03	.10D+04
.476159993922920D-05	.476046647743890D-03	.679643468709690D-06	.679414792909030D-03	.378835916519170D+00	.34D+03	.10D+04
.952319987845840D-05	.951866675077110D-03	.271642562342520D-05	.271274315736380D-02	.614155173301700D+00	.69D+03	.10D+04

Table 6. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 200 modules of 500 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116249999516340-08	.581249823522460-06	.101359198811930-11	.202737659993350-09	.116229057312010-03	.840-01	.200+03
.232499997032680-08	.116249930928740-05	.405424305238710-11	.810851191745950-09	.232453114624020-03	.170+00	.200+03
.464999994065350-08	.232499726735000-05	.162160056760950-10	.324337069701470-08	.464916229210050-03	.330+00	.200+03
.929999983130700-08	.464998912926010-05	.648669867819860-10	.129734124137970-07	.929594009916990-03	.670+00	.200+03
.185999997626140-07	.929995663630220-05	.259465920970920-09	.518931924227130-07	.185829401016240-02	.130+01	.200+03
.371999995252280-07	.185998267835110-04	.103784780769440-08	.207569567803460-06	.371307134628300-02	.270+01	.200+03
.743999990504560-07	.371993076136170-04	.415126254205140-08	.830252167807740-06	.741237401982280-02	.540+01	.200+03
.148799993100910-06	.743972314390520-04	.166040205196170-07	.332079863847590-05	.147698531614070-01	.110+02	.200+03
.297599996261820-06	.148788927930100-03	.664078474155170-07	.132814817495610-04	.293215513229370-01	.210+02	.200+03
.595199992403650-06	.297555717715340-03	.265565524640300-06	.531117015125090-04	.577833056449890-01	.430+02	.200+03
.119039998490730-05	.595022896025670-03	.106173540202760-05	.212324649067920-03	.112227737903590+00	.860+02	.200+03
.238079996561460-05	.118968173980480-02	.424273160772040-05	.849188206490300-03	.211868358715060+00	.170+03	.200+03
.476159993922920-05	.237796811317390-02	.169373034953350-04	.339175831758750-02	.378835916519170+00	.340+03	.200+03
.952319987845840-05	.475028149400050-02	.674811409572400-04	.134860117300030-01	.614155173301700+00	.680+03	.200+03

Table 7. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 100 modules of 1000 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116249998516340-08	.116249930928740-05	.405424305238710-11	.405425526484040-09	.116229057312010-03	.840-01	.100+03
.232499997032680-08	.232499726705000-05	.162168056760950-10	.162168528805730-08	.232453114624020-03	.170+00	.100+03
.464999994065350-08	.464599812926010-05	.648269867819860-10	.648670615832620-08	.464916229248050-03	.230+00	.100+03
.929999988130700-08	.929995663630220-05	.259465526970920-09	.259465964547180-07	.929594039916990-03	.670+00	.100+03
.185999997626140-07	.185998267835110-04	.103784780769440-08	.103784789123870-06	.185829401016240-02	.130+01	.100+03
.371999995252280-07	.371973076136170-04	.415126254205140-08	.415126170608610-06	.371307134628300-02	.270+01	.100+03
.743999990504560-07	.743972314390520-04	.166040205196170-07	.166040069760070-05	.741237401962260-02	.540+01	.100+03
.148799998100910-06	.148786927930100-03	.664078674155170-07	.66[illegible]591D-05	.147698521614070-01	.110+02	.100+03
.297599996201820-06	.297553717715340-03	.265865524640300-06	.265962033721770-04	.293215513229370-01	.210+02	.100+03
.595199992403650-06	.595022398025670-03	.106173540202760-05	.106167960351800-03	.577853056449890-01	.430+02	.100+03
.119039998480730-05	.118969173980480-02	.424273160772040-05	.424184069307400-03	.112227737903590+00	.860+02	.100+03
.238079996961460-05	.237796811317390-02	.169730366953350-04	.169231111725260-02	.211860358715060+00	.170+03	.100+03
.476159993922920-05	.475592314940005-02	.679811409572400-04	.672562286647270-02	.376635916519170+00	.340+03	.100+03
.952319987845840-05	.947799781372900-02	.267794464282550-03	.264275480637920-01	.614155173301700+00	.690+03	.100+03

Table 8. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 20 modules of 5000 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116249998516340D-08	.581248303312130D-05	.101354424852930D-09	.202709096730480D-08	.116229057312010D-03	.84D-01	.20D+02
.232499997032680D-08	.116249322814480D-04	.405413966286790D-09	.810828093555930D-08	.232458114624020D-03	.17D+00	.20D+02
.464999994065350D-08	.232497294239410D-04	.162162465400240D-08	.324324937600600D-07	.464916229248050D-03	.33D+00	.20D+02
.929999988130700D-08	.464989182981800D-04	.648624706722780D-08	.129724935557520D-06	.929594039916990D-03	.67D+00	.20D+02
.185999997626140D-07	.929956744471080D-04	.259429778909360D-07	.518859429990410D-06	.185829401016240D-02	.13D+01	.20D+02
.371999995252280D-07	.185962700698880D-03	.103755828720350D-06	.207511452930690D-05	.371307134628300D-02	.27D+01	.20D+02
.743999990504560D-07	.371930811832910D-03	.414894686051600D-06	.829786101679090D-05	.741237401962280D-02	.54D+01	.20D+02
.148799998100910D-06	.743723291137160D-03	.165855025842380D-05	.331704825254630D-04	.147698521614070D-01	.11D+02	.20D+02
.297599996201820D-06	.148639345794070D-02	.662598186261520D-05	.132511295893080D-03	.293215513229370D-01	.21D+02	.20D+02
.595199992403650D-06	.297157606372630D-02	.264933133034560D-04	.528633480097910D-03	.577833056449390D-01	.43D+02	.20D+02
.119039998480730D-05	.593432186315030D-02	.105230559680290D-03	.210250856198720D-02	.112727737908590D+00	.86D+02	.20D+02
.238079996961460D-05	.118334275503250D-01	.416775958866990D-03	.830259802450440D-02	.211860359715060D+00	.17D+03	.20D+02
.476159993922920D-05	.235268250930620D-01	.163448976043250D-02	.321871429820510D-01	.378835916519170D+00	.34D+03	.20D+02
.952319987845840D-05	.465001386871640D-01	.628569764451320D-02	.118482756979130D+00	.614155173301700D+00	.69D+03	.20D+02

Table 9. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 10 modules of 10,000 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116249998516340-08	.116249322614480-04	.405413966286790-09	.405414045390180-08	.116229057312010-03	.840-01	.100+02
.232499997032680-08	.232497294239410-04	.162162465400240-08	.162162469008460-07	.232458114624020-03	.170+00	.100+02
.464999994065350-08	.464989182981800-04	.648624706722780-08	.648624697846990-07	.464916229249850-03	.330+00	.100+02
.929999988130700-08	.929956744471080-04	.259429778909360-07	.259429748584390-06	.929594039916590-03	.670+00	.100+02
.185999997626140-07	.185982700658880-03	.103755828720350-06	.103755780282710-05	.185829401016240-02	.130+01	.100+02
.371999995252280-07	.371930811832910-03	.414694686051600-06	.414693911515610-05	.371307134628300-02	.270+01	.100+02
.743999990504560-07	.743723291137160-03	.165855025842380-05	.165853768000330-04	.741237401962280-02	.540+01	.100+02
.148799998100910-06	.148689345794070-02	.662598186261520-05	.662578429973250-04	.147698521614070-01	.110+02	.100+02
.297599996201820-06	.297157606372630-02	.264838133034560-04	.264351690954510-03	.293215513229370-01	.210+02	.100+02
.595199992403650-06	.593432186315030-02	.105230559680290-03	.105180743042890-02	.577333056449890-01	.430+02	.100+02
.119039998480730-05	.118334275503250-01	.416775952866990-03	.415995161095490-02	.112227737903350+00	.860+02	.100+02
.238079996961460-05	.235268250930620-01	.163448976043250-02	.162252000473460-01	.211840358715060+00	.170+03	.100+02
.476159993922920-05	.465001336871640-01	.628569764451320-02	.611085030628590-01	.378835916519170+00	.340+03	.100+02
.952319987845840-05	.908380144764030-01	.222555267166090-01	.209667893072560+00	.614155173301700+00	.69D+03	.100+02

Table 10. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 100,000 modules of 1 line each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116250000077590-11	.116238962899470-11	-.277555756156290-16	.138758449175210-11	.119209289550780-06	.840-04	.100+06
.232500000155180-11	.232486252471630-11	.000000000000000+01	.138758449175210-11	.238418579101560-06	.170-03	.100+06
.465000000310360-11	.464987770509850-11	-.277555756156290-16	.138758449175210-11	.476837158203130-06	.330-03	.100+06
.930000000620710-11	.929983367692370-11	.000000000000000+01	.138758449175210-11	.953674316406250-06	.670-03	.100+06
.186000000124140-10	.185958438872810-10	.000000000000000+01	.138758449175210-11	.184774439880370-05	.130-02	.100+06
.372000000248280-10	.371998959414200-10	-.277555756156290-16	.138758449175210-11	.369548879760740-05	.270-02	.100+06
.744000000496570-10	.743998612717790-10	-.277555756156290-16	.138758449175210-11	.745096059692380-05	.540-02	.100+06
.148800000099310-09	.148799805810280-09	.000000000000000+01	.138758449175210-11	.149011611938480-04	.110-01	.100+06
.297600000198630-09	.297599847542960-09	-.277555756156290-16	.138758449175210-11	.297427177429200-04	.210-01	.100+06
.595200000397260-09	.595199778352650-09	.000000000000000+01	.138758449175210-11	.595450401306150-04	.430-01	.100+06
.119040000794500-08	.119039980650550-08	.000000000000000+01	.138758449175210-11	.119030475616460-03	.860-01	.100+06
.238080000158900-08	.238079958489340-08	-.277555756156290-16	.138758449175210-11	.238060951232910-03	.170+00	.100+06
.476160000317800-08	.476159978113340-08	.832667268468870-16	.111021331017370-10	.476062297821040-03	.340+00	.100+06
.952320000635610-08	.952319978431150-08	.319189119579730-15	.348942752305070-10	.951886177062990-03	.690+00	.100+06

Table 11. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 10,000 modules of 10 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116250000007759D-11	.116248538573060D-10	-.277555756156290D-16	.138652977987870D-12	.119209289550780D-06	.84D-04	.10D+05
.232500000015518D-11	.232493860702780D-10	-.277555756156290D-16	.138652977987870D-12	.238416579101560D-06	.17D-03	.10D+05
.465000000031036D-11	.464998040072830D-10	.000000000000000D+01	.138652977987870D-12	.476832158203130D-06	.33D-03	.10D+05
.930000000620710D-11	.929993439369580D-10	-.277555756156290D-16	.138652977987870D-12	.953674316406250D-06	.67D-03	.10D+05
.186000000124140D-10	.185999868285160D-09	-.277555756156290D-16	.138652977987870D-12	.184774398880710D-05	.13D-02	.10D+05
.372000000248280D-10	.371999861470410D-09	-.277555756156290D-16	.138652977987870D-12	.369548797607420D-05	.27D-02	.10D+05
.744000000496570D-10	.743999833963120D-09	.000000000000000D+01	.138652977987870D-12	.745059059692380D-05	.54D-02	.10D+05
.148800000099310D-09	.148799983445970D-08	.000000000000000D+01	.138652977987870D-12	.149011611938480D-04	.11D-01	.10D+05
.297600000198630D-09	.297599977999417D-08	.693889390390720D-16	.138758449175210D-11	.297427174252080D-04	.21D-01	.10D+05
.595200000397260D-09	.595199980968350D-08	.152655665885960D-15	.166514024790840D-11	.595450401306150D-04	.43D-01	.10D+05
.119040000079450D-08	.119039997999778D-07	.402455846426620D-15	.485705919928140D-11	.119030475616460D-03	.86D-01	.10D+05
.238080000158900D-08	.238079995718010D-07	.173472347597680D-14	.177633741049730D-10	.238060951232910D-03	.17D+00	.10D+05
.476160000317800D-08	.476159987411460D-07	.674436437459780D-14	.680703549083010D-10	.476062297821040D-03	.34D+00	.10D+05
.952320000635610D-08	.952319953728690D-07	.272143418911240D-13	.272282071889230D-09	.951886177062990D-03	.69D+00	.10D+05

Table 12. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 4000 modules of 25 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116250000077590-11	.290623775045520-10	-.277555756156290-16	.553723733531800-13	.119209289550780-06	.840-04	.400+04
.232500000155180-11	.581249076647690-10	-.277555756156290-16	.553723733531800-13	.238418579101560-06	.170-03	.400+04
.465000000310360-11	.116249856962900-09	-.277555756156290-16	.553723733531800-13	.476837158203130-06	.350-03	.400+04
.930000000620710-11	.232499824948110-09	.000000000000000+01	.553723733531800-13	.953674316406250-06	.670-03	.400+04
.186000000124140-10	.464999816429670-09	.000000000000000+01	.553723733531800-13	.184774398833710-05	.130-02	.400+04
.372000000248280-10	.929999841026150-09	-.277555756156290-16	.553723733531800-13	.369548797607420-05	.270-02	.400+04
.744000000496570-10	.185999984858580-08	.000000000000000+01	.553723733531800-13	.739058059692390-05	.540-02	.400+04
.148800000099310-09	.371999984993720-08	-.277555756156290-16	.553723733531800-13	.149011611938460-04	.110-01	.400+04
.297600000198630-09	.743999985231000-08	.124900090270330-15	.832514612802980-12	.297427177429200-04	.210-01	.400+04
.595200000397260-09	.148799997046200-07	.666133814775090-15	.310847181328460-11	.595450401386150-04	.430-01	.400+04
.119040000079450-08	.297599994369960-07	.266453525910040-14	.111021331017370-10	.119030475616460-03	.860-01	.400+04
.238080000158900-08	.595199981384690-07	.105748743095550-13	.425491308853050-10	.238060951232910-03	.170+00	.400+04
.476160000317800-08	.119039992876880-06	.424660306919120-13	.170308059321030-09	.476062297321040-03	.340+00	.400+04
.952320000635610-08	.238079971653930-06	.170030656221240-12	.680511064166110-09	.951886177062990-03	.680+00	.400+04

Table 13. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 2000 modules of 50 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116250000077590-11	.581249076647690-10	-.277555756156290-16	.276029199497430-13	.119209289550780-06	.840-04	.200+04
.232500000155180-11	.116249856962900-09	-.277555756156290-16	.276029199497430-13	.238418579101560-06	.170-03	.200+04
.465000000310360-11	.232499824948110-09	.000000000000000+01	.276029199497430-13	.476337158203130-06	.330-03	.200+04
.930000000620710-11	.464999816429670-09	.000000000000000+01	.276029199497430-13	.953674316406250-06	.670-03	.200+04
.186000000124140-10	.929999841026150-09	-.277555756156290-16	.276029199497430-13	.184774398803710-05	.130-02	.200+04
.372000000248280-10	.185999984858580-08	.000000000000000+01	.276029199497430-13	.369548797607420-05	.270-02	.200+04
.744000000496570-10	.371999984982720-08	-.277555756156290-16	.276029199497430-13	.745058059692380-05	.540-02	.200+04
.148800000099310-09	.743999985231000-08	.124900090270330-15	.416167100780740-12	.149011611938480-04	.110-01	.200+04
.297600000198630-09	.148799997046200-07	.666133814775090-15	.155415957880930-11	.297427177429200-04	.210-01	.200+04
.595200000397260-09	.297599994369960-07	.266453525910040-14	.555099022380550-11	.595450401306150-04	.430-01	.200+04
.119040000079450-08	.595199981384690-07	.105748743095550-13	.212744544203500-10	.119030475616460-03	.860-01	.200+04
.238080000158900-08	.119039992376880-06	.424660306919120-13	.851539394552960-10	.238060951232910-03	.170+00	.200+04
.476160000317800-08	.238079971653930-06	.170030656221340-12	.340255448816330-09	.476062297821040-03	.340+00	.200+04
.952320000635610-08	.476159886797500-06	.680192013024410-12	.136043937226660-08	.951682177662990-03	.690+00	.200+04

Table 14. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 1000 modules of 100 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116250000077590-11	.116249856962900-09	-.277555756156290-16	.137528877175440-13	.119209239550780-06	.840-04	.100+04
.232500000155180-11	.232499824948110-09	.000000000000000+01	.137528877175440-13	.238418579101560-06	.170-03	.100+04
.465000000310360-11	.464999816429670-09	.000000000000000+01	.137528877175440-13	.476837158203130-06	.330-03	.100+04
.930000000620710-11	.929999841026150-09	-.277555756156290-16	.137528877175440-13	.953674316406250-06	.670-03	.100+04
.186000000124140-10	.185999998358580-08	.000000000000000+01	.137528877175440-13	.184774398803710-05	.130-02	.100+04
.372000000248280-10	.371999984982720-08	-.277555756156290-16	.137528877175440-13	.369548797607420-05	.270-02	.100+04
.744000000496570-10	.743999985231000-08	.124900090270330-15	.208041917026950-12	.745058059692380-05	.540-02	.100+04
.148800000099310-09	.148799999704620-07	.666133814775090-15	.777803461571720-12	.149011611938480-04	.110-01	.100+04
.297600000198630-09	.297599999436996-07	.266453525910040-14	.277539102810920-11	.297427177429200-04	.210-01	.100+04
.595200000397260-09	.595199998138469-07	.105748743095550-13	.106371439434460-10	.595450401306150-04	.430-01	.100+04
.119040000079450-08	.119039992876830-06	.424660306919120-13	.425768864609210-10	.119030475616460-03	.860-01	.100+04
.238080000158900-08	.238079971653930-06	.170030656221340-12	.170127661958120-09	.238060951232910-03	.170+00	.100+04
.476160000317800-08	.476159806797500-06	.680192013824410-12	.680219575111000-09	.476062297821840-03	.340+00	.100+04
.952320000635610-08	.952319547067870-06	.272069866635860-11	.272078870544590-08	.951886177062990-03	.690+00	.100+04

Table 15. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 200 modules of 500 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116250000077590-11	.581249839926020-09	-.277555756156290-16	.260902410786910-14	.119209289550780-06	.84D-04	.20D+03
.232500000155190-11	.116249981862990-08	.000000000000000D+01	.260902410786910-14	.238418579101560-06	.17D-03	.20D+03
.465000000310360-11	.232499980379330-08	.000000000000000D+01	.260902410786910-14	.476837158203130-06	.33D-03	.20D+03
.930000000620710-11	.464999984350900-08	.416333634234430-16	.276029199497430-13	.953674316406250-06	.67D-03	.20D+03
.186000000124140-10	.929999979804030-08	.249800180540660-15	.747873984963120-13	.184774398803710-05	.13D-02	.20D+03
.372000000249280-10	.185999996654700-07	.971445146547010-15	.205196970526340-12	.369548797607420-05	.27D-02	.20D+03
.744000000496570-10	.371999991644060-07	.416333634234430-14	.851943515733920-12	.745058059692380-05	.54D-02	.20D+03
.148800000099310-09	.743999971491990-07	.165423230669150-13	.333465199897630-11	.149011611938480-04	.11D-01	.20D+03
.297600000198630-09	.143799983858310-06	.664329702360080-13	.132919508732950-10	.297427177429200-04	.21D-01	.20D+03
.595200000397260-09	.297599955775830-06	.265662492004990-12	.531518024038390-10	.595450401306150-04	.43D-01	.20D+03
.119040000079450-08	.595199823094640-06	.106280262368590-11	.212575609892520-09	.119030475616460-03	.86D-01	.20D+03
.238080000158900-08	.119039929213920-05	.425116886138000-11	.850251660744480-09	.238060951232910-03	.17D+00	.20D+03
.476160000317800-08	.238079716730070-05	.170046060565810-10	.340093629647150-08	.476062297821040-03	.34D+00	.20D+03
.952320000635610-08	.476158866663520-05	.680179940149020-10	.136036013287380-07	.951886177062990-03	.69D+00	.20D+03

Table 16. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 100 modules of 1000 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116250000077590-11	.116249998186299D-08	.000000000000000D+01	.126287869051110-14	.119209289550780-06	.84D-04	.10D+03
.232500000155180-11	.232499980379330-08	.000000000000000D+01	.126287869051110-14	.236418579101560-06	.17D-03	.10D+03
.465000000310360-11	.464999984350900-08	.416333634234430-16	.137528877175440-13	.476837158203130-06	.33D-03	.10D+03
.930000000620710-11	.929999979804030-08	.249800180540660-15	.372757368517900-13	.953674316406250-06	.67D-03	.10D+03
.186000000124140-10	.185999996654700-07	.971445146547010-15	.102501340748520-12	.184774379880710-05	.13D-02	.10D+03
.372000000248280-10	.371999991649060-07	.416333634234430-14	.425909307821830-12	.369548779607420-05	.27D-02	.10D+03
.744000000496570-10	.743999971491990-07	.135423230669150-13	.166722191607960-11	.745058059692380-05	.54D-02	.10D+03
.148800000099310-09	.148799988858310-06	.664329702360080-13	.664590604770860-11	.149011611938460-04	.11D-01	.10D+03
.297600000198630-09	.297599955775830-06	.265662472004990-12	.265757971185110-10	.297427177429200-04	.21D-01	.10D+03
.595200000397260-09	.595199823094640-06	.106289262368590-11	.106287700862850-09	.595450401306150-04	.43D-01	.10D+03
.119040000079450-08	.119039929213920-05	.425116886138000-11	.425125781799980-09	.119030475616460-03	.86D-01	.10D+03
.238080000158900-08	.238079716730070-05	.170046060565810-10	.170046904415240-08	.238660951232910-03	.17D+00	.10D+03
.476160000317800-08	.476158866663520-05	.680179940149020-10	.680180063561330-08	.476682297821040-03	.34D+00	.10D+03
.952320000635610-08	.952315466068440-05	.272069713980190-09	.272069785034470-07	.951986177062990-03	.69D+00	.10D+03

Table 17. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 20 modules of 5000 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.116250000077590-11	.581249982867240-08	.693889390390720-16	.260902410786910-14	.119208289550780-06	.840-04	.200+02
.232500000155180-11	.116249997961230-07	.416333634234430-15	.903449386288720-14	.238418579101560-06	.170-03	.200+02
.465000000310360-11	.232499999522450-07	.165145674912990-14	.348193698095060-13	.476837158203130-06	.330-03	.200+02
.930000000620710-11	.464999987681570-07	.649480469405720-14	.132061028779160-12	.953674316406250-06	.670-03	.200+02
.186000000124140-10	.929999995073010-07	.258959520493820-13	.519834175705110-12	.184774398803710-05	.130-02	.200+02
.372000000248280-10	.185999982707520-06	.103722586075610-12	.207650563410770-11	.369548797607420-05	.270-02	.200+02
.744000000495570-10	.371999930887100-06	.415167900058560-12	.830517599137440-11	.745058059692380-05	.540-02	.200+02
.148800000099310-09	.743999723593070-06	.166057445571970-11	.332117805479370-10	.149011611938480-04	.110-01	.200+02
.297600000198630-09	.148799889374000-05	.664245047854450-11	.132850258571790-09	.297427177429200-04	.210-01	.200+02
.595200000397260-09	.297599557354260-05	.265695659917850-10	.531392790881210-09	.595450401306150-04	.430-01	.200+02
.119040000079450-08	.595198229072500-05	.106277899266870-09	.212555804901540-08	.119030475616430-03	.860-01	.200+02
.238080000158900-08	.119039291554270-04	.425107199442110-09	.850214601499920-08	.238060951232910-03	.170+00	.200+02
.476160000317800-08	.238077166075380-04	.170039514413300-08	.340079041039050-07	.476062297821040-03	.340+00	.200+02
.952320000635610-08	.476148664079050-04	.680131057029240-08	.136026204605730-06	.951886177062990-03	.690+00	.200+02

Table 18. Module and System Failure (1-Reliability) Data for 100,000 lines of code divided into 10 modules of 10,000 lines each.

Failures/ Line/Hr.	Single Non-Redundant Module Failure Function	TMR Module Failure Function	TMR System Failure Function	Non-Redundant System Failure Function	Errors/ 100k lines/ month	Total Number of Modules
.11625000007759D-11	.11624999796123D-07	.41633363423443D-15	.44825254619241D-14	.11920928955078D-06	.84D-04	.10D+02
.23250000015518D-11	.23249999592245D-07	.16514567491299D-14	.17291723608537D-13	.23841857910156D-06	.17D-03	.10D+02
.46500000310036D-11	.46499998768157D-07	.64948046940572D-14	.65988891026158D-13	.47683715820313D-06	.33D-03	.10D+02
.93000000620071D-11	.92999995607301D-07	.25895952049382D-13	.25979218776229D-12	.95367431640625D-06	.67D-03	.10D+02
.18600000124140D-10	.18599998270752D-06	.10372258607561D-12	.10381695503270D-11	.18477439880371D-05	.13D-02	.10D+02
.37200000248280D-10	.37199993088710D-06	.41516790005858D-12	.41524700344908D-11	.38954877607422D-05	.27D-02	.10D+02
.74400000496557D-10	.74399972359307D-06	.16605744557197D-11	.16605813946136D-10	.74505805692380D-05	.54D-02	.10D+02
.14880000099311D-09	.14879988937400D-05	.66424504785445D-11	.66425046019170D-10	.14901161193848D-04	.11D-01	.10D+02
.29760000198863D-09	.29759955735426D-05	.26569565991785D-10	.26569631217388D-09	.29802717742920D-04	.21D-01	.10D+02
.59520000397726D-09	.59519822907250D-05	.10627788926687D-09	.10627789204243D-08	.59604401306153D-04	.43D-01	.10D+02
.11904000007945D-08	.11903929155427D-04	.42510719944211D-09	.42510729519885D-08	.11903847561646D-03	.86D-01	.10D+02
.23808000015890D-08	.23807716607538D-04	.17003951441330D-08	.17003952176853D-07	.23808095123291D-03	.17D+00	.10D+02
.47616000031780D-08	.47614886407905D-04	.68013105702924D-08	.68013104578823D-07	.47682297821045D-03	.34D+00	.10D+02
.95232000063561D-08	.95227465640432D-04	.27203083480254D-07	.27203080212035D-06	.95188617706299D-03	.69D+00	.10D+02

Table 19. Variables used in Fortran Programs Listed in Figures 7 and 8.

Variable	Definition
ELAM1	Number of software Failures/Line/Hour
ALINES	Number of lines/module
ELAMDA	Number of software failures/module/hour
PROB	Reliability of one non-redundant module
R1MOD	Reliability of one TMR module
ANUMMD	Number of modules in the program
RNONRD	Reliability of non-redundant system
RSYS	Reliability of redundant system
SERRMO	Expected number of software errors per month
P1	Probability of Failure of one non-redundant module
R1	Probability of Failure of one TMR module
RS	Probability of Failure of redundant system
RN	Probability of Failure of non-redundant system

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