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THERMAL RELIABILITY MANAGEMENT IN PCB DESIGN

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ABSTRACT

This paper investigates the extent to which the thermal reliability of components as a function of their location on a convectively cooled printed circuit board (PCB) needs to be considered in the design process. A technique is then presented so that a near optimal solution can be efficiently obtained.

KEYWORDS

Thermal reliability management, MTBF, printed circuit board

INTRODUCTION

Electronic components are typically dissipating more heat, while fine line and surface mount technologies are enabling more components to be placed closer together on a PCB. Presently, besides routing criteria, thermal management dictates the placement of the components. However, although the individual component reliability is directly related to temperature, a PCB which is optimally designed with respect to thermal conditions may not satisfy thermal reliability constraints [1,2]. This is because different components typically have different resistances, heat dissipation factors and thermal reliability sensitivities. As a result, the mean time between failure (MTBF) of a printed circuit board (PCB) as a function of the associated component failure rate characteristics must be considered as an additional criterion for effective PCB design.

DISCUSSION OF RESEARCH

In this article, we focus on determining the thermal and thermal reliability characteristics of microelectronic components mounted on the external sides of coplanar PCBs comprised of two boards interconnected by fin-stock. Heat is dissipated by the components and removed from the system via forced convection of air passing through the fin-stock. The transfer of heat depends on the thermal resistances between the bases of the components and the fin-stock as well as the air temperature, heat transfer coefficient and air mass flow rate.

Standard forced convection equations using finite difference techniques were used to calculate the thermal distributions and junction temperatures of the components on the PCB. From this information, the MIL HDBK 217 D equations for the failure rate were used to calculate the total failure rate and MTBF (assuming an exponentially distributed, series system) for the PCB.

For exploratory purposes, tests were conducted on two sets of seven TTL components selected randomly from MIL HDBK 217 D. A list of their thermal and reliability attributes are given in Table 1. The reliability equations were taken from the MIL HDBK 217 D. Without loss of generality, the environmental pi factor is 0.6, the quality pi factor is 0.5 and learning pi factor is 1.0.

TABLE 1a : COMPONENTS FOR SET 1

TTL I.D.	POWER (W)	θjc (C/W)	Complexity	Fn. Pins
00105 - D	0.24	80	6	14
00205 - A	0.22	90	12	14
01009 - A	0.47	90	34	14
01102 - F	0.80	10	19	16
01602 - D	0.20	90	4	14
01503 - Z	0.63	150	56	24
01801 - F	0.77	60	100	16

TABLE 1b : COMPONENTS FOR SET 2

TTL I.D.	POWER (W)	θjc (C/W)	Complexity	Fn. Pins
00101 - A	0.04	90	1	11
00302 - D	0.40	150	4	14
00602 - E	0.55	80	36	14
01101 - L	0.80	40	63	24
01306 - F	0.50	90	57	16
01102 - E	0.99	20	19	16
01102 - F	0.80	40	19	16

The minimum and maximum average temperature and MTBF were calculated for all 7! = 5040 arrangements of each set on the PCB. The data was placed into bins for graphing purposes. The average temperature and MTBF distributions are shown in figures 1a,b and 2a,b. An interesting feature of this analysis is that the temperature distribution is symmetric. It can be shown that this is true on purely theoretical grounds, and expressions can be derived for the maximum and minimum average component temperatures. The distribution of average temperatures may be adequately represented by a beta distribution. The MTBF distribution is not well defined for the case of only 7 components.

Tables 2a and 2b give the particular arrangements and associated values for the minimum and the maximum average temperature and the total MTBF for each set of 7 components. For set 2, the MTBF corresponding to the minimum temperature (103.1C) gives a close approximation to, but not the best MTBF. For set 1, the best MTBF has associated with it a higher average temperature than that associated with the worse case MTBF. This shows that optimal MTBF values are not necessarilty proportional to temperature as one may expect from intuition.

TABLE 2a

AVERAGE TEMPERATURE	MTBF	ARRANGEMENTS
123.84 (MAX)	3.45	4 7 6 3 1 2 5
111.46 (MIN)	3.69	5 2 1 3 6 7 4
119.16	4.93 (MAX)	6 7 3 5 2 1 4
116.15	2.60 (MIN)	4 1 2 5 3 7 6

TABLE 2b

AVERAGE TEMPERATURE	MTBF	ARRANGEMENTS
119.77 (MAX)	6.3	6 7 4 3 2 5 1
103.1 (MIN)	11.09	1 5 2 3 7 4 6
109.03	11.6 (MAX)	5 3 4 7 1 2 6
113.16	6.0 (MIN)	6 1 2 7 4 3 5

The weak relation between the average temperature and reliablity of the arrangements can also be demonstrated by subdividing the arrangements into subgroups (in this case we chose 10 subgroups) forming a 10X10 matrix containing the number of arrangements which correspond to a particular average temperature and MTBF. Tables 3a and 3b display the matrix for component sets 1 and 2 respectively.

A diagonal line drawn through Tables 3a and 3b can be used to visualize the degree of correlation between the average temperature of the components and the MTBF. The actual value of the correlation coefficient is 0.13 for set 1 and -0.63 for set 2. Generally a correlation coefficient as low as 0.13 would be considered without correlation and one with a value of -0.63 would be considered a weak correlation at best. In fact, the positive value for component set # 1 indicates the counter-intuitive result that one would expect a better MTBF for arrangements yielding higher average component temperatures. It is apparent that not all arrangements with low average temperatures gives good MTBF values, as is commonly assumed. Thus design guidelines based on thermal management procedures, such as placing with respect to the component power dissipation, should not be used.

TABLE 3a

MTBF INCREASING
------------->

										T
12	7	1	18	18	6	0	0	0	0	E
60	35	13	55	53	25	21	10	0	0	M
70	75	24	62	54	94	18	55	7	0	P
120	132	57	70	73	118	57	51	32	2	E
115	169	93	74	101	125	100	45	69	12	R
124	163	92	74	73	113	117	43	63	36	A
77	138	120	80	53	76	120	54	50	33	T
35	103	98	43	47	34	61	38	27	17	U
2	38	52	47	34	28	32	41	26	11	R
0	3	20	25	23	11	7	19	8	0	E

TABLE 3b

MTBF INCREASING
------------->

										T
0	0	0	0	0	0	14	39	33	4	E
0	0	0	1	8	62	113	77	52	9	M
0	1	13	33	57	100	139	93	60	7	P
22	55	55	68	113	172	155	82	16	8	E
52	83	73	112	139	112	134	80	11	6	R
89	105	108	123	133	136	101	37	22	2	A
92	123	115	138	107	87	61	26	5	0	T
117	132	83	73	59	30	1	0	0	0	U
93	105	64	30	6	6	0	0	0	0	R
50	22	6	0	0	0	0	0	0	0	E

The determination of an optimal or near optimal arrangement of components is a complex task due to the multi-objective, nonlinear, location-dependent nature of the problem. A sure method of determining the optimal MTBF arrangement for a set of components is by ennumeration. Table 4 shows the cost of evaluation in terms of computer time as a function of the number of components in the set. Obviously, a more efficient means of determining an optimium or a near optimium set arrangement is needed.

TABLE 4

No. of Components.	No. of Arrangements.	IBM PC AT Computer processing time (minutes)
4	24	0.2
5	120	0.8
6	720	4
7	5040	28
8	40320	224
9	362880	2016
10	3628800	20160

A STATISTICAL SOLUTION

From the disscussion above, it is evident that direct consideration of the PCB thermal reliability is necessary to guarantee a reliable design. However, for realistic board sizes, with quantities of components in the hundreds, a comparision of all possible arrangements would be prohibitively costly, if not computationally impossible. Several optimization techniques for solving such combinatoric problems exist, most notably simulated annealing [6] and it's derivatives [7]. We will offer here, a simple technique which will result in near optimal arrangements.

If the exact statistical distribution of the MTBF of the PCB over all of the possible component arrangements were known, one could compute the number of randomly selected arrangements which would need to be investigated to insure, to a certain confidence level, that at least one of the arrangements tested was within a desired amount of the optimum. Such a formula is easily derived to be

$$N = \log(1 - CL) / \log(1 - Pr(MTBF > MTBF\ desired))$$

where

N = number of arrangements to be investigated
CL = confidence level
Pr(x>y) = the probability of selecting a value of MTBF larger than y.

However, figures 2a,b show that the MTBF distribution is not a simple one, and obtaining an analytic estimate of the distribution function would be difficult at best. The question is then to estimate a value of N apriori for the unknown distribution of MTBF. We will derive an order of magnitude estimate and show that for the case of seven components, satisfactory results are obtained. Chebyshevs inequality states that the probability of obtaining a result larger than k standard deviations from the mean of any distribution is less than or equal to $1/k^2$, or

$$\Pr(\text{avg}-k\ \text{sig} < x < \text{avg}+k\ \text{sig}) <= 1/k^2$$

This formula may be applied to yield an estimate for N by replacing the inequality by an equality and assuming that the MTBF distribution is symmetric about the mean. The resulting formula for the number of random trials which need be investigated to obtain a desired MTBF is

$$N = \log(1-CL)/\log(1-1/k^2)$$

For a confidence level of 95% (CL=.95) and a desired MTBF level at least two standard deviations from the mean (k=2) the above formula gives N=23. This value is an order of magnitude estimate (it is in fact a lower bound) on the number of arrangements which must be considered to obtain an MTBF level which is satisfactory.

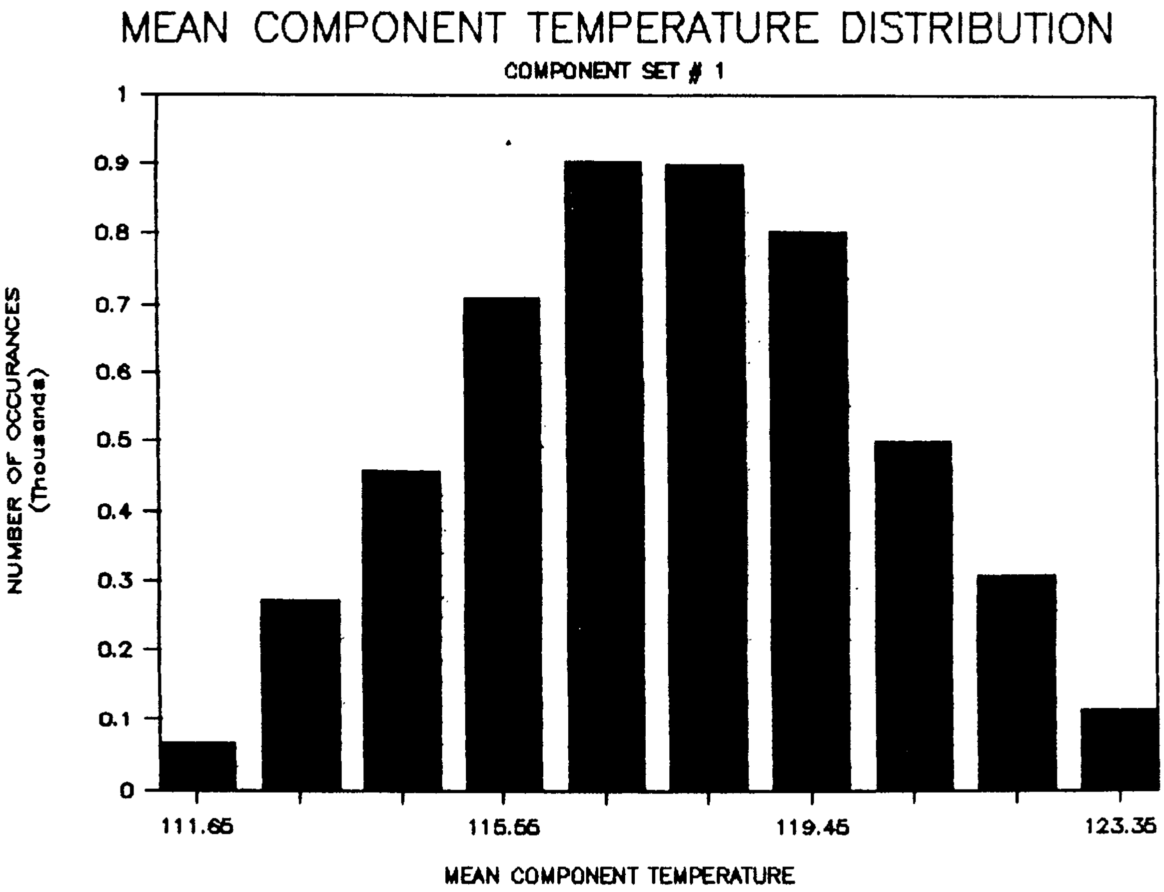
The component sets #1 and #2 were investigated by testing 23 random arrangements of each. This was done 1000 times for each component set, and the resulting maximum MTBF obtained for each random selection of 23 arrangements noted. The distribution of these values are shown in figures 3a,b. It can be seen that in all cases, the arrangements which would be selected from the 23 random samples are near the absolute optimum MTBF.

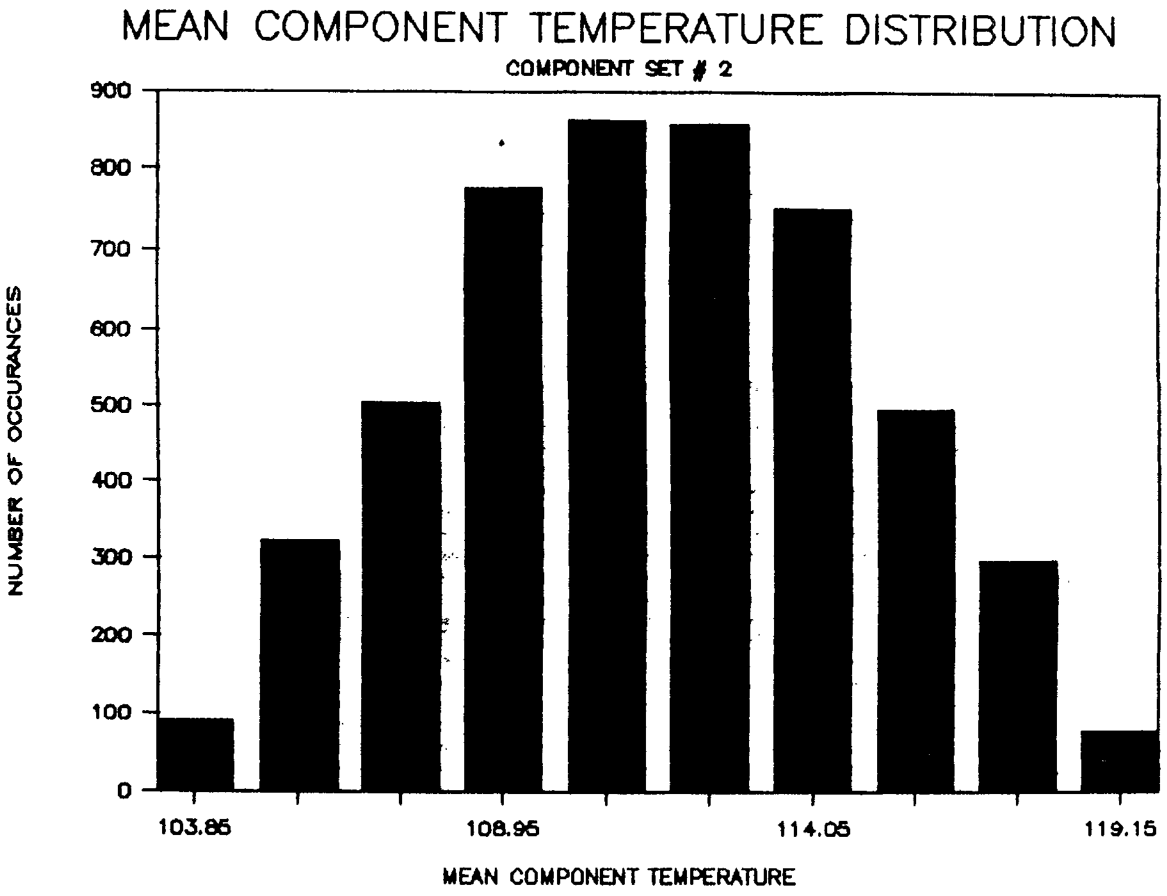
CONCLUSIONS

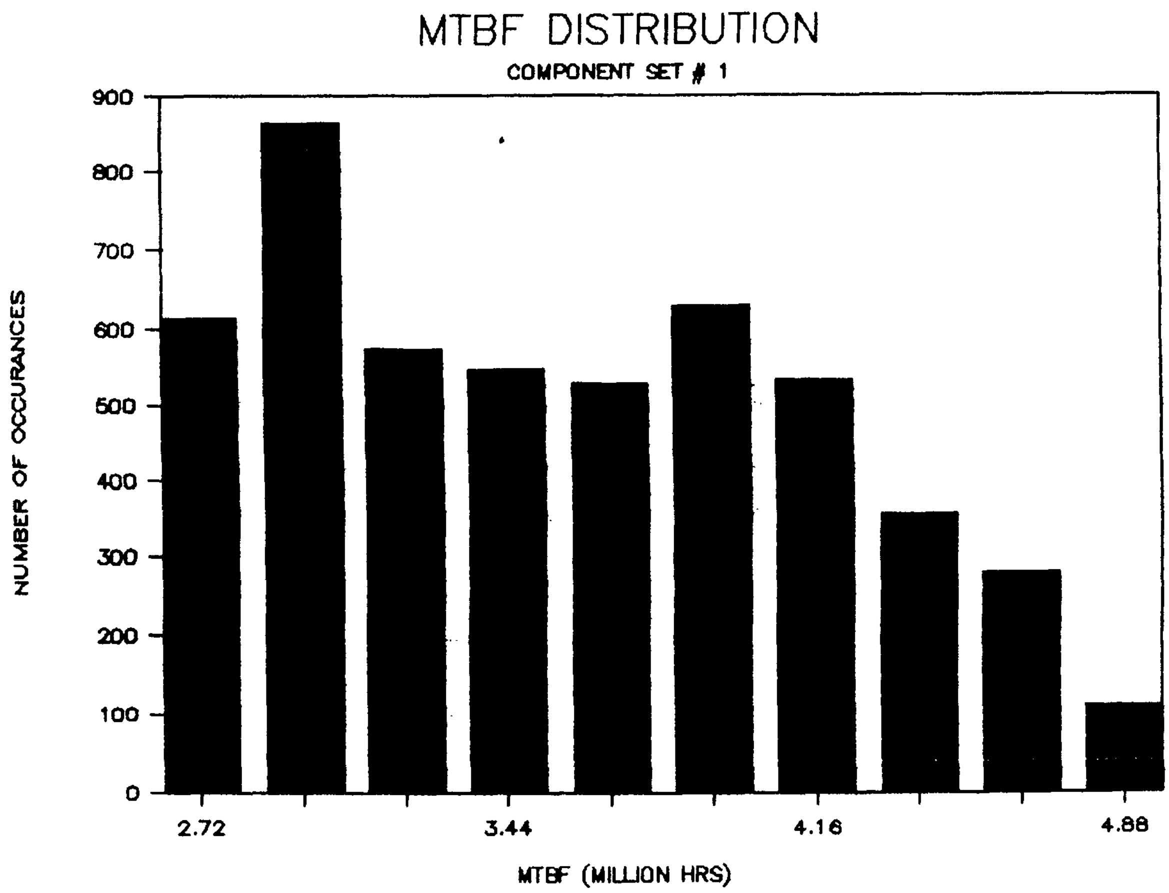
We have shown that the PCB temperature and reliability states are highly dependent on the component arrangements. We have also shown that neither a minimization of the average PCB temperature nor an ordering of components based solely on component power dissipation will result in an optimal thermal reliability design. This was further supported by a statistical correlation between the temperature measure and system reliability as a function of component arrangement.

Selecting the best arrangement out of the large population of arrangements is rarely cost and time effective. However, the simple random sampling technique presented in this paper is an efficient and practical statistical solution to the problem which gives an approximation to the optimium arrangement.

Further work is underway to strengthen the estimate provided for the selection size N. This includes an analysis of the actual statistical distribution of the MTBF, and estimates of the absolute maximum and minimum values which can be used to estimate N for absolute MTBF values, as opposed to relative MTBF values.

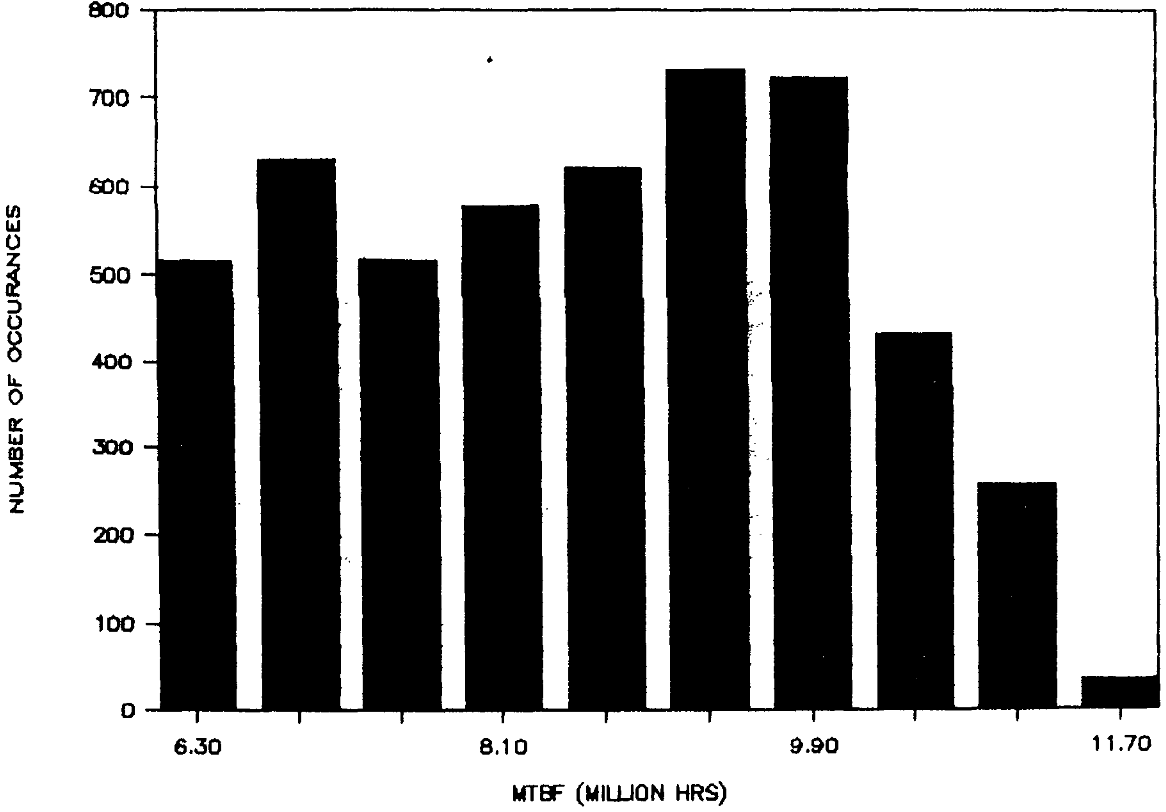

MEAN COMPONENT TEMPERATURE DISTRIBUTION
COMPONENT SET # 1
NUMBER OF OCCURANCES
(Thousands)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
111.65
115.55
119.45
123.35
MEAN COMPONENT TEMPERATURE


MEAN COMPONENT TEMPERATURE DISTRIBUTION
COMPONENT SET # 2
NUMBER OF OCCURANCES
900
800
700
600
500
400
300
200
100
0
103.85
108.95
114.05
119.15
MEAN COMPONENT TEMPERATURE



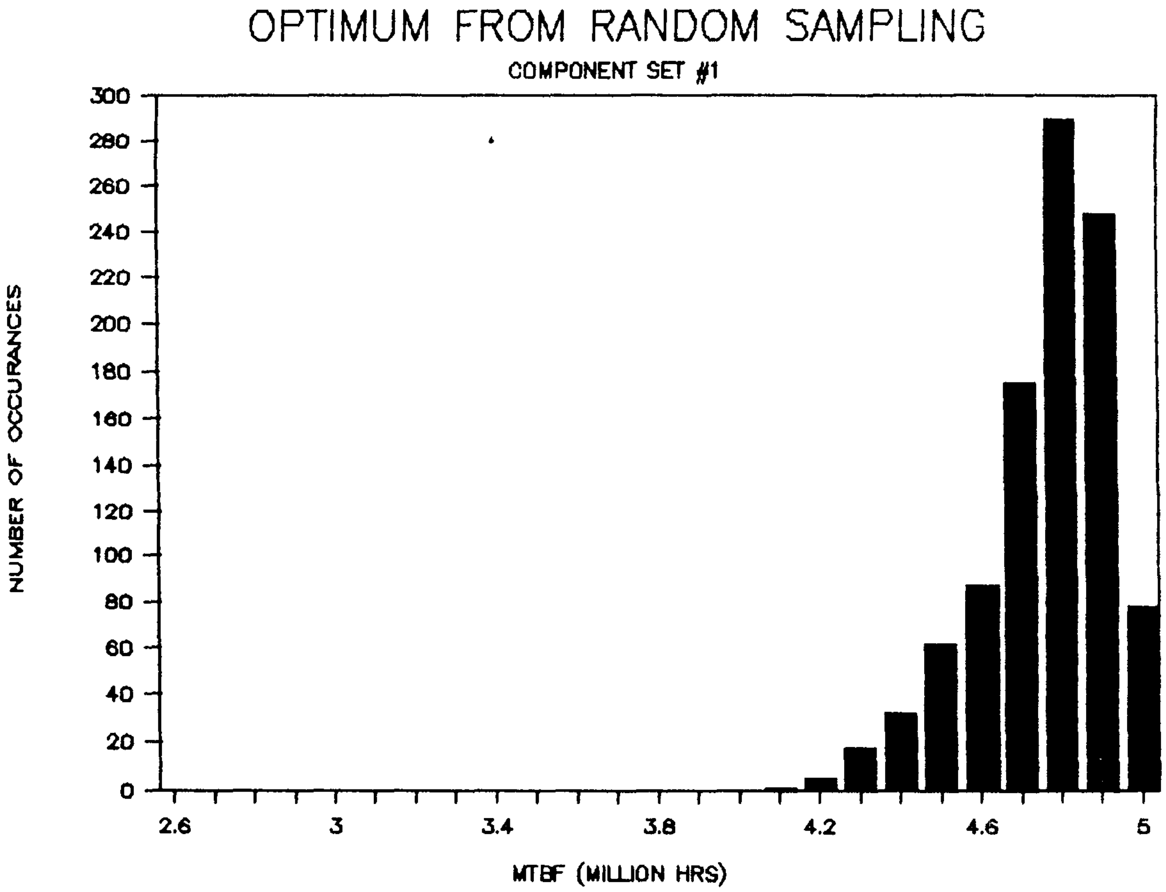
MTBF DISTRIBUTION

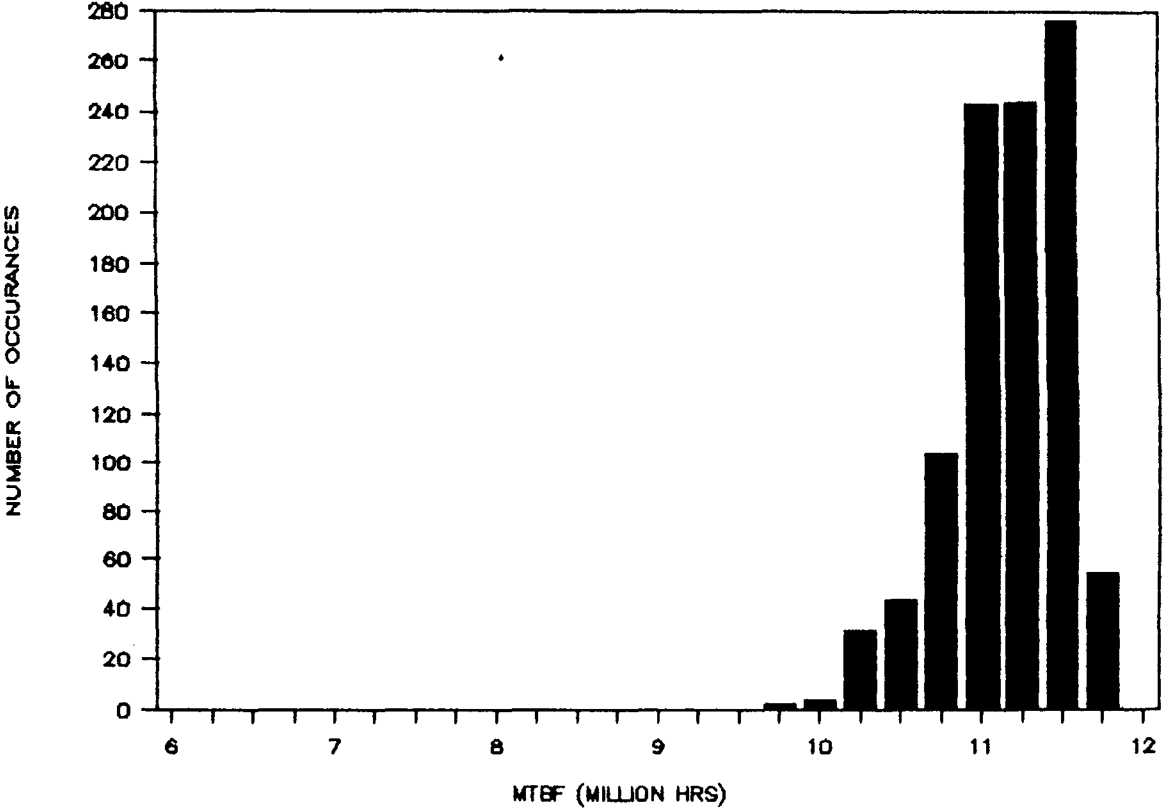
COMPONENT SET # 1



MTBF DISTRIBUTION

COMPONENT SET # 2


OPTIMUM FROM RANDOM SAMPLING
COMPONENT SET #1
NUMBER OF OCCURANCES
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
2.6
3
3.4
3.8
4.2
4.6
5
MTBF (MILLION HRS)



OPTIMUM FROM RANDOM SAMPLING

COMPONENT SET #2

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BIOGRAPHIES

Dr. Pecht. received an MS in Electrical Engineering and Ph.D in mechanics from the University of Wisconsin. He has worked as a consultant on the Astro I NASA space telescope project, and conducted research with Westinghouse Defense and Electronics Center on various mechanical engineering aspects of electronic packaging. Presently Dr. Pecht consults on issues related to the reliable design of printed circuit boards and is an Assistant Professor in the Mechanical Engineering Department at the University of Maryland.

Dr. Palmer received his BS, MS and Ph.D degrees in Mechanical Engineering from the University of Maryland , where he is currently an assistant professor. He has conducted research in the area of Thermo-Fluid Mechanics for the Department of Transportation, NBS , and Ford Motor Co. He is currently conducting research in the thermal designs of reliable printed wiring boards for the thermal designs of reliable printed wiring boards for the Westinghouse Defense and Electronics Center and in Computational Fluid Dynamics for the Ford Motor Company.

Joseph Naft is Director of the Computer Aided Design Laboratory of the Engineering Research Center of the Univeristy of Maryland. He is responsible for providing guidance within the College of Engineering on the development of its CAD program and for Maryland companies on the selection and implementation of CAD systems. His duties include procuring computer hardware and software , arranging research partnerships, and presenting CAD seminars. Mr, Naft is also a consultant to the Institute for Defense Analyses of Alexandria, VA. for whom he has performed research into the design of a RAMCAD workstation. Prior to joining the university, Mr. Naft was an engineering group leader for the Boeing Co. where he was involved with Computer Aided Design. Mr. Naft holds a B.S in Aerospace Engineering from Case Western Reserve University and an M.S. in Physics from Vanderbilt University.