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Reliability Measurement of Fault-Tolerant Onboard Memory System under Fault Clustering

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Abstract – *Advances in spaceborne vehicular technology have made possible the long-life duration of the mission in harsh cosmic environments. Reliability and data integrity are commonly emphasized requirements of spaceborne solid-state mass storage systems, because faults due to the harsh cosmic environments—such as extreme radiation—can be experienced throughout the mission. Acceptable dependability for these instruments have been achieved by using redundancy and repair. Reconfiguration (repair) of memory arrays using spare memory lines is the most common technique for reliability enhancement of memories with faults. Faulty cells in memory arrays are known to show spatial locality. This physical phenomenon is referred to as* **fault clustering**. *This paper initially investigates a* **quadrat-based fault model** *for memory arrays under clustered faults to establish a sound foundation of measurement. Then, long-life dependability of a fault-tolerant spaceborne memory system with hierarchical active redundancy, which consists of spare columns in each memory module and redundant memory modules, is measured in terms of reliability (i.e., the conditional probability that the system performs correctly throughout the mission) and mean-time-to-failure (MTTF, i.e., the expected time that a system will operate before it fails).*

Keywords – *Onboard memory systems, Memory reconfiguration (repair), Hierarchical active redundancy, Clustered faults, Quadrat-based fault model, Reliability, Mean-time-to-failure.*

I. INTRODUCTION

Advances in spaceborne vehicular technology have made possible the long-life duration of missions in harsh cosmic environments [8], [9], [10]. Reliability and data integrity are commonly emphasized requirements of spaceborne solid-state mass storage systems, because faults due to the harsh cosmic environments—such as extreme radiation—can be experienced throughout the mission [8], [9], [10]. Acceptable dependability for these solid-state mass storage instruments have been commonly achieved by using redundancy and repair. Reconfiguration (repair) of memory arrays using spare memory lines is the most common technique for reliability enhancement of memories with faults [1], [2], [4], [5], [6], [7].

To accurately model the faulty memory arrays, a proper fault model must be introduced. It is well known that defects in VLSI circuits tend to occur in clusters due to defects that span multiple circuit elements [4], [5], [11], [13]. This physical phenomenon is referred to as *defect clustering*. Attempts to deal with defect clustering have focused mainly on models involving compounded poisson distributions [4], [5], [13]. In these models, the wafer is divided into multiple regions and within each region, the number of defects is modeled as Poisson. Models that use compounded distributions are quadrat-based because they assume different distributions in different regions (quadrats) of the wafer. For quadrat-based models, defects occur s-dependently in the same quadrat, while occurrences of defects in different quadrats are s-independent [4]. An alternative approach to modeling defects is the center-satellite approach [11] wherein there are separate distributions describing the locations of cluster centers and the locations of defects within a cluster. While some aspects of the center-satellite approach make it quite well-suited for modeling defect clustering, the resulting models can have more parameters: making the problem of parameter estimation more complex than in quadrat-based models [4]. Exploitation of a clustered fault model, such as the quadrat-based model, makes it possible to accurately measure the reliability of memory arrays with clustered faults.

Solid-state mass memories for spaceborne applications may experience excessive interference and damage due to harsh cosmic environments [8], [9], [10]. In [8], error correcting codes are used to cope with particle-induced bit errors—an extended Reed-Solomon code circumvents soft errors while maintaining a low-hardware implementation of coding and checking. The memory system proposed in [9] is also designed for spaceborne applications and uses two levels of active redundancy, where faulty columns in a memory module are repaired by spare columns and malfunctioned modules are replaced by module redundancy. Circuits for radiation-hardened memories are also introduced in [10], where an orthogonal shuffle-type of write-read arrays, error correction through weighted bidirectional codes, and associative iterative repair circuits are exploited to harden memories against interference and damage due to excessive radiation.

The objective of this paper is to thoroughly measure the dependability of a fault-tolerant onboard memory system under fault clustering, and achieving more accurate prediction of reliability (i.e., the conditional probability that the system performs correctly throughout a time interval) and mean-time-to-failure ($MTTF$, i.e., the expected time that a system will operate before it fails). Thereby, allowing manufacture of more dependable mission-specific onboard memory systems in terms of reliability and $MTTF$ while maintaining minimal redundancy.

The organization of this paper is as follows: In the next section, review and preliminaries related to this research work will be given. In Section III, a fault-tolerant memory system with two levels of active redundancy proposed in [9] is reviewed. Reliability measurements for non-fault-tolerant and fault-tolerant memory modules with a clustered fault model are discussed in Sections IV and V, respectively. Reliability measurement of a fault-tolerant onboard memory system consisting of such fault-tolerant memory modules is investigated in Section VI. Parametric simulation and its results are given in Section VII. Discussion and conclusions are in the final section.

II. REVIEW AND PRELIMINARIES OF CLUSTERED FAULT MODEL

The following notation is used throughout this work:

- n : number of rows and columns in an array, excluding spares.
- A_n : a $n \times n$ memory array with n rows and n columns.
- s : number of spare columns.
- $a_{i,j}$: an element of A_n.
- m_n : number of rows and columns in a quadrat.
- η : n/m_n.
- p_1 : $\Pr\{$a quadrat is FP$\}$ (see below).
- p_2 : fault arrival rate of a memory cell within FP quadrat.
- p_3 : fault arrival rate of a memory cell within FR quadrat (see below).
- λ : parameter of a Poisson random variable.
- M : number of fault-free memory modules required for the system to be functional.
- N : number of total memory modules including spare modules.
- S : $N - M$ (i.e., number of redundant modules).
- t : time.
- R : reliability, the conditional probability that the system performs correctly throughout Δt.

The following assumptions are made in this work:

1. Quadrats can be one of two types: *Fault Prone Quadrat* (denoted by FP) and *Fault Resistant Quadrat* (denoted by FR). FPs are prone to have faults while FRs resists faults.
2. Within any quadrat, faults occur s-independently.
3. A quadrat is FP with probability p_1, s-independently of other quadrats.
4. Occurrence of faults in FP quadrats is determined by p_2.
5. Occurrence of faults in FR quadrats is determined by p_3.
6. $p_2 \gg p_3$ & $p_3 \approx 0$
7. $\overline{p}_1 \gg p_1$ & $\eta \cdot p_1 \leq 1$
8. η is an integer.

For memory arrays, some of the most challenging problems are the achievement of acceptable reliability and the minimization of redundancy area (overhead) [1], [2], [4], [5], [12]. If more redundancy area is provided, a highly reliable memory reconfiguration is possible, but more cost due to the additional overhead is unavoidable. Thus, an appropriate balance of acceptable reliability and redundancy area is desirable for high-reliability, low-cost manufacturing of memory arrays.

In this paper, a $n \times n$ memory array, A_n, is partitioned into quadrats containing $m_n \times m_n$ cells. Assumptions given above dictate the occurrence of faults within such an array. Assumption (1) defines what it means for a quadrat to be FP or FR: the array is divided into 'quadrats with a high density of faulty cells' and 'quadrats with a low density of faulty cells'. The *a priori* probability of a cell being faulty is $p_1 \cdot p_2 + \overline{p}_1 \cdot p3$. However, if some of the neighbors of a cell are known to be faulty, the probability of that cell's being faulty increases toward p_2 since it is more likely that the cell lies in a FP quadrat. Figure (1) illustrates the effect of the Clustered-Fault model. Figure (1a) uses the quadrat-based fault model with $n = 16$, $m_n = 4$, $p_1 = 0.1$, $p_2 = 0.5$ and $p_3 = 0.02$ to generate the faulty memory array. Figure (1b) uses a random fault model with failure-probability = 0.068 which was chosen to make the expected number of faults the same in both illustrations.

A faulty column (row) containing more than one faulty cell is referred to as *Connective Faulty Column (CFC) (CFR)* [2]. The memory array in Figure(1a) has 8 CFCs and the one in Figure (1b) has 13 CFCs. Importance of the fault-clustering is shown in Figure (2), wherein both of the faulty memory arrays in Figure (1) are repaired by spare columns. The memory array given in Figure (2a) requires 8 spare lines while the memory given in Figure (2b) needs 14 spare lines.

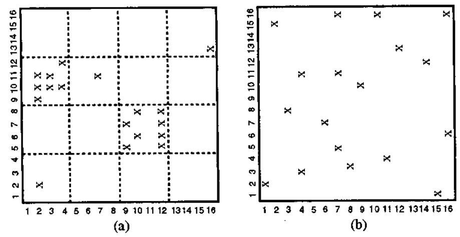

Fig. 1. Fault Arrays generated with: a. Clustered-Fault Model b. Random-Fault Model

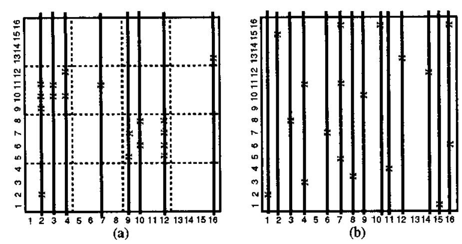

Fig. 2. Repaired Fault Arrays generated with: a. Clustered-Fault Model b. Random-Fault Model

The average number of faulty cells covered by one spare line is referred to as *covering ratio*. For example, covering ratio of the reconfiguration given in Figure (2a) is 2.25 while covering ratio of the other reconfiguration given in Figure (2b) is 1.2857. It is quite intuitive that fewer spare lines would be required to repair a given memory array if faulty cells show spatial locality (i.e., fault clustering).

III. FAULT-TOLERANT ONBOARD MEMORY ARCHITECTURE

In this section, a fault-tolerant memory system with two levels of active redundancy proposed in [9] is reviewed. A total of $N - M = S$ spare memory modules is provided in the system and each spare module can substitute for any of the M primary memory modules. Consequently, the memory system can tolerate up to S complete memory module failures before the memory system becomes inoperable. Each $n \times n$ module also uses column sparing as the means of providing s spare columns of memory. If a memory module fails, then the column containing that module is eliminated from the system and replaced with a spare column. If the memory module runs out of spare columns, then the entire module is replaced with a spare module. This type of redundancy is often referred to as two-level redundancy: the first level being the spare columns and the second level being the spare memory modules. Both forms of reconfiguration are active techniques, and they require that the fault be detected, located, and successfully removed from the system. Figure (3) shows the architecture of the fault-tolerant memory system for spaceborne applications in detail. Reliability of the given fault-tolerant onboard memory system will be measured in the following sections.

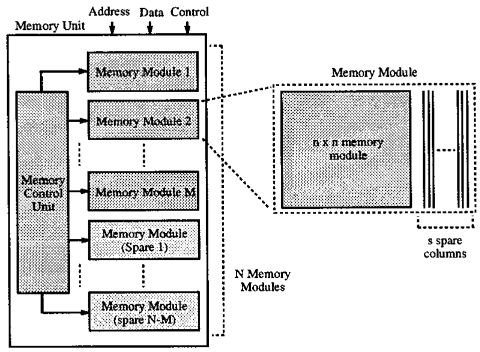

Fig. 3. Architecture of fault-tolerant onboard memory system

IV. RELIABILITY MEASUREMENT OF NON-FAULT-TOLERANT MEMORY MODULE WITH CLUSTERED FAULTS MODEL

The given $n \times n$ memory module A_n has η^2 quadrats. For example, memory module shown in Figure (1) can be parameterized as $n = 16$, $m_n = 4$ and $\eta = 4$. A quadrat is FP with probability p_1, s-independently of other quadrats. Pr{quadrat is FP} = p_1 and Pr{quadrat is FR} = $\overline{p}_1$, formally. Fault arrival rate in a FP quadrat is $\lambda_{FP} = p_2 \cdot m_n^2$ and fault arrival rate in a FR quadrat is $\lambda_{FR} = p_3 \cdot m_n^2$. Then, reliability of FP is determined by the exponential failure law $R_{FP}(t) = e^{-\lambda_{FP}t}$ and reliability of FR is $R_{FR}(t) = e^{-\lambda_{FR}t}$. Each column of quadrats in the given memory array is referred to as *quadrat-column* where each quadrat-column has η quadrats. Since Pr{quadrat is FP} = p_1 and Pr{quadrat is FR} = $\overline{p}_1$, expected number of FP quadrats in a quadrat-column is $p_1 \cdot \eta$ and expected number of FR quadrats in a quadrat-column is $\overline{p}_1 \cdot \eta$. So, reliability of a quadrat-column is

$$\begin{aligned} R_{QC}(t) &= (p_1 e^{-\lambda_{FP}t} + \overline{p}_1 e^{-\lambda_{FR}t})^{\eta} \\ &\approx (R_{FP}(t))^{p_1 \cdot \eta} \cdot (R_{FR}(t))^{\overline{p}_1 \cdot \eta} \end{aligned} \tag{1}$$

Finally, overall reliability of a non-fault-tolerant memory module A_n becomes

$$R_{NFTA_n}(t) = (R_{QC})^{\eta} \tag{2}$$

V. RELIABILITY MEASUREMENT OF FAULT-TOLERANT MEMORY MODULE WITH CLUSTERED FAULT MODEL

The given memory array A_n consists of approximately $\eta^2 \cdot p_1$ FP quadrats and $\eta^2 \cdot \bar{p}_1$ FR quadrats. For each FP quadrat, $\Pr\{\text{a column in FP quadrat is faulty}\} = 1 - \Pr\{\text{a column in FP quadrat is fault-free}\}$ is

$$1 - (1 - p_2)^{m_n} \tag{3}$$

Furthermore, the expected number of faulty columns in a FP quadrat becomes

$$m_n \cdot (1 - (1 - p_2)^{m_n}) \tag{4}$$

Since $p_2 \gg p_3$, $\eta \cdot p_1 \leq 1$, and $p_3 \approx 0$, the FR quadrats are essentially fault-free and the FP quadrats primarily dictate the locations of the faulty cells. So the expected number of faulty columns in a quadrat-column is primarily determined by the faulty columns in FP quadrats. Thus, the expected number of faulty columns in a quadrat-column is

$$\lambda_{QC} \approx m_n \cdot (1 - (1 - p_2)^{m_n \cdot \eta \cdot p_1}) \tag{5}$$

And the overall expected number of faulty columns in a memory module A_n becomes

$$\lambda_{A_n} = \lambda_{QC} \cdot \eta \tag{6}$$

So, the failure rate of a single column can be estimated as

$$\lambda_{\text{col}} = \lambda_{A_n} / n \tag{7}$$

and the reliability of a single column can be expressed as

$$R_{\text{col}}(t) = e^{-\lambda_{\text{col}} t} \tag{8}$$

Each memory module consists of n memory columns and s spare memory columns and a quorum of n out of the total of $n + s$ columns are required to function for the memory module to function. Thus, the reliability of the fault-tolerant memory module with s spare columns can be written as

$$\begin{aligned} R_{FTA_n}(t) &= \sum_{i=0}^{s} \binom{n+s}{i} R_{\text{col}}(t)^{n+s-i} \cdot \overline{R_{\text{col}}(t)}^{\,i} && (9) \\ &\approx e^{-\lambda A_n (n+s)} \cdot \sum_{i=0}^{s} (\lambda_{A_n}(n+s))^i / i! && (10) \end{aligned}$$

VI. RELIABILITY MEASUREMENT OF THE FAULT-TOLERANT ONBOARD MEMORY SYSTEM

The fault-tolerant onboard memory system consists of N fault-tolerant memory modules and M of these memory modules must be functional, where column failures of each module are repaired by spare columns and failed modules are replaced by spare modules. The system uses two levels of hierarchical active redundancy. Therefore, reliability of the given fault-tolerant memory system can be expressed as

$$R(t) = \sum_{i=0}^{N-M} \binom{N}{i} R_{FTA_n}(t)^{N-i} \cdot (1.0 - R_{FTA_n}(t))^i \tag{11}$$

In addition to the reliability, the mean time to failure ($MTTF$) is a useful measurement to specify the quality of a system since the $MTTF$ is the expected time that a system will operate before the first failure occurs. Therefore, it can be used to measure the system operation life without failure. The $MTTF$ is defined in terms of the reliability function as

$$MTTF = \int_0^{\infty} R(t)dt \tag{12}$$

which is valid for any reliability function that satisfies $R(\infty) = 0$.

VII. PARAMETRIC SIMULATION

The effect of the fault clustering and redundancy amount on the reliability of the fault-tolerant memory system will be studied through numerical experiments in this section. Parameters used in this simulation are summarized in Table I. The unit time interval is a week.

In Figure (4), the reliability enhancement ability of spare column redundancy in a memory module is visualized. R of the non-fault-tolerant memory module ($s = 0$) calculated by Equation (2) along with R of the fault-tolerant memory module with different numbers of spare columns from 4 to 32 calculated by Equation (9) are shown. Note that $R_{NFTA_n}(1) = 0.960161458504244$ and $R_{NFTA_n}(2) = 0.921910026397004$,which means that reliability of the non-fault-tolerant memory module becomes less than 0.95 in two weeks. Typical requirements of a long-life application are to have a 0.95, or greater, probability of being operational at the end of a ten-year period. Thus, the non-fault-tolerant memory module must be hardened to be operational for longer mission time. In the case of $s = 32$ (i.e., 32 spare columns are provided), $R_{FTA_n}(530) = 0.950083569136458$ and $R_{FTA_n}(531) = 0.949069751640994$ where it successfully endures more than 10 years of mission time while maintaining $R_{FTA_n} > 0.95$ at 25% (i.e., $32/128 = 0.25$) redundancy overhead.

In Figure (5)-(8), the reliability enhancement ability of module redundancy in a memory system is investigated. Each figure has five plots varying the number of spare columns from 0 to 32. For example, $S = 6$ and $s = 32$ means that the memory system consists of $16 + 6 = 22$ total modules, including spare modules, and each module has 32 spare columns. For

TABLE I

SUMMARY OF SIMULATION PARAMETERS

Parameter	n	n^2	η^2	s	M	S	$M \times n^2$	p_1	p_2
Value	128	16K	32	variable	16	variable	256K	5×10^{-4}	5×10^{-3}

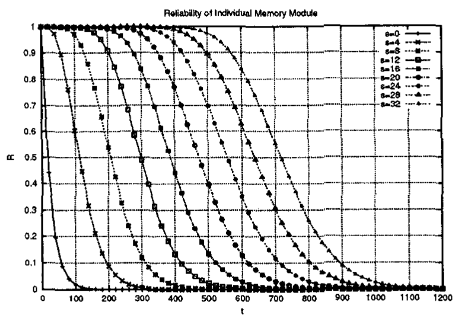

Fig. 4. Reliability of individual memory module

the memory system with no redundancy (i.e., $S = 0$ and $s = 0$), $R(1) = 0.521805083796637$, which means it would not maintain $R > 0.95$ for even a week. If 32 spare columns are applied, the memory system will maintain $R > 0.95$ for about 9 years since $R(428) = 0.950233141259701$ and $R(429) = 0.948538560295286$. The reliability of the memory system can be further enhanced by exploiting module redundancy. The memory system with $s = 32$ and $S = 6$ satisfies the requirement of $R > 0.95$ for more than 12 years because $R(599) = 0.951682181131270$ and $R(600) = 0.948490237398006$. To meet $R > 0.95$ for 10 years, the minimal overhead of these systems is with $S = 2$ and $s = 32$.

Another useful measurement of the fault-tolerant onboard memory system quality is mean-time-to-failure ($MTTF$), which is the expected time that a system will operate before a failure occurs. Figure (9) shows $MTTF$'s of three different memory module configurations of 32×32, 64×64, and 128×128 with different numbers of spare columns from 0 to 32. For example, $MTTF_{A_n} = 25.101321$ for 32×32 memory module without spare columns, which implies that the expected time that the memory module will operate before a failure occurs is only about 25 weeks while the same memory module with 32 spare columns has $MTTF = 11{,}161.738703$ weeks.

$MTTF$s of the 256K non-fault-tolerant (i.e., $s = 0$ and $S = 0$) and fault-tolerant memory systems with various combinations of s and S (i.e., from 1 to 32 for s and from 2 to 8 for S) are given in Figure (10). $MTTF$ of the non-fault-tolerant memory system, 2.091197 weeks, can be extended to 10,643.743596 weeks by exploitation of two-level active redundancy of $s = 32$ and $S = 6$. Thus, the results given in Figures (9) and (10) confirm the fault-tolerant ability of the two-level active redundancy technique.

Intelligent exploitation of the proposed measurement estimation technique makes possible the design and manufacture of balanced onboard memory systems satisfying reliability and mission duration requirements while maintaining minimal redundancy.

VIII. DISCUSSION AND CONCLUSIONS

As advances in spaceborne vehicular technology make possible the long-life duration of missions in harsh cosmic environments, reliability and data integrity become commonly emphasized requirements of spaceborne solid-state mass storage systems, because faults due to the harsh cosmic environments—such as extreme radiation—can be experienced throughout the mission. In addition, it is well known that faults show spatial locality on VLSI circuits. Thus, a reliability measurement and estimation technique for the fault-tolerant onboard memory system under fault clustering has been proposed and validated throughout the parametric simulation in this paper. Thereby, intelligent exploitation of the proposed measurement and estimation technique makes possible the design and manufacture of balanced onboard memory systems satisfying the reliability and mission duration requirements while maintaining minimal redundancy. For example, according to the simulation results given in this paper, the sample 256K fault-tolerant onboard memory system with 32 spare columns in each memory module and 6 redundant modules has more than 0.95 probability of being operational at the end of a 10 years and its mean-time-to-failure ($MTTF$) exceeds 232 years.

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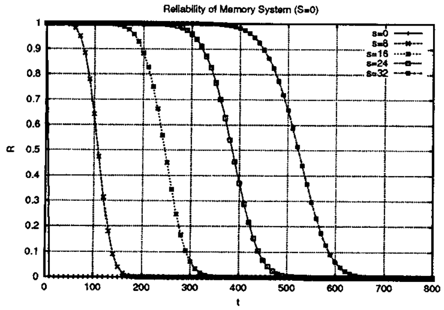

Fig. 5. Reliability of memory system without module redundancy

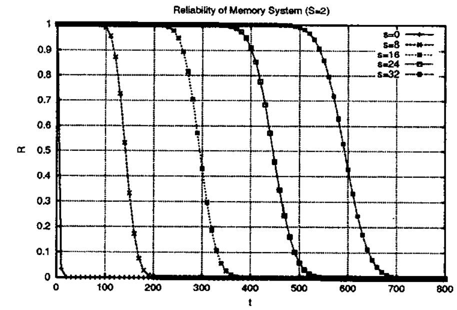

Fig. 6. Reliability of memory system with two redundant modules

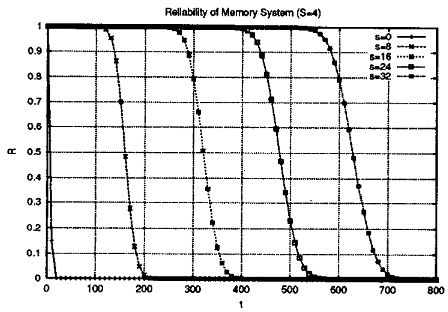

Fig. 7. Reliability of memory system with four redundant modules

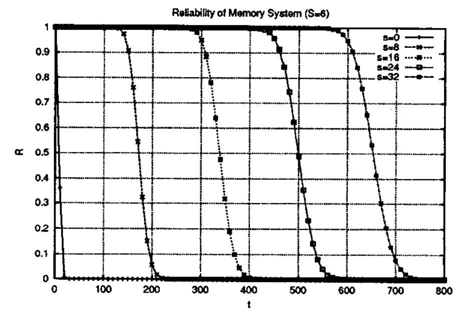

Fig. 8. Reliability of memory system with six redundant modules

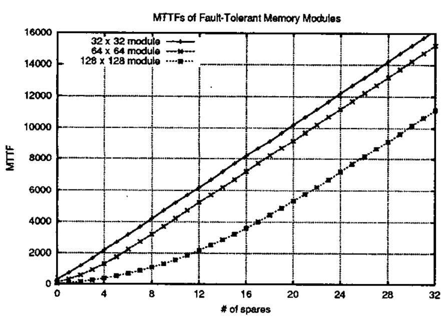

Fig. 9. MTTFs of fault-tolerant memory modules

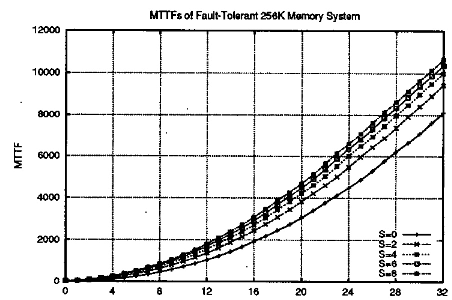

Fig. 10. MTTFs of fault-tolerant 256K memory system

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