An Efficient Test Pattern Selection Method for Improving Defect Coverage with Reduced Test Data Volume and Test Application Time

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Abstract—Testing using n -detection test sets, in which a fault is detected by n ($n > 1$) input patterns, is being increasingly advocated to increase defect coverage. However, the data volume for an n -detection test set is often too large, resulting in high testing time and tester memory requirements. Test set selection is necessary to ensure that the most effective patterns are chosen from large test sets in a high-volume production testing environment. Test selection is also useful in a time-constrained wafer-sort environment. We use a probabilistic fault model and the theory of output deviations for test set selection—the metric of output deviation is used to rank candidate test patterns without resorting to fault grading. To demonstrate the quality of the selected patterns, we present experimental results for resistive bridging faults and non-feedback zero-resistance bridging faults in the ISCAS benchmark circuits. Our results show that for the same test length, patterns selected on the basis of output deviations are more effective than patterns selected using several other methods.

I. INTRODUCTION

Shrinking process technologies and the use of new materials such as copper interconnects and high-K dielectrics are leading to increasingly complex defects for integrated circuits (ICs) [1], [2]. It is not always possible to accurately model these defects or predict their occurrences. A single spot defect is likely to affect several logic gates and multiple defects on a die are likely. The locations of these defects are unpredictable. The failure probability of a gate due to a defect depends also on factors such as die temperature and power supply variations. As a result, it is no longer adequate to rely only a deterministic fault model, especially a fault model that targets only single faults. In addition, many real defects are difficult to model by existing fault models; examples of such defects include resistive opens and shorts, crosstalk, and interconnect defects. Thus while classical fault models are widely used in industry [3]–[6], it is also important to focus on alternative methods to catch defects that are not fully understood.

It has been shown in the literature that n -detection test sets, where each stuck-at fault is targeted by n ($n > 1$) different patterns, are effective for detecting unmodeled defects [7]–[10]. As the number of unique detections for each fault increases, the defect coverage usually improves compared with other test generation methods. An advantage of this approach is that even when n is very large, n -detection test sets can be generated using existing single stuck-at ATPG tools with reasonable computation time.

However, the data volume of an n -detection test set is often too large, resulting in long testing time and high tester memory requirement [11], [12]. This is because the n -detection method simply tries to detect each single stuck-at fault n times, and does not use any other metric to evaluate the contribution of a test pattern towards increasing the defect coverage. It has been reported in the literature that the sizes of n -detection test sets tend to grow linearly with n [12]. Therefore, test selection is necessary to ensure that the most effective test patterns are chosen from large test sets during time-constrained and high-volume production testing [13]. Due to test

time constraints, it is often not possible to apply all the n -detection patterns, even for relatively small values of n [14]. Test selection is also useful in a time-constrained wafer-sort environment. Even if test data volume and test application time are reduced using test compression, test pattern selection can still be used to reorder a test set. If highly effective test patterns are applied first, a defective chip can fail earlier, further reducing test application time in an abort-at-first-fail environment. Moreover, test compression is not effective if the patterns are delivered without a significant fraction of don't-care bits. In such cases, test set selection can be a practical method to reduce test time and test data volume.

The test set selection problem can be addressed using a probabilistic fault model, recently published in [15], that allows any number of gates in the IC to fail probabilistically. Tests for this fault model, determined using the theory of output deviations, can be used to supplement tests for classical fault models, thereby increasing test quality and reducing the probability of test escape. In this paper, we use the output deviation metric for test selection. We also indirectly generate an n -detection test set by selecting efficient patterns based on output deviation from a larger n' -detection test set ($n' > n$). To evaluate the quality of the selected test patterns, we determine the coverage that they provide for resistive bridging faults [16] and single non-feedback zero-resistance bridging faults (s-NFBFs). Experimental results show that patterns selected using the probabilistic fault model and output deviations provide higher bridging fault coverage than patterns selected using other methods.

We also use metrics for gate exhaustive (GE) testing [17] to evaluate the effectiveness of deviation-based test sets. In a recent production test experiment, more than 50,000 chips were analyzed to understand the correlation between the number of defective chips screened by a set of test patterns and the coverage provided by these test patterns with respect to various test metrics [18]. The GE metric was found to have higher correlation compared to the SSL and the bridge coverage estimate metrics. Therefore we also consider GE metrics to evaluate deviation-based test sets. Our experiments show that deviation-based test sets outperform n -detect test sets for several GE metrics.

The remainder of this paper is organized as follows. Sections II introduces the probabilistic fault model and the theory of output deviations. The design of experiments and some experimental results are reported in Section IV. Section V concludes this paper and outlines directions for future work.

II. THE PROBABILISTIC FAULT MODEL AND THE THEORY OF OUTPUT DEVIATIONS

The *confidence level* of a single-output gate encompasses all the different input combinations of the gate, and for a given input combination, it provides the probability that the gate output

Fig. 1. 2-input NAND gate and an illustrative example.

for the corresponding input combination. The probability that a gate output is correct can be different for the various input combinations.

Definition 1: The confidence level R_i of a gate G_i with m inputs and a single output is a vector with 2^m components, defined as: $R_i = (r_i^{(00\dots00)} r_i^{(00\dots01)} r_i^{(00\dots10)} \dots r_i^{(11\dots11)})$, where each component of R_i denotes the probability that the gate output is correct for the corresponding input combination.

For example, r_i^{00} is the probability that the output of a 2-input G_i is correct under input 00. If $m = 2$ for a logic gate, we have $R_i = (r_i^{(00)} r_i^{(01)} r_i^{(10)} r_i^{(11)})$.

The above gate-level confidence level vectors can be generated in a number of ways, e.g., using layout information, inductive fault analysis [19], and failure data analysis. It can also be estimated using simple transistor-level failure probabilities. Our objective here is not to develop new techniques for determining confidence level vectors, but rather to use these as inputs for the computation of output deviation. In practice, deviation-based test patterns can be generated using multiple sets of confidence level vector estimates.

Consider the 2-input NAND gate shown in Fig. 1(a). Suppose each transistor can be stuck-open due to a defect, i.e., it cannot be switched on, with probability α . Similarly, suppose each transistor can be stuck-on due to a defect, i.e., it cannot be switched off, with probability β . Next let us consider input combination $x_1x_2 = 00$. If only stuck-open faults are considered, the NAND gate produces the correct output for this combination with probability $r^{(00)} = (1 - \alpha)^2$ because the gate produces an incorrect output only if both transistors are stuck-open. Likewise, if we only consider stuck-on faults, the probability that the NAND gate produces the correct output for input 00 is $r^{(00)} = (1 - \beta)^2$.

Next we associate signal probabilities $p_{i,0}$ and $p_{i,1}$ with each line i in the circuit, where $p_{i,0}$ and $p_{i,1}$ are the probabilities for line i to be at logic 0 and 1, respectively. Obviously we have $p_{i,0} + p_{i,1} = 1$. The calculation of the signal probabilities is along the same lines as introduced in [20], and used later in [21]. To reduce the amount of computation as in [20], [21], signal correlations due to reconvergent fanout are not considered here.

Let i be the output of a two-input gate G . Let j and k denote the input lines for this gate. If G is a NAND gate, we have:

$$\begin{aligned} p_{i,0} &= p_{j,1}p_{k,1}r_i^{(11)} + p_{j,0}p_{k,0}(1 - r_i^{(00)}) \\ &\quad + p_{j,0}p_{k,1}(1 - r_i^{(01)}) + p_{j,1}p_{k,0}(1 - r_i^{(10)}) \\ p_{i,1} &= p_{j,0}p_{k,0}r_i^{(00)} + p_{j,0}p_{k,1}r_i^{(01)} \\ &\quad + p_{j,1}p_{k,0}r_i^{(10)} + p_{j,1}p_{k,1}(1 - r_i^{(11)}) \end{aligned}$$

Likewise, the signal probabilities can be easily computed for other gate types.

Figure 1(b) shows a simple circuit consisting of three gates G_1 , G_2 , and G_3 with confidence level vectors (0.9 0.9 0.9 0.8), (0.8 0.9 0.9 0.9), and (0.8 0.9 0.9 0.9), respectively. For the three different deterministic input vectors 0000, 0101, and 1111, the signal

Input pattern, z	$p_{e,0}$	$p_{e,1}$	$p_{f,0}$	$p_{f,1}$	$p_{z,0}$	$p_{z,1}$
0000, 0	0.1	0.9	0.2	0.8	0.886	0.114
0101, 0	0.1	0.9	0.9	0.1	0.837	0.163
1111, 1	0.8	0.2	0.9	0.1	0.396	0.604

TABLE I
SIGNAL PROBABILITIES FOR DIFFERENT INPUT COMBINATIONS

probabilities are determined and presented in Table I. The fault-free values at the output z are also listed in the first column of Table I.

In [22], probabilistic transfer matrices (PTMs), which are similar to confidence level vectors, have been used for generating test patterns for soft errors caused by single-event upsets. The focus of this work however is on test pattern selection for permanent faults. Signal correlation due to reconvergent fanouts is accounted for in [22] using tensor products, hence PTMs may not scale well for large circuits.

We next use the concept of signal probabilities to develop the notion of output deviations. We then describe how to determine deviation-based test patterns that can be used to enrich test sets.

For any logic gate (or primary output) g in a circuit, let its fault-free output value for any given input pattern t_j be d , $d \in \{0, 1\}$. The output deviation $\Delta_{g,j}$ of g for input pattern t_j is defined as $p_{g,\bar{d}}$, where $\bar{d}$ is the complement of d . Intuitively, the deviation for an input pattern is a measure of the likelihood that the gate output is incorrect for that input pattern.

Next we formally define the probabilistic fault model for a combinational circuit $\mathcal{C}$.

Definition 2: A combinational circuit $\mathcal{C}$ is defined as $\mathcal{C} = \{\mathcal{G}, \mathcal{PI}, \mathcal{Z}, \mathcal{R}\}$, where $\mathcal{G} = \{G_1, G_2, \dots, G_N\}$ is the set of logic gates in $\mathcal{C}$, $\mathcal{PI}$ and $\mathcal{Z}$ are the sets of primary inputs and outputs respectively, and $\mathcal{R} = \{R_1, R_2, \dots, R_N\}$ is the set of confidence level vectors of the gates in $\mathcal{G}$.

Definition 3: A probabilistic fault model $\mathcal{F}$ for circuit $\mathcal{C}$ is defined as follows: (i) Each gate G_i can fail independently of other gates; (ii) the fault behavior of $\mathcal{C}$ is defined by R_i .

Under this fault model, the expected output values of the circuit in response to an input pattern is no longer deterministic. Rather, it is given by the signal probabilities at primary outputs. Note that the circuit behavior is assumed to be deterministic after manufacturing; the probabilistic fault model is only used during test development for pattern grading.

The probability that t_j will produce an observable error at z_i for fault model $\mathcal{F}$ is directly proportional to $\Delta_{z_i,j}$. The goal of testing is to apply those vectors to $\mathcal{C}$ that produce large deviations at the output. Therefore, the concept of output deviations offers a promising method for modeling pattern quality. From now on, we only consider output deviations at outputs and use the terms “output deviation” and “deviation” interchangeably.

III. TEST PATTERN SELECTION

In this section, we attempt to select a relatively small number of test patterns, using the output deviations, from a repository test set T_{rep} that contains a much larger number of test patterns. The selected test set should provide high defect coverage.

We choose to use an n_0 -detection test set as T_{rep} ($n_0 = 15$ for smaller benchmark circuits and $n_0 = 7$ for larger benchmark circuits). To generate T_{rep} , we first run Atalanta [23], a single stuck-at fault ATPG tool, to generate n_0 test patterns for each single stuck-at fault. (It is not guaranteed that Atalanta can generate n_0 patterns for each fault, but instances when it fails to do so are rare.) Since these test patterns contain unspecified bits (Xs), they are further compacted and randomly-filled to form T_{rep} .

For comparison purposes, we also generate a group of n -detection test sets ($n = 2, 3, \dots, 8$) as baseline test sets by randomly

Procedure Subset(n)
Input: n , n_0 -detection test set T_0 ,
 $T_0 = \{T_0[1], T_0[2], \dots, T_0[m]\}$
Output: n -detection test set T_n ($n < n_0$)

```

1:  $T_n = \emptyset$ ;
2: for  $i = 1$  to  $m$ 
3:   do fault simulation using the pattern  $T_0[i]$ ;
4:   if  $T_0[i]$  detects some faults that are detected
5:     less than  $n$  times by  $\{T_0[1], T_0[2], \dots, T_0[i-1]\}$ 
6:     add  $T_0[i]$  to  $T_n$ ;
7:   if all faults are detected  $n$  times
8:     break;
9: end for

```

Fig. 2. Procedure to generate an n -detection test set from a n_0 -detection test set ($n < n_0$).

Pattern ID	Output deviations		
	Port A	Port B	Port C
t1	0.9	0.2	0.7
t2	0.8	0.3	0.4
t3	0.6	0.7	0.8
t4	0.2	0.6	0.5
t5	0.7	0.4	0.9
t6	0.3	0.1	0.2

(a) Test patterns and output deviations.

Port A	t1	t2	t5	t3	t6	t4
Port B	t3	t4	t5	t2	t1	t6
Port C	t5	t3	t1	t4	t2	t6

(b) Outcome of the sorting procedure (Matrix X).

Fig. 3. An example to illustrate the sorting of T_{rep} based on output deviations.

test patterns from T_{rep} . Each time a test pattern is selected, we perform fault simulation and drop those faults that are already detected n times. This procedure, as outlined in Fig. 2, continues until all faults are detected n times. The set T_{rep} is randomly reordered before being provided as input to Procedure Subset. Therefore, although this procedure goes through T_0 sequentially (line 2), it tends to select patterns from T_0 randomly. The test sets selected using output deviations are compared to these n -detection test sets in terms of their sizes and defect coverage.

Next, we sort T_{rep} such that test patterns with high deviations can be selected earlier than test patterns with low deviations. For each primary output (PO), all test patterns in T_{rep} are sorted in descending order based on their output deviations. The result is stored in a matrix X with M rows and P columns, where M is the number of POs and P is the number of test patterns in T_{rep} . The element in the i -th row and the j -th column is the test pattern that has the j -th highest output deviation at the i -th PO. Fig. 3 illustrates this sorting procedure. From matrix X , a new ordered test set T'_{rep} can be obtained using Procedure Deviation_Sort shown in Fig. 4. For the example in Fig. 3, the resulting sorted test set is $T'_{rep} = \{t_1, t_3, t_5, t_2, t_4, t_6\}$.

We next describe three different ways to select a small number of

Procedure Deviation_Sort
Input: X , M , P
Output: T'_{rep}

```

1: while  $|T'_{rep}| < P$ 
2:   for  $i = 1$  to  $P$ 
3:     for  $j = 1$  to  $M$ 
4:       if  $X[i][j] \notin T'_{rep}$ 
5:         add  $X[i][j]$  to  $T'_{rep}$ ;
6:       break;
7:     end if
8:   end while

```

Fig. 4. Procedure to select patterns with high deviations.

Procedure Reverse_Deviation_Sort
Input: X , M , P , $threshold$
Output: T'_{rep}

```

1: while  $|T'_{rep}| < P$ 
2:   for  $i = 1$  to  $P$ 
3:     for  $j = M$  down to 1
4:       if  $(X[i][j] \notin T'_{rep})$  and
4:          $(X[i][j]$  has no deviations higher than  $threshold$ 
4:         at any PO)
5:         add  $X[i][j]$  to  $T'_{rep}$ ;
6:       break;
7:     end if
8:   end while

```

Fig. 5. Procedure to reverse_sort test patterns on the basis of deviations.

patterns from T'_{rep} , such that the resulting test sets can be compared with the baseline n -detection test sets.

Method 1: Generate an n -detection test set using Procedure Subset shown in Fig. 2. However, unlike the baseline n -detection test sets, the input to Procedure Subset is T'_{rep} instead of T_{rep} , such that test patterns with high deviations are selected first. Therefore, the resulting test set is an optimized n -detection test set that usually contains a smaller number of patterns and achieves a higher defect coverage than its baseline n -detection test set.

Method 2: Select patterns with high output deviations from T'_{rep} . The test patterns in T'_{rep} are selected sequentially to form the resulting test set.

Method 3: Select patterns with low output deviations from T'_{rep} using Procedure Reverse_Deviation_Sort shown in Fig. 5. Procedure Reverse_Deviation_Sort takes an extra input $threshold$, and ensures that only test patterns with output deviations not higher than $threshold$ are selected (line 4). The parameter $threshold$ is different for different circuits such that a reasonable number of test patterns are selected.

IV. EXPERIMENTAL RESULTS

All experiments were performed on a Pentium 4 PC running Linux with a 2.6 Ghz processor and 1G memory. The program to compute output deviations was implemented using C++. It took approximately 80 seconds to compute the deviations for 10,000 vectors for a full-scan version of the largest benchmark circuit (s38584). Atalanta and its associated simulation engine are used to generate n -detection test sets and to perform fault simulation. The PROBE simulator [16] is used to compute the coverage of resistive bridging faults. We also implemented a bridging fault simulator to calculate the coverage of single non-feedback, zero-resistance bridging faults (sNFBFs). Due to the limitation of file size, for circuits c7552 and s9234 the set T_{rep} is a 7-detection test set; for other circuits, the set T_{rep} is a 15-detection test set.

To eliminate any bias in the comparison of different methods for test set selection, we use two arbitrarily chosen sets of confidence level vectors for our experiments. These vectors are defined separately for each gate type. For example, for a 2-input NAND gate, we use 1) "low confidence level" vector: $R^{NAND2} = (0.8^{(00)}, 0.8^{(01)}, 0.8^{(10)}, 0.7^{(11)})$, and 2) "high confidence level" vector: $R^{NAND2} = (0.95^{(00)}, 0.95^{(01)}, 0.95^{(10)}, 0.85^{(11)})$. Since both sets of confidence level vectors yield similar results, we only report results obtained using the "high confidence level" set.

Gate exhaustive (GE) testing metrics are computed using an in-house simulation tool based on the fault simulation program FSIM [24]. We use the three different GE metrics listed in Table II.

The metric *score* is the total number of distinct observed input combinations of all the gates, defined as $\sum_{i=1}^N \sum_{j=0}^{2^{n_i}-1} f_i(j)$, where N is the total number of gates in the circuit, and n_i is the number of inputs of gate i . An *observed input combination* of a gate is an input combination that is applied to the gate inputs with the ga

Metric	Definition
score	Total number of all distinct observed input combinations of all gates.
exp-cnt	Number of gates that are exhaustively tested.
ratio	average observed input combinations ratio over all gates.

TABLE II
GATE EXHAUSTIVE TESTING METRICS

Fig. 6. Results for s-NFBF faults for two representative ISCAS-85 circuits.

being sensitized to at least one observation point such as a primary output or a scan cell. Function $f_i(j)$ is defined to be 1 if and only if the binary combination corresponding to the decimal number j is applied to the inputs of gate i , and at the same time, the response of gate i is observed at some observation points [17].

The metric *exp-cnt* simply counts the number of gates that are exhaustively tested. A gate is exhaustively tested if and only if all of its possible input combinations are applied and observed. The metric *ratio* is defined as $\sum_{i=1}^N \frac{\sum_{j=0}^{2^{n_i}-1} f_i(j)}{2^{n_i}-1} / N$; i.e., for each gate, we first calculate the ratio of observed input combinations to the number of all possible input combinations, and then obtain the average ratio over all gates.

We first present experimental results for the coverage obtained for s-NFBFs with the various test sets that we considered. We varied the test length to compare the effectiveness of the different tests. The first

Fig. 7. Results for s-NFBF faults for two representative ISCAS-89 circuits.

set T_1 is determined using the procedure *Deviation_Sort*; it contains patterns with high deviations. Fault simulation is not necessary to obtain this test set. The second test set T_2 contains patterns selected at random from the base test set T_{rep} . The third test set T_3 is determined using the procedure *Reverse_Deviation_Sort*, i.e., it contains patterns with low deviations. The final test set is determined using fault simulation for 5-detection and therefore is named as T_5 instead of T_4 . It is obtained from Procedure *Subset* by setting $n = 5$.

Fig. 6–7 show that T_1 consistently provides higher fault coverage than the other test sets. The coverage for T_5 increases with test length, but it is considerably less than that for T_1 for shorter test lengths that may be desired for time-constrained production testing. Moreover, fault grading is required to generate T_5 from T_{rep} , which may not be feasible in a production testing environment.

Next we present experimental results obtained for resistive bridging faults using the PROBE fault simulator. For these experiments, we again used the test sets T_1 , T_3 , and T_4 . In addition, we generated another test set T_5^* using Method I described in Section III. Fault grading (based on resistive shorts) is combined with deviation-based ranking to generate this 5-detect test set, referred to as “Sorted 5-detection”.

Fig. 8 shows that T_1 and T_5^* , the only two test sets that are obtained by selecting patterns with high deviations, consistently provide

Fig. 8. Results for resistive bridging faults for the two largest ISCAS-85 circuits.

Circuit	Test set	n					
		3	4	5	6	7	8
c5315	T_n	900	1077	1235	1359	1472	1584
	T_n^*	433	540	657	773	877	973
c6288	T_n	178	221	260	300	339	383
	T_n^*	103	131	153	182	215	244
c7552	T_n	1192	1491	1775	2032	2291	-
	T_n^*	799	1024	1244	1462	1664	-

TABLE III
NUMBER OF PATTERNS IN T_n^* AND T_n FOR DIFFERENT VALUES OF n .

Circuit	Test set	# patterns	score	exp-cnt	ratio
c5315	T_3^*	433	9,388	1461	88.75%
	T_3	433	8,150	1155	78.04%
	T_5^*	657	9,776	1474	88.87%
	T_5	657	8,903	1230	82.30%
	T_5^*	103	7,846	712	81.85%
c6288	T_3^*	103	7,696	658	80.30%
	T_3	103	7,857	723	81.96%
	T_5^*	153	7,729	679	80.64%
	T_5	153	7,729	679	80.64%
	T_5^*	1244	11,759	1977	86.68%
c7552	T_3^*	799	11,300	1851	84.79%
	T_3	799	11,814	1988	86.75%
	T_5^*	1244	11,502	1895	85.51%
	T_5	1244	11,502	1895	85.51%
	T_5^*	654	8,005	2263	92.78%
s5378	T_3^*	654	7,949	2239	92.31%
	T_3	654	8,032	2276	92.93%
	T_5^*	1039	8,008	2264	92.79%
	T_5	1039	8,008	2264	92.79%
	T_5^*	907	14,234	4073	88.43%
s9234	T_3^*	907	14,151	4064	88.16%
	T_3	907	14,269	4094	88.53%
	T_5^*	1372	14,235	4083	88.42%
	T_5	1372	14,235	4083	88.42%
	T_5^*	1372	14,235	4083	88.42%

TABLE IV
GATE EXHAUSTIVE TESTING RESULTS FOR SOME REPRESENTATIVE ISCAS BENCHMARK CIRCUITS.

fault coverage than the other test sets. In some cases the coverage of T_5^* is slightly higher than that of T_1 , but in most cases the coverages of T_5^* and T_1 are the same. Therefore, in a production testing environment, T_1 may be a better choice than T_5^* since we do not need fault grading to generate T_1 .

We next present the coverage for resistive bridging faults obtained using different n -detection test sets. For each value of n , we consider two test sets: the “Sorted n -detection” test set (T_n^*), obtained using output deviations and fault grading, and the baseline “ n -detection” test set (T_n), obtained using only fault grading. Since T_n^* always contains fewer test patterns than T_n , for the sake of fair comparison, T_n is truncated to the size of T_n^* . Table III lists the number of patterns in T_n^* and T_n for different values of n . Fig. 9 shows that T_n^* consistently provides higher fault coverage than T_n .

Finally, we present results for the GE metrics obtained using deviation-sorted n -detect test sets (T_n^*) and n -detect test sets (T_n) that do not use deviations ($n = 3$ or 5). T_n is truncated to ensure a fair comparison for the same number of patterns. Table IV lists the results for some representative ISCAS benchmark circuits. As can be seen from Table IV, T_n^* provides higher values for all the three GE metrics.

V. CONCLUSIONS

We have shown that the output deviation is an effective metric to model the quality of test patterns. Pattern ranking based on output deviations offers a useful method for test-set selection during high-volume and time-constrained production testing. Experimental results show that for the same test length, test patterns selected using output deviations are consistently more effective than patterns selected using other methods. We have evaluated pattern grading using the fault coverage for resistive shorts and non-feedback bridging faults, and several gate exhaustive metrics. As part of ongoing work

Fig. 9. Results for resistive bridging faults for the two largest ISCAS-85 circuits.

comparing this method with other test pattern ranking techniques, such as a greedy algorithm which uses fault grading and ranks patterns based on the number of (modeled) faults detected with each pattern.

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