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Vital Area Analysis Using SETS MASTER

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VITAL AREA ANALYSIS USING SETS

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ABSTRACT

This report describes the use of the Set Equation Transformation System (SETS) for vital area analysis. Several concepts are introduced which enable the analyst to construct more efficient SETS user programs to perform vital area analysis. The advantages of performing the transformation of variables without first determining the minimal cut sets of the fault tree are discussed. A "bottom-up" approach to solving a fault tree is presented. The techniques described for vital area analysis are also suitable and efficient for many kinds of common cause analysis.

ACKNOWLEDGMENT

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VITAL AREA ANALYSIS USING SETS

1. Introduction

Vital area analysis [1, 2] is the analytical procedure
used to systematically identify the areas of a nuclear power
plant that require physical protection. As part of the U. S.
Nuclear Regulatory Commission (USNRC) review of security
plans, vital area analyses are being performed for all nuclear
power plants. Sandia National Laboratories and Los Alamos
National Scientific Laboratory are providing technical and
computational support to the USNRC, Office of Nuclear Material
Safety and Safeguards for the analysis. This report describes
how to construct a Set Equation Transformation System (SETS)
user program which can identify vital areas in a manner signi-
ficantly more efficient than the previous SETS methodology.

Vital area analysis begins with a fault tree, F, whose
primary events are sabotage actions that can lead to the
undesired release of radioactive material. In addition to
the fault tree, a set of Boolean equations, L, is required.
Set L contains one equation for each primary event in F.
This equation identifies the location, or logical combina-
tions of locations, where that primary event can occur.

The increased efficiency of the SETS user program to be
described is a result of the following conditions:

- The set L is added to the equation file after the
  fault tree is loaded but before the fault tree
  analysis is executed by a SETS user program.

● The fault tree analysis portion of the SETS user program implements a "bottom-up" solution rather than traditional "top-down" techniques.

2. Fault Tree Modelling and Analysis

The mathematical model of primary events and their combinatorial relationships is a set of interrelated Boolean equations. The fault tree is a graphical representation of this set. For the sabotage fault tree where primary events are sabotage actions, the set will be denoted by S.

The mathematical techniques used to analyze a fault tree model are applications of Boolean algebra, particularly the application of Boolean identities which produce equivalent Boolean equations. The use of SETS for fault tree analysis applies a minimal cut set algorithm [3] to the set S. The goal is to determine a Boolean equation which represents all of the minimal cut sets for the top event (or some other intermediate event) of the fault tree. Minimal cut sets for an intermediate or top event represent the fundamental ways that the event can occur in terms of the occurrence of primary events.

Since the analysis begins with a fault tree but is achieved using techniques based in Boolean algebra, some concepts and terminologies of fault tree analysis will be related to those of Boolean algebra.

The primary events of a fault tree are represented by independent Boolean variables in the set S. Each gate

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(intermediate event) in the fault tree is denoted by a dependent variable in the set S. Furthermore, each gate in the fault tree corresponds to an equation in S; the left side is the gate's dependent variable, and the right side is a logical combination of the variables representing the gate's inputs. The logical combination of variables is determined by the gate symbol (OR, AND, XOR, etc.) which is seen on the fault tree plot.

By the process of repeated substitution, any dependent variable can ultimately be expressed as a logical combination of independent Boolean variables. This is equivalent to saying that any intermediate event can be expressed as a logical combination of primary events. After the equation for a dependent variable is determined solely in terms of independent variables, a sequence of equation manipulations (called expansion and simplification, in [3]) produces a Boolean equation in disjunctive normal form. This equation is tantamount to a listing of the minimal cut sets for the gate represented by the dependent variable. The terms of the equation consist of only independent variables interpreted as primary events.

3. Vital Area Analysis

The previous methodology for vital area analysis sought first to derive a Boolean equation for the top event in terms of the primary events (sabotage actions) from the original

fault tree. However, because of the size and complexity of most fault trees, this method requires excessive amounts of computer and analyst time. Furthermore, it is entirely possible that the Boolean equation which represents all minimal cut sets may be unobtainable despite the advanced techniques described in Section 4 of [3]. When this occurs, truncation must be employed, meaning that terms of order "n" or more* are ignored. In short, the Boolean equation which represents the solution to the fault tree is not complete. Such a truncated solution would make the subsequent vital area analysis incomplete also, that is, some of the vital locations may not be identified.

The new methodology for vital area analysis does not attempt to solve the Boolean equations derived from F. Instead, the set S ∪ L of equations is solved. (S is the set of equations derived from F.) This amounts to solving a location fault tree, i.e., a fault tree with locations or areas as primary events. The set S ∪ L defines such a fault tree, because each primary event (independent variable) in S is further developed into areas by an associated equation in L. Thus, the variables which are independent in S become dependent variables in S ∪ L and locations are represented by the independent variables of S ∪ L.

In contrast to the <u>location tree</u> in Figure 3.6 of [1], the <u>location fault tree</u> defined by S ∪ L is larger than

---

*n is a positive integer chosen by the analyst.

the original fault tree. The difference is due to the
fact that the location tree allows primary events of the
original fault tree to be replaced by locations or logical
combinations of locations. The <u>location tree</u> includes
no sabotage actions, only those locations of possible
action. Once this replacement is made, the original fault
tree structure is changed--gates are coalesced or removed
entirely depending on inputs. While this step reduces
the general complexity of the fault tree, it also requires
the formation of the location tree.

The location fault tree, set S ∪ L, uses the primary
events of the original tree and further develops each primary
event into logical combinations of locations where they can
occur. Although S ∪ L defines a larger fault tree, it is
much easier to solve (i.e., find the Boolean equation repre-
senting all minimal cut sets of the top gate) since there are
substantially fewer primary events. A typical reactor sabo-
tage fault tree has over 200 primary events which represent
sabotage actions, but only about 30 areas for these actions
to occur. The "bottom-up" solution technique exploits this
situation by developing every equation only in terms of
independent variables. Since there are approximately only
30 independent variables, even large equations simplify to a
manageable size at each step of the procedure. Finally, it
is not necessary to plot the fault tree defined by the set
S ∪ L, since the "bottom-up" technique uses only the informa-
tion available in the plot of the original fault tree.

4. Bottom Up Algorithm

In general, the "bottom-up" solution technique is suitable for a fault tree with a large number of replicated primary events relative to the tree's total number of primary events. An approximate ratio of the number of replicated primary events to the total number of primary events, used as a guide post for applying the bottom-up technique, has not been established; but the fault tree defined by S ∪ L has nearly all its primary events replicated, making it an excellent candidate for this approach.

The "bottom-up" algorithm seeks to determine an ordering on attempted gate solutions which guarantees that each gate solution equation consists of only primary events (independent variables). Vital area analysis using this technique begins with a careful examination of the (original sabotage) fault tree plot. In order to clarify the procedure, the following definitions are necessary.

The <u>fault tree plot</u> is comprised of several fault tree segments. (See Figure 1 for a graphical representation of segment relationships within a plot.) The definitions of the different types of fault tree segments are based on the plot created by the <u>Fault Tree Drawing Program</u> (FTDP) [4].

A <u>fault tree segment</u> is a connected set of gates for which one gate (the top) is developed until its branches terminate in primary events or other events, defined by user criteria to be treated as primary events.

There are three distinct types of segments for vital area analysis fault trees. The Major Fault Tree Segment (MFTS) develops the top gate of the fault tree down to primary events and transfer-in symbols. A transfer-in symbol made by the FTDP denotes the input of a replicated gate. An Intermediate Fault Tree Segment (IFTS) has a replicated gate as its top, with an associated transfer-out symbol. This multiple output event is developed down to primary events and transfer-in symbols. An IFTS contains at least one transfer-in symbol. A Terminal Fault Tree Segment (TFTS) also has a replicated gate as its top, with an associated transfer-out, but is developed down to only primary events.

In fault trees with a single top event and at least one replicated event, there is only one MFTS, and there is at least one TFTS. In fault trees with a single top event and no replicated events, the MFTS is the same as the TFTS. It is assumed that vital area analysis fault trees have at least one replicated gate, yielding a distinct MFTS and TFTS. Every replicated gate defines the top of a fault tree segment, consequently the fault tree decomposition is unique.

The MFTS contains the top event of the fault tree and is drawn by the FTDP as the leftmost segment on the plot. Each transfer-in located within the MFTS corresponds to a transfer-out symbol associated with the top gate of an IFTS or a TFTS. The transfer-out symbol is located at the top of the IFTS or TFTS and its gate is plotted down to other transfer-ins or primary events. Each segment is plotted to

the right of the previous one, but in no particular order. TFTS's are often the rightmost segments of the plot.

It is assumed that the Forced Transfer Option of the FTDP is not used when plotting the fault tree. This option enables gates with a single output to be plotted with a transfer-out symbol. If this option is not used, all and only those gates with multiple outputs are plotted with a transfer-out symbol. Also, it is visually helpful if the Levelling Option of the FTDP is not used. This option causes segments to be drawn where they fit on the plot page, other than at the top of the plot. Occasionally this option will reduce the amount of paper used in a plot, but it forces the analyst to search the entire plot for occurrences of IFTS's and TFTS's. Without the option, the top symbol of each segment (major, intermediate, terminal) is plotted on the top edge of the plot sheet so the identification of every fault tree segment, no matter which type, is straight-forward.

Once the original fault tree (sabotage) is plotted, the next step of the analysis is to algorithmically determine the order in which gate solutions are to be attempted. The "bottom-up" algorithm concentrates on providing gate solution equations whose right-hand side consists of only independent Boolean variables. This is accomplished by beginning with the TFTS's at the bottom of the fault tree and building the solution, segment by segment, to the top gate.

The fault tree solution being sought is a representative Boolean equation for the top gate which is a minimal Boolean

expression of independent variables in disjunctive normal
form. A segment solution is a similar concept except the
equation is for the top gate of the segment. The equation
represents the family of all minimal cut sets, the fundamental
ways the event can occur.

The methodology for finding a "bottom-up" fault tree solu-
tion is based on the identification and solution of a certain
sequence of all of the fault tree segments. Each event of
the fault tree is contained in at least one segment and the
set of all fault tree segments completely cover the tree.

Viewing the fault tree as a set of segments, each segment
can be labeled "solved" (subset D) or "unsolved" (subset N).
Initially all segments are unsolved, i.e., $D = \Phi$. Ulti-
mately, to obtain the fault tree solution, all segments are
members of D, but to be efficient, the order of attempted
solution is important.

The essential criteria for determining this sequence
is that no segment solution be attempted unless it contains
only primary events or all of its replicated gates (transfer-
ins) have been previously solved.

The TFTS's are replicated gates developed solely into
primary events. For this reason, the TFTS's are the first
to be solved. They may be attempted in any order, using the
techniques shown in [3]. These TFTS's become members of
subset D, the "solved" subset. The pool of segment solutions
is used to continue the analysis process by providing transfer-
in solutions for other segments.

The analyst determines the next segment to solve based
on the segment's transfer-in symbols and the subset of solved
segments. All TFTS's are solved, so the next attempted
solution is an IFTS with only TFTS's as transfer-ins. Once
solved, the IFTS is a member of D and is available as a
transfer-in solution to any other IFTS or the MFTS.

The solution process continues, decreasing the unsolved
subset, N, until one segment is left, the MFTS. The technique
to solve this segment (which is the fault tree solution)
requires identification and solution of several intermediate
events. The procedure is necessary partly because of the
size and complexity of the MFTS, but is dependent upon the
number and complexity of the transfer-in solutions. Solving
the MFTS in this fashion reduces the number of terms in the
solution equation at each step.

Again, this portion of the solution process requires
examination of the fault tree plot. It is necessary to
identify the intermediate gates to be solved and determine
the solution sequence before attempting a top gate solution.
The following algorithm successfully identifies all such
gates.

Begin by finding all transfer-in symbols in the MFTS.
Follow each symbol's output upward until an AND gate (see
Figure 2) is encountered (possibly going through several
gates of other types). Form a list containing all AND gates
encountered in this manner, but do not duplicate gates.
This list identifies the intermediate gates which are to

be solved; the sequence of solution is determined by the transfer-in symbol's distance from the top gate.

Starting at the lowest level of the MFTS (the top gate is the highest), examine the segment horizontally. The FTDP plots equi-level* events on the same horizontal line. If this horizontal line contains any gates of the list, solve them (in any order). Continue moving toward the top gate (level-by-level), solving identified gates at each level that contains them. Once the list is exhausted, the top gate is solved. The resultant equation is the fault tree solution.

An outline for application of the "bottom-up" fault tree solution technique is as follows:

A. Obtain a fault tree plot to be analyzed.

B. Identify all TFTS, put them at the top of a solution list. This list will ultimately become the solution sequence for SETS implementation.

C. Identify an IFTS which has all its transfer-ins on the solution list. Put this IFTS on the solution list.

D. Repeat C until all IFTS's are on the solution list.

E. Identify all intermediate AND gates in the MFTS which are eventual outputs of its transfer-ins.

---

*One can define the concept of "level" of an event as a distance, i.e., the minimum number of gates plus one encountered from the output of an event to its eventual input into the top gate. The top gate is at the zero'th level.

F. Add these gates to the solution list based on their

distance from the top gate--those farthest away

are added first, those nearest are added last.

5. SETS Implementation

In vital area analysis, each sabotage action (primary

event) is developed into a location or logical combination

of locations where the action could occur. This, in effect,

transforms the primary events of the fault tree from sabotage

actions to sabotage action locations. Sabotage actions become

intermediate events (gates) of the fault tree. Event deve-

lopment is accomplished by loading an additional block of

equations which contains a transformation equation for each

primary sabotage event.

To implement the bottom-up technique, the first lines

of a SETS user program read and load the fault tree as well

as a transformation block:

```
RDFT(SABOTAGE-FT).
RDINPBLK(LOC-TRANS).
LDBLK(LOC-TRANS).
```

The pattern for the solution of all gates (tops of

segments as well as intermediate gates) is:

```
SUBINEQN(GT,GT).
REDUCEQN(GT,GT).
```

It is important to notice that the new equation (second

parameter) replaces the old one. This insures the correct

intermediate equation is propagated toward the solution.

Following the order established by the algorithm (see Section IV), the SETS user program consists of a SUBINEQN and REDUCEQN for each gate identified by the algorithm. The general outline for the program is:

A. Load the fault tree, load the transformation block;

B. SUBINEQN and REDUCEQN on all TFTS top gates (any order);

C. SUBINEQN and REDUCEQN on all IFTS top gates in the correct order (Section IV);

D. SUBINEQN and REDUCEQN on specified gates in the MFTS in the correct order;

E. SUBINEQN and REDUCEQN on the top fault tree gate;

F. Form a block containing the solution equation.

G. Print the solution equation.

The use of the techniques described in this report has resulted in considerable savings in both analyst time and computer time for the vital area analyses conducted thus far. Computer run times have been reduced from over 1,000 seconds to less than 200 seconds for the majority of the location fault trees analyzed using this approach. Similarly, analyst time required to solve a typical location fault tree has been reduced from several days to several hours. Before the techniques described in this report were employed, the minimal cut set equation for the sabotage fault tree often had to be truncated before a set of vital areas could be identified. The use of truncation implies that some of the vital areas may not be included in the set of vital areas

identified. The location fault trees analyzed using the techniques described in this report have all been solved without resorting to truncation.

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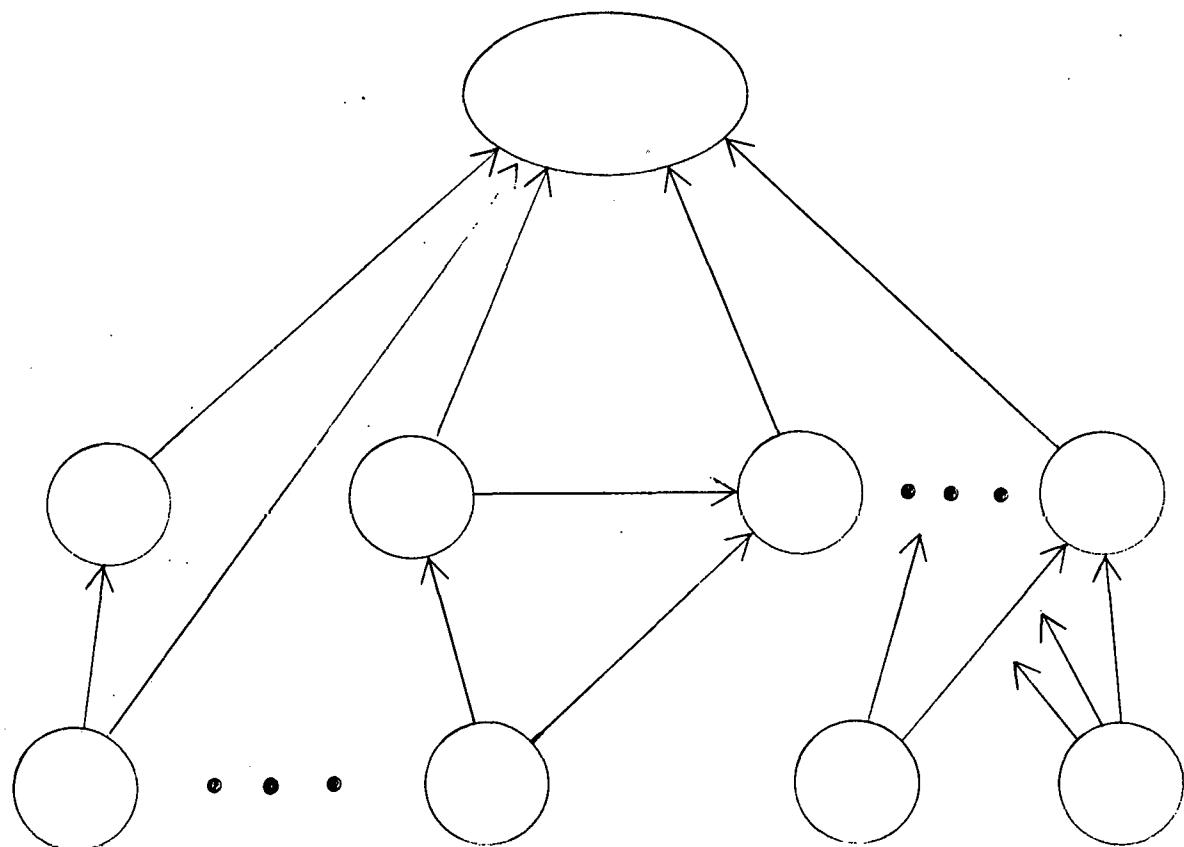
Major Fault Tree Segment
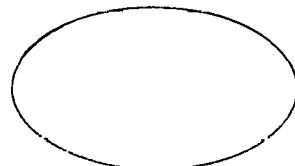
Intermediate Fault Tree Segment
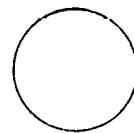
Terminal Fault Tree Segment
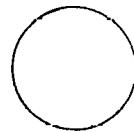
Figure 1.   Graphical Representation of Segment Relation-
ships in a Fault Tree Plot.

GATES
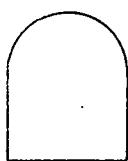
AND Gate
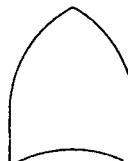
OR Gate

EVENTS
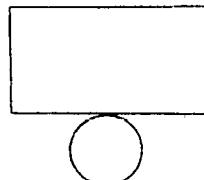
· PRIMARY Event
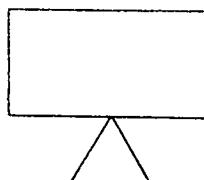
TRANSFER-IN

TRANSFER-OUT

Figure 2. Significant Symbols of the Fault Tree Plot.

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