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November 10, 1981

Mr. Frank D. Coffman
Systems Interaction Branch
Division of Systems Integration
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Dear Frank:

In response to your recent request, the following deliverables have been sent to you in response to your needs for the project "Development of Systems Interaction Regulatory Guidance" (FIN B2339).

1. Letter report, "Interpretation of Single Failure Criteria for a Systems Interaction Analysis," dated May 6, 1981

2. Letter report, "Systems Interaction Analysis Demonstration Example," dated May 6, 1981

3. Draft letter report, "The Systems Interaction Branch Approach to Systems Interaction in LWR's," dated May 7, 1981

4. Draft letter report providing Sections 4.0, 5.0, 6.0 and Appendix B for the Systems Interaction Interim Guidelines report, dated August 21, 1981

5. Draft paper, "Development of Regulatory Guidance on Systems Interactions," dated September 9, 1981

In addition to these five letter reports, there were a number of letters or other informal responses providing comments or recommendations regarding the various stages of developing the interim guidelines.

I trust this information will meet your needs.

Sincerely,

Dick

R. D. Widrig
Project Manager

RDW:llm

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May 6, 1981

Mr. Frank Coffman
Systems Interaction Branch
Division of Systems Integration
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Washington, D.C. 20555

Dear Frank:

Enclosed is an information package on SI analysis consisting of two informal reports and a summary:

1. "Interpretation of Single Failure Criterion for a Systems Interaction Analysis"

2. "Systems Interaction Analysis Demonstration Example"

These reflect some of my thoughts with regard to an SI analysis and show how I, an an analyst, would approach a problem.

The first discusses the use of the single failure criterion for characterizing adverse SIs. The second is a continuation of the Browns Ferry 3 example from the Battelle "state-of-the-art" report. It extends the SI analysis through the evaluation phase.

It is hoped that these will serve as useful "food for thought" with regard to preparation of the upcoming regulatory guidance on SIs. Do not hesitate to call if you have any questions or comments. Also, thank you for reviewing the paper which Arn Plummer and I are submitting to the ANS Risk Assessment Meeting.

Sincerely yours,

Ray

Ray Gallucci,
Research Engineer
Energy Systems Department

RHVG:jf

Enclosures

PDR

cc: P. Cybulskis, Battelle-Columbus (with full enclosure)

SUMMARY

The following two reports consider the use of the single failure criterion in a systems interaction (SI) analysis and demonstrate such an analysis in the context of the Browns Ferry 3 incident. Several topics are discussed which bear potentially significant impact on the nature of an SI analysis. These are highlighted here.

An SI analysis fits naturally into an overall safety analysis and is most efficient when performed as an integral part. This is so because, in order to identify adverse SIs, the analyst must develop the same model that he would need for a general safety analysis. Focusing solely on events designated as adverse SIs and ignoring other events that must inevitably be identified in the process seems somewhat artificial.

The use of the single failure criterion to denote some threshold level of system/function degradation characteristic of an adverse SI leads to inconsistencies. A more appropriate criterion would be the requirement that an adverse SI degrade a safety function such that redundancy (whether it be between frontline or support systems, subsystems, or components) no longer exists at some level. This includes all violations of the single failure criterion as well as other types of failures with equal safety impact.

Similarly, inclusion of common cause as a necessary requirement for an SI can lead to confusion. Certain types of independent failures among shared components also constitute SIs but are not strictly common-cause events. Rather than concentrate on a general definition of an SI, it might be better to focus on classes of SIs, of which three have been identified:

1. Any failure of a support system component
2. Any failure of a non-support system component that is shared by at least two frontline sytems
3. A common-cause failure of at least two components in at least two frontline systems.

Any one of these that degrades a safety function such that redundancy no longer exists at some level constitutes an adverse SI.

The actual goal of an SI analysis is to identify and evaluate events that degrade a safety function such that redundancy no longer exists at some level. SI events that accomplish this are deemed adverse. However, other non-SI events can also accomplish that and be of equal importance with adverse SIs from a qualitative or quantitative viewpoint. Emphasizing only the events that meet the criteria for being labeled SIs while overlooking these other equally important events is inconsistent. Including an SI analysis as an integral part of an overall safety analysis avoids this problem.

INTERPRETATION OF SINGLE FAILURE CRITERION FOR A SYSTEMS INTERACTION ANALYSIS

In the latest draft letter report from the Systems Interaction (SI) Branch[1], use of the "single failure" criterion is advocated for evaluating SIs. This is said to be consistent with existing NRC regulations and avoids the need to perform probabilistic analysis for SI evaluation. Appendix A of 10CFR, Part 50[2] states that a fluid or electric system is considered to be designed against a single failure if no such failure results in a loss of the capability of the system to perform its safety function. Thus, if a system A has redundant components A_1 and A_2, any failure that fails both A_1 and A_2 violates the single failure criterion. A failure of A_1 or A_2 separately would not. Such a failure merely degrades A by reducing redundancy from 1-out-of-2 to 1-out-of-1 (non-redundant).

The effect of the single failure criterion upon safety functions must be examined. Safety functions are generally designed with redundancy at the system or sub-system level to ensure that failure of a single system or sub-system does not fail the function. Consider two safety functions, F_1 and F_2. F_1 is served by only one system. However, this system has two redundant sub-systems. Thus, should both sub-systems fail from a single failure, both the system and the function (F_1) will also fail. In this case, violation of the single failure criterion for the system likewise fails the function.

F_2 is served by two systems which are redundant. Each system likewise has two redundant sub-systems. In this case, violation of the single failure criterion for either system (as a result of a single failure of both of its sub-systems) merely degrades the function (F_2). Its redundancy at the system level drops from 1/2 to 1/1, but it does not fail.

The apparent difference between these two situations stems from an interpretation of system vs. sub-system. In the case of F_1, the distinction between function and system is grammatical only, since they are the same from a design viewpoint. Thus, as for F_2, redundancy is provided at the level immediately below the function, whether this level be labeled as "system" or "sub-system". The key point is that violation of the single failure criterion degrades the safety function by reducing the redundancy at its first level from 1/2 to 1/1.

What if a safety function (F_3) were served by three redundant systems? Violation of the single failure criterion for any one of them would merely decrease F_3's redundancy from 1/3 to 1/2. From conversations with the SI Branch, it seems apparent that such degradation is not severe enough to merit consideration as an "adverse" SI.

It is possible for a safety function to have a 1/2 redundancy exhibited at a level below the first. Consider safety function F_2 described earlier. Designate the redundant systems as A and B with each pair of redundant sub-systems designated by subscripts 1 and 2. Each sub-system (which may more conveniently be thought of as a major component of the subsystem) is subject to an independent failure, which will be designated with a prime. In addition, assume there are dependencies between sub-systems within the same system and between sub-systems in the different systems such that:

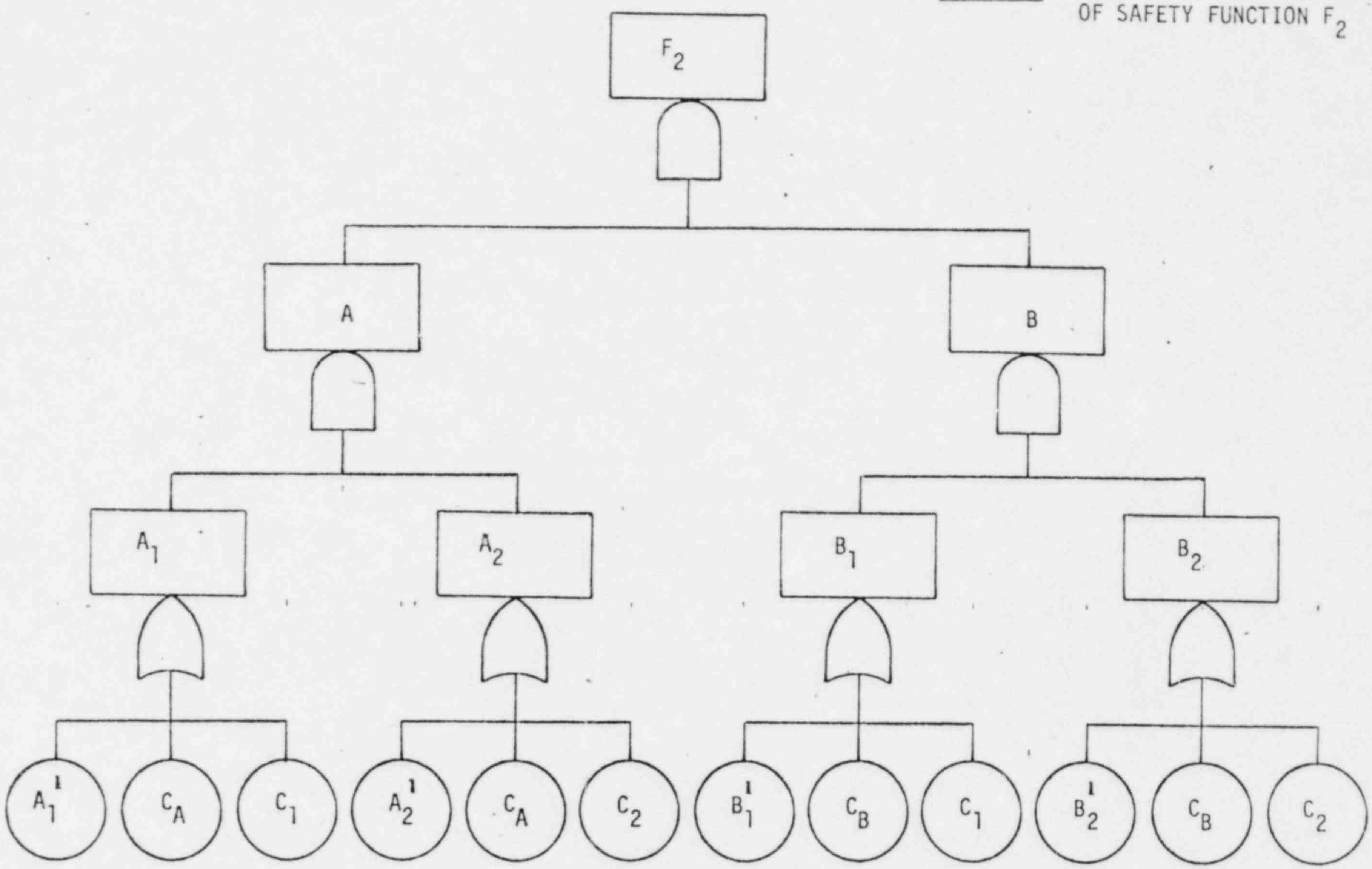
1. A_1 and A_2 are subject to single failure C_A
2. B_1 and B_2 are subject to single failure C_B
3. A_1 and B_1 are subject to single failure C_1
4. A_2 and B_2 are subject to single failure C_2

A fault tree for failure of F_2 is shown in Figure 1. From the list of minimal cut sets, it is apparent that any one of the dependent failures (labeled C) will degrade F_2 by reducing redundancy from 1/2 to 1/1. However, only C_A or C_B will violate the single failure criterion since C_A results in failure of A, and C_B in failure of B. C_1 or C_2 alone degrades each system by decreasing the redundancy between each system's sub-systems from 1/2 to 1/1. This is not a violation of the single failure criterion as it is presently defined.

From a logical, non-probabilistic viewpoint, the dependent failures are all of equal importance so far as failure of F_2 is concerned. By the very nature of SIs, the types of failures characterized by C_A, C_B, C_1, and C_2 will be of concern if they degrade the safety function to a non-redundant state. Thus, although C_1 and C_2 do not separately violate the single failure criterion as defined, they merit as much consideration as do C_A and C_B in an SI analysis.

What all this suggests is that violation of the single failure criterion is inadequate as a necessary condition for an adverse SI. A more appropriate criterion would require an adverse SI to degrade a safety function such that redundancy no longer exists at some level. This includes violations of the single failure criterion as well as other failures such as those between the systems that were examined earlier. Such a criterion is especially desirable from a fault tree viewpoint because it enables the analyst to discard all minimal cut sets of order 3 or greater once they have been resolved for dependencies. Only failures in one and two-element minimal cut sets (resolved for dependencies) can degrade a safety function to a degree of non-redundancy.

FIGURE 1. FAULT TREE FOR FAILURE OF SAFETY FUNCTION F_2



Minimal Cut Sets:

2-Element	3-Element		4-Element
$C_A C_B$	$A_1' A_2' C_B$	$A_2' B_2' C_1$	$A_1' A_2' B_1' B_2'$
$C_1 C_2$	$A_1' B_1' C_2$	$B_1' B_2' C_A$	

REFERENCES

1. Systems Interaction Branch, "The Systems Interaction Branch Approach to Systems Interactions in LWRs," Draft Staff Summary Letter Report; U.S. Nuclear Regulatory Commission (February 1981).

2. Code of Federal Regulations, vol. 10, Energy; Office of the Federal Register, General Services Administration.

SYSTEMS INTERACTION ANALYSIS DEMONSTRATION EXAMPLE

One of the essential safety functions for a nuclear power plant is the ability to achieve and maintain reactor subcriticality. In order to demonstrate a systems interaction analysis, this safety function will be examined during the transition from power operation to hot shutdown. The analysis is an extension of that performed for the Browns Ferry 3 Partial Failure-to-Scram in NUREG/CR-1896.[1] The preliminary work used to develop the fault trees for the "Reactor Control" safety function is described in Appendix B of that report and will not be repeated here.

Slight modifications of the fault trees is necessary to adapt them for computer analysis. These consist of elimination of a 3/185 majority-vote gate for HCU failures and resulting combination of hardware failures in the HCU subtree. Also, passive failures of hydraulic components (such as the SIV drain line) are ignored to establish consistency in the level of resolution between the CRS and SLC fault trees. These modifications have been incorporated into the fault trees used in this example (Figures 1 - 10).

The computer program MFAULT[2] is employed to find the cut sets for the failure paths of the CRS and SLC systems. Thus, a cataloguing scheme must be established for the gates and component failures on the fault trees. This scheme is listed in Table 1. Note that all gates are prefixed with "A" while all component failures are prefixed with "X".

Table 2 lists all the minimal cut sets (MCSs) of lengths one through four for CRS failure. Theoretically, all MCSs, regardless of length, are needed to identify all possible common-cause failures. Six elements in an eight-element MCS may be subject to a single common-cause failure, thereby generating a "new" MCS of length three. An example of this will appear later when the MCSs for SLC are resolved for dependencies.

Table 3 lists all the MCSs of lengths one through five for SLC failure. Unlike the case for CRS, the five-element sets have been retained; their number is manageable and there are no four-element sets. Table 4 lists all the MCSs of lengths one through four for Reactor Control failure. These are the Boolean "AND" combination of the CRS and the SLC MCSs.

At this point, it is instructive to note the magnitu.. of the analysis. Without having begun to identify dependencies, and with limiting the analysis to MCSs of relatively low order, the number of MCSs generated so far are:

CRS failure path ⟶ 325
SLC failure path ⟶ 72
Reactor Control failure ⟶ 291

And, it must be remembered that the degree of detail incorporated into the fault trees is relatively limited. For example, circuit breakers and cables have been ignored on the electrical fault trees for simplicity. Including such detail would increase the complexity.

The common-cause analysis focuses on the elements of the MCSs. While it is possible to have included all the dependent events on the original trees, this would have been entailed resolution of all the events for common cause. By starting from the MCSs, one needs only resolve some of the total number of events. Of course, one must recognize the risk of overlooking some dependent events because only the shorter-length MCSs have been retained.

The SI Branch draft letter report[3] refers to 2 types of SIs: external and functional events. These correspond basically to 2 types of common-cause events, often referred to as spatial and generic. Each of these categories spans a wide spectrum of factors. Even though completeness can never be guaranteed, it is safe to say that identification of the majority of these factors requires resolution to a fine level. This necessitates a very detailed analysis. For example, spatial dependencies can include fire and flooding effects and susceptibility to missiles.

Generic dependencies can include human errors in various forms (latent, such as miscalibration, and dynamic, such as operator error) as well as manufacturing defects and functional dependencies.

In this example, the dependencies are identified broadly as generic and spatial, without any further resolution. Components of similar types performing the same functions, such as 4160/480v AC Common transformers, are assumed to be subject to a common generic failure, denoted by the letter "G". Components located near one another are postulated to be subject to a common spatial failure, denoted by "S". Credit can be given for physical separators, such as walls. However, judgment must be employed since even components in separate rooms may be subject to common spatial failure (e.g. - flooding). This broad use of the terms generic and spatial in the demonstration analysis does not guarantee that all such potential dependencies will be accounted for. Components in different systems performing dissimilar functions can still be subject to a common generic failure such as miscalibration. The common-cause analysis performed here is intended only to be demonstrative; no specific conclusions regarding the actual plant should be drawn.

The component failures contained in the CRS MCSs from Table 2 are listed in Table 5 along with their locations. From this list, generic and spatial failures can be presumed, as listed in Table 6. Note that each component, whether it be subject to a dependent failure or not, is assumed to be subject to an independent failure, denoted by "I". From a fault tree viewpoint, the resolution for dependencies effectively transforms unresolved component failure "X" into an OR gate with inputs "I", "G", and "S". There may be more than one of each type of input "G" and "S". For convenience, component failures not subject to any common-cause failure with other components on the trees are left unresolved (as "X").

Once the component failures have been resolved for dependencies, it is necessary to incorporate this resolution into the unresolved MCSs.

This results in "new" MCSs, thereby increasing their overall number. Thus, to keep the analysis tractable, it is advantageous to eliminate longer-element MCSs. Unlike the parallel elimination performed for unresolved MCSs, this stage of elimination runs a negligible risk of overlooking important dependencies. The events in each set are now "independent," assuming that the common-cause analysis is essentially exhaustive. However, this does not "recapture" any dependencies lost earlier when the longer, unresolved MCSs were ignored.

The question arises as to what length MCSs should be retained. The SI Branch draft letter report expresses favoritism for use of the "single failure" criterion for evaluating SIs. However, as discussed elsewhere, this can be translated into a more general requirement that an adverse SI must degrade a safety function to a degree where redundancy no longer exists at some level. Only failures in one and two-element MCSs (resolved for dependencies) can so degrade a safety function and, therefore, qualify as adverse SIs. Since the CRS and SLC fault trees are related to overall function failure through an AND gate, any three-element or longer MCS from either tree can be ignored. Even within each tree itself, no single event in a three-element or longer MCS can degrade the system such that redundancy is lost at some level. Thus, only the one and two-element MCSs (resolved for dependencies) need be retained. This simplifies the subsequent analysis.

Table 7 lists the resolved MCSs for CRS failure. Note that the number of one-element sets has been increased from 4 to 13, while the number of two-element sets has been increased from 19 to 79. Each of the additional MCSs results from resolution of the original ones (including the three and four-element sets) for dependencies. Thus, each of these contains at least one common-cause element, either generic (G) or spatial (S).

It is instructive to note that the resolution for dependencies introduces MCSs with commonalities among components not previously contained in the MCSs of the same length. For example, prior to the resolution of the original MCSs, the only one-element sets were failures of CRS components.

Following resolution, common-cause failures of non-CRS components (RBEDS exhaust fans, Control Air compressors, and AC Reactor Building Vent boards), as well as dependent failures among CRS components not previously in one-element sets, become "new" one-element MCSs. Similar trends among the two-element MCSs are apparent, as manifested by the addition of numerous sets containing common-cause failures among electrical components.

Resolution of the original MCSs for SLC for dependencies follows the same procedure as that for CRS. The component failures contained in the SLC MCSs from Table 3 are listed in Table 8 along with their locations. Dependencies among the various components are categorized as generic or spatial in Table 9. The identification of G40 as a generic common cause between failures X191 and X192 (4.16 kV AC Shutdown buses) merits some discussion. Earlier, it was mentioned that dependence among elements in an MCS results in generating a "new", shorter MCS containing the dependency. The MCSs for SLC contained no failures of any of the "40" components (4.16kV AC Unit boards) up through the five-element sets (see Table 3). However, referring to the fault tree in Figure 9, it is apparent that for each five-element MCS containing both X191 and X192, there would be a corresponding nine-element MCS containing X41 through X46. For example, five-element MCS {X181, X183, X184, X191, X192} has a corresponding nine-element one {X181, X183, X184, X41, X42, X43, X44, X45, X46}. Generic dependencies among the "180" and the "190" components produces a two-element MCS {G180, G190} from the five-element one. Similarly, generic dependence among the "40" components creates a two-element MCS {G180, G40} from the nine-element one. Although a generic commonality among six components may be unlikely, this serves to illustrate that discarding the long MCSs prior to resolution can result in omission of rather short MCSs containing dependencies. Such a problem cannot be alleviated without complicating the analysis greatly (imagine the number of nine-element MCSs). The analyst can only accept this shortcoming and be aware of it.

Note that resolution results in "creating" one-element MCSs for SLC where none existed previously (see Table 10). Each of these is a dependent failure, not only among SLC components, but also among electrical ones. Thus, the number of one-element sets increases from 0 to 10, while that for two-element ones goes from 8 to 12 (the additional ones containing commonalities among electrical components).

Finally, the resolved MCSs for CRS and SLC can be combined (through a logical AND - see Figure 1) to yield resolved sets for the overall safety function. These are listed in Table 11. The fact that the CRS and SLC failures are connected through an AND gate (for Reactor Control failure) also necessitates reviewing the list of unresolved MCSs for Reactor Control (Table 4) to check for dependencies among previously unencountered groupings of components. For example, components 201-203 are combined in four-element MCSs for the overall safety function, but all three had never been grouped together in the CRS or SLC MCSs. It just so happens that the only commonality among all three is a generic one (G200). Since 202 and 203 had been previously combined in the SLC MCSs, G200 had implicitly been included. Generally, this is not always the case (although it does turn out to be in this demonstration example) and must be explored when the TOP gate is an AND gate. This complication is not encountered with a TOP OR gate.

Before resolution, there were no one nor two-element MCSs for Reactor Control (see Table 4). Following resolution, there are still no one-element sets, but 157 two-element sets appear, each containing at least one common-cause failure. Longer-element sets are not identified since they would not lead to the decrease in redundancy at some level necessary to constitute an adverse SI. Note that the elements of these MCSs are assumed to be independent since, theoretically, all commonalities have been accounted for. Also note that, even within the degree of detail used in this analysis, one cannot ensure that all the two-element MCSs have been identified since the longer-element MCSs were discarded prior to resolution.

From a logic viewpoint (without considering probability), each two-element MCS is equivalent to one another with regard to the TOP event. The importance of each element depends upon the number and the length of the MCSs in which it appears. The concept of an adverse SI seeks to distinguish among elements, which may be logically equivalent, based upon the event's effect upon systems. For example, consider MCS elements I342, G310, and G420. Each appears in ten two-element MCSs. Thus, from a logic viewpoint, their importances are equal. However, I342 refers to independent failure of the SIV drain valve, G310 to common generic failure of several CRS diaphragm-operated valves, and G420 to common generic failure of the Control Air compressors. Each of these is a one-element MCS for CRS failure (see Table 7). Thus, failure of any one will fail CRS. However, since each failure is part of a two-element MCS for Reactor Control failure, occurrence of any one only degrades this safety function. An additional failure is required to fail Reactor Control. However, each of the failures I342, G310, and G420 is sufficient to degrade the function to a non-redundant level.

Is each one an adverse SI? The draft letter report from the SI Branch implies that, in addition to degrading a safety function to a non-redundant level, an adverse SI must also result from common cause and involve at least two systems. I342 fails on both accounts. It is not a common-cause event, nor does it involve two systems (being a failure in a frontline system only - CRS). G310 is a common-cause event, but it involves only the CRS system. G420 is a common-cause event, and it also involves two systems, those being Control Air and CRS (through the loss of Control Air). Thus, of the three, only G420 would constitute an adverse SI.

Some confusion can arise when a support system component is considered. I91 and S91 are each contained in three two-element MCSs. Thus, their logical importances are the same. However, I91 refers to independent failure of 480v AC Common Board 1, while S91 refers to common spatial failure of this board with 4160/480v AC Common Transformers 1A and 1B. The latter is clearly an adverse SI since it results from a common cause and involves two systems (being a failure in a support system, it can only manifest itself through a frontline system). However, while I91 involves two systems (being a failure in a support system), it is not a common-cause failure in the support system. However, tracing through the fault trees, it is seen to affect frontline systems through the Control Air (via compressor C) and 250v DC systems (via the four battery chargers). Thus, while I91 corresponds to independent failure of 480v AC Common Board 1, the failure itself has an effect upon multiple components (at least to the point of degradation). As such, it would appear to be the type of event that should be treated as an adverse SI. In effect, I91 represents a common-cause event affecting Control Air Compressor C and the four 250v DC battery chargers.

Event I92 illustrates an added complication. It also has the same logical importance as I91 and represents an independent failure in a support system (480V AC Common Board 2). However, unlike I91, its failure affects only Control Air Compressor D (and none of the 250v DC battery chargers). At first, this would not appear to affect multiple components. However, in tracing farther up through the fault trees, I92 is seen to affect the availability of Control Air (A500), which subsequently can prevent the SIV drain valve and the west and east bank SDV vent valves from opening. Thus, it has an effect upon multiple components. In fact, I91 has this same effect as I92, but this was not examined earlier for I91 since its "common cause" effect was evident at a lower level in the fault trees. Thus, I92 would also be an adverse SI.

What is becoming evident here is a seeming need to "trace back" through the fault trees for certain events to determine whether or not they are adverse SIs. With these relatively simple fault trees, this is not a problem. However, with much larger and more detailed trees, such tracing back could prove very difficult and time-consuming since a large number of MCSs would surely be involved. Since support system failures affect the safety function only through frontline systems, it seems safe to assume that any failure of a support system component (independent or dependent) that degrades a safety function to a non-redundant level constitutes an adverse SI. This accounts for multiple failures of frontline systems' components due to failure of a single support component.

If a non-support component is shared by two frontline systems, any failure of it will automatically affect the two systems and be an SI. However, for components in different frontline systems, only a common-cause failure among them will constitute an SI. What is becoming apparent is that a common cause is not a necessary criterion for an SI. Certain types of independent failures constitute SIs too. Thus, three classes of SIs can be identified:

1. Any failure of a support system component
2. Any failure of a non-support system component that is shared by at least two frontline systems
3. A common-cause failure of at least two components in at least two frontline systems.

An adverse SI is an SI that degrades a safety function such that redundancy no longer exists at some level. In an SI analysis, what one is actually searching for are the adverse SIs since only these SIs produce the threshold level of degradation. It might be better termed an "adverse SI analysis."

As has been seen, the designation of an adverse SI attempts to distinguish among events that may, from a logical viewpoint, have equal importance. The value of doing so can be questioned since the assignment of the label "adverse SI" to one event but not to another of equal importance seems to be impractical. In order to identify adverse SIs, the analyst must develop the same model he would use for a general safety analysis, complete with identification of hardware and other independent failures in preparation for and in addition to resolution for dependencies. The focus has been placed on only the portion of the MCS elements designated as adverse SIs. It seems somewhat artificial to ignore the other elements that must inevitably be identified in the process. Unless adverse SIs can be identified without requiring the accompanying detail of a regular safety analysis, it seems inconsistent to focus only on certain events when others have equal importance from a logical viewpoint. An SI analysis fits naturally into an overall safety analysis and is most efficient when performed as an integral part.

The adverse SIs (and other events not constituting SIs) have been identified; the analysis now continues with their evaluation. Table 11 lists all the two-element MCSs (resolved for dependencies) for failure of the Reactor Control safety function during the transition from the Power Operation to the Hot Shutdown mode. Of the 35 distinct failure events comprising the 157 MCSs, 12 do not fall into any of the three categories of SIs previously identified. These 12 are the following:

I310	G310
I320	S310
I342	G320
I353	G430
I363	S430
	G440
	G450

These correspond to independent and common-cause failures of components within single frontline systems (CRS, SLC, and RWC), uncharacteristic of SIs. However, as will be demonstrated, some of these rank very high in importance from a logic viewpoint with respect to other failures that are classified as adverse SIs.

A relatively simple, qualitative way of ranking the MCS elements is to tabulate the number of times each appears in the sets of each specific length. Since only two-element MCSs have been identified (there are no one element ones), the qualitative importance of the various failure events depends solely upon the number of times they appear among the 157 two-element sets. Normally, any one-element MCS event would be qualitatively more important than any appearing solely in multi-element MCSs. The failure events are listed in their order of qualitative importance in Table 12. Note that the 12 failures not deemed to be SIs are included in this list.

While ranking the failure events by their qualitative importances provides some measure as to their relative contribution to Reactor Control failure, one can only infer that one event is "more" or "less" important than another. A numerical measure of their relative importances requires a quantitative evaluation. Although the structural importance measure[4] can provide this without requiring probabilistic estimates, such a ranking scheme is prohibitive for the number of failure events involved here (35) without computer aid. Further, a probabilistic evaluation provides a better measure as to the "true" importances of the failure events, especially if all lead to similar consequences. Ideally, both the probability and the consequence should be evaluated to obtain a risk-based importance. However, such an evaluation is much more complex than a mere probabilistic one and unnecessary when trying to obtain a relative measure of the quantitative importances of failure events with similar consequences. This is the case here since the demonstration example is restricted to one safety function during specific plant modes.

A detailed search for failure data is not warranted for merely illustrating a probabilistic importance evaluation. Thus, for the failure events that have been identified, failure rates from WASH-1400[5] will be used rather loosely for the sake of supplying numerical values. Tables III 4-1 and III 4-2 of WASH-1400 list demand and time failure rates for the mechanical and electrical components encountered in the WASH-1400 analyses.

For components under continuous operation (such as 250v DC batteries), an interval of one month is assumed between inspections. Thus, if such a component has a time failure rate of λ_T, the average unavailability can be approximated as:

$$\bar{A} = 1/2\ \lambda_T\ (720\ \text{hrs})$$

For components demanded at the onset of scram (such as SLC pumps), a mission time of two hours is assumed, since this would be the maximum time required to shut down using the SLC system. Thus, if such a component has a demand failure rate of λ_D and a time failure rate (given start) of λ_T, the average unavailability can be approximated as:

$$\bar{A} = \lambda_D + 1/2\ \lambda_T\ (2\ \text{hrs})$$

The independent component failure probabilities listed in Table 13 are these average unavailabilities either for continuous or demand operation.

For generic dependencies (among identical component types), the failure probability is approximated as:

$$\left(\begin{array}{c}\text{Individual}\\ \text{Failure}\\ \text{Probability}\end{array}\right)^{\left.1\middle/\begin{array}{l}\text{Minimum \# of Identical Components}\\ \text{Required to Manifest the Common-}\\ \text{Cause Failure (at least 2)}\end{array}\right.}$$

In this example, the minimum number is 2 in all cases except for G210 (common generic failure of 250V DC batteries), where it is 3. For spatial dependencies, the failure probability is approximated as:

$$(.01)^{\left.1\middle/\begin{array}{l}\text{Minimum \# of Nearby Components Required}\\ \text{to Manifest the Common-Cause Failure (at least 2)}\end{array}\right.}$$

The minimum number is 2 in all cases. The value .01 is arbitrary.

Table 14 lists all the failure probabilities calculated for the events in the two-element MCSs for Reactor Control. The independent failure probabilities used in deriving these are taken from Table 13. The values in Table 14 can then be used to calculate the failure probability of each of the 157 MCSs for Reactor Control listed in Table 11 (two-element sets only). The sum of these is 5×10^{-5} and represents the conditional probability of failure of the Reactor Control safety function given that it is needed during the transition from the Power Operation to the Hot Shutdown mode.

The probabilistic importance of each of the 35 failure events in the MCSs can be calculated as follows:

Let S_n correspond to the n^{th} MCS, of which there are a total of N.

$$\therefore P(TOP) = \sum_{n=1}^{N} P(S_n)$$ where P (•) represents the probability of •

If event X is an element of each MCS S_i, $i = 1,2,\ldots,m$ (where $m \leq N$), then the importance of event X is:

$$I(X) = \sum_{i=1}^{m} P(S_i) \Big/ P(TOP) = \sum_{i=1}^{m} P(S_i) \Big/ \sum_{n=1}^{N} P(S_n)$$

These importances are listed in Table 15. Included are the 12 failure events that are not SIs.

While the qualitative importances are capable only of showing the rank of the failure events, the probabilistic importances can establish not only the rank but also the quantitative relationship among the events. For example, Table 12 indicates that G170 is more important than G150. However, Table 15 indicates that G170 is more important than G150 by a factor of 5. The probabilistic importances convey more information than the qualitative ones, assuming that the failure data used is accurate.

It is interesting that some of the failure events not constituting SIs are of high importance in either ranking system. In fact, using probabilistic importance, two of the top three events are not SIs. This seems to emphasize earlier comments that assigning a label of "adverse SI" to one event but not to another of high importance is somewhat impractical, especially when such events will automatically be identified during the search for adverse SIs.

Note that the two ranking schemes do not necessarily yield similar results. For example, none of the events ranked first through fifth qualitatively are ranked fourth or above probabilistically, and vice versa. Especially large discrepancies are found between the two ranks of the following events:

EVENT	RANK	
	QUALITATIVE	PROBABILISTIC
I310	11	34
G210	2	20
G160	5	23
G310	11	28
I423	30	14
I424	30	14
G200	4	17
G150	2	14
G440	6	17
G450	6	17

Whatever ranking scheme an analyst employs (these two are by no means the only ones), the results must be tempered with a recognition of the method's limitations. For example, considering events G170 and G150 again, one might be falsely tempted to assume that G170 is only slightly more important than G150 based on qualitative importance since their respective numbers of MCS appearances are 22 and 21. No quantitative interpretation can be placed on these numbers; they are useful only for determining rank. Under the probabilistic ranking, quantitative evaluation can be made. However, the restriction of data accuracy and the requirement of consequence similarity still must be recognized.

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4. Barlow, R. and F. Proschan, Statistical Theory of Reliability and Life Testing; Holt, Rinehart and Winston, Inc., (1975).

5. Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400 (NUREG 75-014); U.S. Nuclear Regulatory Commission, (October 1975).

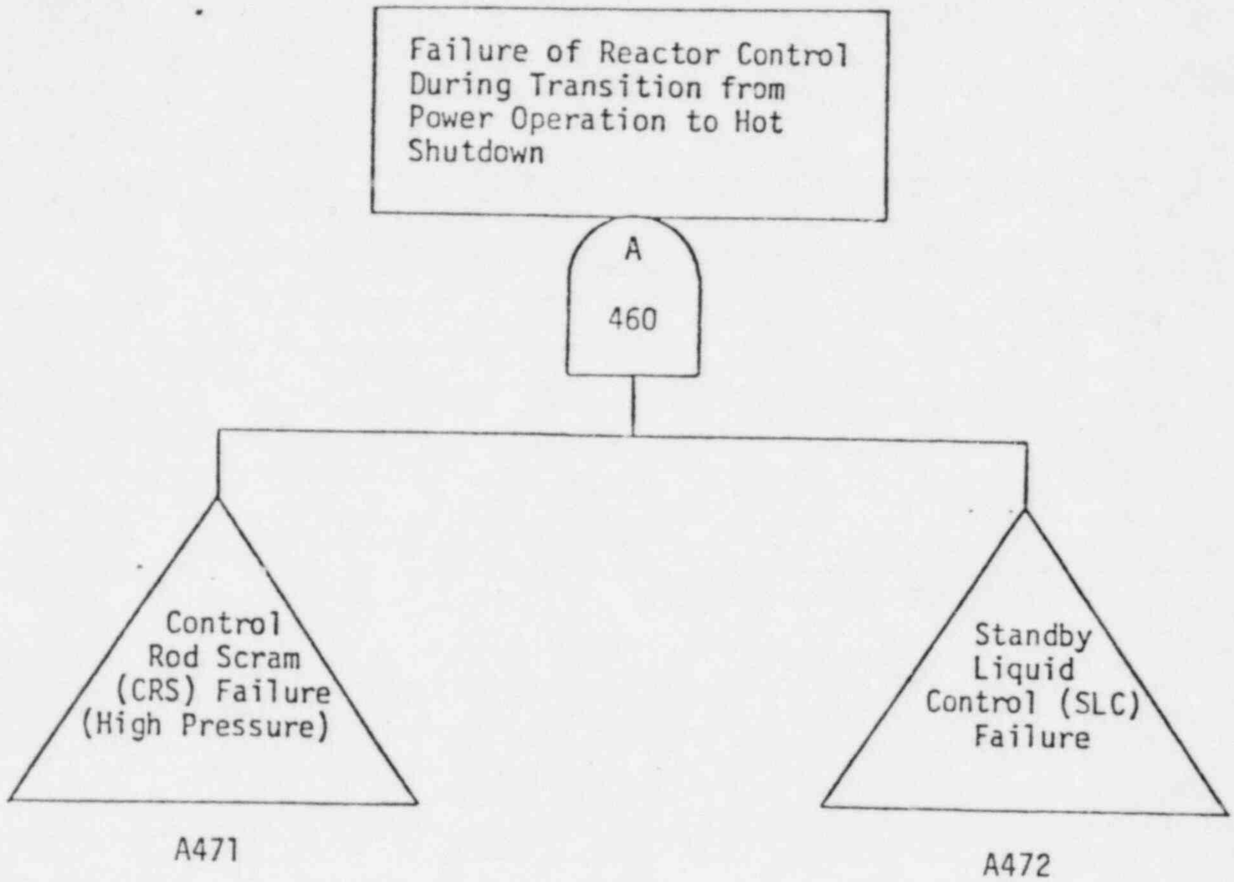
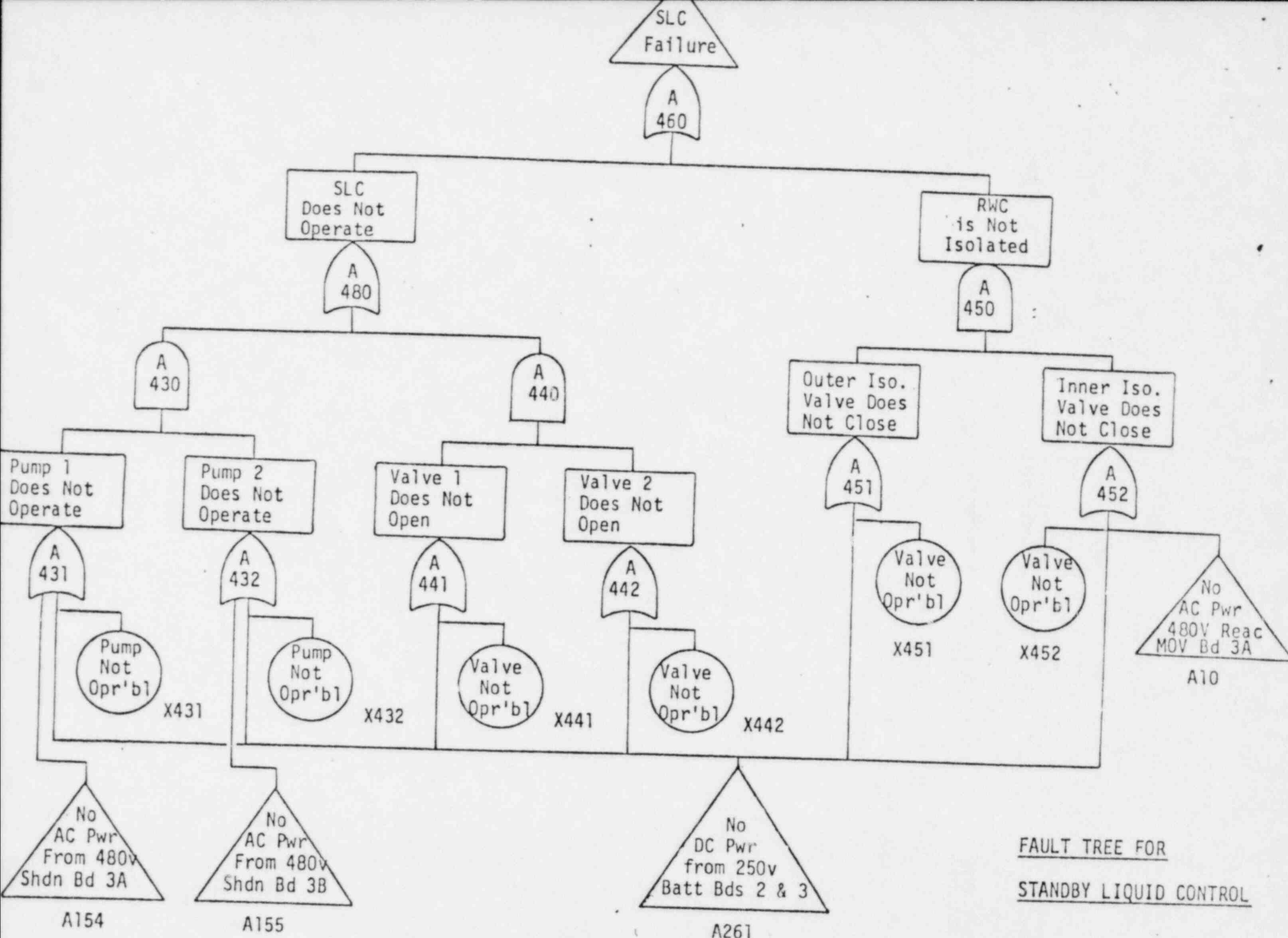


FIGURE 1

TOP OF FAULT TREE FOR REACTOR CONTROL DURING TRANSITION FROM POWER OPERATION TO HOT SHUTDOWN



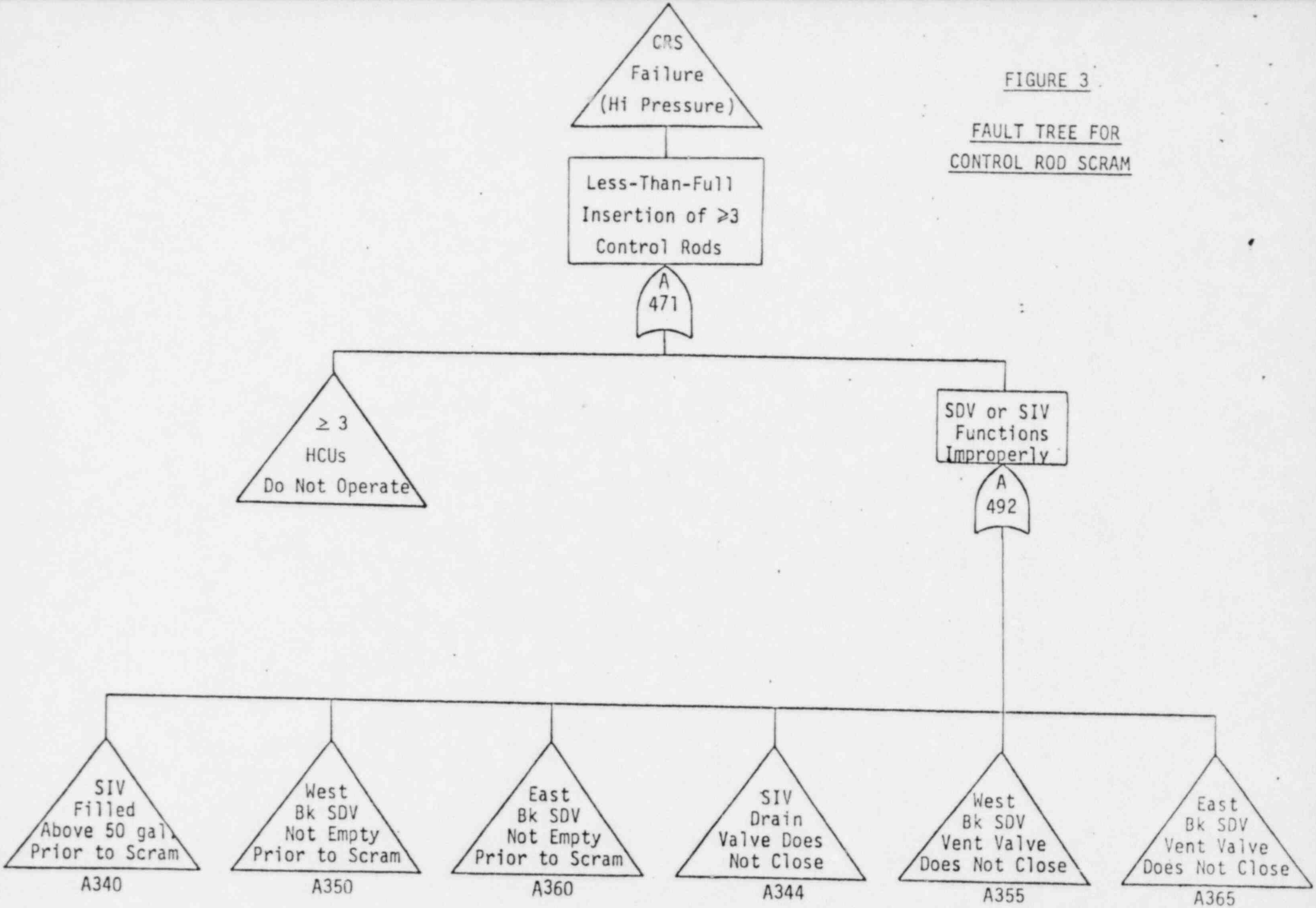
FAULT TREE FOR

STANDBY LIQUID CONTROL

FIGURE 2

FIGURE 3

FAULT TREE FOR CONTROL ROD SCRAM



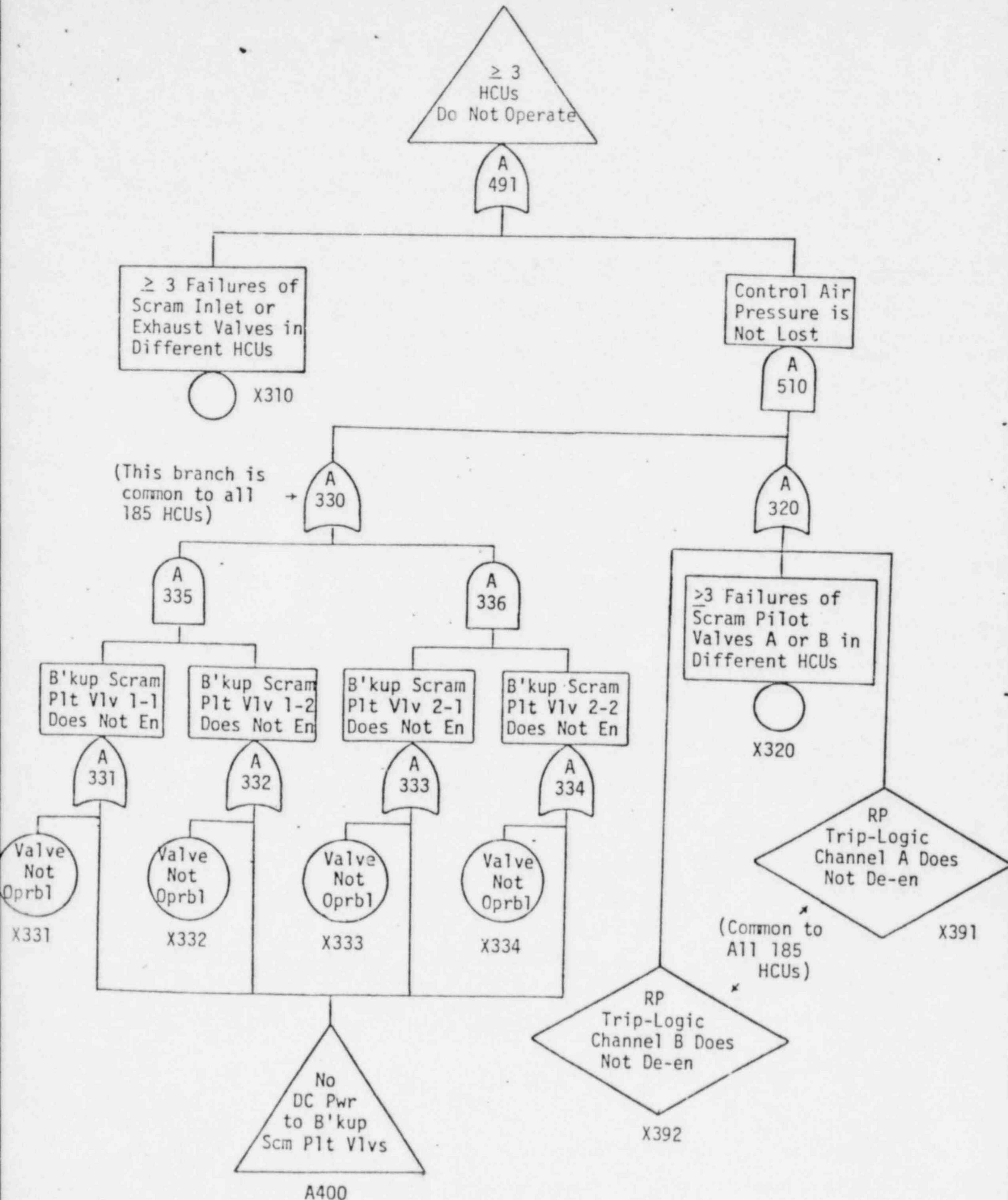


FIGURE 3 (cont.)

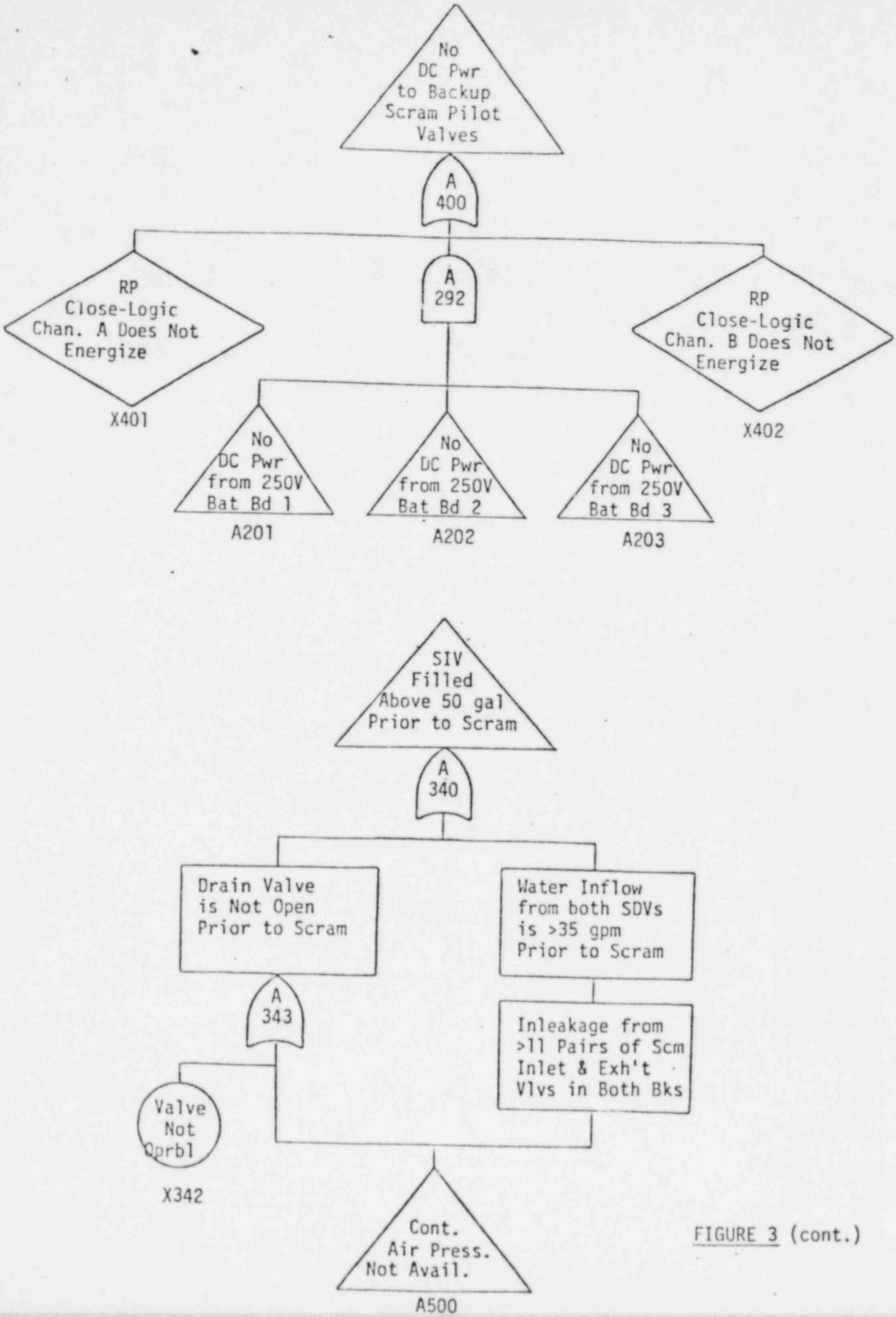


FIGURE 3 (cont.)

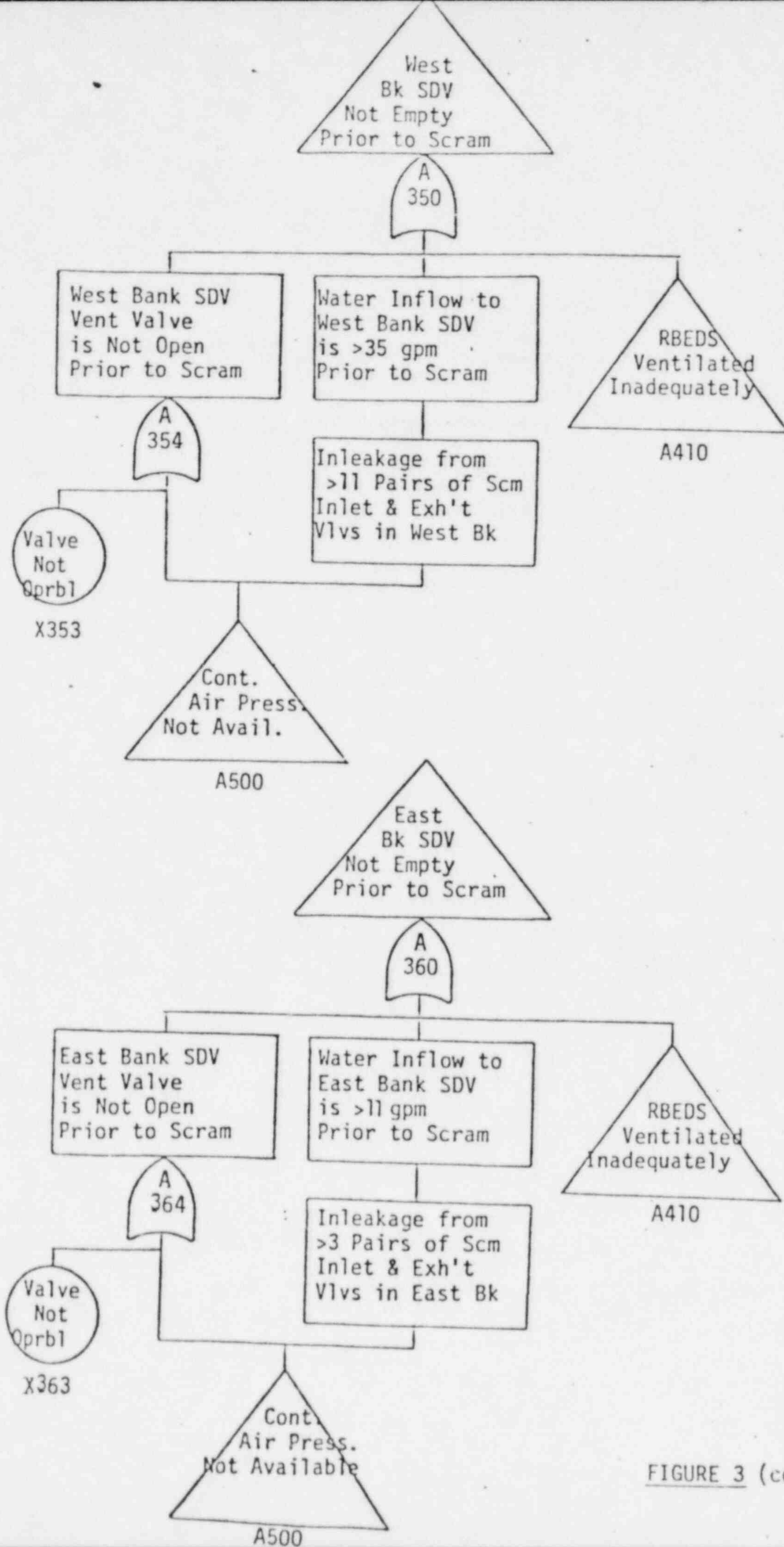


FIGURE 3 (cont.)

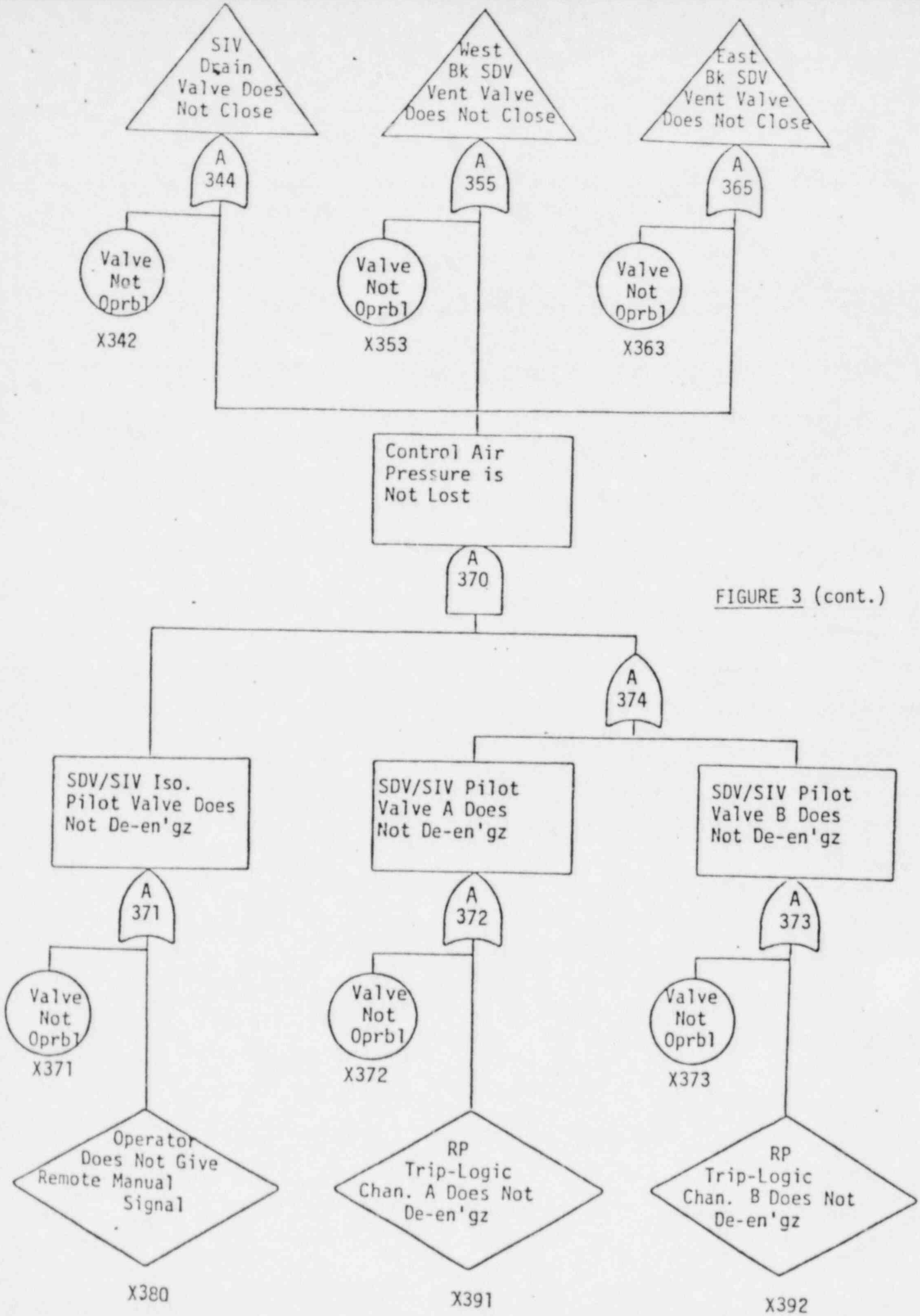


FIGURE 3 (cont.)

BUILDING EQUIPMENT DRAIN

SUMP (VENTILATION) &

CONTROL AIR

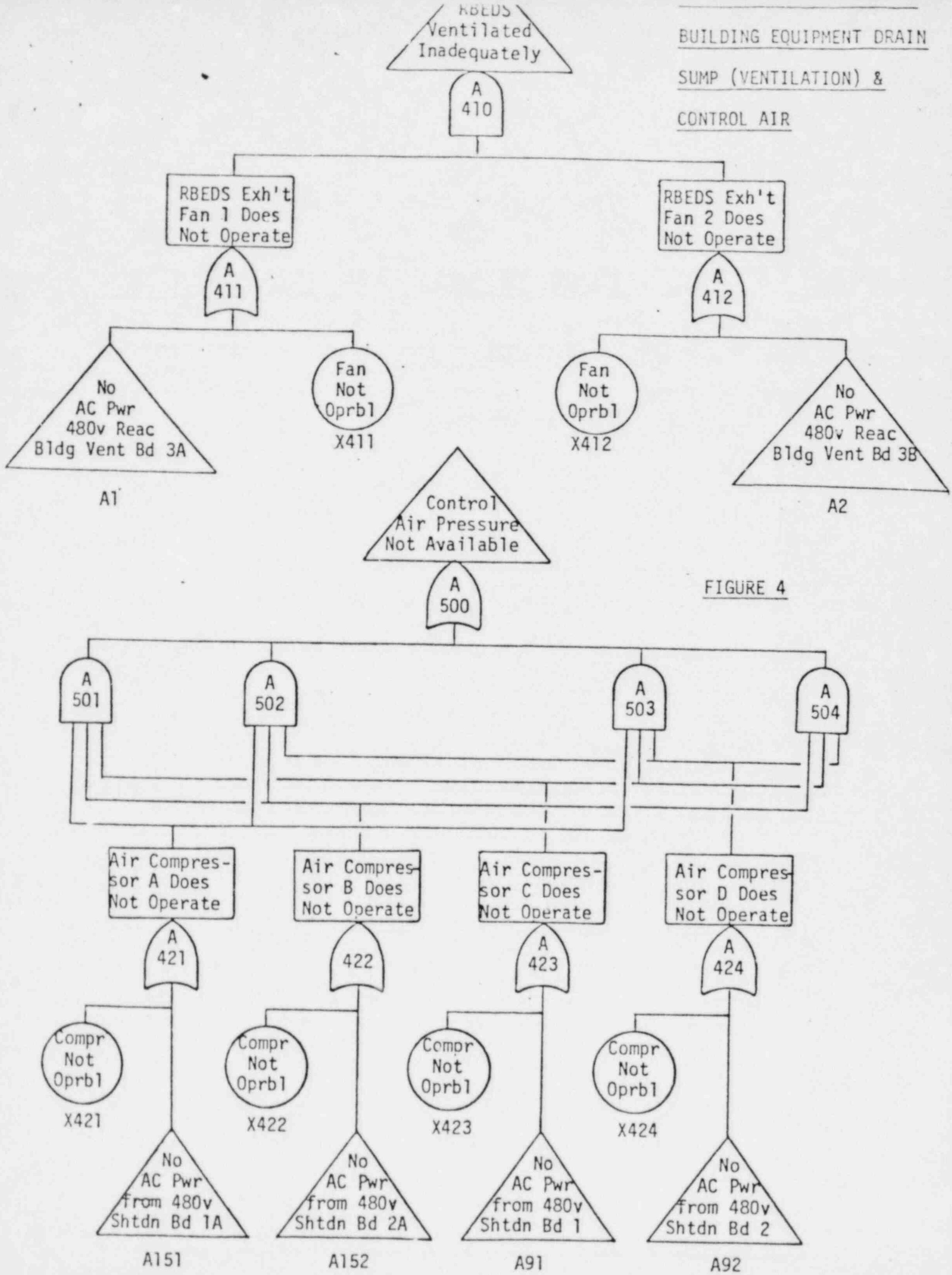


FIGURE 4

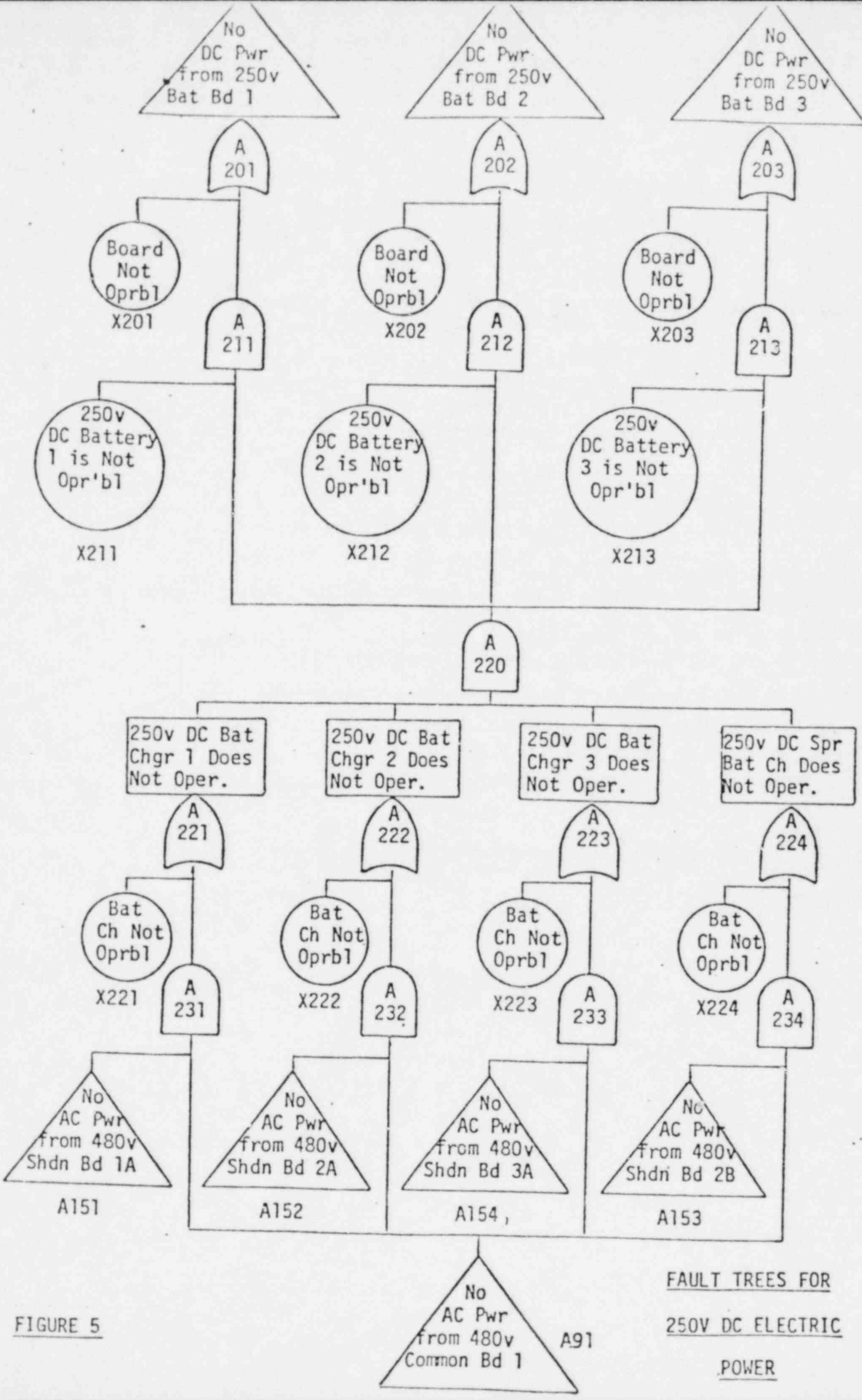
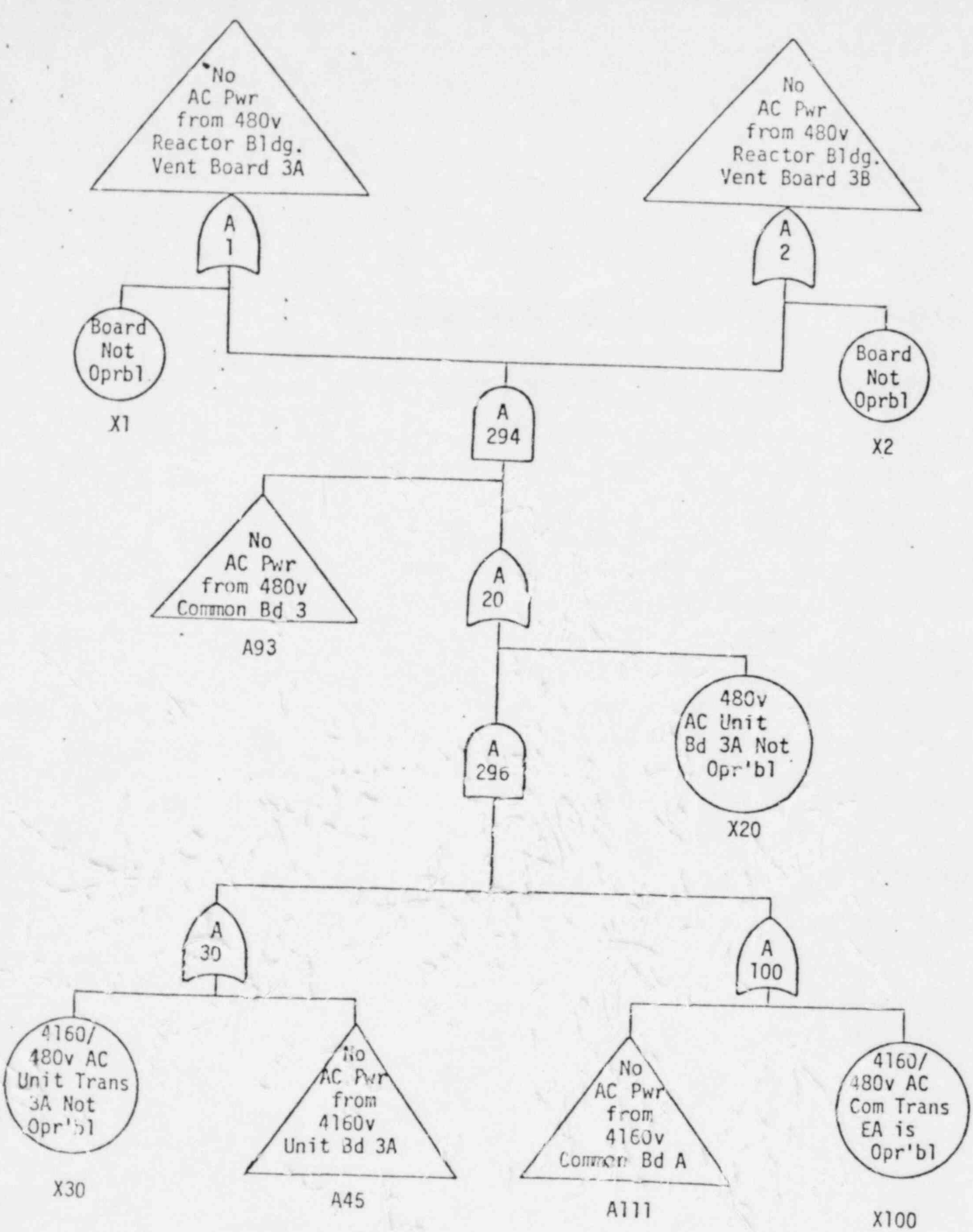


FIGURE 5

FAULT TREES FOR 250V DC ELECTRIC POWER



FAULT TREES FOR AC REACTOR BUILDING VENTILATION ELECTRIC POWER

FIGURE 6

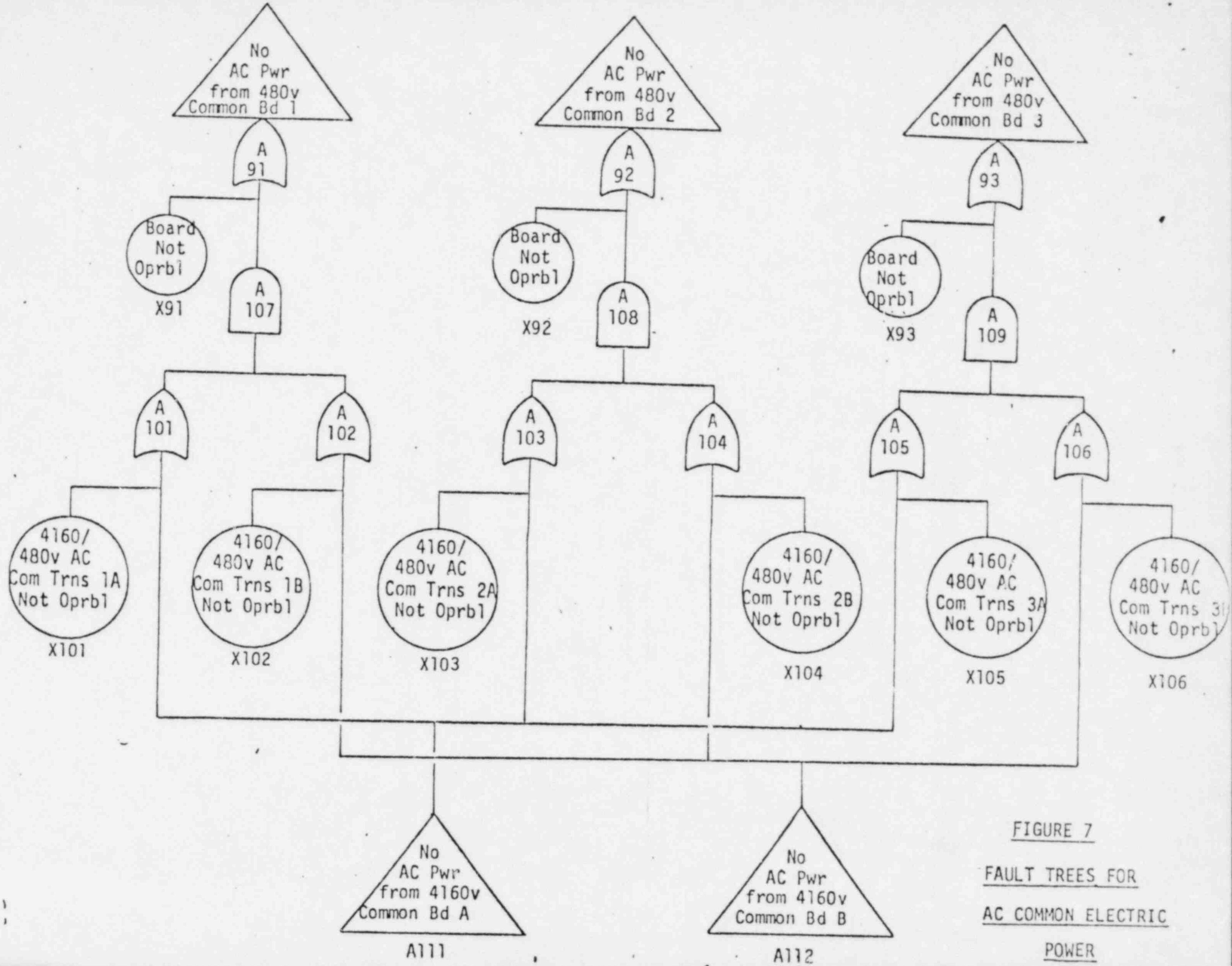


FIGURE 7

FAULT TREES FOR AC COMMON ELECTRIC POWER

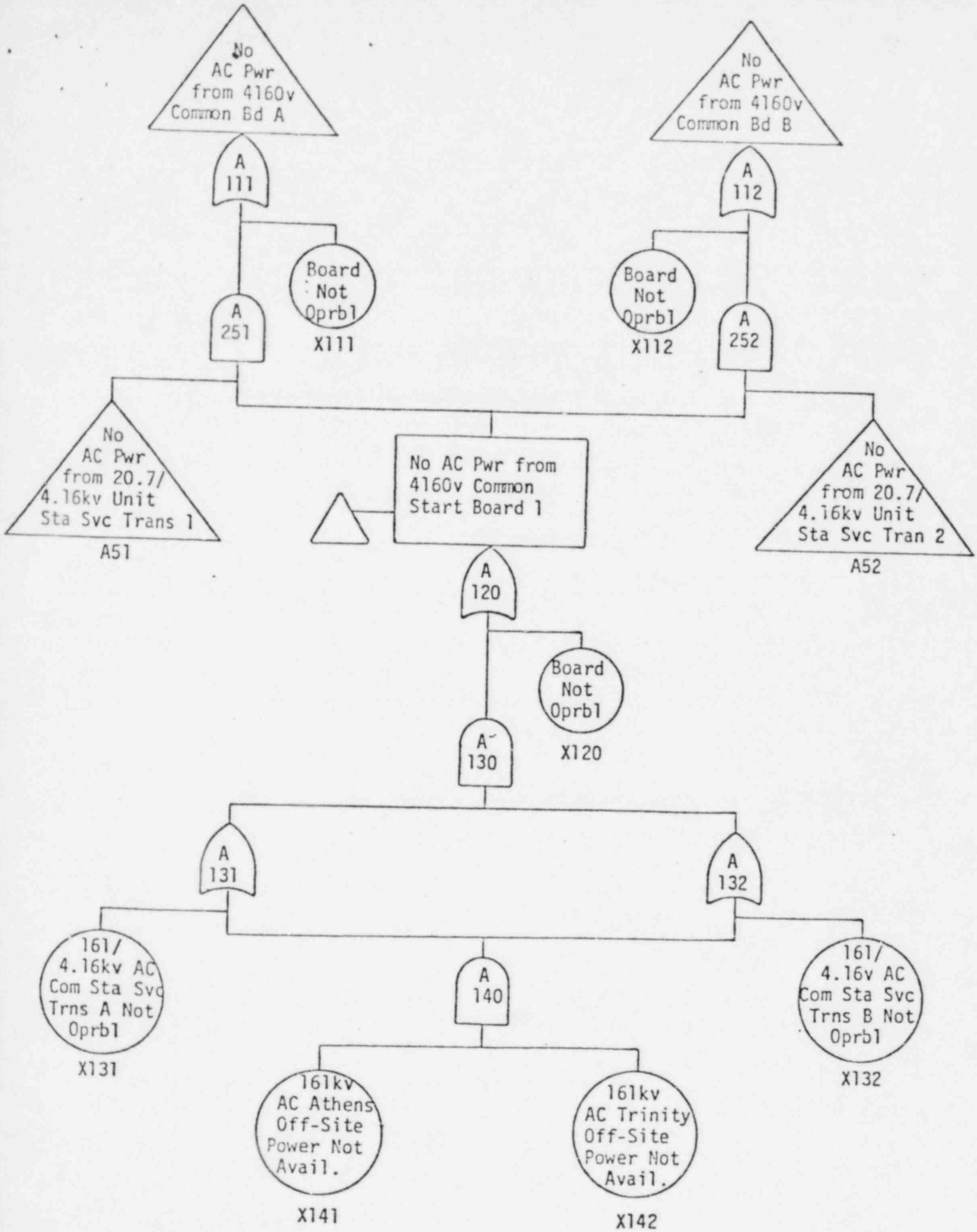


FIGURE 7 (cont.)

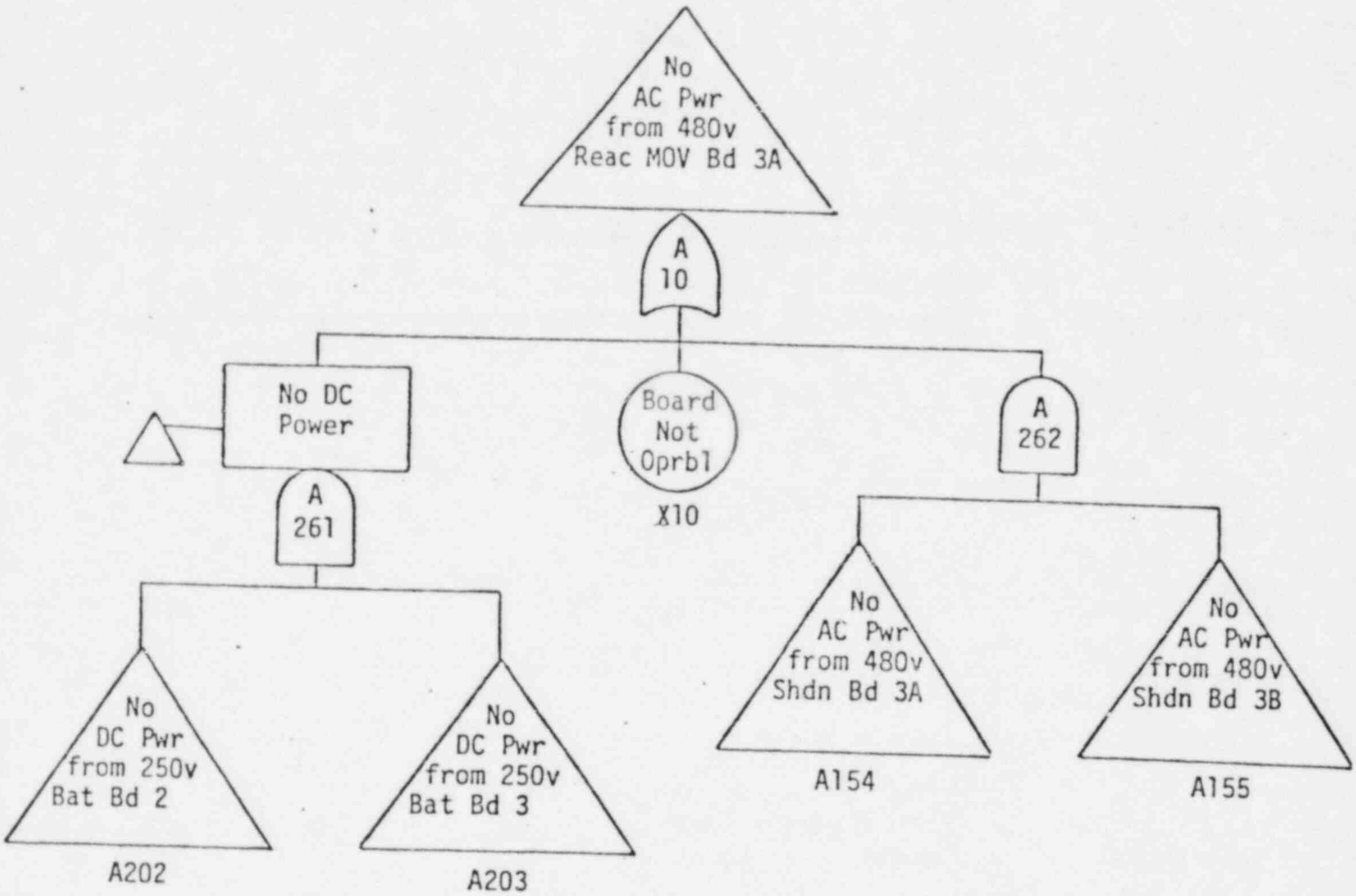


FIGURE 8

FAULT TREE FOR AC REACTOR MOTOR-OPERATED VALVE ELECTRIC POWER

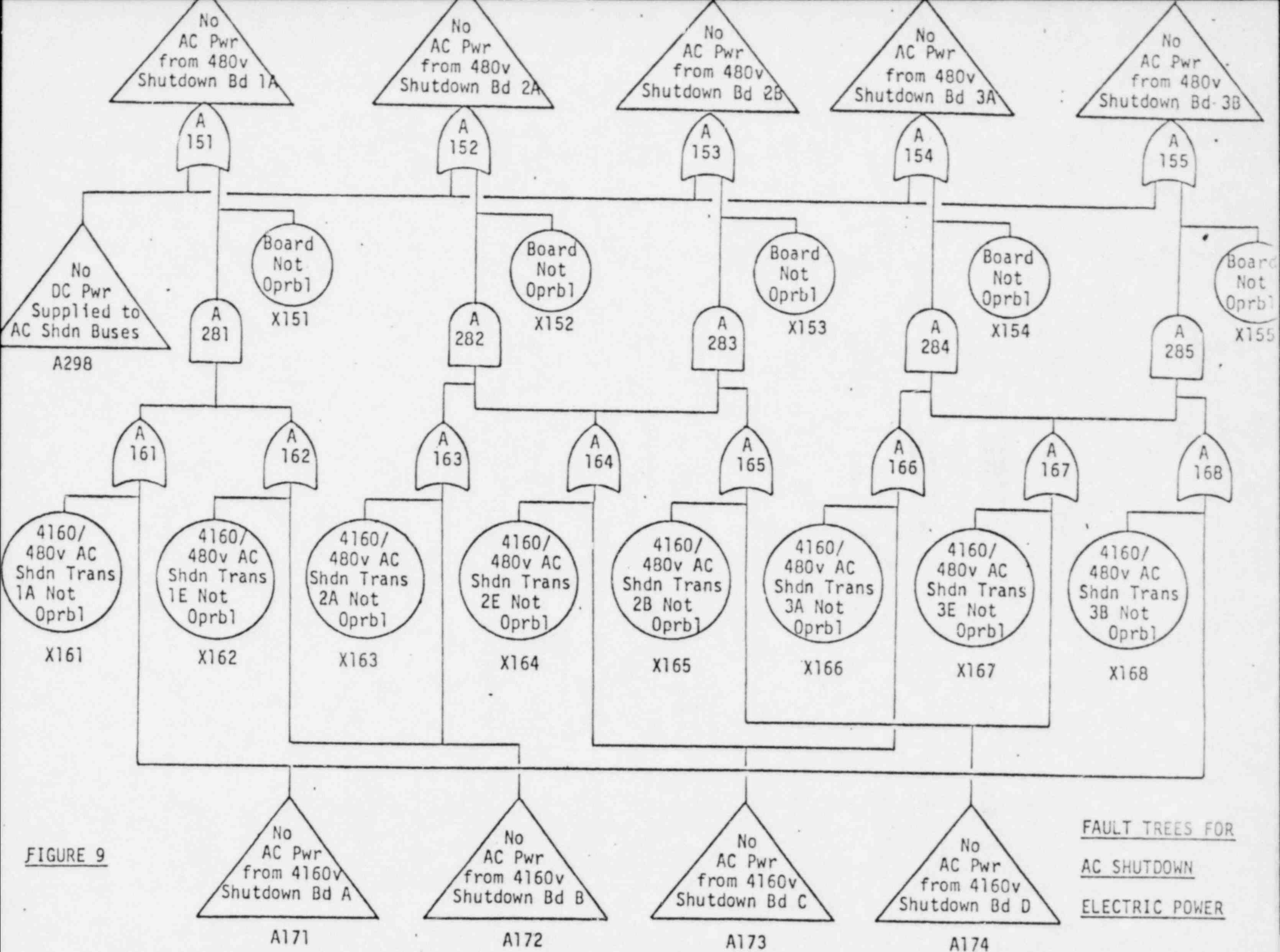


FIGURE 9

FAULT TREES FOR AC SHUTDOWN ELECTRIC POWER

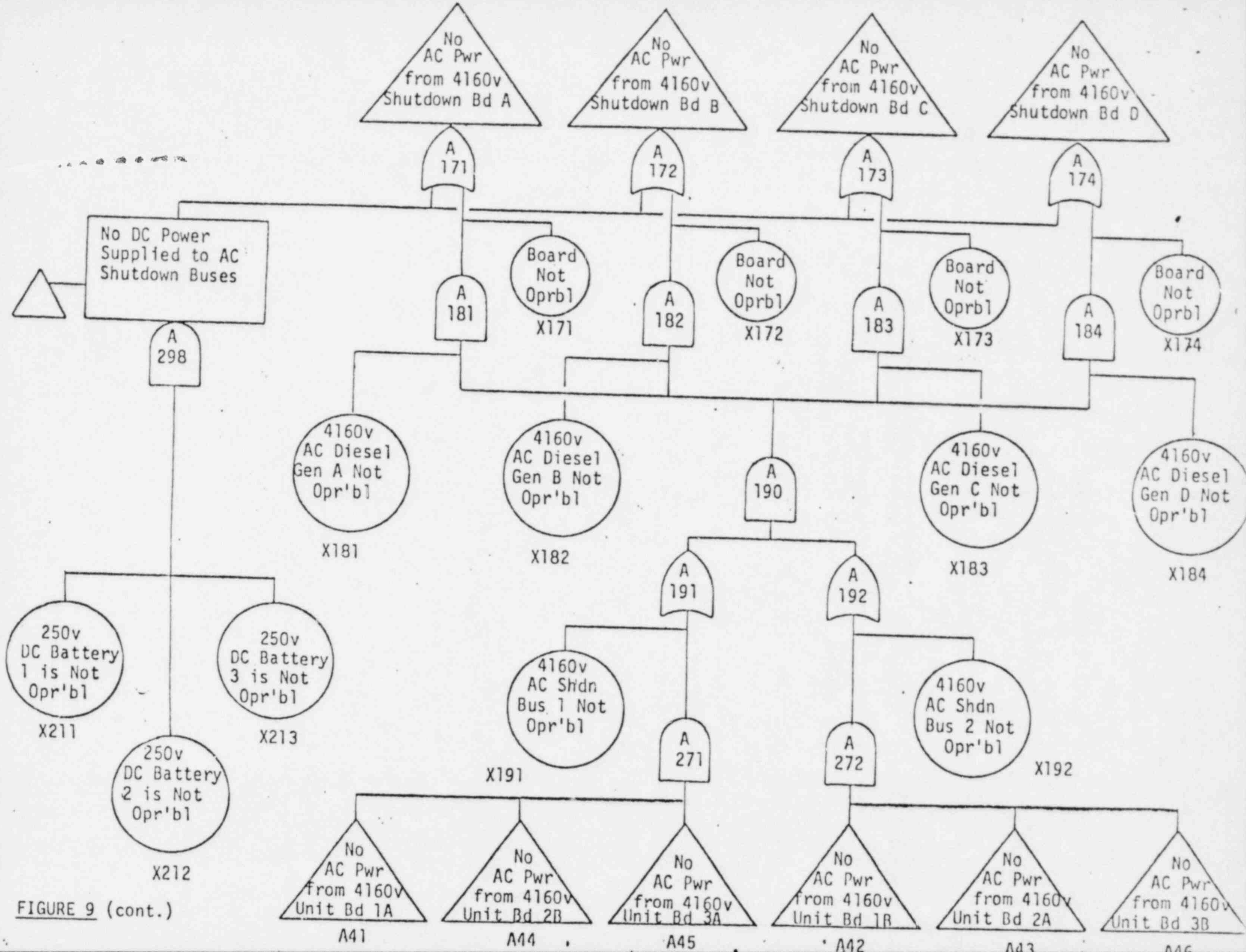
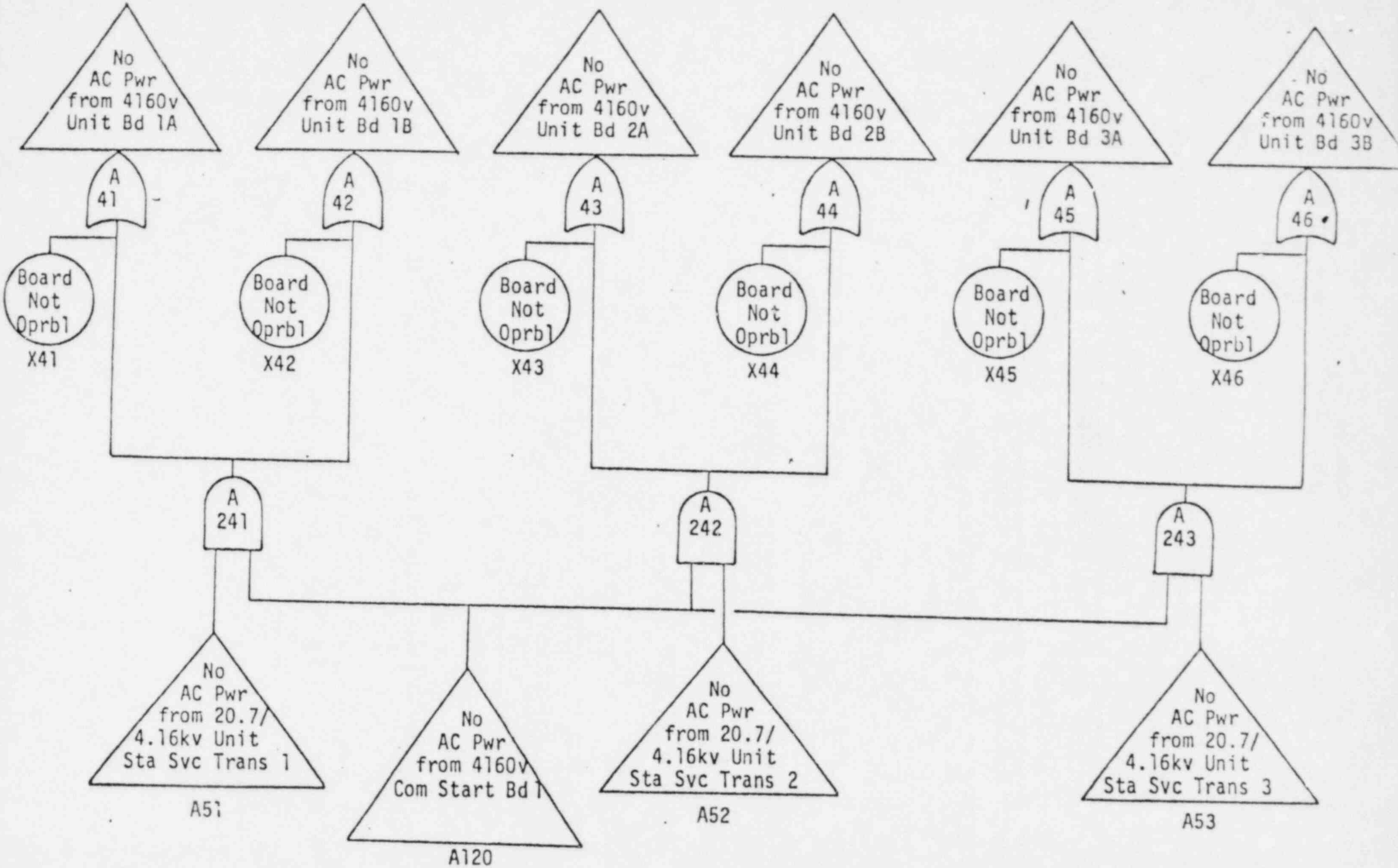


FIGURE 9 (cont.)



FAULT TREES FOR AC UNIT ELECTRIC POWER

FIGURE 10

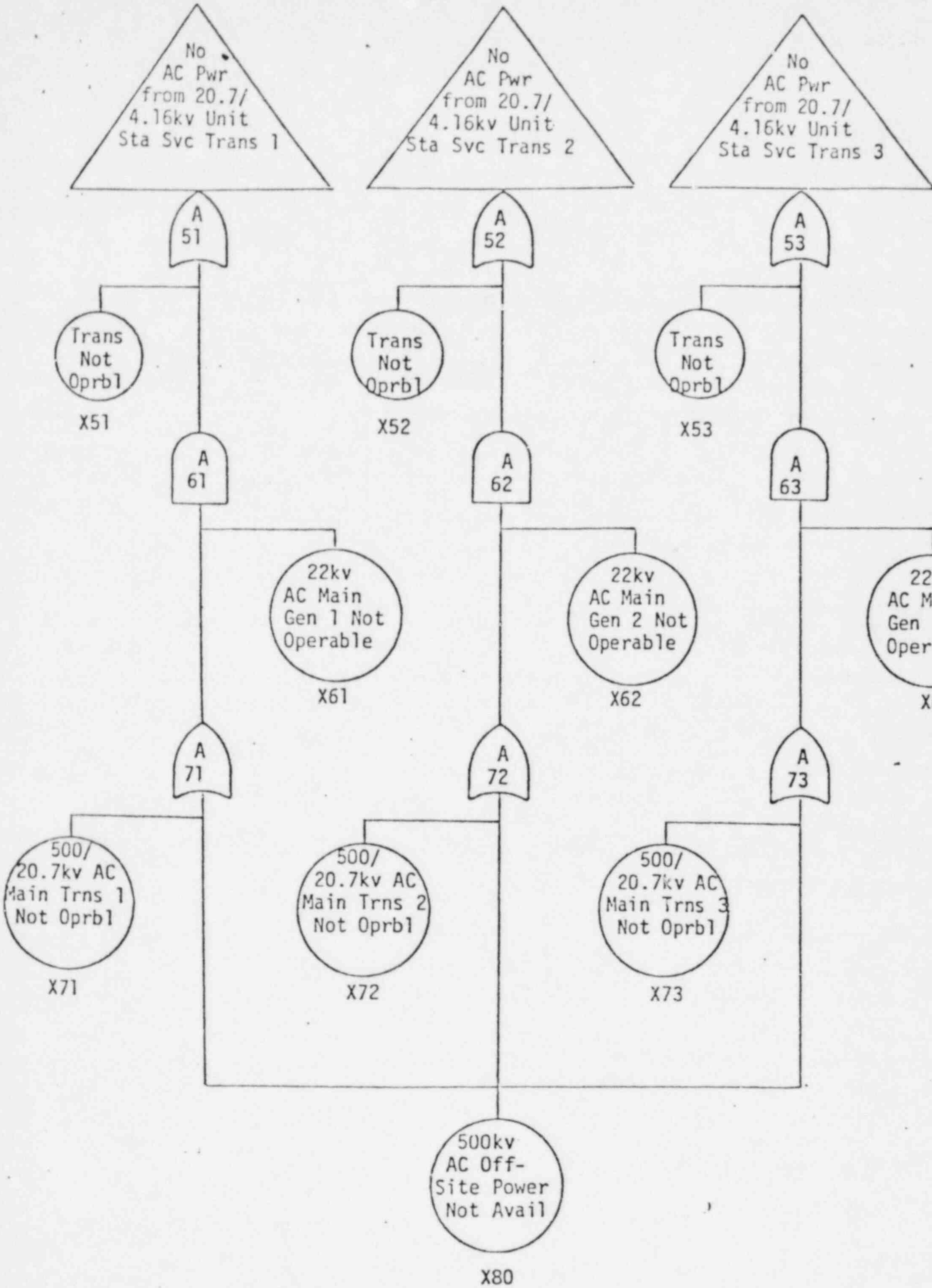


FIGURE 10 (cont.)

TABLE 1

BERING SCHEME FOR FAULT TREES FOR COMPUTER RUNS

Numbers	Systems	Components
1-9	AC Reactor Bldg Vent	480v AC Boards
10-19	AC Reactor MOV	480v AC Board
20-29	AC Unit	480v AC Boards
30-39	"	4160/480v AC Transformers
40-49	"	4.16 kV AC Boards
50-59	"	20.7/4.16 kV AC Transformers
60-69	"	22 kV AC Generators
70-79	"	500/20.7 kV AC Transformers
80-89	"	500 kV AC Off-Site Power
90-99	AC Common	480v AC Boards
100-109	"	4160/480v AC Transformers
110-119	"	4.16 kV AC Boards
120-129	"	4.16 kV AC Start Board
130-139	"	161/4.16 kV AC Transformers
140-149	"	161 kV AC Off-Site Power
150-159	AC Shutdown	480v AC Boards
160-169	"	4160/480v AC Transformers
170-179	"	4.16 kV AC Boards
180-189	"	4.16 kV AC Generators
190-199	"	4.16 kV AC Buses
200-209	250v DC	250v DC Battery Boards
210-219	"	250v DC Batteries
220-229	"	250v DC Battery Chargers
230-299	Other Gates for Electrical Components	
310-319	CRS	HCU Scram Inlet & Exhaust Valves
320-329	"	HCU Scram Pilot Valves
330-339	"	Backup Scram Pilot Valves
340-349	"	SIV Valve
350-359	"	West Bank SDV Valve
360-369	"	East Bank SDV Valve

Numbers	Systems	Components
370-379	CRS	SDV/SIV Pilot Valves
380-389	"	Manual Signal
390-399	RP	Trip-Logic Channels
400-409	"	Close-Logic Channels
410-419	RBEDS	Exhaust Fans
420-429	Control Air	Air Compressors
430-439	SLC	Pumps
440-449	"	Valves
450-459	RWC	Isolation Valves
460-512	Other Gates for Non-Electrical Components	

TAB. 1 (cont)

TABLE 2. CRS Minimal Cut Sets Prior to Resolution for Dependencies

1-Element

X310
X363
X353
X342

2-Element

X320	X401
↓391	↓401
392	401
320	402
391	402
392	402
371	373
373	380
371	392
380	392
371	372
372	380
371	391
380	391
411	412
1	412
2	411
1	2
20	93

3-Element

X320	X333	X334
↓333	↓334	↓391
333	334	392
320	331	332
331	332	391
331	332	392
422	423	424
152	423	424
91	422	424
91	152	424
92	422	423
92	152	423
91	92	422
91	92	152
111	112	422
111	112	152
421	423	424
151	423	424
91	421	424
91	151	424
92	421	423
92	151	423
91	92	421
91	92	151
111	112	421
111	112	151
421	422	424
151	422	424
152	421	424
151	152	424
92	421	422
92	151	422
92	152	421
92	151	152
421	422	423
151	422	423
152	421	423
151	152	423
91	421	422
91	151	422
91	152	421
91	151	152
30	93	100
45	93	100
30	93	111
45	93	111
20	105	106
20	105	111
30	106	111
45	106	111
20	105	112
20	111	112
30	111	112
45	111	112

4-Element

X201	X202	X203	X320
↓201	↓202	↓203	↓391
201	202	203	392
163	164	423	424
164	172	423	424
163	173	423	424
172	173	423	424
91	163	164	424
91	164	172	424
91	163	173	424
91	172	173	424
101	102	422	424
101	102	152	424
102	111	422	424
102	111	152	424
101	112	422	424
101	112	152	424
92	163	164	423
92	164	172	423
92	163	173	423
92	172	173	423
91	92	163	164
91	92	164	172
91	92	163	173
91	92	172	173
92	101	102	422
92	101	102	152
92	102	111	422
92	102	111	152
92	101	112	422
92	101	112	152
92	111	112	422
92	111	112	152
103	104	422	423
103	104	152	423
91	103	104	422
91	103	104	152
104	111	422	423
104	111	152	423
91	104	111	422
91	104	111	152
102	104	111	422
102	104	111	152
103	112	422	423
103	112	152	423
91	103	112	422
91	103	112	152
101	103	112	422
101	103	112	152

TABLE 2. (cont.)

4-Element (cont.)

X111	X112	X163	X164
↓111	↓112	↓164	↓172
111	112	163	173
111	112	172	173
51	112	120	422
51	112	120	152
52	111	120	422
52	111	120	152
51	52	120	422
51	52	120	152
161	162	423	424
152	171	423	424
161	172	423	424
171	172	423	424
91	161	162	424
91	162	171	424
91	161	172	424
91	171	172	424
101	102	421	424
101	102	151	424
102	111	421	424
102	111	151	424
101	112	421	424
101	112	151	424
92	161	162	423
92	162	171	423
92	161	172	423
92	171	172	423
91	92	161	162
91	92	162	171
91	92	161	172
91	92	171	172
92	101	102	421
92	101	102	151
92	102	111	421
92	102	111	151
92	101	112	421
92	101	112	151
103	104	421	423
103	104	151	423
91	103	104	421
91	103	104	151
104	111	421	423
104	111	151	423
91	104	111	421
91	104	111	151
102	104	111	421
102	104	111	151
103	112	421	423
103	112	151	423
91	103	112	421
91	103	112	151
101	103	112	421
101	103	112	151

4-Element (cont.)

X111	X112	X161	X162
↓111	↓112	↓162	↓171
111	112	161	172
111	112	171	172
51	112	120	421
51	112	120	151
52	111	120	421
52	111	120	151
51	52	120	421
51	52	120	151
161	162	422	424
162	171	422	424
161	172	422	424
171	172	422	424
152	161	162	424
152	162	171	424
152	161	172	424
152	171	172	424
163	164	421	424
151	163	164	424
164	172	421	424
151	164	172	424
161	164	172	424
164	171	172	424
163	173	421	424
151	163	173	424
172	173	421	424
151	172	173	424
161	172	173	424
171	172	173	424
211	212	213	424
92	161	162	422
92	162	171	422
92	161	172	422
92	171	172	422
92	152	161	162
92	152	162	171
92	152	161	172
92	152	171	172
92	163	164	421
92	151	163	164
92	164	172	421
92	151	164	172
92	161	164	172
92	164	171	172
92	163	173	421
92	151	163	173
92	172	173	421
92	151	172	173
92	161	172	173
92	171	172	173
92	211	212	213

TABLE 2. (cont.)

4-Element (cont.)

X 103	X 104	X 421	X 422
↓103	↓104	↓151	↓422
103	104	152	421
103	104	151	152
104	111	421	422
104	111	151	422
104	111	152	421
104	111	151	152
103	112	421	422
103	112	151	422
103	112	152	421
103	112	151	152
161	162	422	423
162	171	422	423
161	172	422	423
171	172	422	423
152	161	162	423
152	162	171	423
152	161	172	423
152	171	172	423
163	164	421	423
151	163	164	423
164	172	421	423
151	164	172	423
161	164	172	423
164	171	172	423
163	173	421	423
151	163	173	423
172	173	421	423
151	172	173	423
161	172	173	423
171	172	173	423
211	212	213	423
91	161	162	422
91	162	171	422
91	161	172	422
91	171	172	422
91	152	161	162
91	152	162	171
91	152	161	172
91	152	171	172
91	163	164	421
91	151	163	164
91	164	172	421
91	151	164	172
91	161	164	172
91	164	171	172
91	163	173	421
91	151	163	173
91	172	173	421
91	151	172	173
91	161	172	173
91	171	172	173
91	211	212	213

4-Element (cont.)

X101	X102	X421	X422
↓101	↓102	↓151	↓422
101	102	152	421
101	102	151	152
102	111	421	422
102	111	151	422
102	111	152	421
102	111	151	152
101	112	421	422
101	112	151	422
101	112	152	421
101	112	151	152
53	93	100	120
53	93	111	120
30	51	93	120
45	51	93	120
51	53	93	120
30	100	105	106
45	100	105	106
53	106	111	120
30	100	105	112
45	100	105	112
53	111	112	120
20	51	106	120
30	51	106	120
45	51	106	120
51	53	106	120
20	51	112	120
30	51	112	120
45	51	112	120
51	53	112	120
20	52	105	120
20	52	111	120
30	52	111	120
45	52	111	120
52	53	111	120
20	51	52	120
30	51	52	120
45	51	52	120
51	52	53	120

TABLE 3. SLC Minimal Cut Sets Prior to Resolution for Dependencies

1-Element

None

2-Element

X441	X442
X202	X203
X431	X432
X154	X432
X155	X431
X154	X155
X451	X452
X10	X451

3-Element

X211	X212	X213
X166	X167	X432
X167	X173	X432
X166	X174	X432
X173	X174	X432
X155	X166	X167
X155	X167	X173
X155	X166	X174
X155	X173	X174
X167	X168	X431
X154	X167	X168
X166	X167	X168
X167	X168	X173
X168	X174	X431
X154	X168	X174
X166	X168	X174
X168	X173	X174
X167	X171	X431
X154	X167	X171
X166	X167	X171
X167	X171	X173
X171	X174	X431
X154	X171	X174
X166	X171	X174
X171	X173	X174

4-Element

None

5-Element

X167	X183	X191	X192	X432
X174	X183	X191	X192	X432
X166	X184	X191	X192	X432
X173	X184	X191	X192	X432
X183	X184	X191	X192	X432
X155	X167	X183	X191	X192
X155	X174	X183	X191	X192
X155	X166	X184	X191	X192
X155	X173	X184	X191	X192
X155	X183	X184	X191	X192
X167	X168	X183	X191	X192
X168	X174	X183	X191	X192
X167	X171	X183	X191	X192
X171	X174	X183	X191	X192
X168	X184	X191	X192	X431
X154	X168	X184	X191	X192
X166	X168	X184	X191	X192
X168	X173	X184	X191	X192
X168	X183	X184	X191	X192
X171	X184	X191	X192	X431
X154	X171	X184	X191	X192
X166	X171	X184	X191	X192
X171	X173	X184	X191	X192
X171	X183	X181	X191	X192
X167	X181	X191	X192	X431
X154	X167	X181	X191	X192
X166	X167	X181	X191	X192
X167	X173	X181	X191	X192
X167	X181	X183	X191	X192
X174	X181	X191	X192	X431
X154	X174	X181	X191	X192
X166	X174	X181	X191	X192
X173	X174	X181	X191	X192
X174	X181	X183	X191	X192
X181	X184	X191	X192	X431
X154	X181	X184	X191	X192
X166	X181	X184	X191	X192
X173	X181	X184	X191	X192
X181	X183	X184	X191	X192

TABLE 4. Reactor Control Minimal Cut Sets Prior to Resolution for Dependencies

3-Element

X310	X441	X442
↓	X202	X203
	X431	X432
	X154	X432
	X155	X431
	X154	X155
	X451	X452
	X10	X451
X363	X441	X442
↓	X202	X203
	X431	X432
	X154	X432
	X155	X431
	X154	X155
	X451	X452
	X10	X451
X353	X441	X442
↓	X202	X203
	X431	X432
	X154	X432
	X155	X431
	X154	X155
	X451	X452
	X10	X451
X342	X441	X442
↓	X202	X203
	X431	X432
	X154	X432
	X155	X431
	X154	X155
	X451	X452
	X10	X451

4-Element

X201	X202	X203	X320
↓201	↓202	↓203	↓391
201	202	203	392
211	212	213	91
211	212	213	92
211	212	213	423
211	212	213	424
320	401	441	442
391	401	↓	↓
392	401		
320	402		
391	402		
392	402		
371	373		
373	380		
371	392		
380	392		
371	372		
372	380		
371	391		
380	391		
411	412		
1	412		
2	411		
1	2		
20	93		
320	401	202	203
391	401	↓	↓
392	401		
320	402		
391	402		
392	402		
371	373		
373	380		
371	392		
380	392		
371	372		
372	380		
371	391		
380	391		
411	412		
1	412		
2	411		
1	2		
20	93		

TABLE 4. (cont.)

4-Element (cont.)

X320	X401	X431	X432
391	401		
392	401		
320	402		
391	402		
392	402		
371	373		
373	380		
371	392		
380	392		
371	372		
372	380		
371	391		
380	391		
411	412		
1	412		
2	411		
1	2		
20	93		

320	401	X154	X432
391	401		
392	401		
320	402		
391	402		
392	402		
371	373		
373	380		
371	392		
380	392		
371	372		
372	380		
371	391		
380	391		
411	412		
1	412		
2	411		
1	2		
20	93		

320	401	X155	X431
391	401		
392	401		
320	402		
391	402		
392	402		
371	373		
373	380		
371	392		
380	392		
371	372		
372	380		
371	391		
380	391		
411	412		
1	412		
2	411		
1	2		
20	93		

4-Element (cont.)

X320	X401	X154	X155
391	401		
392	401		
320	402		
391	402		
392	402		
371	373		
373	380		
371	392		
380	392		
371	372		
372	380		
371	391		
380	391		
411	412		
1	412		
2	411		
1	2		
20	93		

320	401	X451	X452
391	401		
392	401		
320	402		
391	402		
392	402		
371	373		
373	380		
371	392		
380	392		
371	372		
372	380		
371	391		
380	391		
411	412		
1	412		
2	411		
1	2		
20	93		

320	401	X10	X451
391	401		
392	401		
320	402		
391	402		
392	402		
371	373		
373	380		
371	392		
380	392		
371	372		
372	380		
371	391		
380	391		
411	412		
1	412		
2	411		
1	2		
20	93		

TABLE 4. (cont.)

4-Element (cont.)

X310 ↓	X211	X212	X213
	X166	X167	X432
	X167	X173	X432
	X166	X174	X432
	X173	X174	X432
	X155	X166	X167
	X155	X167	X173
	X155	X166	X174
	X155	X173	X174
	X167	X168	X431
	X154	X167	X168
	X166	X167	X168
	X167	X168	X173
	X168	X174	X431
	X154	X168	X174
	X166	X168	X174
	X168	X173	X174
	X167	X171	X431
	X154	X167	X171
	X166	X167	X171
	X167	X171	X173
	X171	X174	X431
	X154	X171	X174
	X166	X171	X174
	X171	X173	X174
X363 ↓	X211	X212	X213
	X166	X167	X432
	X167	X173	X432
	X166	X174	X432
	X173	X174	X432
	X155	X166	X167
	X155	X167	X173
	X155	X166	X174
	X155	X173	X174
	X167	X168	X431
	X154	X167	X168
	X166	X167	X168
	X167	X168	X173
	X168	X174	X431
	X154	X168	X174
	X166	X168	X174
	X168	X173	X174
	X167	X171	X431
	X154	X167	X171
	X166	X167	X171
	X167	X171	X173
	X171	X174	X431
	X154	X171	X174
	X166	X171	X174
	X171	X173	X174

4-Element (cont.)

X353 ↓	X211	X212	X213
	X166	X167	X432
	X167	X173	X432
	X166	X174	X432
	X173	X174	X432
	X155	X166	X167
	X155	X167	X173
	X155	X166	X174
	X155	X173	X174
	X167	X168	X431
	X154	X167	X168
	X166	X167	X168
	X167	X168	X173
	X168	X174	X431
	X154	X168	X174
	X166	X168	X174
	X168	X173	X174
	X167	X171	X431
	X154	X167	X171
	X166	X167	X171
	X167	X171	X173
	X171	X174	X431
	X154	X171	X174
	X166	X171	X174
	X171	X173	X174
X342 ↓	X211	X212	X213
	X166	X167	X432
	X167	X173	X432
	X166	X174	X432
	X173	X174	X432
	X155	X166	X167
	X155	X167	X173
	X155	X166	X174
	X155	X173	X174
	X167	X168	X431
	X154	X167	X168
	X166	X167	X168
	X167	X168	X173
	X168	X174	X431
	X154	X168	X174
	X166	X168	X174
	X168	X173	X174
	X167	X171	X431
	X154	X167	X171
	X166	X167	X171
	X167	X171	X173
	X171	X174	X431
	X154	X171	X174
	X166	X171	X174
	X171	X173	X174

TABLE 5. Component Failures in CRS Minimal Cut Sets Prior to Resolution for Dependencies

FAILURE #	SYSTEM	COMPONENT	LOCATION BUILDING	LOCATION ELEV.	LOCATION COORDS.
X1	AC Reactor Bldg. Vent (Unit 3 only)	480v AC Reactor Bldg. Vent Board 3A	Unit 3 Reactor Bldg	734	$QN/R_{18}R_{19}$
X2		480v AC Reactor Bldg. Vent Board 3B		565	$UT/R_{18}R_{19}$
X20	AC Unit	480V AC Unit Board 3A	Turbine Bldg	586	$DC/T_{11}T_{12}$
X30		4160/480v AC Unit Transformer 3A			
X45		4.16 kV AC Unit Board 3A		604	$CB/T_{16}T_{17}$
X51		20.7/4.16 kV AC Unit Station Service Transformer 1	Switchyard		
X52		20.7/4.16 kV AC Unit Station Service Transformer 2			
X53		20.7/4.16 kV AC Unit Station Service Transformer 3			
X91	AC Common	480v AC Common Board 1	Turbine Bldg.	586	KJ/T_6T_7
X92		480v AC Common Board 2		604	CB/T_6T_8
X93		480V AC Common Board 3		586	$HG/T_{11}T_{12}$
X100		4160/480v AC Common Transformer EA		604	$CB/T_{12}T_{13}$
X101		4160/480v AC Common Transformer 1A		586	KJ/T_6T_7
X102		4160/480v AC Common Transformer 1B			
X103		4160/480v AC Common Transformer 2A		604	CB/T_7T_8
X104		4160/480v AC Common Transformer 2B			CB/T_6T_7
X105		4160/480v AC Common Transformer 3A		586	$HG/T_{11}T_{12}$
X106		4160/480v AC Common Transformer 3B			

TABLE 5. (cont.)

FAILURE #	SYSTEM	COMPONENT	LOCATION		
			BUILDING	ELEV.	COORDS.
X111	AC Common (cont.)	4.16kv AC Common Board A	Turbine Bldg	604	CB/T_1T_2
X112		4.15kv AC Common Board B			$CB/T_{10}T_{11}$
X120		4.16 kV AC Common Start Board 1			BA/T_1T_2
X151	AC Shutdown	480v AC Shutdown Board 1A	Unit 1 Reactor Bldg	621	$TS/R_1R_{1.5}$
X152		480v AC Shutdown Board 2A	Unit 2 Reactor Bldg		$TS/R_{13}R_{13.5}$
X161		4160/480v AC Shutdown Transformer 1A	Unit 1 Reactor Bldg		$TS/R_1R_{1.5}$
X162		4160/480v AC Shutdown Transformer 1E		639	TR/R_1R_2
X163		4160/480v AC Shutdown Transformer 2A	Unit 2 Reactor Bldg	621	$TS/R_{13}R_{13.5}$
X164		4160/480v AC Shutdown Transformer 2E		639	$TR/R_{13}R_{14}$
X171		4.16 kV AC Shutdown Board A	Unit 1 Reactor Bldg	621	SP/R_1R_2
X172		4.16 kV AC Shutdown Board B		593	
X173		4.16 kV AC Shutdown Board C	Unit 2 Reactor Bldg	621	$SP/R_{13}R_{14}$
X201	250v DC	250v DC Battery Board 1	Unit 1 Reac. Bldg.	593	$PN/R_{3.5}R_4$
X202		250v DC Battery Board 2	Unit 2 Reac. Bldg.		$PN/R_{9.5}R_{10}$
X203		250v DC Battery Board 3	Unit 3 Reac. Bldg.		$PN/R_{18}R_{18.5}$
X211		250v DC Battery 1	Unit 1 Reac. Bldg.		$PN/R_{2.5}R_{3.5}$
X212		250v DC Battery 2	Unit 2 Reac. Bldg.		$PN/R_{10}R_{11}$
X213		250v DC Battery 3	Unit 3 Reac. Bldg.		$PN/R_{18.5}R_{19.5}$

FAILURE #	SYSTEM	COMPONENT	LOCATION BUILDING	LOCATION ELEV.	LOCATION COORDS.
X310	Control Rod Scram (High Pressure)	3 or More Diaphragm-Operated Scram Inlet or Exhaust Valves	Unit 3 Reactor Bldg	565	SQ/ $R_{15}R_{16}$(West) $R_{20}R_{21}$(East)
X320		3 or More Three-way Solenoid Scram Pilot Valves A or B			
X331		Three-way Solenoid Backup Scram Pilot Valve 1-1			
X332		Three-way Solenoid Backup Scram Pilot Valve 1-2			
X333		Three-way Solenoid Backup Scram Pilot Valve 2-1			
X334		Three-way Solenoid Backup Scram Pilot Valve 2-2			
X342		Diaphragm-Operated SIV Drain Valve			
X353		Diaphragm-Operated West Bank SDV Vent Valve			
X363		Diaphragm-Operated East Bank SDV Vent Valve			
X371		Three-way Solenoid SDV/SIV Pilot Valve A			
X372		Three-way Solenoid SDV/SIV Pilot Valve B			
X373		Three-way Solenoid SDV/SIV Isolation Pilot Valve			
X380		Remote Manual Signal		617	PN/$R_{16}R_{19}$
X391	Reactor Protection	Trip-Logic Channel A			
X392		Trip-Logic Channel B			
X401		Close-Logic Channel A			
X402		Close-Logic Channel B			

TABLE 5. (cont.)

FAILURE #	SYSTEM	COMPONENT	LOCATION		
			BUILDING	ELEV.	COORDS.
X411	Reactor Building Equipment Drain Sump (Ventilation only)	RBEDS Exhaust Fan 1	Unit 3 Reactor Bldg.	576	$VU/R_{19}R_{20}$
X412		RBEDS Exhaust Fan 2			
X421	Control Air	Air Compressor A	Turbine Bldg.	565	MJ/T_1T_2
X422		Air Compressor B			
X423		Air Compressor C			
X424		Air Compressor D			

TABLE 6. Dependencies Among Component Failures in CRS Minimal Cut Sets

	Dependencies	
Component Failures	Generic	Spatial
X1, X2	G0	---
X20, X30	---	S20
X51-X53	G50	S50
X91-X93	G90	---
X91, X101, X102	---	S91
X92, X103, X104	---	S92
X93, X105, X106	---	S93
X100-X106	G100	---
X111, X112	G110	---
X111, X120	---	S111
X151, X152	G150	---
X151, X171	---	S151
X152, X173	---	S152
X161-X164	G160	---
X171-X173	G170	---
X201-X203	G200	---
X201, X211	---	S201
X202, X212	---	S202
X203, X213	---	S203
X211-X213	G210	---
X310-X373	---	S310
X310, X342, X353, X363	G310	---
X320, X331-X334, X371-X373	G320	---
X391, X392	G390	---
X401, X402	G400	---
X391-X402	---	S390
X411, X412	G410	S410
X421-X424	G420	S420

TABLE 7. CRS Minimal Cut Sets Following Resolution for Dependencies

1-Element

I310
I363
I353
I342
G310
S310
S390
G320
G410
S410
G0
G420
S420

2-Element

I320	I401
I391	I401
I392	I401
I320	I402
I391	I402
I392	I402
I371	I373
I373	I380
I371	I392
I380	I392
I371	I372
I372	I380
I371	I391
I380	I391
I411	I412
I1	I412
I2	I411
I1	I2
I20	I93

2-Element (cont.)

I152	G90
I20	G90
I93	S20
I152	G110
I151	G90
I151	G110
I92	G150
I91	G150
I20	S93
I20	G100
I20	G110
I30	G110
I320	G200
I391	G200
I392	G200
I424	G170
I424	G210
I92	G170
I92	G210
I423	G170
I423	G210
I91	G170
I91	G210
I30	G100
I120	G50
I120	S50
I320	G400
I391	G400
I392	G400
I401	G390
I402	G390
I371	G390

2-Element (cont.)

I380	G390
X45	G110
X45	G100
G90	S20
G90	G150
G90	S152
G110	G150
G110	S152
G90	S151
G110	S151
G150	S92
G150	S91
S20	S93
G100	S20
G110	S20
G90	G160
G90	G170
G110	G160
G110	G170
G170	S92
G210	S92
G90	G210
G100	G150
G170	S91
G210	S91
G50	S111
S50	S111
G390	G400

TABLE 8. Component Failures in SLC Minimal Cut Sets Prior to Resolution for Dependencies

FAILURE #	SYSTEM	COMPONENT	LOCATION		
			BUILDING	ELEV.	COORDS.
X10	AC Reactor MOV (Unit 3 Board 3A only)	480v AC Reactor MOV Board 3A	Unit 3 Reactor Bldg	621	$RP/R_{20}R_{21}$
X154	AC Shutdown	480v AC Shutdown Board 3A			$SR/R_{20}R_{20.5}$
X155		480v AC Shutdown Board 3B			$SR/R_{20.5}R_{21}$
X166		4160/480v AC Shutdown Transformer 3A			$SR/R_{20}R_{20.5}$
X167		4160/480v AC Shutdown Transformer 3E		639	$SR/R_{20}R_{21}$
X168		4160/480v AC Shutdown Transformer 3B		621	$SR/R_{20.5}R_{21}$
X171		4.16 kV AC Shutdown Board A	Unit 1 Reactor Building		$SP/R_{1}R_{2}$
X173		4.16 kV AC Shutdown Board C	Unit 2 Reactor Bldg		$SP/R_{13}R_{14}$
X174		4.16 kV AC Shutdown Board D		593	
X181		4.16 kV AC Diesel Generator A	Diesel Generator	565	Room A
X183		4.16 kV AC Diesel Generator C			Room C
X184		4.16 kV AC Diesel Generator D			Room D
X191		4.16 kV AC Shutdown Bus 1			
X192		4.16 kV AC Shutdown Bus 2			

TABLE 8. (cont.)

FAILURE #	SYSTEM	COMPONENT	LOCATION BUILDING	LOCATION ELEV.	LOCATION COORDS.
X431	Standby Liquid Control	Positive-Displacement Pump 1	Unit 3 Reactor Bldg.	639	$QP/R_{19}R_{20}$
X432		Positive-Displacement Pump 2			
X441		Explosive Valve 1			
X442		Explosive Valve 2			
X451	Reactor Water Cleanup (Isolation Only)	DC Motor-Operated Isolation Valve (Outside drywell)			
X452		AC Motor-Operated Isolation Valve (inside drywell)		Inside Drywell	

TABLE 9. Dependencies Among Component Failures in SCL Minimal Cut Sets

Component Failures	Dependencies Generic	Dependencies Spatial
X10, X154, X155	--	S10
X154, X155	G150	--
X166-X168	G160	--
X171, X173, X174	G170	--
X181, X183, X184	G180	S180
X191, X192	G190, G40*	--
X431, X432	G430	--
X431-X442	--	S430
X441, X442	G440	--
X451, X452	G450	--

* For each minimal cut set containing X191 & X192, there is a corresponding, longer-element minimal cut set containing X41 through X46, all of which are subject to a generic failure (G40).

TABLE 10. SLC Minimal Cut Sets Following Resolution for Dependencies

1-Element	2-Element
S10	I441 I442
G150	I202 I203
G160	I431 I432
G170	I154 I432
G200	I155 I431
G210	I154 I155
G430	I451 I452
S430	I10 I451
G440	G180 G190
G450	G190 S180
	G180 G40
	G40 S180

TABLE 11. Reactor Control Minimal Cut Sets Following Resolution for Dependencies

1-Element

None

2-Element

I310 S10
I363 ↓
I353
I342
I310 G150
I363 ↓
I353
I342
I310 G160
I363 ↓
I353
I342
I310 G170
I363 ↓
I353
I342
I310 G200
I363 ↓
I353
I342
I310 G210
I363 ↓
I353
I342

2-Element (cont.)

I310 G430
I363 ↓
I353
I342
I310 S430
I363 ↓
I353
I342
I310 G440
I363 ↓
I353
I342
I310 G450
I363 ↓
I353
I342
I320 G200
I391 G200
I392 G200
I91 G150
I92 G150
I91 G210
I92 G210
I91 G170
I92 G170
I423 G210

2-Element (cont.)

I424 G210
I423 G170
I424 G170
G310 S10
S310 ↓
S390
G320
G410
S410
G0
G420
S420
G310 G150
S310 ↓
S390
G320
G410
S410
G0
G420
S420
G310 G160
S310 ↓
S390
G320
G410

TABLE II. (cont.)

2-Element (cont.)

S410 G160
↓
G0
G420
S420
G310 G170
↓
S310
S390
G320
G410
S410
G0
G420
S420
G310 G200
↓
S310
S390
G320
G410
S410
G0
G420
S420
G310 G210
↓
S310
S390

2-Element (cont.)

G320 G210
↓
G410
S410
G0
G420
S420
G310 G430
↓
S310
S390
G320
G410
S410
G0
G420
S420
G310 S430
↓
S310
G390
G320
G410
S410
G0
G420
S420
G310 G440

2-Element (cont.)

S310 G440
↓
S390
G320
G410
S410
G0
G420
S420
G310 G450
↓
S310
S390
G320
G410
S410
G0
G420
S420
G90 G150
G110 G150
G150 S92
G150 S91
G100 G150
G210 S92
G210 S91
G90 G210

TABLE 11. (cont.)

2-Element (cont.)

G90	G160
G110	G160
G90	G170
G110	G170
G170	S92
G170	S91

TABLE 12. QUALITATIVE IMPORTANCES OF FAILURE EVENTS IN REACTOR CONTROL MINIMAL CUT SETS RESOLVED FOR DEPENDENCIES

RANK	EVENT	# OF TIMES APPEARING IN 2-ELEMENT SETS	RANK	EVENT	# OF APPEARANCES
1	G170	22	11	S390	10
2	G150	21	11	G410	10
2	G210	21	11	S410	10
4	G200	17	11	G420	10
5	G160	16	11	S420	10
6	S10	14	24	G90	4
6	G430*	14	25	I91	3
6	S430*	14	25	I92	3
6	G440*	14	25	S91	3
6	G450*	14	25	S92	3
11	I310*	10	25	G110	3
11	I342*	10	30	I423	2
11	I353*	10	30	I424	2
11	I363*	10	32	I320*	1
11	G0	10	32	I391	1
11	G310*	10	32	I392	1
11	S310*	10	32	G100	1
11	G320*	10			

* Not an SI

TABLE 13. INDEPENDENT FAILURE PROBABILITIES FOR COMPONENTS IN REACTOR CONTROL MINIMAL CUT SETS RESOLVED FOR DEPENDENCIES

COMPONENTS	WASH-1400 FAILURE MODES*	WASH-1400* FAILURE RATE	CALCULATED FAILURE PROBABILITY
Electric Boards, Buses	Wires, open circuit or short to ground	3×10^{-6}/hr	.001
Electric Transformers	Transformers, open circuit (primary or secondary)	1×10^{-6}/hr	4×10^{-4}
Diesel Generators	Diesel Generators (complete plant):		
	failure to start	.03/demand	.03
	failure to run, given start (emergency conditions)	.003/hr	
Electric Batteries	Battery Power Systems (wet cell), failure to provide proper output	3×10^{-6}/hr	.001
Electric Logic Channel	Wires, short to power	1×10^{-8}/hr	4×10^{-6}
Diaphragm-Operated Valves	Air/Fluid-Operated Valves, failure to operate	3×10^{-4}/demand	3×10^{-4}
Solenoid-Operated Valves	Solenoid-Operated Valves, failure to operate	.001/demand	.001

TABLE 13. (continued)

COMPONENTS	WASH-1400 FAILURE MODES*	WASH-1400* FAILURE RATE	CALCULATED FAILURE PROBABILITY
Motor-Operated Valves	Motor-Operated Valves, failure to operate	.001/demand	.001
Explosive Valves	Any Valve, failure to operate	(maximum value for all valves) .001/demand	.001
Pumps	Pumps: failure to start	.001/demand	
	failure to run, given start (normal environment)	3×10^{-5}/hr	.01
Fans	Pumps, failure to run, given start	3×10^{-5}/hr	.01[⊕]
Air Compressors	Pumps, failure to run, given start	3×10^{-5}/hr	.01[⊕]

*Selected from Tables III 4-1 and III 4-2.

[⊕]Assumed to have already started prior to need for scram (failure probability calculated as 1/2 λ_T [720 hrs])

TABLE 14. FAILURE PROBABILITIES FOR EVENTS IN REACTOR CONTROL MINIMAL CUT SETS RESOLVED FOR DEPENDENCIES

FAILURE EVENT	COMPONENTS INVOLVED	FAILURE PROBABILITY
G0	480v AC Reactor Building Vent Boards	$(.001)^{\sqrt{2}} = 6 \times 10^{-5}$
S10	480v AC Reactor MOV Board and 480v AC Shutdown Boards 3A and 3B	$(.01)^{\sqrt{2}} = .001$
G90	480v AC Common Boards	$(.001)^{\sqrt{2}} = 6 \times 10^{-5}$
I91	480v AC Common Board 1	.001
I92	480v AC Common Board 2	.001
S91	480v AC Common Board 1 and 4160/480v AC Common Transformers 1A and 1B	$(.01)^{\sqrt{2}} = .001$
S92	480v AC Common Board 2 and 4160/480v AC Common Transformers 2A & 2B	$(.01)^{\sqrt{2}} = .001$
G100	4160/480v AC Common Transformers	$(4 \times 10^{-4})^{\sqrt{2}} = 2 \times 10^{-5}$
G110	4.16 kv AC Common Boards	$(.001)^{\sqrt{2}} = 6 \times 10^{-5}$
G150	480v AC Shutdown Boards	$(.001)^{\sqrt{2}} = 6 \times 10^{-5}$
G160	4160/480v AC Shutdown Transformers	$(4 \times 10^{-4})^{\sqrt{2}} = 2 \times 10^{-5}$
G170	4.16 kv AC Shutdown Boards	$(.001)^{\sqrt{2}} = 6 \times 10^{-5}$

TABLE 14 (continued)

FAILURE EVENT	COMPONENTS INVOLVED	FAILURE PROBABILITY
G200	250v DC Battery Boards	$(.001)^{\sqrt{2}} = 6 \times 10^{-5}$
G210	250v DC Batteries	$(.001)^{\sqrt{3}} = 6 \times 10^{-6}$
I310	$\geq$ 3 CRS HCU Diaphragm-Operated Scram Inlet or Exhaust Valves in Different HCUs	$(3 \times 10^{-4})^3 = 3 \times 10^{-11}$
G310	CRS Diaphragm-Operated Valves	$(3 \times 10^{-4})^{\sqrt{2}} = 1 \times 10^{-5}$
S310	CRS Valves	$(.01)^{\sqrt{2}} = .001$
I320	$\geq$ 3 CRS HCU Solenoid-Operated Scram Pilot Valves in Different HCUs	$(.001)^3 = 1 \times 10^{-9}$
G320	CRS Solenoid-Operated Valves	$(.001)^{\sqrt{2}} = 6 \times 10^{-5}$
I342	CRS Diaphragm-Operated SIV Drain Valve	3×10^{-4}
I353	CRS Diaphragm-Operated West Bank SDV Vent Valve	3×10^{-4}
I363	CRS Diaphragm-Operated East Bank SDV Vent Valve	3×10^{-4}

TABLE 14. (continued)

FAILURE EVENT	COMPONENTS INVOLVED	FAILURE PROBABILITY
S390	RP Logic Channels	$(.01)^{\sqrt{2}} = .001$
I391	RP Trip-Logic-Channel A	4×10^{-6}
I392	RP Trip-Logic-Channel B	4×10^{-6}
G410	RBEDS Exhaust Fans	$(.01)^{\sqrt{2}} = .001$
S410	RBEDS Exhaust Fans	$(.01)^{\sqrt{2}} = .001$
G420	Control Air Compressors	$(.01)^{\sqrt{2}} = .001$
S420	Control Air Compressors	$(.01)^{\sqrt{2}} = .001$
I423	Control Air Compressor C	.01
I424	Control Air Compressor D	.01
G430	SLC Pumps	$(.01)^{\sqrt{2}} = .001$
S430	SLC Pumps and Explosive Valves	$(.01)^{\sqrt{2}} = .001$
G440	SLC Explosive Valves	$(.001)^{\sqrt{2}} = 6 \times 10^{-5}$
G450	RWC Motor-Operated Isolation Valves	$(.001)^{\sqrt{2}} = 6 \times 10^{-5}$

TABLE 15. PROBABILISTIC IMPORTANCES OF FAILURE EVENTS IN REACTOR CONTROL MINIMAL CUT SETS RESOLVED FOR DEPENDENCIES

RANK	EVENT	PROBABILISTIC IMPORTANCE
1	S10	.1
1	G430*	.1
1	S430*	.1
4	S310*	.07
4	S390	.07
4	G410	.07
4	S410	.07
4	G420	.07
4	S420	.07
10	G170	.04
11	I342*	.02
11	I353*	.02
11	I363*	.02
14	I423	.01
14	I424	.01
14	G150	.01
17	G200	.008
17	G440*	.008
17	G450*	.008
20	G0	.004
20	G210	.004
20	G320*	.004
23	G160	.003
24	I91	.002
24	S91	.002
24	I92	.002
24	S92	.002
28	G310*	7×10^{-4}
29	G90	2×10^{-4}
29	G110	2×10^{-4}
31	G100	2×10^{-5}
32	I391	5×10^{-6}
32	I392	5×10^{-6}
34	I310*	2×10^{-9}
35	I320*	1×10^{-9}

*Not an SI