ESTIMATION, UNCERTAINTY ANALYSIS, AND SENSITIVITY ANALYSIS:

DIRECTIONS FOR RMIEP

Robert G. Easterling
Floyd W. Spencer
Kathleen V. Diegert

Statistics, Computing, and Human Factors Division
Sandia National Laboratories
Albuquerque, New Mexico 87110

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APPENDIX D

Use of the Maximus Methodology for

Confidence Bound Calculations in Fault Trees--Trial Problem

Introduction

To demonstrate the use of the Maximus Methodology [3] for confidence bound calculations in fault trees, a dominant accident sequence from the Interim Reliability Evaluation Program: Analysis of the Arkansas Nuclear One-Unit 1 Nuclear Power Plant [1] was chosen for analyses. The sequence chosen was the $B(1.2)D_1C$ sequence, which denotes a reactor coolant pump seal rupture or a rupture in the RCS piping in the range of .38" to 1.2" (B(1.2)) followed by failure of the high pressure injection system (D_1) and reactor building spray injection system (C).

The Maximus Methodology was developed for system reliabilities modeled by block diagrams. Block diagrams are generally not as extensive as fault tree models for nuclear plant accident sequences. This trial problem was initiated to answer the question--Can Maximus still be used and if so with what modifications?

In this paper, the calculation of confidence bounds in several cases will be considered. The cases illustrate the distinction between data-based and data-free estimates as outlined in the guidelines [2] for the PRA Methods Develoment Program. In case 1, the estimates given for each event are treated as being data-based and recovery is not considered. Case 2 is like case 1 in the treatment of event data, but the probability of recovery (as subjectively determined) is added. In case 3, the probability of the accident sequence is considered as being estimated by both data-based and subjectively-based estimates with recovery probabilities also considered as subjectively determined. The consideration of recovery is an explicit recognition that even though a particular accident sequence may occur it will not necessarily lead to core melt. Human intervention may restore things if done correctly and in a timely manner. The recovery action, however, takes place after the accident sequence has occurred.

Case 3 reflects the most realistic situation for accident sequences in that some of the basic event probability estimates are data based, some are subjectively determined, and recovery is included. However, the other cases are worth considering as they may be applied at intermediate steps, and it is the first case that is comparable to the uncertainty analysis done in reference 1. For all the cases, the information available was in the form of point estimates and error factors, as well as the associations of events whose probabilities were considered as being estimated from the same data base. For the example problems considered here, those estimates considered as data based are translated into pseudo-data by finding the occurrences in demands (or operating time) that gives the same point estimate and gives the error factor times the point estimate as a 95% upper statistical confidence bound. If the probability of the event is considered to be subjectively estimated, the interval ℓ, u, where ℓ = (point estimate/error factor) and u = (point estimate · error factor) is taken as the subjective interval and the point estimate is taken as the nominal value in carrying out the uncertainty analysis as described in Reference 2. The above procedure of converting to pseudo-data is not being recommended. It is used here to obtain "data" for the sake of illustration.

In the accident sequence considered, B(1.2) is the initiating event and D_1C represents the hardware and system failures that are modeled in the fault tree. The event B(1.2) has an estimated occurrence rate of .02/reactor year. For illustration purposes, we will derive the overall uncertainties in each case by considering the failure rate of B(1.2) as a constant and also considering it as having been estimated by 2 occurrences in 100 reactor years.

Case 1. All probabilities considered as data based--no recovery

This problem was originally approached by considering the dominant 500 cut sets for the sequence of reference 1. The estimated occurrence rate from the 500 cut sets is approximately 98% of the estimate that would result considering the top 1,355 cut sets. The 500 dominant cut sets are comprised of 135 different basic events. In order to represent D_1C in a series-parallel arrangement, the 500 cut sets were examined in a factored form. The series-parallel arrangement derived from this factored form is given in Figure 1. The numbers inside the boxes are the number of serial basic events that comprise that segment of the sequence. Although constructed from considering the dominant 500 cut sets, the system of Figure 1 has 1,289 cut sets. This is because the representation of the system is block form introduced cut sets not in the original 500. These additional cut sets were then verified to be actual cut sets of the system.

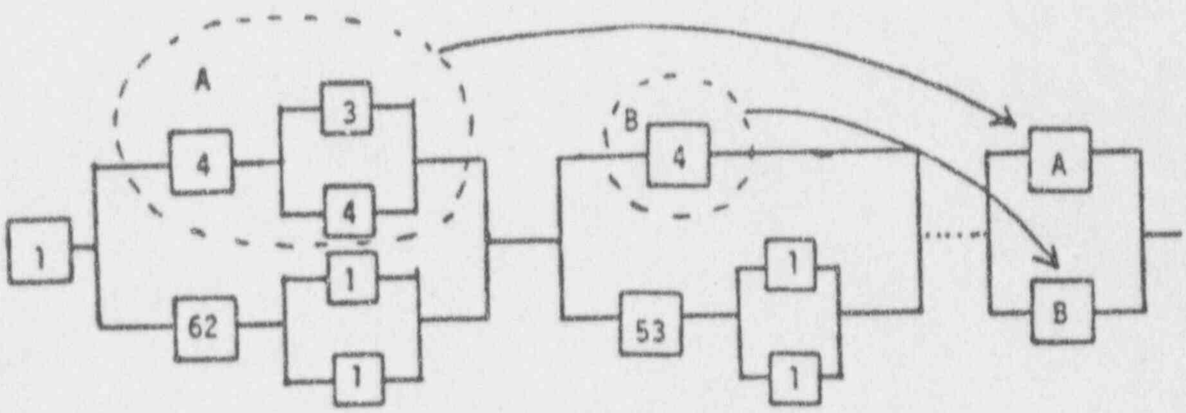


Figure 1. A series-parallel representation of the dominant cut sets of $B(1.2)D_1C$. The A and B terms are repetitions of the same group of components with the same structure.

In Appendix C of reference 1, dominant minimal cut sets in terms of independent subtrees were given. The series-parallel arrangement implied by the configuration given in Appendix C is consistent with that shown in Figure 1, except that the parallel arrangements of Figure 1 contain single events that were not included in reference 1. By considering both the independent subtrees given in reference 1 and the elements included in the top 500 cut sets, the representation of Figure 2 is obtained. In Figure 2, each block is one or more basic events in series and those blocks labeled the same are repeats of the same chain of events. The blocks labeled P, Q, a, and b represent events not listed in reference 1 but contained in the top 500 cut sets. As the total contribution of these were small and they had very little effect on the uncertainty calculations, they are left out of the present analysis.

The events contained in each block are enumerated in the Appendix in Table A2. Those blocks (A through O) that were derived from reference 1 are documented by inclusion in the Appendix of the appropriate table from that reference. Also added to the tables are identifiers for the population type. Those events whose probabilities are estimated from the same data sources have the same population type identifier. In order not to double or multiple the same data in the overall uncertainty estimate, the available data is divided among those events to which the data apply (see Reference 3). In this example, pseudo-data are constructed by finding the number of occurrences in time that would give the same point estimate and for which the 95% upper confidence bound equals the point estimate times the error factor. The intent is to illustrate the analysis with statistical data that correspond, at least roughly, to the subjective estimates and uncertainty assessments in Reference 1. This gives rise to the following two equations (for the Poisson-type data, these are exact; for binomial-type data, these are based on very good approximations):

$$f/T = \hat{P}$$

$$\frac{\chi^2(2f + 2; .95)}{2T} = \hat{p} \cdot EF .$$

Here, $\chi^2(df; \alpha)$ denotes the α percentile of the chi-square distribution with df degrees of freedom. The values f and T are the pseudo data of f occurrences in T time (or demands) and p and EF are the given point estimate and error factor.

By substituting the first equation into the second, the T values cancel and f is the solution of:

$$\chi^2(2f + 2; .95)/f = 2 \cdot EF .$$

The solution of the above equation when EF = 3 is f = 2.20 and when EF = 10, f is .37. The denominator (demand or time) is calculated in each case by dividing f by the point estimate.

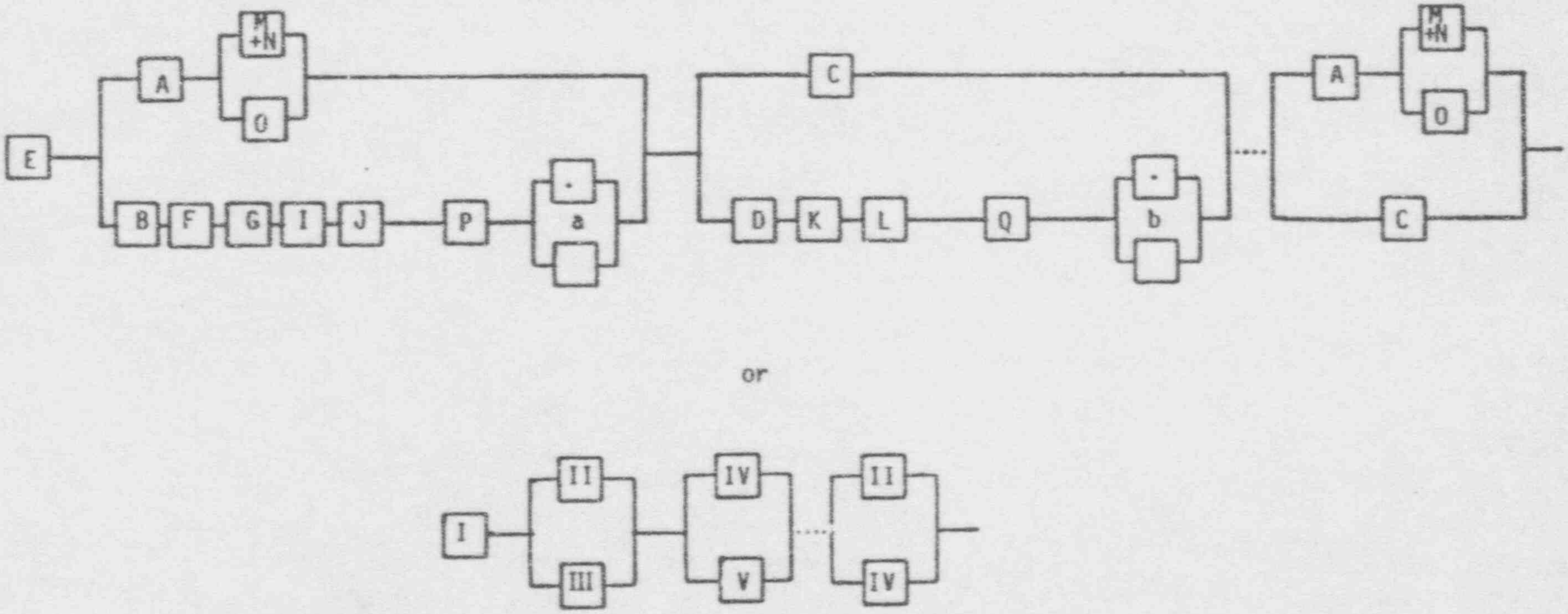


Figure 2. Series-parallel arrangement for B(1.2)D$_1$C. Each block is one or more basic events in series. Those blocks labeled the same represent the same event.

The various population types and derived pseudo-data are given in Table A3. Some of the population types have events that have different point estimates. This situation is taken to reflect the case where a rate λ is estimated for all the events of interest, but the actual rate for a particular event i is λt_i. In the Poisson case, if λ is estimated by f occurrences in T time, then the estimate of λt is equivalent to f occurrences in time T/t. To handle those population types that had different point estimates within them, the largest point estimate is taken as the λ estimate and smaller point estimates have associated with them a time factor for adjustment. For example, consider that two event probabilities, one estimated at 1.1(-3) and one at 3.3(-3), are considered to be from the same population type. Both have error factors of 3 so that we take f = 2.2. Using the larger of the two as reflecting the λ to be estimated, we take T = 2.2/3.3(-3) = 667 as the applicable data. If 3.3(-3) is the estimate for λ, then 1.1(-3) must correspond to an estimate of $\lambda/3$. Therefore, if we divide the applicable data between the two events, giving 1.1 failures in 333.3 time units for estimating each λ independently, this is equivalent to using 1.1 failures in 1,000 time units for estimating $\lambda/3$. And, thus, the time factor of the second event would be given as 3. The various factors by which times are adjusted are given in Table A4 in the Appendix.

The Maximus method for calculating confidence bounds was applied to the system of Figure 2. The effective number of tests was calculated and combined with the total failure estimate to calculate the effective number of failures. The last parallel arrangement (Branches II and IV in Figure 2) was not originally considered in deriving the effective number of tests because it does not represent an independent subsystem but rather is included in the system to represent an additional cut set not present in the parallel-series arrangement. The effective tests for the two branches (II and IV) derived from the first part of the system when combined in a parallel arrangement exceed that originally calculated for the system. Therefore, this cut set does not affect the effective failure number calculation.

Computer Program

There currently exists a Fortran program that calculates effective data for series-parallel systems given component data and using the Maximus methodology. Figure 3 is an example output of this program for the system under consideration here. The inputs to the program are the system description and the component data. In this example, each of the components (events) from the same population type are labeled with the same alphabetic character. Differences in the numeric value following the alphabetic character are needed because of the potentially different test quantities to be assigned in the unpooling process.

The system equation is recursive, where each set of parentheses encloses a subsystem which may contain other subsystems. For example, in the system description of Figure 3, subsystem 1, which is represented as (1*a2b2c2c2g2j1), is a series (denoted by the "*") subsystem representing the independent subtree labeled LPI1408B-VCC-LF in the ANO analysis. Subsystem 1 is itself an element of the subsystem labeled 16 in the description. Subsystem 16 combines subsystem 1 in series with subsystem 14, which is the subsystem that combines the parallel arrangement of M+N and O of Figure 2.

From Figure 3, it is seen that the overall effective data are roughly 1.2 failures in 1,430 tests. This analysis does not include the additional cut sets represented by the parallel arrangement of II with IV appended to the system in Figure 2. If we combine those systems from Figure 3 that make up the added cut sets (subsystems 16 and 3), the effective n far exceeds 1,430. Therefore, 1,430 is used as the overall system effective test size and the overall system point estimate of 9.2(-4) gives the effective data of roughly 1.3 failures in 1,430 tests. The upper 95% confidence limit on the sequence occurrence rate, based on 1.3 failures in 1,430 tests is 3.7(-3).

If the point estimate divided into the upper 95% bound is taken to be the error factor, then the error factor from this data would be 4.0. Contrast this with the error factor of 3 that is given in the ANO report. However, note that the lower 95% bound on 1.3 failures in 1,430 tests is given by 8.3(-5) and if the point estimate divided by this lower limit is taken to be the error factor, then 11 ($\approx 9.2 \div .83$) would be taken as the error factor.

In the methodology used for the ANO report, the distribution on the top event would not have a lognormal distribtuion, and, therefore, the error factor determination could suffer from inconsistencies similar to those discussed above. It would make more sense to compare the results of these two methods by looking directly at the uncertainty intervals. Uncertainty intervals from the ANO report method are not directly available but from the values given in Table 8-4 of reference 1, we can infer that the median of the derived distribution was 1.25(-3). With this value and an error factor of 3, the upper 95th percentile must have been approximately 3.75(-3) as compared to 3.7(-3) derived from the Maximus methodology. Thus, the two methods produce upper uncertainty bounds that are virtually the same in this particular example. However, there is a vast difference in the interpretations from the methods. By use of the Maximus methodology, statistical confidence bounds are stressed. That is, one is asking how high the probability of the sequence D_1C might be and still be consistent with the available data on the individual events. The degree of "consistency" is determined by the confidence level. On the other hand, a Monte Carlo method such as used in ANO, requires the placement of distribution functions on each of the individual event probabilities. These distribution functions do not correspond to anything that we have specifically modeled, and therefore, they reflect an added mathematical level that is often referred to as the "analyst degree-of-belief."

The above analysis reflects only the D_1C portion of the sequence. If the .02/reactor year occurrence rate for B(1.2) is considered as constant, then the overall uncertainty analysis would correspond to that of 1.3 failures in 71,400 reactor years. The lower and upper 95% bounds are then given by 1.7(-6) and 7.3(-5), respectively.

If the .02/reactor year rate is considered as coming from 2 occurrences in 100 years, the effective overall data is .61 occurrences in 33,200 reactor years (see Reference 3 for combining algorithm) and the lower 95% confidence limit is 1.9(-7) ~~and the upper 95% confidence limit is 1.9(-7)~~ and the upper 95% confidence limit is 1.2(-4).

	SUBSYSTEM		EQUIVALENT FAILURES	EQUIVALENT TESTS	MLE OF RELIABILITY
A	1		1.3678	163.30	0.9916
MIN	12		0.4837	14.60	0.9669
O	13		0.2489	17.80	0.9860
	14		0.0786	169.72	0.9995
	16	II	1.4428	163.30	0.9912
B	2		0.8107	35.70	0.9773
F	6		0.3735	35.70	0.9895
G	7		0.3699	35.70	0.9896
I	8		0.2782	55.70	0.9950
J	9		0.1760	35.70	0.9951
	17	III	1.8718	35.70	0.9476
	15	II par III	0.6608	1426.54	0.9995
C	3	IV	1.1048	131.90	0.9916
D	4		0.8084	33.30	0.9757
K	10		0.2987	59.60	0.9950
L	11		0.1642	33.30	0.9951
	19	V	1.1306	33.30	0.9660
	18	IV par V	0.4062	1428.38	0.9997
	0		1.2089	1426.54	0.9992

Current system description is:

```
(0*e1(15+(16*(1*a2b2c2c2g2j1)(14+(12*a5a5a6b4b4b4b4ce2e2e2f1f1j3 4j414o2ptu1
(13*a7a7b5b5c3e3e3f2g4j5j515o3)))(17*(2*a1b1deeeeeeeefg1g1jlou)
(6*ab1c1g1j)(7*ab1g1j)(8*a3b1j11o1)(9*a1b1eeejk)))(18+(3*a8b3c4c4g3j3)
(19*(4*a9bd1e4e4e4e4e4e4e4f3ggj212o4u2)(10*a4bj213o5)(11*a9be4e4e4j2k))))
```

COMPONENT	FAILURES	TESTS	Test factor - see Table A4
a	0.3406	103.20	
a1	0.1135	103.20	3
a2	0.4653	423.00	3
a3	0.0106	105.60	33
a4	0.0106	105.60	33
a5	0.0317	28.80	3
a6	0.0950	28.80	
a7	0.0409	37.20	3
a8	0.3340	303.60	3
a9	0.1162	105.60	3
b	0.1192	59.60	
b1	0.1114	55.70	
b2	0.5990	299.50	
b3	0.4024	201.20	
b4	0.0348	17.40	
b5	0.0726	36.30	
c	0.0022	21.80	
c1	0.0176	175.70	
c2	0.0278	278.10	
c3	0.0027	27.20	

Figure 3. Output from Maximus Method Code for $B(1.2)D_1C$ Sequence

Press return to continue

c4	1.0609	10609.00	
d	0.1928	35.70	
d1	0.1798	33.30	
e	0.0036	35.70	
e1	2.1133	21133.00	
e2	0.0016	16.00	
e3	0.0020	20.00	
e4	0.0033	33.30	
f	2.1672	21671.50	
f1	0.0016	15.90	
f2	0.0019	19.20	
f3	0.0278	277.50	
g	0.1365	33.30	
g1	0.1464	35.70	
g2	0.6695	163.30	
g3	0.5408	131.90	
g4	0.0730	17.80	
g5	0.0599	14.60	
j	0.1189	118.90	
j1	0.6434	643.40	

Press return to continue

j2	0.1223	122.30	
j3	0.4191	419.10	
j4	0.0378	37.80	
j5	0.0520	50.20	
k	1.1000	2037.00	
l	0.9675	261.50	
l1	0.4396	261.36	2.2
l2	0.5206	140.70	
l3	0.2394	140.80	2.2
l4	0.0167	16.65	3.7
l5	0.0203	20.35	3.7
o	1.3370	3109.40	
o1	0.6856	3109.30	1.95
o2	0.0041	18.53	1.95
o3	0.0045	22.58	2.15
o4	0.1115	259.20	
o5	0.0571	259.20	1.95
p	2.2000	2200.00	
t	0.3680	46.00	
u	0.0435	217.40	9

Press return to continue

u1	0.0036	18.00	9
u2	0.3229	179.40	
v	2.1990	733.00	

Figure 3 (Continued)

The data for each of the components (events) in Figure 3 result from the unpooling process. The algorithm used for unpooling is presented in the Appendix.

Case 2. Recovery Added

Some of the failure events in D_1C can be "recovered," or corrected, thus preventing the sequence from progressing to core melt. Thus, it is more "realistic" to incorporate recovery events and their probabilities into the models.

Of more interest than whether a given sequence, such as $B(1.2)D_1C$, occurs is the case that it occurs and is not recovered from, thus leading to a severe consequence such as core melt. Case 2 considers the event of the accident sequence occurring and no recovery taking place. In probabilistic notation, the parameter of interest is written as follows:

$$Pr(B(1.2)D_1C \text{ and no recovery}) = Pr(\text{no recovery}|B(1.2)D_1C) \cdot Pr(B(1.2)D_1C) ,$$

where $Pr(A|B)$ denotes the conditional probability of A when B is known to have occurred. For uncertainty analysis, if $Pr(\text{no recovery}|B(1.2)D_1C)$ was considered to be a known constant, then the effective number of tests (or effective time) derived for the uncertainty analysis of $Pr(B(1.2)D_1C)$ would be divided by the value of $Pr(\text{no recovery}|B(1.2)D_1C)$ to give the effective test size for the estimate of $Pr(B(1.2)D_1C$ and no recovery). Because estimated recovery probabilities will most likely be subjective in nature (i.e., not directly data based) and the uncertainty in recovery factors will be treated by an interval analysis, $Pr(\text{no recovery}|B(1.2)D_1C)$ is treated as being constant. Its value is calculated by the ratio, $Pr(B(1.2)D_1C$ and no recovery)/$Pr(B(1.2)D_1C)$.

The conditional probability of no-recovery for $B(1.2)D_1C$ in reference 1 was calculated to be .22. This value was arrived at by calculating the probability of nonrecovery for each subtree and then taking the probability of nonrecovery for a cut set to be the minimum probability of nonrecovery amongst the subtrees represented in the cut set. This is the procedure that would be followed on the original fault tree instead of on the cut sets from the independent subtrees.

Using the value of .22 for the probability of nonrecovery and the effective data of 1.31 failures in 1,430 tests from case 1, we get that the uncertainty bounds for the estimate of D_1C, considering recovery would be based on 1.31 failures in 1430/.22 ≈ 6500 tests. If the initiating event rate is included in the analysis as having a value of .02, then the uncertainty bounds are based on 1.3 failures in 324,000 reactor years. In this case, the lower and upper 95% confidence bounds are given by 3.7(-7) and 1.6(-5), respectively.

If the initiating event rate is considered as 2 occurrences in 100 reactor years, then the uncertainty bounds are based on .61 failures in 151,000 reactor years and the confidence limits are given by 4.1(-8) for the lower 95% limit and 2.7(-5) for the upper 95% confidence limit.

The recovery model is such that for any given minimal cut set the probability of nonrecovery is the minimum of the probabilities of nonrecovery amongst the individual terms of the cut set. For the D_1C sequence, as approximated by the system of Figure 2, the nonrecovery for subtrees A, C, and E are 1. Therefore, a very good approximation to the probability of D_1C including recovery is obtained by modeling each of the basic events of subsystems III and V from Figure 2 as a parallel arrangement of the basic event with the event of no recovery for that basic event. The uncertainty analysis in this case is easily accomplished by altering the test quantities for those events in III and V by dividing the old test quantities by the probability of nonrecovery for that event. This was done with the data in Figure 3. The effective test quantity for the parallel arrangement of II with III (from Figure 2) was 7690 and that from the parallel arrangement of IV with V was 5790. These were derived without re-unpooling the data for the new system. If the unpooling algorithm was followed specific to the new model, the effective test quantity would be greater than 5790 but less than 7690. The suggested method that gives an effective test quantity of 6500 is roughly in the range that would be obtained if the Maximus methodology was rerun for the parallel-series system discussed above that closely approximates the model with recovery.

Case 3. Overall uncertainty analysis amongst subjective- and data-based estimates

Cases 1 and 2 provide the bases for calculating uncertainty intervals when some of the estimates are subjective and some are data based. In this section, they are combined to demonstrate a complete analysis using the Maximus methodology combined with other features of the guidelines (Reference 2). For this example, five of the population types from the analysis of case 1 were chosen randomly to be considered as subjective estimates. The data types chosen to be subjective were those labeled a, f, j, -, and o in Table A3.

The set up and recommended display for uncertainty analysis contained in the Guidelines (Reference 2) is briefly reviewed. Assume the parameter of interest, Prob(B(1.2)D_1C and no recovery), is expressed as a function, $f(\theta, \omega)$, where $\underline{\omega}$ is a vector of parameters subjectively estimated and $\underline{\theta}$ is a vector of parameters for which data are available for estimation purposes. In the present example, $\underline{\omega}$ contains not only the parameters from population types labeled a, f, j, ℓ, and o, but also all recovery factors.

We define $\eta_\ell(\underline{\omega})$ and $\eta_u(\underline{\omega})$ to be the lower and upper 95% statistical confidence limits based on $\underline{\theta}$ evaluated at a specific $\underline{\omega}$. With this notation, the quantities of interest for an uncertainty display are the overall extremes,

$$L = \min_{\underline{\omega}} \eta_\ell(\underline{\omega}) , \qquad U = \max_{\underline{\omega}} \eta_u(\underline{\omega}) ,$$

the differences in point estimates over the range of subjectively determined estimates,

$$\min_{\underline{\omega}} f(\underline{\theta}^*, \underline{\omega}) \quad \text{and} \quad \max_{\underline{\omega}} f(\underline{\theta}^*, \omega) ,$$

where $\underline{\theta}^*$ represents the point estimates from the data. Also of interest are the data uncertainty interval at the nominal subjective points,

$$\eta_\ell(\underline{\omega}^*) \quad \text{and} \quad \eta_u(\underline{\omega}^*) ,$$

and, of course, the overall nominal assessment, $f(\underline{\theta}^*, \underline{\omega}^*)$.

The basis for calculating the lower and upper bounds using the Maximus methodology has been given in cases 1 and 2. For the purposes of this example, the probability of nonrecovery factors (n) are taken to range over $(n/2, 2 \cdot n)$ unless $2n > 1$ in which case the upper limit is 1. The other subjectively determined types are assumed to range over $(p/EF, p \cdot EF)$, where p is the nominal point estimate and EF is the error factor given for that population type. The recovery factors are given in Table A2, taken from the ANO report (Reference 1).

Since $f(\underline{\theta}, \underline{\omega})$ is an increasing function with respect to each component of the vector $\underline{\omega}$, the minimum and maximum of $f(\theta^*, \underline{\omega})$ is easily calculated by substituting the minimums for all the components of $\underline{\omega}$. Thus, all the events of types a, f, j, ℓ, and o are evaluated at their point estimate divided by the error factor and all the probabilities of nonrecovery are halved. For example, consider the subtree labeled A. Subtree A has 6 events (See Table A2) of which the events LPI6164-BOO-LF and 6164B-CBL-LF are considered as subjectively determined, and, therefore, lower estimates for them are taken to be (1E-3)/3 and (1.1E-3)/3. The lower estimate for subtree A then becomes 7.0(-3). The probability of nonrecovery is taken to be .5 for the lower bound analysis since the original probability of nonrecovery was taken to be 1 (see footnote in Table A2).

When the Maximus methodology is applied in order to calculate $\min_{\omega} \eta_\ell(\underline{\omega})$, the approach of cases 1 and 2 are used where the subjectively determined estimates have been evaluated at their lower points. Thus, subtree A would be modeled as having 4 events for which data are available, but the point estimate for the subtree would be taken to be 7(-3), thus reflecting the impact of the subjectively determined estimates. This can be done because the Lindstrom-Madden method for determining effective test quantities depends only on the number of tests in the components. The effective failures is then determined by the point estimate times the effective test quantity.

Table 1 presents the results of such an analysis. These results are also graphically presented in Figure 4. It is worthwhile here to discuss the interpretation of the display in Figure 4. The nominal point estimate is represented by the slash in the box. The overall uncertainty (allowing the subjectively based paramaeter estimates to be anywhere in their range, combined with 95% statistical confidence bounds on the data-based estimates) is represented by the end marks. If the uncertainty surrounding the data-based estimates were eliminated, the total uncertainty interval would shrink down to the endpoints of the box. If the ranges (uncertainty) around the subjectively determined estimates were eliminated, leaving only the data-based uncertainty, the interval would be given by the "*s".

The incorporation of the estimate for the initiating rate in the uncertainty analysis is just as it was in the previous cases. Table 2 and Figure 5 reflect the total uncertainty on the estimate of the occurrence rate for $B(1.2)D_1C$ including recovery.

Summary

The purpose of this exercise was to demonstrate the feasibility of using the Maximus methodology for calculating statistical confidence bounds for fault tree sequences. The analysis was done incorporating all the factors that will be present in applying the methodology to the La Salle PRA. These factors include a mixture of subjectively-based and data-based estimates and recovery factors, including uncertainty in the recovery factors. When compared to the uncertainty interval generated by placing distributions on all parameters and performing a Monte Carlo analysis, the Maximus methodology produced an upper 95% confidence limit that was in the same range (perhaps a little smaller). An exact comparison is difficult because of the practice of converting uncertainty analysis results to error factors.

In the process of applying the Maximus methodology, an algorithm was developed for the unpooling of data used to estimate several parameters. The unpooling of the data is accomplished in a manner as not to be overly conservative. The algorithm is presented in the appendix. The existing Maximus code was altered during this exercise so there would be no absolute constraints on the size of the system or the number of components (units) that could be input to the Maximus method program.

The Maximus methodology applies to parallel-series configurations. For systems that are more general than parallel-series, the Maximus methodology can be used with some modifications. However, the closer the configuration from the fault tree is to a parallel-series arrangment, the easier it is to implement the Maximus method. For this reason, the expression of the sequences in terms of independent subtrees greatly facilitates the implementation.

Table 1. Combination of Subjective- and Data-Based Uncertainties for Estimate of Probability of D_1C

	Without Recovery	Prob. of Nonrecovery	With Recovery
Nominal point	9.2(-4)	.22	2.0(-4)
$\min_{\omega} f(\underline{\theta}^*, \underline{\omega})$	6.1(-4)	.14	8.5(-5)
$\max_{\omega} f(\underline{\theta}^*, \omega)$	2.3(-3)	.22	5.2(-4)
$\eta_\ell(\omega^*)$	8.3(-5)	.22	1.8(-5)
$\eta_u(\omega^*)$	3.7(-3)	.22	8.1(-4)
based on	1.3 failures/ 1420 tests		1.3 failures/ 6450 tests
L	3.5(-5)	.14	4.8(-6)
based on	1.04 failures/ 1690 tests		1.04 failures/ 12200 tests
U	6.9(-3)	.22	1.5(-3)
based on	2.3 failures/ 980 tests		2.3 failures/ 4450 tests

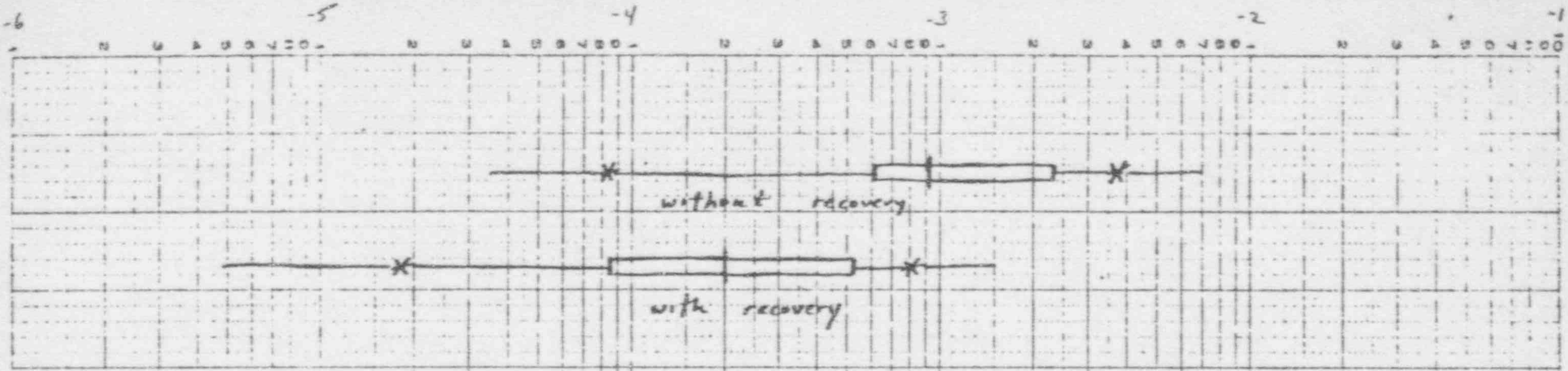


Figure 4. Uncertainty presentation for the D_1C sequence.

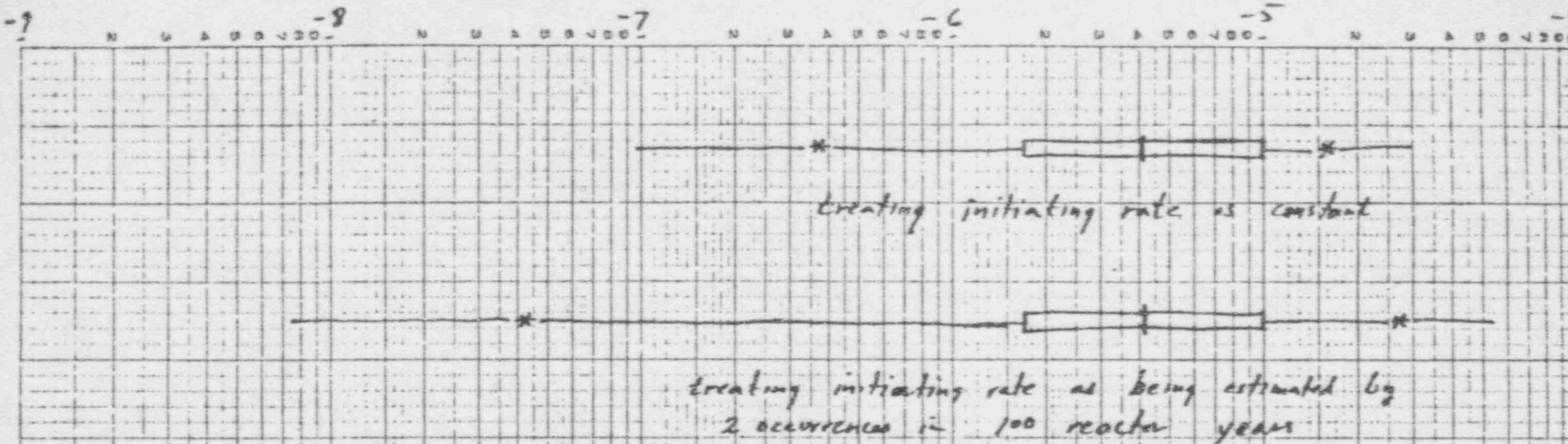


Figure 5.
Total uncertainty presentation for $B(1.2)D_2C$,
(including recovery).

APPENDIX

Data

Table A1 is representation of $B(1.2)D_1C$ in terms of independent subtrees that is given in reference 1. The subtrees are labeled A-O to correspond with the labeling in this paper. Table A2 contains the individual elements that comprise the independent subtrees. Added to the tables are small letter designators (e.g., a, b, v, etc.) for population types. Thus, all events labeled a are considered to be estimated from the same data. In Table A3, the population types are enumerated, with the assumed data also given.

Those population types marked with '*' in Table A3 contain events with different point estimates. A listing of the different point estimates and the resulting T factors are given in Table A4. The T factors are necessary to adjust the equivalent test quantity in the unpooling process. For example, the 206 tests on population type u would be used to estimate a , but in two cases, the parameter applied in the model is /9. When the 206 tests are apportioned between the occurrence of λ and the two occurrences of $\lambda/9$, those quantities used for estimating $\lambda/9$ are increased by a factor of 9. This adjustment properly accounts for the data being used to estimate $\lambda/9$ rather than λ.

Table A1. LOCA Accident Sequence Cut Sets or $B(1.2)D_1C$

Initiating Event: B(1.2)   Initiating Event Frequency: .02/yr

Sequence Identifier: $B(1.2)D_1C$ (Sequence 26 on B(1.2) Event Tree, Figure A-1)

Total Sequence: $B(1.2)\bar{K}\bar{D}_1\bar{Y}C$

	Unavailability	Frequency
Sequence (without recovery)	1.E-3	2.E-5/yr
Sequence (with recovery)	2.2E-4	4.4E-6

Dominant Minimal Cut Sets	Unavailability w/o Recovery	Probability of Non-Recovery	Unavailability w/Recovery
(A) LPI1408B-VCC-LF*LF-SWS-VCH4B (B)	1.9E-4	.01	1.9E-6
(C) LPI1407A-VCC-LF*LF-SWS-VCH4A (D)	1.9E-4	.01	1.9E-6
(E) LF-LPI-L25	1E-4	1.	1E-4
(A) LPI1408B-VCC-LF*LF-SWS-S14 (F)	8.2E-5	.01	8.2E-7
(A) LPI1408B-VCC-LF*LF-SWS-S5 (G)	8.2E-5	.01	8.2E-7
(C) LPI1407A-VCC-LF*LPI1408B-VCC LF (A)	6.7E-5	1.	6.7E-5
(A) LPI1408B-VCC-LF*LF-SWS-S2 (I)	4.1E-5	.05	2.1E-6
(A) LPI1408B-VCC-LF*LF-ECS-ROOM100 (J)	4.1E-5	.01	4.1E-7
(C) LPI1407A-VCC-LF*LF-SWS-S1 (K)	4.1E-5	.4	1.6E-5
(C) LPI1407A-VCC-LF*LF-ECS-ROOM99 (L)	4.1E-5	.01	4.1E-7
(M+N) (LF-RBI-B1+LF-RBI-B9) *LF-HPI-H14 (O) *LF-SWS-VCH4B (B)	1.1E-5	.01	1.1E-7

Table A2

Pipe (or Wire) Segment Local Fault: LPI1408B-VCC-LF (A) System: Low Pressure

Sequence Considered: All denoting D_3, D_2, D_1, or C Critical Time: 15 minutes*

Unavailability w/o Recovery: 8.4E-3 Unavailability w/ Recovery: 1.9E-3

Probability of Non-Recovery: 0.23

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action		q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
LPI1408B-VCC-LF	Y	Local	g	4.1E-3	.25	1.1E-3	4E-3 recoverable, 1E-4 is not
LPI6164-BOO-LF	Y	Local	j	1E-3	.25	2.5E-4	
LPI6164-BOO-CC	Y	Control Room	b	2E-3	.1	2E-4	
6164B-CBL-LF	Y	Local	a	1.1E-3	.25	2.8E-4	
A-LPI-5	--	--		ϵ	--	ϵ	
A-LPI-7	--	--		ϵ	--	ϵ	
ESFU207-UCT-LF	Y	Control Room	c	1E-4	.1	1E-5	
ESFU232-UCT-LF	Y	Control Room	c	1E-4	.1	1E-5	

*For D_3 and D_1, the critical time is <5 min., and P(NR) for them is 1.0. Loss of suction to the HP pumps will fail them is less than 5 minutes.

Table A2
(Continued)

Pipe (or Wire) Segment Local Fault: LF-SWS-VCH4B (B)

System: Emergency Cooling

Sequence Considered: All denoting fault

Critical Time: > 70 minutes

Unavailability w/o Recovery: 2.3E-2

Unavailability w/Recovery: 2.3E-4

Probability of Non-Recovery: 0.01

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
ECSCH4BA-CWV-LF	Y	Local	l 3.7E-3	.01	3.7E-5	For all, recovery action is to manually start portable fans.
5254A-CBL-LF	Y	Local	a 1.1E-3	.01	1.1E-5	
ECS5254A-BOO-LF	Y	Local	j 1E-3	.01	1E-5	
ECS5254A-BOO-CC	Y	Local	b 2E-3	.01	2E-5	
ECS5254A-B-AASF	Y	Local	d 5.4E-3	.01	5.4E-5	
A-ECS-2	Y	Local	o 4.3E-~~3~~4	.01	4.3E-~~5~~6	
A-ECS-15	-	---	ε	---	ε	
SWS608BX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
SWS3900X-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
SWS606BX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
SWS3902X-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
ECS602BX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
ECS604BX-~~XO~~C-LF CC	Y	Local	e 1E-4	.01	1E-6	
ECS601BX-XOC-LF	Y	Local	f 1E-4	.01	1E-6	
ECS6036A-DPC-LF ECS6036A-BPC-LF	Y	Local	g 4.1E-3 4.1E-3	.01	4.1E-5	
ECS600BX-XOC-LF	Y	Local	g e 1E-4	.01	1E-6	
R-HCP-VCH4B-2	Y	Local	u 2E-4	.01	2E-6	
ECS200BX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	

Table A2
(Continued)

Pipe (or Wire) Segment Local Fault: LPI1407A-VCC-LF (C) System: Low Pressure

Sequence Considered: All denoting D_3, D_2, D_1, or C Critical Time: 15 minutes*

Unavailability w/o Recovery: 8.4E-3 Unavailability w/ Recovery: 1.9E-3

Probability of Non-Recovery: 0.23

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
LPI1407A-VCC-LF	Y	Local	g 4.1E-3	.25	1.1E-3	4E-3 recoverable, 1E-4 is not
LPI5164A-BOO-LF	Y	Local	j 1E-3	.25	2.5E-4	
LPI5164A-BOO-LF CC?	Y	Control Room	b 2E-3	.1	2E-4	
5164A-CBL-LF	Y	Local	a 1.1E-3	.25	2.8E-4	
A-LPI-14	--	--	ϵ	--	ϵ	
A-LPI-12	--	--	ϵ	--	ϵ	
ESFU106-UCT-LF	Y	Control Room	c 1E-4	.1	1E-5	
ESFU132-UCT-LF	Y	Control Room	c 1E-4	.1	1E-5	

*For D_3 and D_1, the critical time is <5 min, and the P(NR) for them is 1.0. Loss of suction to the HP pumps will fail them in less than 5 minutes.

Table A2
(Continued)

Pipe (or Wire) Segment Local Fault: LF-SWS-VCH4A (D)

System: Emergency Cooling

Sequence Considered: All denoting fault

Critical Time: > 70 minutes

Unavailability w/o Recovery: 2.5E-2

Unavailability w/Recovery: 2.5E-4

Probability of Non-Recovery: 0.01

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
ECSCH4AB-CWU-LF	Y	Local	l 3.7E-3	.01	3.7E-5	For all, recovery
6254B-CBL-LF	Y	Local	a 1.1E-3	.01	1.1E-5	action is to
ECS6254B-B-AASF	Y	Local	d 5.4E-3	.01	5.4E-5	manually start
ECS6254B-BOO-LF	Y	Local	j 1E-3	.01	1E-5	portable fans.
ECS6254B-BOO-CC	Y	Local	b 2E-3	.01	2E-5	
A-ECS-3	Y	Local	o 4.3E-4	.01	4.3E-6	
R-HCP-VCH4A-3	Y	Local	u 1.8E-3	.01	1.8E-5	
ECS602AX-XOC-F	Y	Local	e 1E-4	.01	1E-6	
ECS604AX-CCC-LF	Y	Local	f 1E-4	.01	1E-6	
ECS601AX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
ECS6034B-DPC-LF	Y	Local	g 4.1E-3	.01	4.1E-5	
A-ECS-14	-	---	ε	--	ε	
ECS600AX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
ECS6034B-~~D~~BPC-LF	Y	Local	g 4.1E-3	.01	4.1E-5	
ECS200AX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
SWS608AX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
SWS3903X-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
SWS606AX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
SWS3905X-XOC-LF	Y	Local	e 1E-4	.01	1E-6	

Table A2
(Continued)

Pipe (or Wire) Segment Local Fault: LF-LPI-L25 (E)

System: Low Pressure

Sequence Considered: All denoting D_1, D_2, D_3, or C

Critical Time: 15 minutes

Unavailability w/o Recovery: 1E-4

Unavailability w/ Recovery: 1E-4

Probability of Non-Recovery: 1

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
LPIOBW1X-XOC-LF	N	--	e 1E-4	1	1E-4	

Table A2
(Continued)

Pipe (or Wire) Segment Local Fault: LF-SWS-S14 (F)

System: Service Water

Sequence Considered: All LOSP

Critical Time: 30 min

Unavailability w/o Recovery: 1E-2

Unavailability w/Recovery: 9.3E-4

Probability of Non-Recovery: 0.09

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
SWS3820A-VOO-LF	Y	Local	g 4E-3	.1	4E-4	
5181A-CBL-LF	Y	Local	a 3.3E-3	.1	3.3E-4	
SWS-5181A-BOO-LF	Y	Local	j 1E-3	.1	1E-4	
SWS-5181A-BOO-CC	Y	Control Room	b 2E-3	.05	1E-4	
ESFU113-UCT-LF	Y	Control Room	c 1E-4	.05	5E-6	

Table A2
(Continued)

Pipe (or Wire) Segment Local Fault: LF-SWS-S5 (G) System: Service Water

Sequence Considered: All LOSP Critical Time: 30 min

Unavailability w/o Recovery: 1E-2 Unavailability w/Recovery: 9.3E-4

Probability of Non-Recovery: 0.09

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
SWS3643A-VOO-LF	Y	Local	g 4E-3	.1	4E-4	
5653A-CBL-LF	Y	Local	a 3.3E-3	.1	3.3E-4	
SWS5653A-BOO-LF	Y	Local	j 1E-3	.1	1E-4	
SWS5653A-BOO-CC	Y	Control Room	b 2E-3	.05	1E-4	
A-SWS-14	-	---	ε	---	ε	

Table A2
(Continued)

Pipe (or Wire) Segment Local Fault: LF-SWS-S2 (I)

System: Service Water

Sequence Considered: All LOSP

Critical Time: 30 minutes

Unavailability w/o Recovery: 5E-3

Unavailability w/Recovery: 4.6E-4

Probability of Non-Recovery: 0.09

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
SWS001BX-COC-LF	--	---	ϵ	---	ϵ	
SWS002BX-COC-LF	--	---	ϵ	---	ϵ	
A-SWS-3	N	---	o 2.2E-4	1	2.2E-4	
SWSOP4BA-PMD-LF	Y	Control Room	l 1.7E-3	.05	8.5E-5	Start standby pump is recovery action
0303-CBL-LF	Y	Control Room	a 1E-4	.05	5E-6	
SWS0303A-BOO-LF	Y	Control Room	j 1E-3	.05	5E-5	
SWS0303A-BOO-CC	Y	Control Room	b 2E-3	.05	1E-4	

Table A2

(Continued)

Pipe (or Wire) Segment Local Fault: LF-ECS-ROOM 100 (J) System: Emergency Cooling

Sequence Considered: All denoting fault Critical Time: > 70 minutes

Unavailability w/o Recovery: 4.9E-3 Unavailability w/Recovery: 4.9E-5

Probability of Non-Recovery: 0.01

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
ECSVC2BA-FAN-LF	Y	Local	k 5.4E-4	.01	5.4E-6	For all, recovery action is to manually start portable fans.
5246A-CBL-LF	Y	Local	a 1.1E-3	.01	1.1E-5	
ECS5246A-BOO-LF	Y	Local	j 1E-3	.01	1E-5	
ECS5246A-BOO-CC	Y	Local	b 2E-3	.01	2E-5	
A-ECS-11	-	---	ϵ	---	ϵ	
ECSC41BX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
ECSC44BX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
ECSC45BX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	

Table A2

(Continued)

Pipe (or Wire) Segment Local Fault: LF-SWS-S1 (K)

System: Service Water

Sequence Considered: All LOSP

Critical Time: 30 minutes

Unavailability w/o Recovery: 5E-3

Unavailability w/Recovery: 2.2E-3

Probability of Non-Recovery: 0.44

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
SWS001CX-COC-LF	--	---	ϵ	—	ϵ	
SWS002CX-COC-LF	--	---	ϵ	--	ϵ	
A-SWS-1	N	---	o 2.2E-4	1	2.2E-4	
SWSOP4CB-PMD-LF	N	---	l 1.7E-3	1	1.7E-3	
0402-CBL-LF	N	---	a 1E-4	1	1E-4	
SWS0402B-BOO-LF	Y	Local	j 1E-3	.1	1E-4	
SWS0402B-BOO-CC	Y	Control Room	b 2E-3	.05	1E-4	

Table A2

Failure Probabilities, With Recovery, of Support System Faults

Pipe (or Wire) Segment Local Fault: LF-ECS-ROOM 99 (L)

System: Emergency Cooling

Sequence Considered: All denoting fault

Critical Time: > 70 minutes

Unavailability w/o Recovery: 4.9E-3

Unavailability w/Recovery: 4.9E-5

Probability of Non-Recovery: 0.01

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
ECSC2DB-FAN-LF	Y	Local	k 5.4E-4	.01	5.4E-6	All subfaults are recoverable by the use of portable fans.
6246B-CBL-LF	Y	Local	a 1.1E-3	.01	1.1E-5	
ECS6246B-BOO-LF	Y	Local	j 1E-3	.01	1E-5	
ECS6246B-BOO-CC	Y	Local	b 2E-3	.01	2E-5	
A-ECS-8	-	---	ϵ	--	ϵ	
ECSC41DX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
ECSC44DX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	
ECSC45DX-XOC-LF	Y	Local	e 1E-4	.01	1E-6	

Table A2

(Continued)

Pipe (or Wire) Segment Local Fault: LF-RBI-B1 + LF-RBI-B9 (M+N)

System: Reactor Building injection/Recirculation

Sequence Considered: All denoting C or F

Critical Time: 70 minutes

Unavailability w/o Recovery: 3.4E-2

Unavailability w/ Recovery: 4.1E-3

Probability of Non-Recovery: 0.12

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
2400B-VCC-LF	Y	Local	g 4.1E-3	.1	5E-4	Crit Time = 30 min, 4E-3 recoverable, 1E-4 is not
6171X-CBL-LF	Y	Local	a 3.3E-3	.1	3.3E-4	
6171X-BOO-LF	Y	Local	j 1E-3	.1	1E-4	
6171X-BOO-CC	Y	Control Room	b 2E-3	.05	1E-4	
A-RBI-5	--	--	ϵ	--	ϵ	
A-1104.05-0	Y	Local	p 1E-3	.03	3E-5	

Table A2

(Continued)

Pipe (or Wire) Segment Local Fault: LF-RBI-B1 + LF-RBI-B9 (Cont.) (M+N)

System:

Sequence Considered:

Critical Time:

Unavailability w/o Recovery:

Unavailability w/ Recovery:

Probability of Non-Recovery:

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
BS48X-CCC-LF	N	--	f 1E-4	1	1E-4	
BW6BX-CCC-LF	N	--	f 1E-4	1	1E-4	
A-RBI-1	N	—	o 2.2E-4	1	2.2E-4	
BS1BX-XOC-LF	N	—	e 1E-4	1	1E-4	
BW5BX-XOC-LF	N	--	e 1E-4	1	1E-4	
0404X-CBL-LF	N	--	a 1.1E-3	1	1.1E-3	
0035B-PMD-LF	N	--	l 1E-3	1	1E-3	
021BX-XOC-LF	N	--	e 1E-4	1	1E-4	
3805B-NCC-LF	Y	Local	✓ 3E-3	.01	3E-5	Crit Time > 70 min

Table A2

(Continued)

Pipe (or Wire) Segment Local Fault: LF-RBI-B1 + LF-RBI-B9 (Cont.) System:
(M+N)

Sequence Considered: Critical Time:

Unavailability w/o Recovery: Unavailability w/ Recovery:

Probability of Non-Recovery:

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
3805B-NCC-CC	Y	Control Room	b 2E-3	.01	2E-5	Crit Time > 70 min
0404B-BOO-LF	Y	Local	j 1E-3	.03	3E-5	
0404B-BOO-CC	Y	Control Room	b 2E-3	.01	2E-5	
U239-UCT-LF	Y	Control Room	c 1E-4	.01	1E-6	
R-HCP-021B-8	Y	Local	u 2E-4	.01	2E-6	Crit Time > 70 min
R-110405-5-21B	Y	Local	t 8E-3	.01	8E-5	Crit Time > 70 min
2B32B-CBL-LF	Y	Local	a 1.1E-3	.03	3.3E-5	
SWS2B32B-BOO-CC	Y	Control Room	b 2E-3	.01	2E-5	
Y02-120-LF	N	--		--		
IEA06BB-TFM-LF	N	--		--		

Table A2

(Continued)

Pipe (or Wire) Segment Local Fault: LF-RBI-B1 + LF-RBI-B9 (Cont.)
(M+N)

System:

Sequence Considered:

Critical Time:

Unavailability w/o Recovery:

Unavailability w/ Recovery:

Probability of Non-Recovery:

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
IEA6143BB-CBL-LF	N	--	ϵ	—	ϵ	
IEA052BB-BCO-LF	Y	--	ϵ	--	ϵ	
IEA6193BB-BCO-LF	Y	--	ϵ	--	ϵ	

Table A2

(Continued)

Pipe (or Wire) Segment Local Fault: LF-HPI-H14 (o)

System: High Pressure

Sequence Considered: All denoting D_3, D_1, or H_1

Critical Time: 60 minutes

Unavailability w/o Recovery: 1.4E-2

Unavailability w/ Recovery: 3.2E-3

Probability of Non-Recovery: 0.23

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
HPIV19CX-CCC-LF	N	--	f 1E-4	1	1E-4	
HPIV20CX-XOC	N	--	e 1E-4	1	1E-4	
A-HPI-4	N	--	o 2E-4	1	2E-4	
A-HPI-5	--	--	ϵ	--	ϵ	
A-HPI-6	--	--	ϵ	--	ϵ	
HPIV18CX-XOC-LF	N	--	e 1E-4	1	1E-4	
HPIP36CB-PMD-LF	N	--	l 1E-3	1	1E-3	
A406B-CBL-LF	N	--	a 1.1E-3	1	1.1E-3	
HPIA406B-BOO-LF	Y	Local	j 1E-3	.05	5E-5	
HPIA406B-BOO-CC	Y	Control Room	b 2E-3	.03	6E-5	

Table A2

(Continued)

Pipe (or Wire) Segment Local Fault: LF-HPI-H14 (Cont.) (o)

System:

Sequence Considered:

Critical Time:

Unavailability w/o Recovery:

Unavailability w/ Recovery:

Probability of Non-Recovery:

Sub-Event Name (See Appendix B)	Is it Recoverable?	Location of Recovery Action	q, w/o Rec.	P(NR)	q, w/ Rec.	Comments
ESFU201-UCT-LF	Y	Control Room	c 1E-4	.03	3E-5	
SWS018CX-XOC-LF	N	--	e 1E-4	1	1E-4	
6214B-CBL-LF	Y	Local	a 1.1E-3	.03	3.3E-5	Recovery time is 60 minutes for rest of sub-events
SWS6214B-BOO-LF	Y	Local	j 1E-3	.03	3E-5	
SWS6214B-BOO-CC	Y	Control Room	b 2E-3	.01	2E-5	
SWS3810B-VCC-LF	Y	Local	g 4.1E-3	.03	1.3E-4	4E-3 recoverable, 1E-4 is not

Table A3. "Population Type" Data

Pop. Type	File No.	Point Estimate	Error Factor	Equiv. Failures	Equiv. Tests	Total Number of Occurrences	Blocks (# Occurrences)
*a	1	3.3(-3)	3	2.20	667	15	A,B,C,D,F,G,I,J,K,L,M+N(3),O(2)
b	2	2.0(-3)	3	2.20	1100	16	A,B,C,D,F,G,I,J,K,L,M+N(4),O(2)
c	3	1.0(-4)	3	2.20	22000	7	A(2),C(2),F,M+N,O
d	4	5.4(-3)	10	.37	69	2	B,D
e	5	1.0(-4)	3	2.20	22000	29	B(8),D(8),E,J(3),L(3),M+N(3),O(3)
f	6	1.0(-4)	3	2.20	22000	5	B,D,M+N(2),O
g	8	4.1(-3)	3	2.20	537	10	A,B(2),C,D(2),F,G,M+N,O
j	11	1.0(-3)	3	2.20	2200	14	A,B,C,D,F,G,I,J,K,L,M+N(2),O(2)
k	12	5.4(-4)	3	2.20	4074	2	J,L
*l	13	3.7(-3)	3	2.20	595	6	B,D,I,K,M+N,O
*o	26	4.3(-4)	3	2.20	5116	6	B,D,I,K,M+N,O
p	28	1.0(-3)	3	2.20	2200	1	M+N
t	40	8.0(-3)	10	.37	46	1	M+N
*u	41	1.8(-3)	10	.37	206	3	B,D,M+N
v	47	3.0(-3)	3	2.20	733	1	M+N

* These types have individual point estimates within the type that differ. See Table A4 for applicable adjustment factors.

Table A4. Population Types With Mixed Point Estimates With Appropriate Test Factors

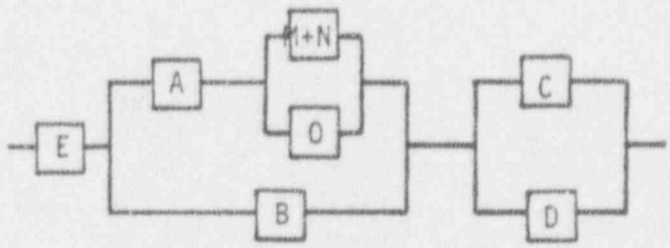
Pop. Type	Point Estimates--Blocks of Occurrence: Base	Point Estimates--Blocks of Occurrence: Other	T Factor
a	3.3(-3) F,G,M+N	1.1(-3) A,B,C,D,J,L,M+N(2),O(2)	3
		1(-4) I,K	33
	3.7(-3) B,D	1.7(-3) I,K	2.2
		1(-3) M+N,O	3.7
o	4.3(-4) B,D	2.2(-4) I,K,M+N	1.95
		2(-4) O	2.15
u	1.8(-3) D	2(-4) B,M+N	9

Unpooling Algorithm

The proposed unpooling scheme unpools each of the data-type populations, compares the test quantities that result to the existing unpooled types, makes adjustments in the current type if necessary, and then moves to the next data type. The process is elaborated on here and illustrated using the D_1C sequence and data from the main report.

Step 1. The system under consideration is broken into series subsystems for which an equivalent test quantity will be recorded and updated with the addition of each population type. Initially, the equivalent test quantity for each subsystem is treated as missing or unassigned. Also calculated at this step is the failure probability for each subsystem. Three values will be used for unpooling purposes.

Example. For the $B(1.2)D_1C$ sequence, the system to be considered is given in Figure A1. The blocks are labeled with the leading block label used in the body of the report.



Point Estimates

A - 8.38(-3)
B - 5.24(-2)
C - 8.38(-3)
D - 3.40(-2)
E - 1.00(-4)
M+N - 3.31(-2)
O - 1.39(-2)

B includes B,F,G,I,J from Figure 2
D includes D,K,L from Figure 2

Figure A1. Overall system in terms of branches for which equivalent test quantities are needed.

Step 2. All data types that appear only once in the total system are assigned and the minimum test quantity for each segment is recorded.

Example. Population types p, t, and v occur singly, all in the M+N branch. Therefore, branch M+N now has a minimum test quantity of 46 from the component of type t.

Step 3. All the data types that have more than one occurrence are ordered according to the number of tests divided by the sum of the reciprocals of the T factors for each occurrence. This represents the quantity that will apply to each occurrence of a population type if a split is done to make each occurrence have the same amount of applicable data. This ordering will be used for purposes of unpooling.

Example. For the $B(1.2)D_1C$ sequence, the ordering is d, g, b, a, u, j, , e, o, k, c, and f. Population type d is considered first as there are, in general, less "data" for each of the occurrences (69/2 = 34.5). Population type g is next with approximately (537/10 =) 53.7 test quantities that can be assigned to each occurrence. Notice that for type a, 10 of the unpooled values will be times a factor of 3, 2 will be times a factor of 33, and 3 will be at the base value (factor of 1). Thus, to unpool so that every occurrence has the same amount of data, the 667 test quantity is divided by $10 \cdot 1/3 + 2 \cdot 1/33 + 3 = 6.39$, to give 104.3 tests to each occurrence.

Step 4. The individual population types are unpooled for each population type in the order determined by step 3. The unpooling is done in such a way as to maximize the effective overall test quantity incorporating the given component with the already unpooled data and the minimum test quantities that apply to each subsystem. Subsystems that have no minimum test quantities as yet assigned are treated as constants.

Example 1. Population type d is the first type to be unpooled, as determined from step 3. Only the subsystem M+N has a test quantity associated with it from the data types with a single occurrence considered in step 2. Considering the point estimate for subsystem O as a constant, the test size of 46 from M+N is equivalent to a test size of 3309 (= 46/1.39(-2)) for the system of M+N in parallel with O. The test size of 3309 would then also apply to the whole subsystem containing A, M+N, and O. If n of the 69 tests on population type d were assigned to the occurrence in subsystem B, then the equivalent test quantity for that combination would be given by 8.84(-3) x 3309 = 29.3 failures in 3309 tests combined in parallel with 5.24(-2) · n failures in n tests. The effective test quantity for the other parallel branch is (69 - n)/8.38(-3) since subsystem C is treated as a constant. Since the effective test quantity increases with n in the first case and decreases with n in the second, the minimum of the two will be maximized when the two expressions above are equal. This occurs when n = 35.7, therefore, population type d is unpooled by considering 35.7 tests in subsystem B and 33.3 tests in subsystem D. The equivalent test quantities are now 3309 for M+N, 35.7 for B, and 33.3 for D. The rest of the subsystems would still be considered as constants (having no equivalent test quantities).

Example 2. It will be instructive to also consider the next population type g here at step 4. There are occurrences of population type g in all but subsystem E. There are single occurrences of type g in subsystems A, M+N, O, and C and there are four occurrences in subsystem B and two occurrences in subsystem D. Let n_A, n_B, ... denote the unpooled test quantity for subsystems A, B, ... The total test quantity is 537, and thus, we want to assign the test quantities such that $n_A + n_{M+N} + n_O + n_C + 4 \cdot n_B + 2 \cdot n_D = 537$, and the overall equivalent system test size is maximized. At this stage, we are not concerned with the equivalent test quantities that have already been assigned to the subsystems in which population type g appears. We perform the optimization problem for g and then compare the equivalent test quantities for g alone to those already assigned and make appropriate adjustments in step 5. The solution of the problem for allocating g is $n_A = 168.4$, $n_B = 35.4$, $n_C = 109.6$, $n_D = 42.6$, $n_{M+N} = 14.5$, and $n_O = 17.7$, with an equivalent system test size of 1450.

A specific method for solving the above problem is not being recommended. The above solution was obtained by programming the Maximus rules for parallel systems on a desk calculator and iterating intelligently to obtain the solution.

Notice in the solution for g that $n_D = 42.6$, but from the unpooling of population type d, the equivalent test size for subsystem D was 33.3. This difference forms the basis for the next step.

Step 5. If, for a specific population type in step 4, any of the equivalent tests for a subsystem exceed the equivalent test quantity already assigned to that subsystem and there is some other subsystem in which the current population type is minimum, then rework step 4, but first allocating the existing equivalent test size to those subsystems where this value was less than that calculated in step 4.

Example. In step 4 for population type g $n_D = 42.6$, which exceeds the existing test size of subsystem D of 33.3 and in all the other subsystems the assignment from type g is the minimum. Therefore, n_D is set to 33.3 and the allocation of the remaining $537 - 2(33.3) = 470.4$ is done for population type g as was done originally in step 4. The result of this step is that $n_A = 163.3$, $n_B = 35.7$, $n_C = 131.9$, $n_D = 33.3$, $n_{M+N} = 14.6$, and $n_O = 17.8$. These are the values used in the overall analysis and are reflected in the allocations of Figure 3.

Step 6. Return to step 4 (and 5) for the next population type.

For all the remaining population types in the example followed, the effective numbers for each branch all exceed that assigned in determining the allocation for type g. Therefore, the combination of data types d and g determine effective quantities for each branch.

The unpooling algorithm as presented is meant to give the flavor of a systematic way to look at the unpooling question. The algorithm has not been completely defined in that the method of optimization for steps 4 and 5 is not specified. In practice, a stepwise method may be the easiest to implement. The different population types that determine the equivalent test quantities may interact to such an extent that the whole procedure would have to be reapplied. For example, in the D_1C case considered here, population types d and g are the determining population types. However, the first time through the algorithm the d population was unpooled assuming some of the subsystem branches were constant. Once population type g was unpooled, one would need to reexamine the unpooling of type d again, and so on between the two, in order to converge to an "optimal" unpooling.

In the case worked here, an equivalent system test quantity of 1427 was obtained, but it is known from g alone that 1450 is an upper bound. Thus, the iterations between population types d and g seemed unnecessary.

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