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Revision 1

AN EVALUATION OF CABLE DAMAGE SUSCEPTIBILITY FROM PULLBY EVENTS AT THE WATTS BAR NUCLEAR PLANT

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Table 3-8. Pullby SWBP Screening Values, Voltage Level: V1/V2, Final Conduit Fill: 60%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	408	1,020	2,040	3,060	4,080	6,119
1.0	0.50	638	1,595	3,190	4,785	6,381	9,571
1.5	0.33	671	1,678	3,356	5,034	6,712	10,068
2.0	0.25	689	1,724	3,447	5,171	6,895	10,342
2.5	0.25	945	2,362	4,725	7,087	9,450	14,174
3.0	0.25	1,164	2,909	5,819	8,728	11,638	17,456
4.0	0.20	1,288	3,220	6,440	9,661	12,881	19,321
5.0	0.20	1,336	3,340	6,680	10,020	13,361	20,041

Table 3-9. Pullby SWBP Screening Values, Voltage Level: V3, Final Conduit Fill: 10%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	22	55	111	166	221	332
1.0	0.50	26	65	130	195	259	389
1.5	0.33	28	71	142	212	283	425
2.0	0.25	32	80	160	240	320	481
2.5	0.25	41	104	207	311	415	622
3.0	0.25	53	133	266	399	532	799
4.0	0.20	59	149	297	446	595	892
5.0	0.20	61	152	303	455	606	910

Table 3-10. Pullby SWBP Screening Values, Voltage Level: V3, Final Conduit Fill: 20%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	44	111	221	332	442	664
1.0	0.50	52	130	259	389	519	778
1.5	0.33	57	142	283	425	566	849
2.0	0.25	64	160	320	481	641	961
2.5	0.25	83	207	415	622	830	1,244
3.0	0.25	106	266	532	799	1,065	1,597
4.0	0.20	119	297	595	893	1,190	1,785
5.0	0.20	121	303	606	910	1,213	1,819

Table 3-11. Pullby SWBP Screening Values, Voltage Level: V3, Final Conduit Fill: 30%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	66	166	332	498	664	995
1.0	0.50	78	195	389	584	778	1,168
1.5	0.33	85	212	425	637	849	1,274
2.0	0.25	96	240	481	721	961	1,442
2.5	0.25	124	311	622	933	1,244	1,866
3.0	0.25	160	399	799	1,198	1,597	2,396
4.0	0.20	178	446	892	1,339	1,785	2,677
5.0	0.20	182	455	910	1,365	1,819	2,729

Table 3-12. Pullby SWBP Screening Values, Voltage Level: V3, Final Conduit Fill: 40%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	88	221	442	664	885	1,327
1.0	0.50	104	259	519	778	1,038	1,557
1.5	0.33	113	283	566	849	1,132	1,698
2.0	0.25	128	320	641	961	1,282	1,923
2.5	0.25	166	415	830	1,244	1,659	2,489
3.0	0.25	213	532	1,065	1,597	2,130	3,194
4.0	0.20	238	595	1,190	1,785	2,380	3,570
5.0	0.20	243	606	1,213	1,819	2,426	3,639

Table 3-13. Pullby SWBP Screening Values, Voltage Level: V3, Final Conduit Fill: 50%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	204	511	1,022	1,532	2,043	3,065
1.0	0.50	240	599	1,198	1,797	2,397	3,595
1.5	0.33	261	654	1,307	1,961	2,615	3,922
2.0	0.25	296	740	1,480	2,220	2,960	4,440
2.5	0.25	383	958	1,916	2,873	3,831	5,747
3.0	0.25	492	1,229	2,459	3,688	4,918	7,376
4.0	0.20	550	1,374	2,748	4,121	5,495	8,243
5.0	0.20	560	1,401	2,801	4,202	5,602	8,403

Table 3-14. Pullby SWBP Screening Values, Voltage Level: V3, Final Conduit Fill: 60%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	600	1,501	3,001	4,502	6,003	9,004
1.0	0.50	704	1,760	3,521	5,281	7,041	10,562
1.5	0.33	768	1,920	3,841	5,761	7,682	11,523
2.0	0.25	870	2,174	4,348	6,522	8,696	13,044
2.5	0.25	1,126	2,814	5,628	8,442	11,256	16,884
3.0	0.25	1,445	3,612	7,224	10,836	14,448	21,672
4.0	0.20	1,615	4,036	8,073	12,109	16,145	24,218
5.0	0.20	1,646	4,115	8,229	12,344	16,459	24,688

Table 3-15. Pullby SWBP Screening Values, Voltage Level: V4, Final Conduit Fill: 10%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	15	38	76	114	151	227
1.0	0.50	17	43	86	128	171	257
1.5	0.33	24	61	122	183	244	366
2.0	0.25	26	66	132	198	264	397
2.5	0.25	34	85	169	254	338	507
3.0	0.25	47	117	234	351	469	703
4.0	0.20	51	128	256	384	512	768
5.0	0.20	52	129	259	388	517	776

Table 3-16. Pullby SWBP Screening Values, Voltage Level: V4, Final Conduit Fill: 20%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	30	76	151	227	303	454
1.0	0.50	34	86	171	257	343	514
1.5	0.33	49	122	244	366	488	731
2.0	0.25	53	132	264	397	529	793
2.5	0.25	68	169	338	507	677	1,015
3.0	0.25	94	234	469	703	937	1,406
4.0	0.20	102	256	512	768	1,025	1,537
5.0	0.20	103	259	517	776	1,034	1,552

Table 3-17. Pullby SWBP Screening Values, Voltage Level: V4, Final Conduit Fill: 30%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	45	114	227	341	454	681
1.0	0.50	51	128	257	385	514	771
1.5	0.33	73	183	366	549	731	1,097
2.0	0.25	79	198	397	595	793	1,190
2.5	0.25	101	254	507	761	1,015	1,522
3.0	0.25	141	351	703	1,054	1,406	2,109
4.0	0.20	154	384	768	1,153	1,537	2,305
5.0	0.20	155	385	776	1,164	1,552	2,327

Table 3-18. Pullby SWBP Screening Values, Voltage Level: V4, Final Conduit Fill: 40%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	61	151	303	454	606	908
1.0	0.50	69	171	343	514	685	1,028
1.5	0.33	98	244	488	731	975	1,463
2.0	0.25	106	264	529	793	1,058	1,587
2.5	0.25	135	338	677	1,015	1,353	2,030
3.0	0.25	187	469	937	1,406	1,875	2,812
4.0	0.20	205	512	1,025	1,537	2,049	3,074
5.0	0.20	207	517	1,034	1,552	2,069	3,103

Table 3-19. Pullby SWBP Screening Values, Voltage Level: V4, Final Conduit Fill: 50%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	140	350	699	1,049	1,398	2,098
1.0	0.50	158	396	791	1,187	1,582	2,373
1.5	0.33	225	563	1,126	1,689	2,252	3,378
2.0	0.25	244	611	1,221	1,832	2,443	3,664
2.5	0.25	312	781	1,562	2,343	3,124	4,687
3.0	0.25	433	1,082	2,164	3,247	4,329	6,493
4.0	0.20	473	1,183	2,366	3,549	4,732	7,098
5.0	0.20	478	1,194	2,389	3,583	4,777	7,166

Table 3-20. Pullby SWBP Screening Values, Voltage Level: V4, Final Conduit Fill: 60%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	411	1,027	2,054	3,082	4,109	6,163
1.0	0.50	465	1,162	2,324	3,487	4,649	6,973
1.5	0.33	662	1,654	3,308	4,962	6,616	9,924
2.0	0.25	716	1,794	3,588	5,382	7,176	10,764
2.5	0.25	918	2,295	4,590	6,885	9,180	13,769
3.0	0.25	1,272	3,180	6,359	9,539	12,718	19,077
4.0	0.20	1,390	3,476	6,951	10,427	13,903	20,854
5.0	0.20	1,404	3,509	7,018	10,527	14,035	21,053

Table 3-21. WBNP Conduit Sorting Criteria, Voltage Level: V1 and V2, Damage Susceptibility Group: A		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75	0-14.99	All
	15-24.99	0-75
	25-34.99	0-50
	35-44.99	0-25
	45-54.99	0-10
1.0, 1.5, 2.0	0-14.99	0-100
	15-24.99	0-50
	25-44.99	0-25
	45-54.99	0-10
2.5	0-14.99	0-75
	15-34.99	0-25
	35-44.99	0-10
3.0, 4.0, 5.0	0-14.99	0-50
	15-24.99	0-25
	25-44.99	0-10

6-11. Analysis Results for Voltage Level V3 Susceptibility Group K 6-15
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EXECUTIVE SUMMARY

THE PROBLEM

Tennessee Valley Authority (TVA) has evidence to suggest that there may be pullby damage to some of the cables in some of the conduits at the Watts Bar Nuclear Plant (WBNP). This evidence consists of two types:

1. Employee allegations of poor installation practices by certain crews and poor quality assurance practices by certain inspectors.

2. In a sample of 37 conduits from which the cables were removed and inspected, 4 conduits were found to contain pullby-damaged cables.

The first of these can be thought of as "soft," "judgmental," or "indirect" evidence. The second is "hard" or "direct," statistical sampling-type of evidence. Since the conduits in question are Class 1E, safety-related, the two categories of evidence, taken together, are sufficient to diminish confidence in the safety of the plants. There are approximately 10,000 Class 1E conduits in the plant. Therefore, there are significant incentives to develop an evaluation program that increases confidence in the safety of the plant without physically inspecting or replacing all cables contained in these conduits.

THE APPROACH

The answer that suggests itself is to view each conduit as a point in the plane formed by the two coordinate axes, likelihood and consequences, as shown in Figure 1. "Likelihood" here means the likelihood that the conduit contains pullby-damaged cables, as governed by physical factors such as length of conduit, percentage of fill, number of cables, number of bends, etc. "Consequence" means the impact on plant safety as measured, for example, by the increase in core melt frequency if the conduit does, in fact, contain damaged cables. With the coordinate axes established this way, points that are high and to the right are of greatest concern, as shown.

The basic idea of this approach then is to set up a gridwork against these coordinate axes, as shown in Figure 2. For each grid box, two questions are asked:

1. How many conduits fall in that box?
2. Of the conduits in that box, what fraction contain pullby damage?

Based on the answers to these questions, decisions can then be made about what to do with the conduits in each grid box.

THE DECISION

As part of the basic idea of the approach, it was originally anticipated that a "principle of triage" would emerge in which it would be concluded that cables installed in the conduits falling in grid boxes to the upper right should be replaced; those falling to the lower left should be accepted as-is; and those intermediate should be studied further through additional

sampling. As it turned out, based on the numerical answers to questions 1 and 2 above, and considering the high cost of further sampling, it was decided to also replace all cables installed in the conduits which were, in the final assessment, determined to be in the moderate category. It also turned out to be quite labor-intensive to establish the consequence categories reflected in the grid, and these results were not readily available in the time frame of this study. Therefore, it was decided to replace all cables in those conduits that were high or moderate on the likelihood axis, without attempting to reduce the number of these conduits on the basis of small consequence.

As it turned out further, the remaining conduits in the low likelihood category, with the exception of one group of 51 conduits, all satisfied TVA engineering criteria for sidewall pressure. The decision was made to evaluate this group of conduits as part of the moderate likelihood category. The net result of these decisions is that all conduits that are accepted as currently installed are both low on the likelihood axis and satisfy the engineering sidewall pressure criteria. All cables in the remaining conduits will be replaced.

IMPLEMENTATION OF THE APPROACH—ESTABLISHING SUSCEPTIBILITY CATEGORIES

To implement the above approach, the voltage level and sidewall bearing pressure were adopted as the key parameters indicating the susceptibility of the conduits to pullby damage. For these parameters, categories of conduits were established, as shown in Tables 1 and 2. Thus, category KV3 denotes all of those conduits containing V3 cables that experienced calculated sidewall pressures greater than 2,000 lb/ft during the pullby operations.

FINDING THE DAMAGE LIKELIHOOD FOR THE SUSCEPTIBILITY CATEGORIES

For each susceptibility category, the following question is now asked:

> Out of all conduits in this category, what fraction contain cables with pullby damage under the assumed conditions?

These fractions are denoted by f_c where c is the category name. Thus, for example, f_{KV3} is the fraction of conduits in category KV3 that contain pullby damage. The question now becomes:

> What are the numerical values of the parameters f_c?

To answer this question, there are two categories of evidence:

E_0 = the engineering judgments of two experts in cable pulling.

E_1 = statistical evidence from the sample of 37 examined conduits.

The procedure will be to combine these two kinds of evidence, using Bayes' theorem, to obtain the final answers in the form of probability curves against the possible numerical values of the f_c.

To carry out this procedure, each of the two experts was first asked to give his estimates for the likelihood of pullby damage in each susceptibility category. These estimates were

documented in terms of probability curves to account for the experts' uncertainties. These curves express the state of knowledge of the experts about the true value of f_c. As an example, Figure 3 shows the curves of the two experts for category KV3.

These curves are saying that, for this conduit category, if the assumed conditions exist, both experts expect that almost all conduits that had pullby operations will contain damaged cables.

In Figure 4, the curves from the two experts are combined to form what is called the "prior" distribution, $p(f_{KV3}|E_0)$. The next step is to update this distribution with the E_1. For category KV3, the evidence E_1 was that, in a sample of six conduits, only one contained pullby damage. This evidence changes the state of knowledge from the prior $p(f_{KV3}|E_0)$ to the "posterior" distribution $p(f_{KV3}|E_0, E_1)$ as shown in Figure 5.

This posterior distribution then represents the final state of knowledge about the defect fraction f_{KV3}.

RESULTS

Posterior curves similar to that of Figure 5 were developed for each of the susceptibility categories. The results are tabulated in Table 3 in the form of percentiles and mean values for the posterior curves for each susceptibility category.

As can be seen in this table, the conduits fall naturally into high, moderate, and low groups. All categories in the low group, with the exception of IV4, also satisfy the TVA engineering criteria for sidewall pressure. Therefore, the decision was made to replace all cables installed in conduits whose final categorization is high or moderate and to evaluate the conduits in group IV4 with the moderate category. All remaining conduits will then not only be in the low likelihood group but also will satisfy the engineering sidewall pressure criteria.

Table 1. WBNP Cable Categories	
Voltage Level	**Cable Characteristics**
V1	Shielded, Instrumentation
V2	Most Are Shielded, Instrumentation
V3	Unshielded, Control and Control Power
V4	Unshielded, Low Voltage Power
V5	Shielded, Medium Voltage Power

Table 2. Sidewall Bearing Pressure Ranges Used To Define Conduit Damage Susceptibility Groups		
Voltage Level	**Group**	**Sidewall Bearing Pressure (lbf)**
V1/V2	A	< 300
	B	300 - 500
	C	500 - 1,000
	D	1,000 - 1,500
	E	1,500 - 2,000
	F	> 2,000
V3/V4	G	< 500
	H	500 - 1,000
	I	1,000 - 1,500
	J	1,500 - 2,000
	K	> 2,000

Table 3. Pullby Damage Likelihood Categories and 80% Confidence Interval Parameters for Final Updated Probability Distributions

LIKELIHOOD OF DAMAGE	VOLTAGE LEVEL	UPDATED PROBABILITY DISTRIBUTIONS FOR CONDITIONAL FREQUENCY OF DAMAGE				
		SUSCEPTIBILITY GROUP	10TH PERCENTILE	50TH PERCENTILE	90TH PERCENTILE	MEAN
LOW	V4	G	0	.0001	.0035	.0026
	V1 AND V2	A	0	.0001	.0035	.0026
	V3	G	0	.0001	.0047	.0035
	V4	H	0	.0001	.0074	.0044
	V1 AND V2	B	0	.0004	.025	.010
	V4	I	0	.0007	.047	.019
	V3	H	0	.0005	.050	.022
MODERATE	V4	J	.0001	.011	.17	.060
	V3	I	0	.0030	.25	.073
	V1 AND V2	D	.022	.11	.31	.16
	V1 AND V2	C	.019	.17	.33	.19
HIGH	V3	K	.17	.29	.49	.33
	V3	J	.0064	.58	.95	.54
	V4	K	.30	.59	.87	.61
	V1 AND V2	E	.48	.72	.88	.73
	V1 AND V2	F	.59	.84	.90	.82

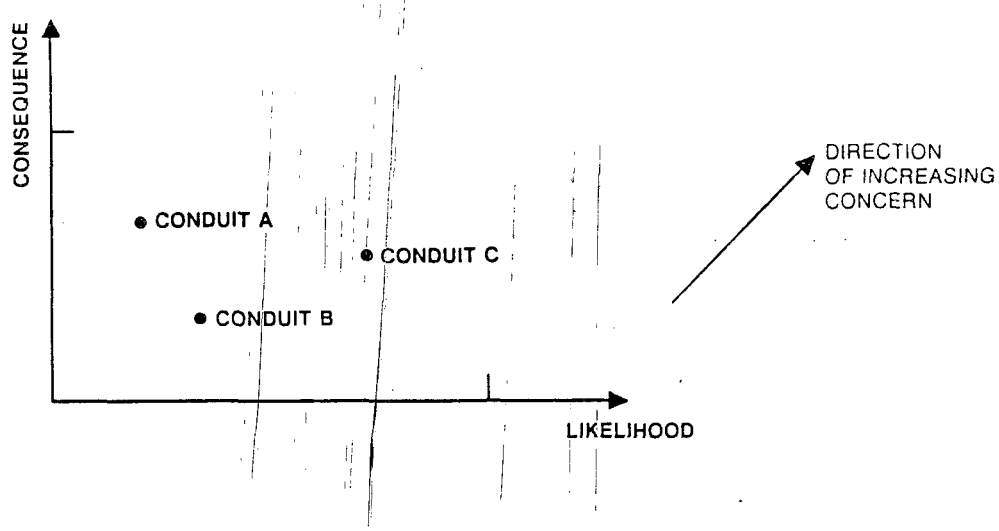

Figure 1. Individual Conduits Represented as Points in a Coordinate Plane

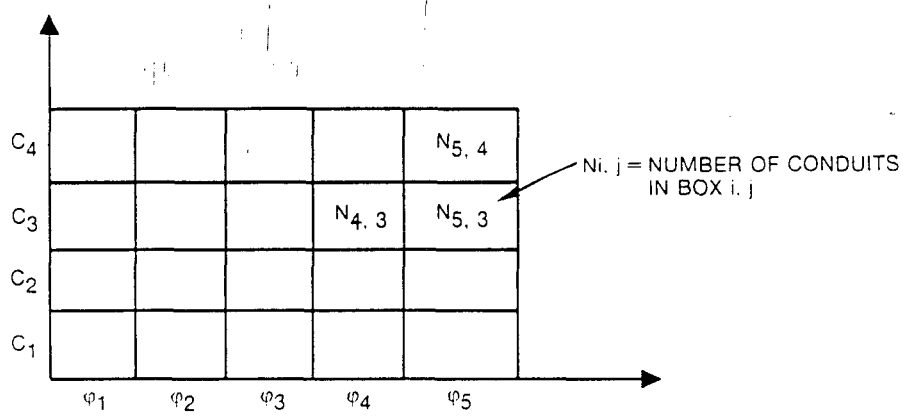

Figure 2. Grid Established by Likelihood and Consequence Categories

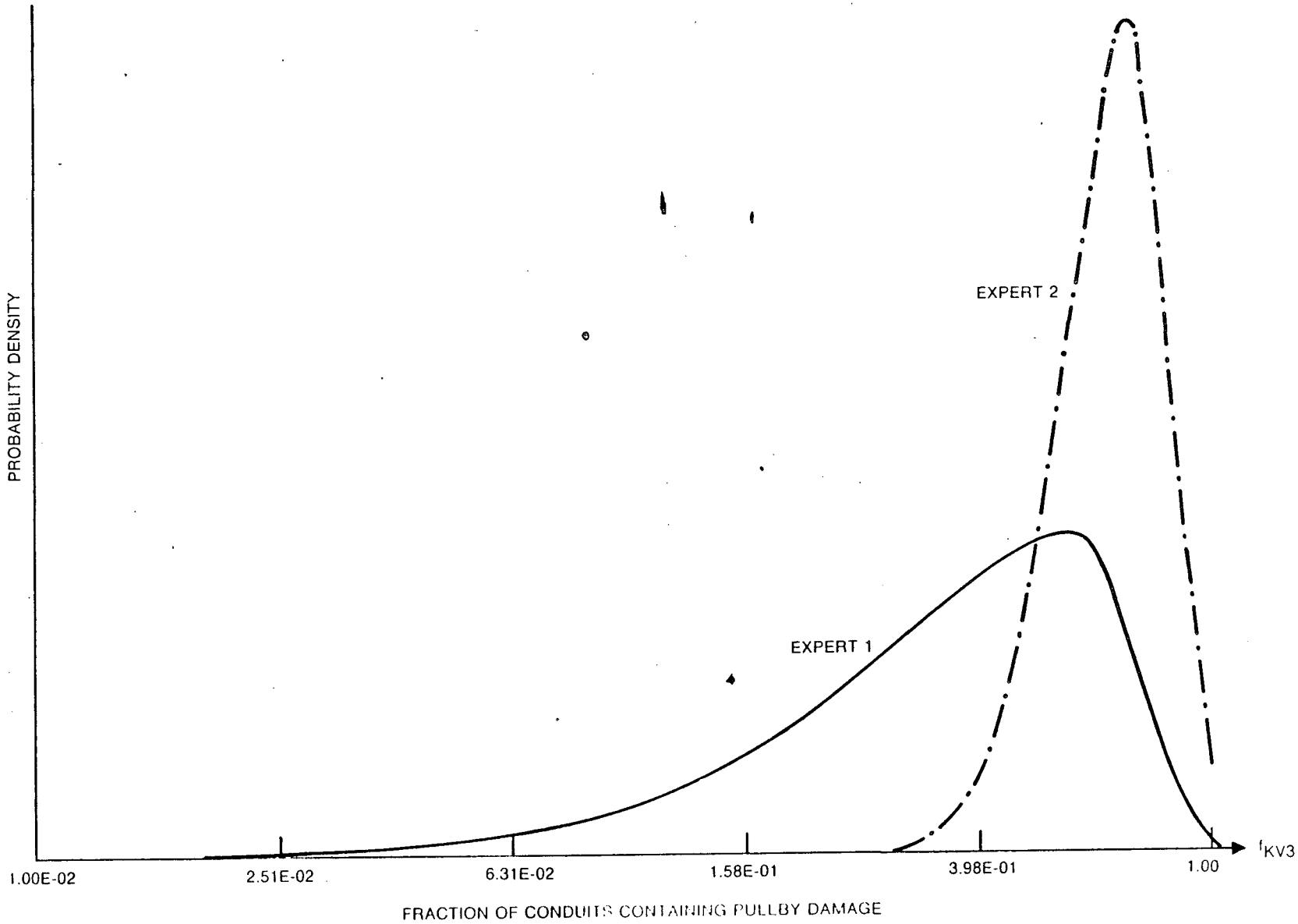

Figure 3. State-of-Knowledge Probability Distributions for the Parameters f_{KV3} As Obtained from Experts 1 and 2

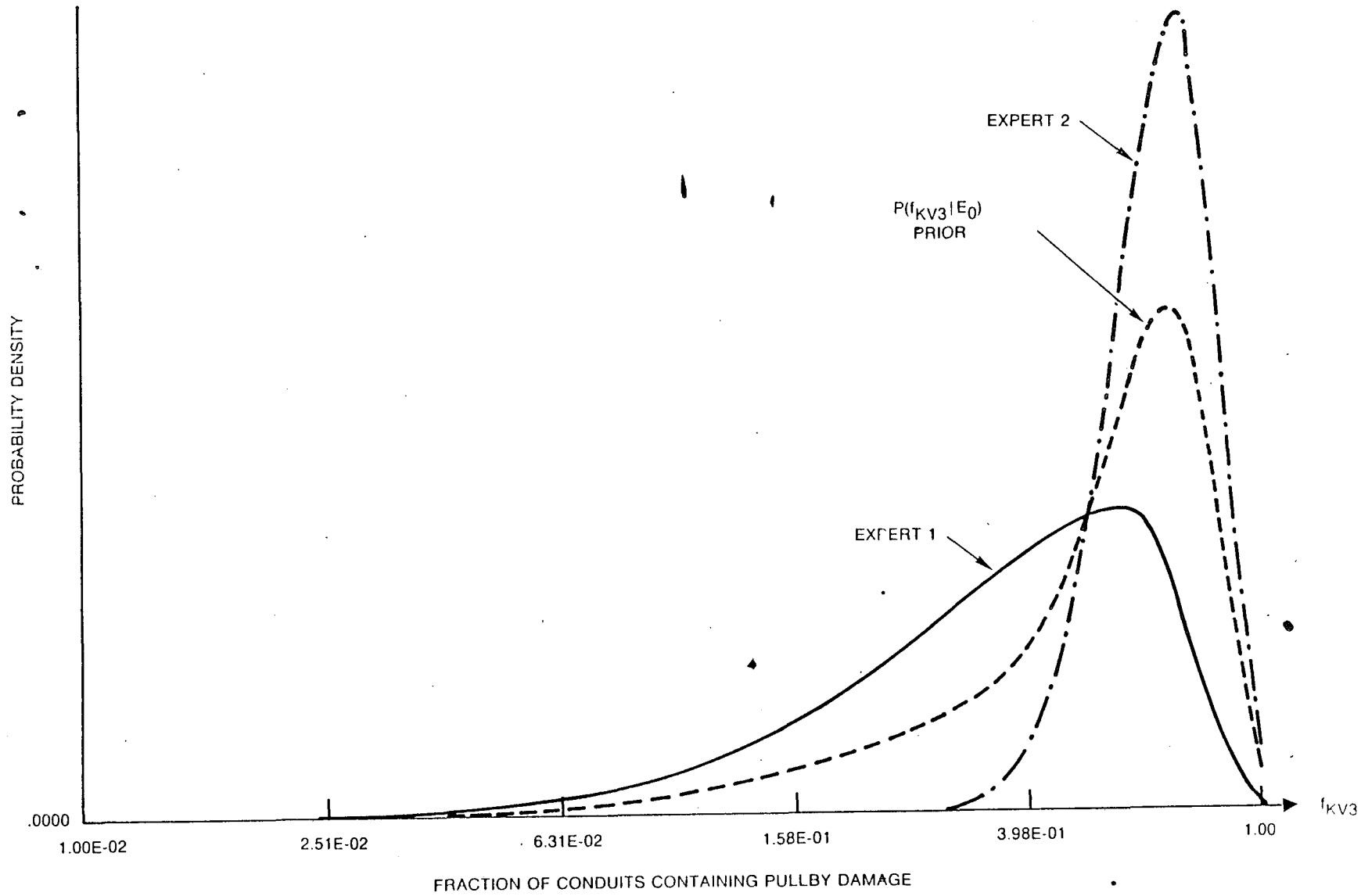

Figure 4. Merging of Two Expert Curves into the Prior Distribution

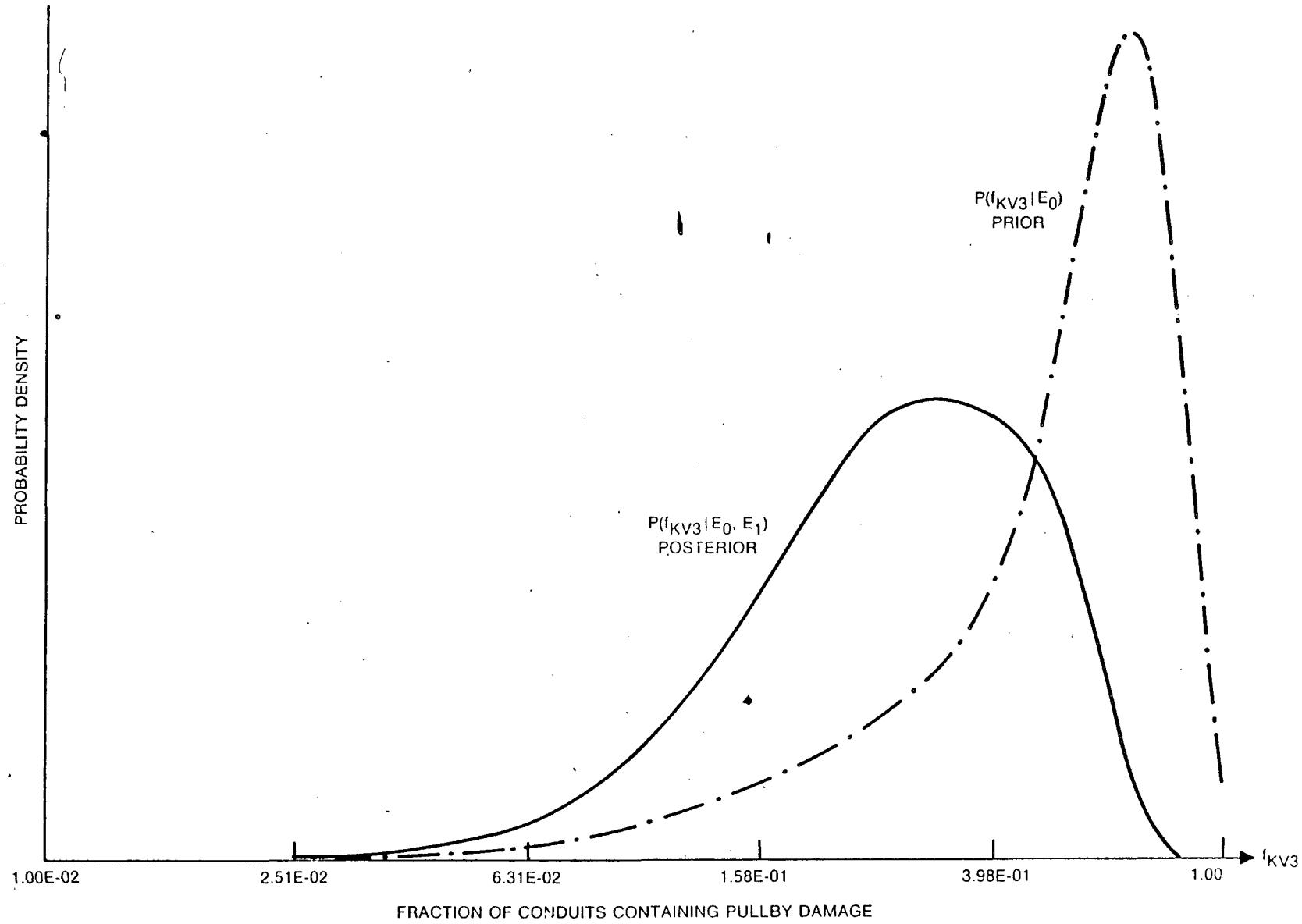

Figure 5. Bayesian Update of Distribution for f_{KV3} Using Evidence E_1

1. INTRODUCTION

As part of a comprehensive evaluation of issues related to the quality of cable installation at the Watts Bar Nuclear Plant (WBNP), the Tennessee Valley Authority (TVA) contacted PLG for assistance in the analysis of cable damage caused by pullby events in safety-related conduits. This report describes the methodology and analytical framework that were developed to organize the evaluation process. It also documents the probabilistic treatment of technical information supplied by experts in the field, the assessment of available sample data, and the results from these analyses. Additional background information about the general issues of cable installation at WBNP and the specific circumstances that led to this study is available in other TVA reports.

The analyses in this study are focused specifically on the development of a set of probability distributions for the likelihood of cable damage at WBNP caused by pullby events in Class 1E safety-related conduits. The technical causes for pullby damage and specific characteristics of the WBNP cable installation process are fundamentally embedded in all analyses performed in this study. Therefore, none of the prior probability distributions, sample data, or results should be used for conclusions about any other cable issue at WBNP. Furthermore, it is recommended that these analyses not be applied for other plant installations without careful understanding of their underlying bases and their relevance to the specific plant being examined.

Sample data were gathered from selected conduits and cables in both Unit 1 and Unit 2 at WBNP. The prior and updated probability distributions use the merged data from both units. Therefore, they apply equally to Unit 1, common, and to Unit 2 cable installations. However, to facilitate input for the Unit 1 licensing process, the final summary information is characterized for applicability to those safety-related conduits and cables required to support safe shutdown of Unit 1.

2. EVALUATION METHODOLOGY

The evaluation methodology for this study is derived from basic principles of statistical inference and probabilistic risk assessment. The first step in the process is the development of a framework that provides a logical structure for optimizing decisions. The goal is to define a systematic cable inspection and replacement program that provides confidence that WBNP can be operated safely and that minimizes unnecessary time and expense for replacement of undamaged cables. It was decided early in the study to focus the analyses at the level of conduit sections rather than on individual cables. Results from preliminary sampling activities and examinations of damaged cables indicated that the most likely causes for damage were pullby events that are related to conduit geometry and general installation practices rather than specific characteristics of the cables themselves.

There are two fundamental reasons for eliminating a particular conduit from further examination:

1. The likelihood that the conduit contains a damaged cable is sufficiently small.

2. The consequences to plant safety are sufficiently small, even if the conduit contains a damaged cable.

To provide a formal structure for the decision process, it is necessary to quantify, or prioritize, these two parameters for each WBNP conduit. A significant amount of information is available to support this quantification effort without physically removing cables from the conduits. For example, the likelihood that a cable was damaged during installation in a particular conduit is determined by such factors as the number of pullby events, percentage of conduit fill, number of cables in the conduit, length and diameter of the conduit, total degrees of bend in the conduit run, type and size of the cables, cable jacket material, lubrication, installation practices, etc. The devices that are connected to each cable in the conduit can also be examined within the quantitative framework of a formal probabilistic risk assessment to determine their relative impacts on the frequency of core damage and offsite releases.

Figure 2-1 shows the basis of the conceptual structure for this analysis framework. The quantified values for cable damage likelihood and plant safety consequences determine the location of each conduit in the coordinate plane defined by these axes. If each parameter is normalized, the entire population of conduits is distributed over a rectangle in this space, as shown in Figure 2-2. Families of "isoconcern contours" can be defined to further guide the conduit evaluation process. Thus, in Figure 2-2, conduits that fall into the upper right corner of the rectangle present the highest level of concern; they have a relatively high likelihood of containing damaged cables, and those cables are very significant to plant safety. Conduits in the lower left corner of this space are of relatively low concern; they are not likely to contain damaged cables, and the safety consequences from those cables are minimal.

The "isoconcern contours" can be used to define thresholds for further conduit examination. For example, it may be most prudent to replace all cables in conduits that fall above a contour that represents high concern. For conduits that fall within levels of moderate concern, a structured sampling program may be warranted to gain more information about the actual frequency of cable damage and the specific damage mechanisms. Rather limited sampling may be indicated for conduits that fall into areas of low concern.

As a practical consideration, it is often more efficient to begin this structuring process by defining categories, or groups, of likelihood and consequence values. These categories effectively subdivide the continuous space within the rectangle shown in Figure 2-2 into a grid. The category bounds acknowledge the uncertainties in estimating precise numerical values for both the likelihood and the consequences from cable damage. They also recognize that practical decisions cannot be made on the basis of detailed individual conduit-by-conduit numerical comparisons. Figure 2-3 shows the conduit evaluation space subdivided into a number of distinct likelihood and consequences categories. For the purposes of final disposition, all conduits that fall within a particular grid space defined by the intersecting categories will be treated the same.

Each grid space in Figure 2-3 is defined by the intersection of a particular likelihood category (e.g., ϕ_i) and a consequence category; e.g., C_j. Within this grid space, there are a number of conduits; e.g., N_{ij}. If the fraction of these conduits that contain damaged cables is designated F_{ij}, a Bayesian analysis can be performed to refine systematically the estimates for the size of this fraction and the uncertainties about those estimates. Figure 2-4 shows the general format for a Bayesian update. The methodology and its bases are described more completely in Appendix A. These principles can be used to develop a structured program for conduit sampling and cable replacement. The process begins with conduits in the grid space of highest concern; i.e., the upper right corner of Figure 2-3. As more information is obtained about the actual fraction of conduits with cable damage in this category and the consequences from that damage, these data can be used to update the corresponding families of likelihood and consequence curves for all other grid locations. Thus, the entire set of Bayes' curves evolves together as successive sampling data are factored into the analysis. At each step of the process, the results from the previous update are used to guide selection of the next group of conduits for sampling. For each grid location, there is a value for the damage fraction below which no further investigation is warranted (e.g., $\hat{F}_{ij}$). This value is determined by the "isoconcern contour" for that location. Once the Bayesian curves show sufficient confidence that the actual level of damage is less than this threshold value (i.e., $F_{ij} < \hat{F}_{ij}$), the sampling and updating process can be stopped.

The final practical consideration for implementing this methodology is to acknowledge the actual sizes of the conduit and cable populations. The total number of safety-related conduits at WBNP exceeds 10,000. There are nearly twice as many individual cables routed through these conduits. Assessment of the consequences from damaged cables within a particular conduit (i.e., numerical evaluation of C_j) requires a rather detailed and time-consuming examination of the loads supplied by each cable. It is somewhat easier to develop estimates for the likelihood of observing damage; i.e., ϕ_i. Therefore, the evaluation methodology that was applied in this study first focused on the formal definition of categories for cable damage likelihood, the development of prior probability distributions for the fraction of conduits with damaged cables in each category, and the use of conduit sampling data to update these estimates. After this phase of the analysis was completed, the results were sufficiently detailed to support final resolution of the pullby damage issue without performing the corresponding consequence evaluations. The sampling plane in Figure 2-3 was thus collapsed to a simple line along the axis for damage likelihood, and the resulting conduit categories were used to prioritize the final program for cable inspections and replacement. Figure 2-5 summarizes the four basic steps for this part of the analysis.

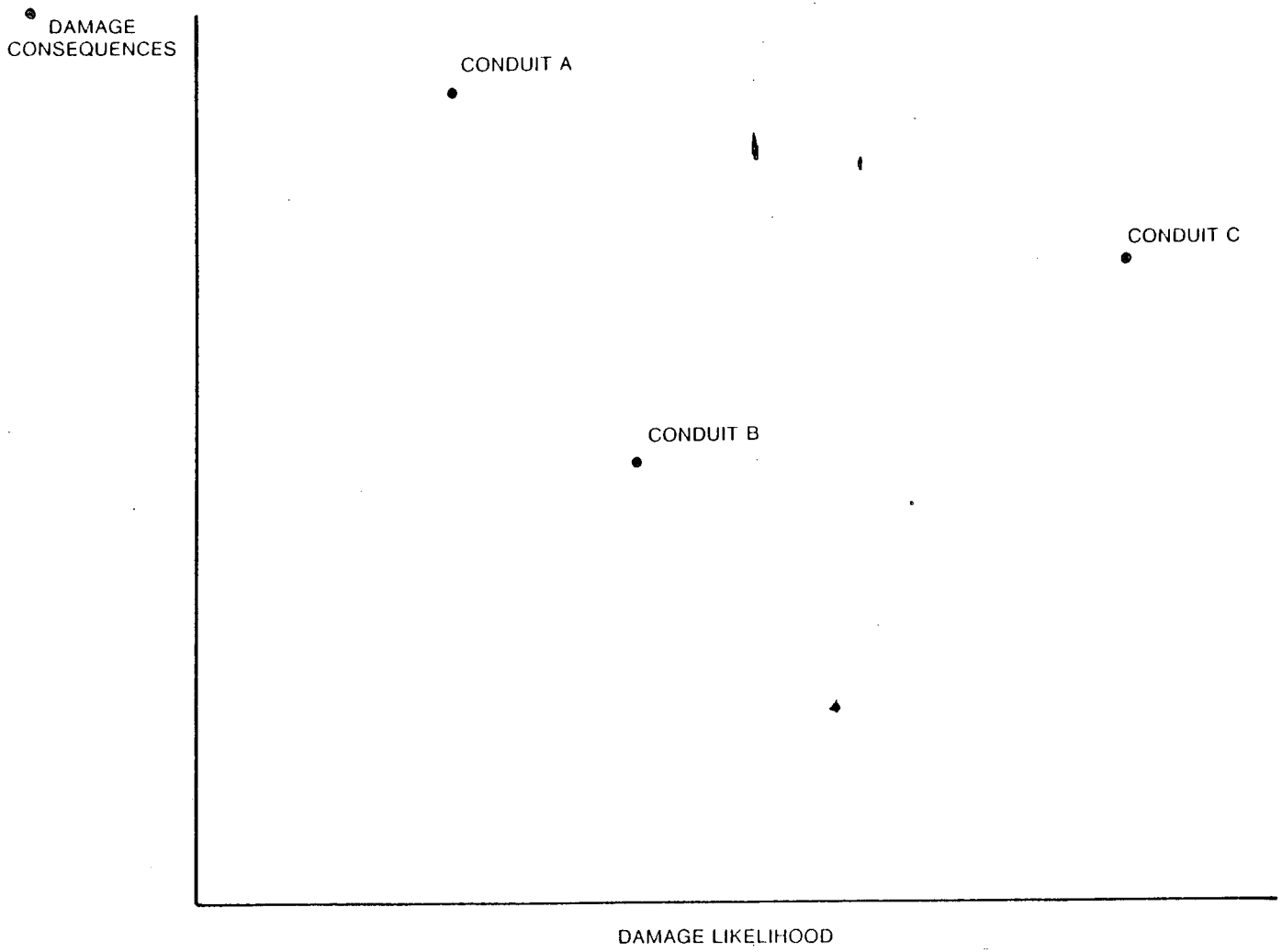

Figure 2-1. Individual Conduits as Points in a Coordinate Plane

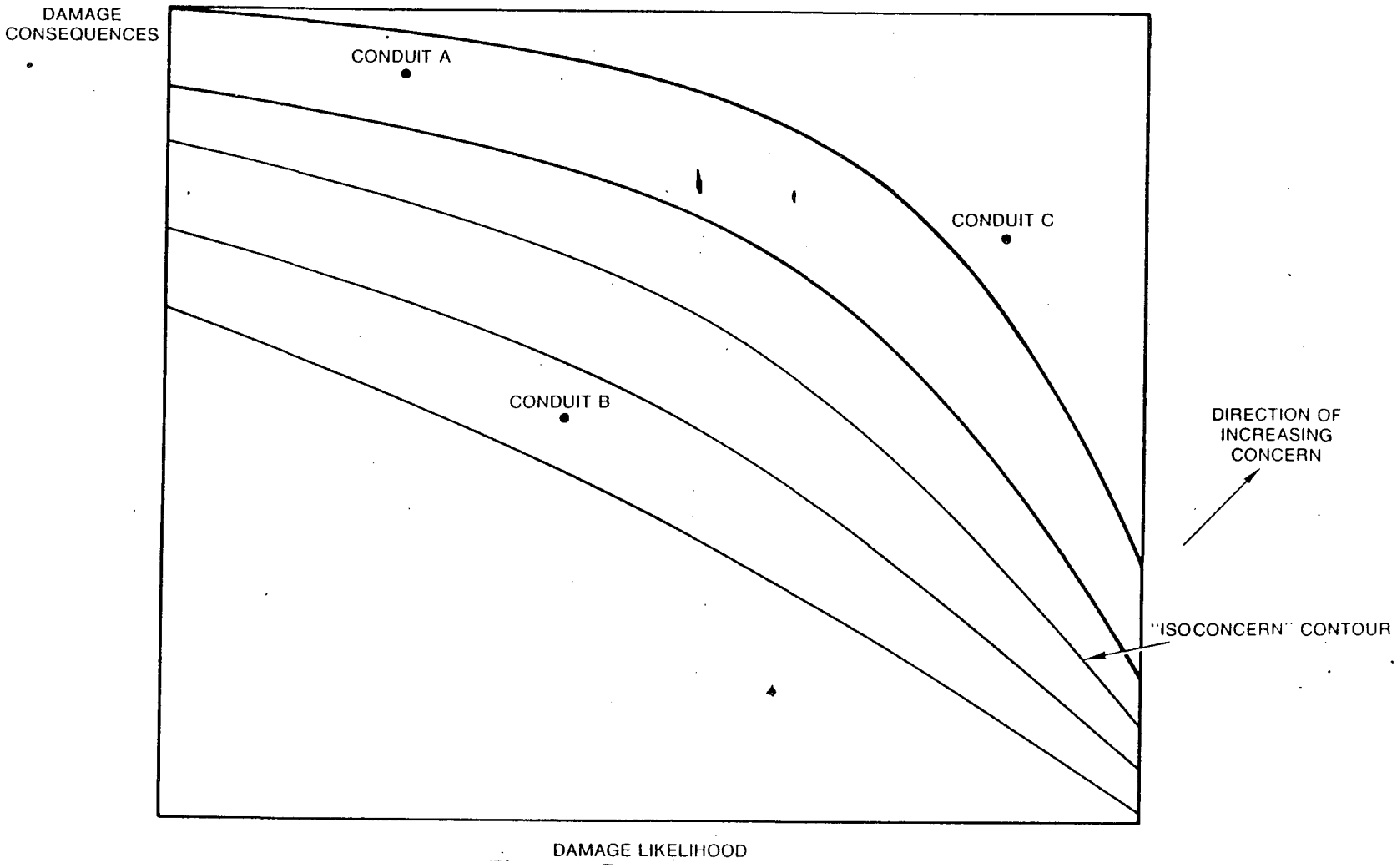

Figure 2-2. Coordinate Plane Showing Lines of Constant Concern

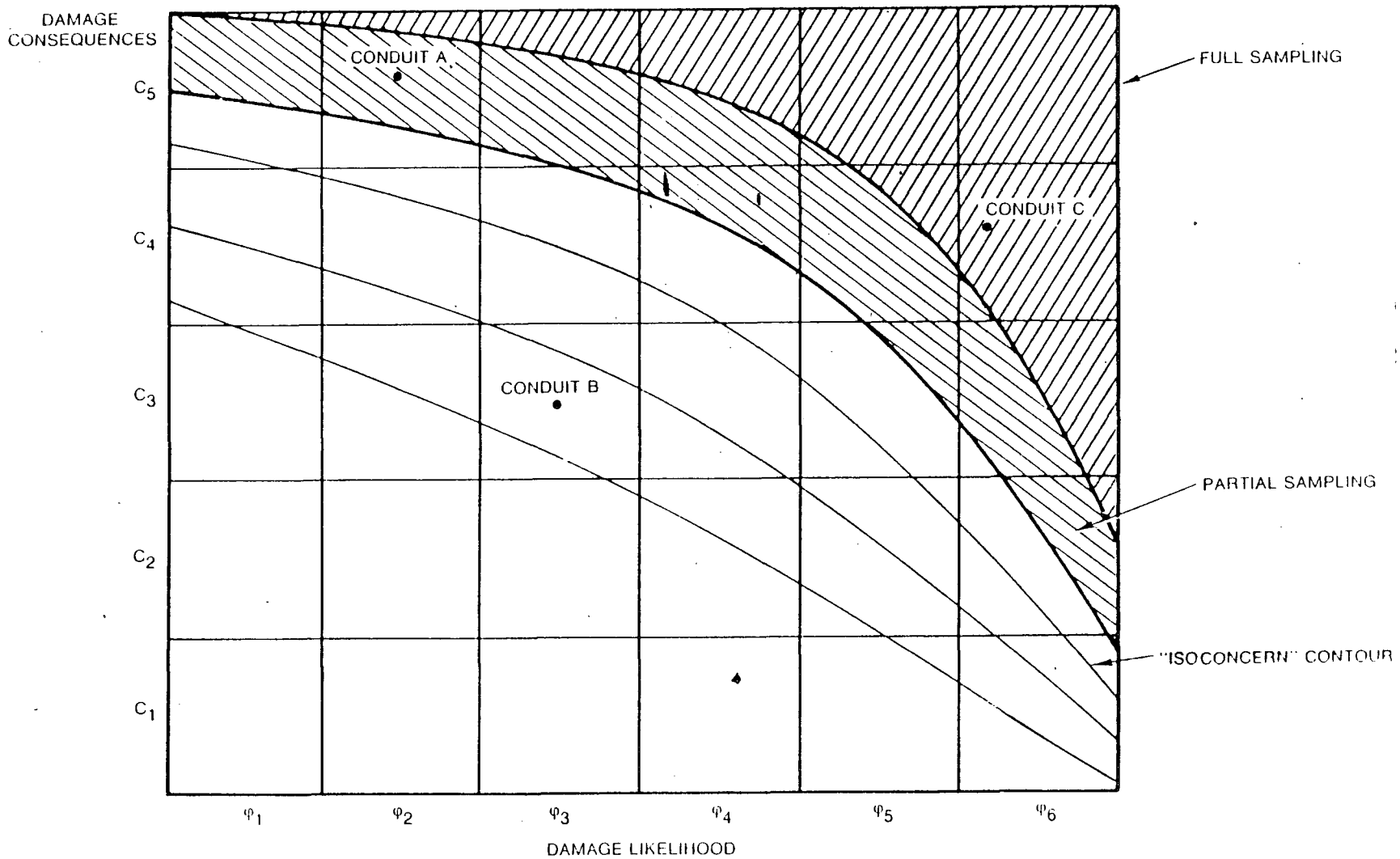

Figure 2-3. Sampling Plane Concept with Grid of Likelihood and Consequence Categories

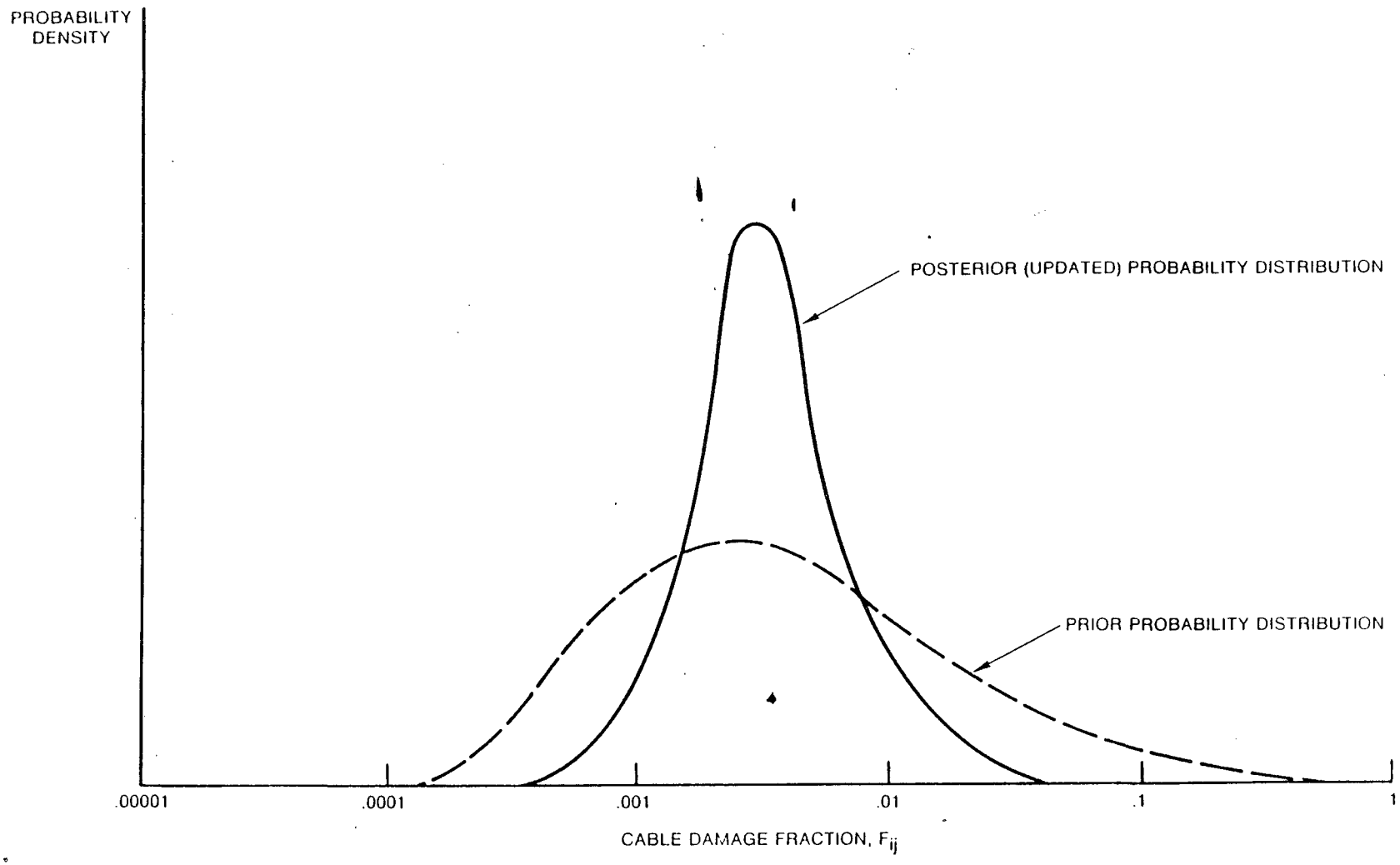

Figure 2-4. Bayesian Estimation of Cable Damage Fraction

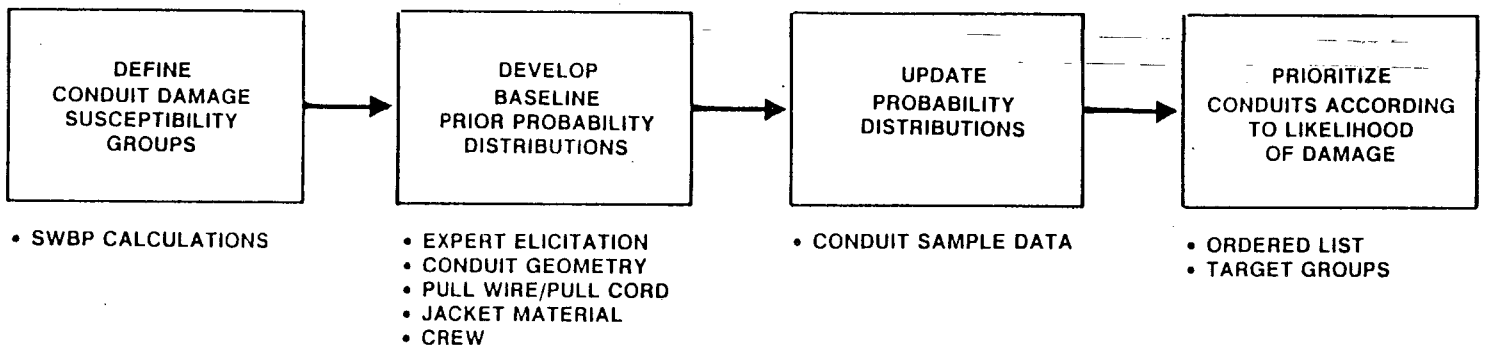

Figure 2-5. Methodology for Estimating the Likelihood of Cable Damage

3. DERIVATION OF CABLE DAMAGE SUSCEPTIBILITY GROUPS

The cables at WBNP are broadly classified into the five general categories listed in Table 3-1. Although there may be minor differences between specific cables within each of these categories, similarities in conductor size, jacket and insulation materials, cable fabrication, and general installation practices justify the treatment of each category as a separate class of cables for this analysis. Cables in category V5 were eliminated from further consideration early in the study. This decision was based on two factors. Experience has shown that pullby events occur very rarely during the installation of this type of cable. Normal TVA construction practice also requires high potential testing of all V5 cables to verify their integrity after installation. Therefore, the remainder of this evaluation is focused on estimating the likelihood of pullby damage to cables in voltage level categories V1 through V4.

One of the most significant factors that determine the likelihood of cable damage during a pullby event is the sidewall bearing pressure (SWBP) that is developed during the pull. Therefore, it was decided at an early stage of this study to use SWBP as an engineering parameter to help determine which conduit configurations exhibit increased susceptibility to pullby damage.

The first step in the conduit grouping process was to define a set of nominal SWBP screening values. Combinations of industry recommendations, TVA standards, and selected testing data were used as the bases for the ranges shown in Table 3-2. Characteristics of the cable construction, jacket material, and insulation determine the differences between the ranges selected for cables in the V1 and V2 voltage categories, when compared with the ranges for cables in the V3 and V4 voltage categories. For example, traditionally cited standards from cable manufacturers indicate that SWBP values less than 300 lb/ft provide very conservative safety margins for V1 and V2 cables; SWBP values less than 500 lb/ft provide similar safety margins for V3 and V4 cables. After extensive analyses and testing, TVA has relaxed these traditional values somewhat for its standard cable installation criteria. The nominal TVA criteria specify SWBP values less than 500 lb/ft for V1 and V2 cables, and SWBP values less than 1,000 lb/ft for V3 and V4 cables. Therefore, groups A, B, G, and H from Table 3-2 all meet currently accepted TVA construction standards. The remaining SWBP ranges were based on testing data from selected cable manufacturers, the Institute of Electrical and Electronics Engineers (IEEE), and the Electric Power Research Institute (EPRI) (References 1 through 6). These tests indicate that SWBP values substantially higher than the traditionally recommended limits will not cause cable damage during controlled pulls. However, the test data are rather limited, and the conclusions have not yet been applied for relaxation of industry guidelines. A nominal SWBP value of 2,000 lb/ft was selected to define groups F and K because very little evidence is available to indicate that these types of cables will remain undamaged if they are pulled with forces that exceed 2,000 lb/ft.

The second step in the grouping process was to sort the WBNP conduits into the appropriate SWBP categories. This step was accomplished through a series of engineering analyses that first determined which conduit configurations could contain cables that experienced each selected SWBP range, if pullby events had occurred during cable installation. An estimate of

the SWBP that a cable would experience during a pullby event was calculated through the following formula:

$$SWBP = W^{*}k^{*}(L/R)^{*}e^{(k^{*}A)} \qquad (3.1)$$

where

SWBP = Sidewall Bearing Pressure (lb/ft)
W = Weight of Cables in the Pullby (lb/ft)
k = Coefficient of Friction
L = Length of Conduit (ft)
R = Radius of Conduit Area Available for Pullby (ft)
A = Total Degrees of Conduit Bend (radians)

The screening calculations used a constant assumed value of 280° for the total number of bends in each conduit segment. The calculation method conservatively positioned all of these bends at the pulling end of the conduit. This has the same effect on SWBP as if each pull had been made through a total of 366° of bends, distributed uniformly along the length of the conduit. A value of 0.75 was used for the coefficient of friction during the pullby, except at higher conduit loadings. If the conduit was ultimately filled between 45% and 55% of its capacity during the pullby, the coefficient of friction was increased to 0.85. If the conduit was filled between 55% and 65% of its capacity, the coefficient of friction was increased to 1.0. All conditions that exceeded 65% of the nominal conduit capacity were conservatively assigned to the highest SWBP range for this analysis.

A series of screening calculations was performed to estimate pullby SWBP for a wide range of conduit diameters, conduit lengths, and initial conduit loadings. Separate calculations were performed for three of the major WBNP cable categories to account for differences in the cable sizes and jacket materials. A relatively large fraction of the total cable weight in the conduit was also assumed for each pullby calculation. This fraction was conservatively derived from examination of the cable and conduit geometry and experience with typical cable installation practices. It ranged from approximately 20% of the total cable weight to approximately 50% of the total cable weight, depending on the conduit size. For each range of conduit lengths, the calculations used the maximum length in the indicated range and assumed that the pullby occurred through the entire length of the conduit with no intermediate pull points. For conduits longer than 100 feet, the calculations used a length of 150 feet with no intermediate pull points. Tables 3-3 through 3-20 summarize the results from these calculations.

It is important to understand the implications from these calculations. The estimated SWBP values are based on the assumption that a pullby has been attempted under the indicated nominal conditions. For example, Table 3-5 applies to cables in the V2 voltage category, with conduits that are finally filled to approximately 30% of their capacity. If a pullby event that involved 25% of the total installed cable weight occurred in a 2-inch conduit segment that is 50 feet long, the resulting SWBP experienced during that pullby would be approximately 381 lb/ft. Similarly, Table 3-12 applies to cables in the V3 voltage category, with conduits that are filled to approximately 40% of their capacity. If a pullby event that involved 25% of the total installed cable weight occurred in a 3-inch conduit segment that is 100 feet long, the resulting SWBP experienced during that pullby would be approximately 2,130 lb/ft.

Tables 3-3 through 3-20 provide a cross-reference index for classifying conduit geometries into SWBP categories. This cross-reference assumes that a pullby event has occurred under the indicated conditions. If a pullby was actually made under less severe conditions, the resulting SWBP would be lower, and the corresponding conduit segment could be reclassified. Examples of factors that could lead to lower calculated SWBP values are smaller fractions of the cables involved in the pullby, fewer degrees of bend in the conduit run, and intermediate pull points in the run. Of course, if no pullby actually occurred in the conduit, it is not a candidate for this analysis.

Contour lines have been drawn in Tables 3-3 through 3-20 to indicate transitions between the SWBP ranges shown in Table 3-1. These contour lines were used to identify which conduits could be sorted into each SWBP group. During the sorting process, conduits with a diameter of 0.5 inch were evaluated according to the same criteria developed for 0.75-inch diameter conduits. Tables 3-21 through 3-36 summarize these sorting criteria. The TVA computerized Conduit and Cable Routing System (CCRS) was accessed to perform these sorts for all conduit segments containing safety-related cables for Unit 1 equipment, common equipment for both units, and Unit 2 equipment identified as being required for safe shutdown of Unit 1. Table 3-37 shows the results from these sorts. As was noted previously, it is important to remember that these calculations and sorts were performed under the presumption that pullby events have occurred in all conduits at WBNP. The results in Table 3-37 show, for example, that even under these conservative assumptions, the computed SWBP values meet TVA installation acceptance criteria for 7,093 of the 7,449 conduits in this population; i.e., the total number of conduits in groups A, B, G, and H. A total of 103 conduits could have SWBP values in excess of 2,000 lb/ft, if pullby events had occurred under the assumed conditions; i.e., the total number of conduits in groups F and K.

Table 3-1. WBNP Cable Categories	
Voltage Level	**Cable Characteristics**
V1	Shielded, Instrumentation
V2	Most Are Shielded, Instrumentation
V3	Unshielded, Control and Control Power
V4	Unshielded, Low Voltage Power
V5	Shielded, Medium Voltage Power

Table 3-2. Sidewall Bearing Pressure Ranges Used To Define Conduit Damage Susceptibility Groups		
Voltage Level	**Group**	**Sidewall Bearing Pressure (lb/ft)**
V1/V2	A	< 300
	B	300 - 500
	C	500 - 1,000
	D	1,000 - 1,500
	E	1,500 - 2,000
	F	> 2,000
V3/V4	G	< 500
	H	500 - 1,000
	I	1,000 - 1,500
	J	1,500 - 2,000
	K	> 2,000

Table 3-3. Pullby SWBP Screening Values, Voltage Level: V1/V2, Final Conduit Fill: 10%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	15	38	75	113	150	225
1.0	0.50	24	59	118	176	235	353
1.5	0.33	25	62	124	186	247	371
2.0	0.25	25	64	127	191	254	381
2.5	0.25	35	87	174	261	348	522
3.0	0.25	43	107	214	322	429	643
4.0	0.20	47	119	237	356	475	712
5.0	0.20	49	123	246	369	492	738

Table 3-4. Pullby SWBP Screening Values, Voltage Level: V1/V2, Final Conduit Fill: 20%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	30	75	150	225	301	451
1.0	0.50	47	118	235	353	470	705
1.5	0.33	49	124	247	371	495	742
2.0	0.25	51	127	254	381	508	762
2.5	0.25	70	174	348	522	696	1,045
3.0	0.25	86	214	429	643	858	1,286
4.0	0.20	95	237	475	712	949	1,424
5.0	0.20	98	246	492	738	985	1,477

Table 3-5. Pullby SWBP Screening Values, Voltage Level: V1/V2, Final Conduit Fill: 30%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	45	113	225	338	451	676
1.0	0.50	71	176	353	529	705	1,058
1.5	0.33	74	186	371	557	742	1,113
2.0	0.25	76	191	381	572	762	1,143
2.5	0.25	104	261	522	783	1,045	1,567
3.0	0.25	129	322	643	965	1,286	1,930
4.0	0.20	142	356	712	1,068	1,424	2,136
5.0	0.20	148	369	738	1,108	1,477	2,215

Table 3-6. Pullby SWBP Screening Values, Voltage Level: V1/V2, Final Conduit Fill: 40%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	60	150	301	451	601	902
1.0	0.50	94	235	470	705	940	1,411
1.5	0.33	99	247	495	742	989	1,484
2.0	0.25	102	254	508	762	1,016	1,524
2.5	0.25	139	348	696	1,045	1,393	2,089
3.0	0.25	172	429	858	1,286	1,715	2,573
4.0	0.20	190	475	949	1,424	1,899	2,848
5.0	0.20	197	492	985	1,477	1,969	2,954

Table 3-7. Pullby SWBP Screening Values, Voltage Level: V1/V2, Final Conduit Fill: 50%							
Conduit Diameter (inches)	Pullby Weight Fraction	Conduit Length (feet)					
		0-10	11-25	26-50	51-75	76-100	> 100
0.75	0.50	139	347	694	1,041	1,389	2,083
1.0	0.50	217	543	1,086	1,629	2,172	3,258
1.5	0.33	228	571	1,142	1,713	2,285	3,427
2.0	0.25	233	587	1,173	1,760	2,347	3,520
2.5	0.25	322	804	1,608	2,412	3,216	4,824
3.0	0.25	396	990	1,980	2,971	3,961	5,941
4.0	0.20	438	1,096	2,192	3,288	4,384	6,576
5.0	0.20	455	1,137	2,274	3,411	4,547	6,821

Table 3-22. WBNP Conduit Sorting Criteria, Voltage Level: V1 and V2, Damage Susceptibility Group: B		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75	15-24.99	76-∞
	25-34.99	51-100
	35-44.99	26-75
	45-54.99	11-25
	55-64.99	0-10
1.0, 1.5	0-14.99	101-∞
	15-24.99	51-100
	25-44.99	26-50
2.0	0-14.99	101-∞
	15-24.99	51-75
	25-34.99	26-50
2.5	0-14.99	76-100
	15-24.99	26-50
	35-44.99	11-25
	45-54.99	0-10
3.0, 4.0, 5.0	0-14.99	51-100
	15-24.99	26-50
	25-44.99	11-25
	45-54.99	0-10

Table 3-23. WBNP Conduit Sorting Criteria, Voltage Level: V1 and V2, Damage Susceptibility Group: C		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75	25-34.99	101-∞
	35-44.99	76-∞
	45-54.99	26-50
1.0, 1.5	15-24.99	101-∞
	25-44.99	51-100
	45-54.99	11-25
	55-64.99	0-10
2.0	15-24.99	76-∞
	25-34.99	51-100
	35-44.99	26-75
	45-54.99	11-25
	55-64.99	0-10
2.5	0-14.99	101-∞
	15-24.99	51-100
	25-34.99	26-75
	35-44.99	26-50
	45-54.99	11-25
	55-64.99	0-10
3.0	0-14.99	101-∞
	15-24.99	51-100
	25-34.99	26-75
	35-44.99	26-50
	45-54.99	11-25
4.0, 5.0	0-14.99	101-∞
	15-24.99	51-100
	25-44.99	26-50

Table 3-24. WBNP Conduit Sorting Criteria, Voltage Level: V1 and V2, Damage Susceptibility Group: D		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75	45-54.99	51-100
	55-64.99	11-25
1.0, 1.5	25-44.99	101-∞
	45-54.99	26-50
2.0	25-34.99	101-∞
	35-44.99	76-100
	45-54.99	26-50
2.5	15-24.99	101-∞
	25-34.99	76-100
	35-44.99	51-100
3.0	15-24.99	101-∞
	25-34.99	76-100
	35-44.99	51-75
	55-64.99	0-10
4.0, 5.0	15-24.99	101-∞
	25-34.99	51-100
	35-44.99	51-75
	45-54.99	11-25
	55-64.99	0-10

Table 3-25. WBNP Conduit Sorting Criteria, Voltage Level: V1 and V2, Damage Susceptibility Group: E		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
1.0, 1.5	45-54.99	51-75
	55-64.99	11-25
2.0	35-44.99	101-∞
	45-54.99	51-75
	55-64.99	11-25
2.5	25-34.99	101-∞
	45-54.99	26-50
3.0	25-34.99	101-∞
	35-44.99	76-100
	45-54.99	26-50
4.0, 5.0	35-44.99	76-100

Table 3-26. WBNP Conduit Sorting Criteria, Voltage Level: V1 and V2, Damage Susceptibility Group: F		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75	45-54.99	101-∞
	55-64.99	26-∞
	65-∞	All
1.0, 1.5, 2.0	45-54.99	76-∞
	55-64.99	26-∞
	65-∞	All
2.5, 3.0	35-44.99	101-∞
	45-54.99	51-∞
	55-64.99	11-∞
	65-∞	All
4.0, 5.0	25-44.99	101-∞
	45-54.99	26-∞
	55-64.99	11-∞
	65-∞	All

Table 3-27. WBNP Conduit Sorting Criteria, Voltage Level: V3, Damage Susceptibility Group: G		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75	0-14.99	All
	15-24.99	0-100
	25-34.99	0-75
	35-44.99	0-50
	45-54.99	0-10
1.0, 1.5, 2.0	0-14.99	All
	15-24.99	0-75
	25-34.99	0-50
	35-44.99	0-25
	45-54.99	0-10
2.5	0-14.99	0-100
	15-24.99	0-50
	25-44.99	0-25
	45-54.99	0-10
3.0	0-14.99	0-75
	15-34.99	0-25
	35-54.99	0-10
4.0, 5.0	0-14.99	0-75
	15-34.99	0-25
	35-44.99	0-10

Table 3-28. WBNP Conduit Sorting Criteria, Voltage Level: V3, Damage Susceptibility Group: H		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75	15-24.99	101-∞
	25-34.99	76-∞
	35-44.99	51-100
	45-54.99	11-25
	55-64.99	0-10
1.0, 1.5, 2.0	15-24.99	76-∞
	25-34.99	51-100
	35-44.99	26-75
	45-54.99	11-25
	55-64.99	0-10
2.5	0-14.99	101-∞
	15-24.99	51-100
	25-34.99	26-75
	35-44.99	26-50
	45-54.99	11-25
3.0	0-14.99	76-∞
	15-24.99	26-75
	25-34.99	26-50
	35-44.99	11-25
4.0, 5.0	0-14.99	76-∞
	15-24.99	26-75
	25-34.99	26-50
	35-44.99	11-25
	45-54.99	0-10

Table 3-29. WBNP Conduit Sorting Criteria, Voltage Level: V3, Damage Susceptibility Group: I		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75	35-44.99	101-∞
	45-54.99	26-50
1.0, 1.5, 2.0	25-34.99	101-∞
	35-44.99	76-100
	45-54.99	26-50
2.5	15-24.99	101-∞
	25-34.99	76-100
	35-44.99	51-75
	55-64.99	0-10
3.0	15-24.99	76-100
	25-34.99	51-75
	35-44.99	26-50
	45-54.99	11-25
	55-64.99	0-10
4.0, 5.0	15-24.99	76-100
	25-34.99	51-75
	35-44.99	26-50
	45-54.99	11-25

Table 3-30. WBNP Conduit Sorting Criteria, Voltage Level: V3, Damage Susceptibility Group: J		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75	45-54.99	51-75
	55-64.99	11-25
1.0, 1.5	35-44.99	101-∞
	45-54.99	51-75
	55-64.99	11-25
2.0	35-44.99	101-∞
2.5	25-34.99	101-∞
	35-44.99	76-100
	45-54.99	26-50
3.0	15-24.99	101-∞
	25-34.99	76-100
	35-44.99	51-75
4.0, 5.0	15-24.99	101-∞
	25-34.99	76-100
	35-44.99	51-75
	55-64.99	0-10

Table 3-31. WBNP Conduit Sorting Criteria, Voltage Level: V3, Damage Susceptibility Group: K		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75, 1.0, 1.5	45-54.99	76-∞
	55-64.99	26-∞
	65-∞	All
2.0	45-54.99	51-∞
	55-64.99	11-∞
	65-∞	All
2.5	35-44.99	101-∞
	45-54.99	51-∞
	55-64.99	11-∞
	65-∞	All
3.0, 4.0, 5.0	25-34.99	101-∞
	35-44.99	76-∞
	45-54.99	26-∞
	55-64.99	11-∞
	65-∞	All

Table 3-32. WBNP Conduit Sorting Criteria, Voltage Level: V4, Damage Susceptibility Group: G		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75	0-24.99	All
	25-34.99	0-100
	35-44.99	0-75
	45-54.99	0-25
	55-64.99	0-10
1.0	0-14.99	All
	15-24.99	0-100
	25-34.99	0-75
	35-44.99	0-50
	45-54.99	0-25
	55-64.99	0-10
1.5	0-14.99	All
	15-24.99	0-100
	25-44.99	0-50
	45-54.99	0-10
2.0	0-14.99	All
	15-24.99	0-75
	25-34.99	0-50
	35-44.99	0-25
	45-54.99	0-10
2.5, 3.0	0-14.99	0-100
	15-24.99	0-50
	25-44.99	0-25
	45-54.99	0-10
4.0, 5.0	0-14.99	0-75
	15-34.99	0-25
	35-54.99	0-10

Table 3-33. WBNP Conduit Sorting Criteria, Voltage Level: V4, Damage Susceptibility Group: H		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75	25-34.99 35-44.99 45-54.99	101-∞ 76-∞ 26-50
1.0	15-24.99 25-34.99 35-44.99 45-54.99	101-∞ 76-∞ 51-100 26-50
1.5	15-24.99 25-44.99 45-54.99 55-64.99	101-∞ 51-100 11-25 0-10
2.0	15-24.99 25-34.99 35-44.99 45-54.99 55-64.99	76-∞ 51-100 26-75 11-25 0-10
2.5	0-14.99 15-24.99 25-34.99 35-44.99 45-54.99 55-64.99	101-∞ 51-100 26-75 26-50 11-25 0-10
3.0	0-14.99 15-24.99 25-44.99	101-∞ 51-100 26-50
4.0, 5.0	0-14.99 15-24.99 25-34.99 35-44.99	76-∞ 26-75 26-50 11-25

Table 3-34. WBNP Conduit Sorting Criteria, Voltage Level: V4, Damage Susceptibility Group: I		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75	45-54.99	51-100
	55-64.99	11-25
1.0	35-44.99	101-∞
	45-54.99	51-75
	55-64.99	11-25
1.5	25-44.99	101-∞
	45-54.99	26-50
2.0	25-34.99	101-∞
	35-44.99	76-100
	45-54.99	26-50
2.5	15-24.99	101-∞
	25-34.99	76-100
	35-44.99	51-100
3.0	15-24.99	101-∞
	25-34.99	51-100
	35-44.99	51-75
	45-54.99	11-25
	55-64.99	0-10
4.0, 5.0	15-24.99	76-100
	25-34.99	51-75
	35-44.99	26-50
	45-54.99	11-25
	55-64.99	0-10

Table 3-35. WBNP Conduit Sorting Criteria, Voltage Level: V4, Damage Susceptibility Group: J		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
1.0	45-54.99	76-100
1.5	45-54.99	51-75
	55-64.99	11-25
2.0	35-44.99	101-∞
	45-54.99	51-75
	55-64.99	11-25
2.5	25-34.99	101-∞
	45-54.99	26-50
3.0	35-44.99	76-100
4.0, 5.0	15-24.99	101-∞
	25-34.99	76-100
	35-44.99	51-75

Table 3-36. WBNP Conduit Sorting Criteria, Voltage Level: V4, Damage Susceptibility Group: K		
Conduit Diameter (inches)	**Percent Fill**	**Conduit Length (feet)**
0.50, 0.75, 1.0	45-54.99	101-∞
	55-64.99	26-∞
	65-∞	All
1.5, 2.0	45-54.99	76-∞
	55-64.99	26-∞
	65-∞	All
2.5	35-44.99	101-∞
	45-54.99	51-∞
	55-64.99	11-∞
	65-∞	All
3.0	25-44.99	101-∞
	45-54.99	26-∞
	55-64.99	11-∞
	65-∞	All
4.0, 5.0	25-34.99	101-∞
	35-44.99	76-∞
	45-54.99	26-∞
	55-64.99	11-∞
	65-∞	All

Table 3-37. Summary of WBNP Conduit Damage Susceptibility Group Populations			
Voltage Level	**Group**	**Number of Conduits***	**Number of Cables***
V1	A	13	38
	B	1	36
	C	1	33
	D	4	71
	E	1	32
	F	2	71
V2	A	816	1,133
	B	156	517
	C	74	411
	D	19	148
	E	5	91
	F	3	51
V3	G	4,223	4,738
	H	366	1,514
	I	78	433
	J	16	113
	K	91	722
V4	G	1,320	886
	H	198	185
	I	51	44
	J	4	6
	K	7	7

*Unit 1, Common, and Unit 2 required for Unit 1.

4. DEVELOPMENT OF PRIOR PROBABILITY DISTRIBUTIONS

The 22 susceptibility groups listed in Table 3-37 are the engineering basis for the cable damage likelihood categories described in Section 2. They are derived from combinations of physical and geometric parameters that affect the likelihood that cables will be damaged during pullby events. The next step in the analysis process is to develop a set of baseline prior probability distributions. These distributions provide initial numerical estimates for the likelihood of cable damage in each susceptibility group. They are the first stage of the Bayesian analyses described in Section 2 and Appendix A.

Very little data are available to document actual cable damage experience during pullby events at either nuclear or nonnuclear facilities. Therefore, the prior probability distributions for this analysis were developed from information supplied by two cable installation experts. This is Bayesian evidence of type E_0, as described in Appendix A, Sections A.1 and A.4. Both experts have several years of experience in actual cable installation practices, and both are familiar with the general installation techniques used at WBNP. They are also well known for their expertise in the evaluation of pullby events. One expert is currently an electrical engineer with TVA. The second individual is an independent consultant in the fields of cable fabrication, installation, and qualification. The information for this analysis was collected during independent interviews conducted on October 5 and October 20, 1989. Both experts were aware that damaged cables had been discovered at WBNP and that the cause for this damage had been traced to pullby events. However, neither expert knew which of the susceptibility groups for this analysis had sustained damage until their respective interviews were completed.

The process for developing the SWBP calculations and the final damage susceptibility groups summarized in Section 3 was described so that each expert understood the bases and assumptions for each conduit category. Examples of the pull chart calculations and sorting tables (e.g., Tables 3-2 through 3-36) were available so that each expert could refer to important physical parameters during his assessments. The sorted data summarized in Table 3-37 were not available during these interviews.

It was also explained that three types of internal configurations had been discovered during initial conduit examinations at WBNP. One configuration is described for this study as a clear path for pullby events. In this configuration, a pullby was accomplished by threading a pull wire or cord through a conduit that contained only previously installed cables. The additional cables were then pulled into the conduit using this wire or cord. The second configuration involved a preexisting pull wire. In this configuration, an insulated wire was initially pulled into the conduit with a bundle of cables in anticipation of later cable pulls. This practice saved time on subsequent pulls by eliminating the need to first thread the wire into the conduit, but the preexisting wire sometimes became entwined with the cables. An entwined pull wire could require increased pull tension and, therefore, increase SWBP during the subsequent pull or directly cause damage to the installed cables as the wire was pulled over the cable jackets. The third configuration was similar to the second, except that it involved a previously installed pull cord. This braided cord, also known as "parachute cord," is quite abrasive when drawn taut. It can cause substantial jacket and insulation damage if it is entwined with a preexisting cable bundle.

Each expert was asked to estimate the likelihood that cable damage would occur if pullby events were made in each susceptibility group. Three sets of estimates were provided for each group: one set for each of the three internal configurations described above. It was noted that the SWBP calculations for each susceptibility group were based on the assumption that pullbys had occurred. For the purposes of this process, cable damage was defined as a condition in which at least one cable in the conduit was cut through the jacket material and insulation to expose the conductor. Both experts combined cable voltage levels V1 and V2 during their assessments.

Tables 4-1 through Table 4-13 summarize the probability distributions derived from the interviews with expert 1. Expert 1 supplied 13 sets of distributions. He felt that voltage levels V3 and V4 cables would behave in a similar manner for pullby SWBP values below approximately 1,500 lb/ft. At pressures above 1,500 lb/ft, he felt that V4 cables would experience somewhat less damage than V3 cables. Therefore, Tables 4-7 through 4-9 apply to both V3 and V4 cables. Tables 4-14 through 4-29 are the probability distributions from expert 2. Expert 2 provided separate distributions for V3 and V4 cables over the full range of SWBP values. Therefore, he supplied a total of 16 sets of distributions. The term "conditional frequency" is used in these tables as a substitute for the term "likelihood." The values in this table column are the estimated fraction of conduits that would contain at least one damaged cable if a pullby were made under the assigned conditions. The table column for "conditional probability" provides a numerical measure of the uncertainty in these estimates. For example, Table 4-4 summarizes the assessments from expert 1 for voltage levels V1 and V2 damage susceptibility group D; i.e., pullby SWBP values between 1,000 lb/ft and 1,500 lb/ft. If a clear path is available for the pullby, this expert estimated that damage would occur in a minimum of 1 in 1,000 conduits to a maximum of 1 in 2 conduits. Although his uncertainty is quite broad, he was most confident that damage would occur in approximately 1 in 10 conduits under these conditions. However, if a preexisting pull cord were left in the conduit, he was much more certain that damage would occur. His assigned range narrowed from a minimum of 1 in 4 conduits to a maximum of 8 in 10 conduits. His best estimate under these conditions was that damage would occur in approximately 4 of every 10 conduits.

Several comments are necessary to place these distributions into the proper perspective. The experts often could not provide very precise estimates for the likelihood of damage. In many cases, it was easiest to elicit a "high" value, a "low" value, and a "best estimate" value. The discussions then focused on "fine tuning" this range to develop intermediate values and to refine the shape of the probability distribution over this range. All numerical probability values were assigned by the interviewer during these discussions. A conscious effort was also made to extend the upper and lower bounds of each distribution, where appropriate, to compensate for the well-documented tendency of technical experts to understate the range of their uncertainty. The experts were encouraged to revise their estimates as necessary to ensure that the groups were evaluated consistently. Both experts practiced this type of self-calibration, and both relied heavily on estimates from preceding groups as a basis for evaluating new groups. It should be emphasized that the goal in this process was not to develop precise numerical estimates for either the conditional frequencies of cable damage or the probabilities assigned to each frequency value. The most important information from this process is the range of damage frequency values estimated for each condition, the general shape of the probability distribution over this range, and the internal consistency of these estimates between groups.

As a final comment on these tabulated distributions, it should be noted that a value of "0" in the conditional frequency column should be interpreted as "no conduits would have any damaged cables under these conditions." A numerical value of 1.0E-05 (1 conduit in 100,000) was arbitrarily assigned for all estimates of "0" during subsequent calculations to account for general human difficulty in comprehending numbers that small. This correction had no measurable effect on the study results. A value of "1.00" in the conditional frequency column should be interpreted as "all conduits would have damaged cables under these conditions." Although this value may also be somewhat imprecise, it was retained as 1.0 during all subsequent calculations.

Results from preliminary evaluations of the WBNP conduit examination data provided the following information:

- Approximately 40% of the conduits were found with no preexisting pull wire or pull cord; i.e., a clear path.
- Approximately 45% of the conduits were found with preexisting pull wire.
- Approximately 15% of the conduits were found with preexisting pull cord.

These fractions were used as multiplicative weights for each corresponding probability distribution. Thus, the final probability distribution from each expert for the likelihood of observing pullby damage in a particular conduit susceptibility group is the weighted sum of the distributions for the three conduit internal configurations. The following equation shows the general form of this combination process for susceptibility group A:

$$EIA = (.40)(EIACP) + (.45)(EIAPW) + (.15)(EIAPC) \tag{4.1}$$

where

EIA = Expert 1 composite probability distribution for the likelihood of cable damage in susceptibility group A.

EIACP = Expert 1 probability distribution for the likelihood of cable damage in susceptibility group A with no preexisting pull wire or pull cord.

EIAPW = Expert 1 probability distribution for the likelihood of cable damage in susceptibility group A with preexisting pull wire.

EIAPC = Expert 1 probability distribution for the likelihood of cable damage in susceptibility group A with preexisting pull cord.

The final composite distributions account for influences from the physical and geometric factors that affect SWBP during a pullby event, and the conduit internal configuration effects from previously installed pull wires or pull cords.

Full evaluation of all field examination data was not completed until after these composite distributions were calculated. After the data were summarized for all of the Unit 1 conduits, it was noted that the initial percentages used above for each of the more severe internal configurations were somewhat conservative. The final field examination data showed the following breakdown:

- Approximately 68% of the conduits were found with no preexisting pull wire or pull cord.
- Approximately 25% of the conduits were found with preexisting pull wire.
- Approximately 7% of the conduits were found with preexisting pull cord.

The initial percentages for preexisting pull wire and pull cord tend to weight each expert's composite probability distribution toward a higher estimated likelihood of damage. Since these effects are relatively small, apply to each conduit group, and are conservative, the distributions were not recomputed to account for the final verified field results for these percentages.

Input was also obtained from experts on the effects from two other factors of concern: the cable jacket material and the cable installation crew work practices. A concern was raised regarding the increased likelihood of damage during pullby events for certain thermoplastic cable jacket materials; e.g., polyvinylchloride (PVC). After consideration of the frictional forces in each damage susceptibility group, it was concluded that the incremental effects from the cable jacket material are negligible at the extremes of the SWBP range. At very low SWBP values (e.g., for groups A and G), it is quite unlikely to damage any type of jacket unless a pull wire or pull cord has been left in the conduit. These foreign materials have essentially the same effect on all jacket materials under low force conditions. At relatively high SWBP values (e.g., for groups D, E, F, J, and K), it is quite likely that the cable jacket would be damaged during a pullby, regardless of the type of material. Therefore, the incremental increase in damage from thermoplastic jackets is also very small in these groups. However, it was concluded that the jacket material could make a difference in the intermediate range of SWBP values, e.g., for groups B, C, H, and I. Figure 4-1 shows the probability distribution developed for the increase in cable damage likelihood if thermoplastic jacket materials are present in these susceptibility groups. The distribution is expressed in terms of a multiplicative increase in the fraction of conduits that would experience damage when this type of jacket is used, compared with more favorable thermoset jacket materials. For example, it shows that the expert felt that the maximum increase in the likelihood of damage from this effect could be nearly a factor of 6. The most likely increase would be to approximately double the number of conduits with damaged cables in these susceptibility groups. A detailed review of the qualification records for safety-related cables in conduits at WBNP identified approximately 55% of the cable population as having thermoplastic jackets.

The final effect to be considered during this analysis is quite emotional and controversial. It evolved from a number of employee allegations that certain cable installation crews at WBNP were not following approved work practices. These allegations led to the identification of a number of "suspect" crew foremen. There was no evidence to indicate that any crews willfully damaged cables. Instead, the concerns focused on installation practices that "cut corners" to improve efficiency at the expense of formal quality control. Concerns were raised that there could be a correlation between these "suspect" crews and the damaged cables discovered in both units. Although the actual cable sampling data do not show a strong correlation, it was decided to also account for this effect probabilistically during the analysis. Figure 4-2 shows the expert probability distributions proposed for the effects from "suspect" crews. These distributions are also expressed in terms of the multiplicative increase in the fraction of conduits that would experience cable damage if the pulls were made by a "suspect" crew, compared with a "nonsuspect" crew. At SWBP values within current TVA allowances (e.g., for groups A, B, G, and H), it was felt that the "suspect" crews could cause a small but measurable increase in the number of damaged cables. The solid curve in

Figure 4-2 shows the maximum value of this effect to be less than three times as many damaged cables, with the most likely value to be only an increase of approximately 25%. These relatively small values reflect the ease of these cable pulls and the belief that the "suspect" screws were not actively violating routine installation practices. The expert believed that the impact from these crews would increase at moderate SWBP values above the current TVA limits; e.g., for groups C and I. The dashed curve in Figure 4-2 shows the effect from the increased difficulty of these cable pulls. The maximum value of the multiplier has increased to approximately 3½ times as many damaged cables, and the most likely effect is to approximately double the frequency of damage. The expert became more uncertain about the effect from "suspect" screws at high SWBP values; e.g., for groups D, E, F, J, and K. At these values, one conclusion could be drawn that the pulls are so difficult that even "expert" crews would be quite likely to damage cables. This conclusion would indicate that the incremental effect from the "suspect" crews would be a negligible increase in the likelihood of damage. On the other hand, if "expert" crews could successfully install the cables under these conditions, crews that "cut corners" would almost certainly cause much more damage. Thus, the dotted curve in Figure 4-2 is quite broad. Its maximum value reaches approximately 5½ times as much damage as a "nonsuspect" crew, and its most likely impact is to nearly triple the number of damaged cables. A confidential list of crews involved with installation of the cables examined at WBNP Unit 1 revealed that a "suspect" crew pulled at least one set of cables into approximately 36% of the sampled conduits.

A minor explanatory comment may be necessary to avoid confusion when reviewing Figures 4-1 and 4-2 and their use in subsequent calculations. These probability distributions are expressed in terms of a multiplicative effect on the likelihood of observing cable damage for each applicable susceptibility group. The experts questioned about these effects felt most comfortable about expressing their state of knowledge in these terms; e.g., "twice as many cables would be damaged." Of course, if the likelihood of damage from other causes is already quite high, strict linear multiplication by these factors is meaningless. In these cases, the adverse effect was judged to simply increase the likelihood of damage to unity; i.e., all conduits would contain damaged cables. This seems to be a reasonable interpretation of the experts' conclusions. For example, if the fraction of conduits that have damaged cables from all other causes combined is equal to or greater than 25%, and the multiplicative effect from "suspect" crews is 4, then the experts believe that all conduits that are worked on by "suspect" crews under these conditions will contain damaged cables. If the likelihood of damage from other causes is less than 25%, then the "suspect" crew effect simply applies as a multiplier.

Table 4-30 lists the equations used to combine each expert prior probability distribution from Tables 4-1 through 4-29 with the appropriate multiplicative impacts from the jacket materials and "suspect" crews summarized in Figures 4-1 and 4-2. The distributions were combined using the PLG computer code STADIC (Reference 7). Figures 4-3 through 4-31 show the results from this combination process for each expert and each damage susceptibility group. The dashed curve in each figure shows the results from the combined effects of conduit geometry, internal configuration, and jacket material. The solid curve is the final prior probability distribution after the effects from the "suspect" crews have been added. The curves were plotted in this format to graphically illustrate the fact that under most conditions, the incremental damage attributed to the "suspect" crews is quite small. In other words, the experts believe that other causes dominate the likelihood that cables will be damaged during pullby events. Therefore, although the "suspect" crew allegations are politically quite sensitive and emotional, these evaluations indicate that the quantitative impact from these

crews is relatively unimportant when compared with other factors that more directly influence the likelihood of damage.

The major parameters of each final probability distribution in Figures 4-3 through 4-31 are summarized in Tables 4-31 through 4-33. Both expert distributions are listed together for each damage susceptibility group to facilitate comparisons. These tables show that the experts were generally in close agreement about the likelihood of pullby damage at very low and very high SWBP values; e.g., for groups A, E, and F for voltage levels VI and V2; groups G, H, and K for voltage level V3; and groups G, H, I, and K for voltage level V4. They differed at intermediate SWBP values. This is quite understandable. It illustrates consensus on conditions that are well known to be acceptable and consensus on conditions that are well beyond normal acceptance criteria. It also illustrates the relatively broad uncertainties that result from a lack of extensive experience and data for pullby events under conditions that marginally exceed normally recommended pulling forces.

Three other minor observations from Tables 4-31 through 4-33 are worth noting. The experts were consistent in their assessments that V4 cables are less likely to experience damage than V3 cables under the same conditions. They were also consistent in their assessments that V1 and V2 cables are more likely to experience damage than V3 cables under the same conditions. It is also apparent that expert 2 was usually somewhat more pessimistic than expert 1 in his assessments of the likelihood of experiencing damage.

The last step in the process of developing the baseline prior probability distributions was to input each final (i.e., solid) expert distribution from Figures 4-8 through 4-31 into the PLG computer code BARP (Reference 8). Each expert was assigned an equal weight, and the two distributions were merged to provide a single prior probability distribution for the likelihood of pullby damage in each of 16 unique damage susceptibility groups. (Cables in voltage levels V1 and V2 are combined in groups A through F for the remainder of this analysis. Cables in voltage levels V3 and V4 are analyzed separately in groups G through K. Thus, the 22 physical groups listed in Table 3-37 are collapsed into 16 analytically different groups.)

Table 4-1. Expert 1 Elicitation Input for Voltage Level V1 and V2 Susceptibility Group A		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	0	1.00
PULL WIRE IN CONDUIT	.001	1.00
PULL CORD IN CONDUIT	.01	1.00

Table 4-2. Expert 1 Elicitation Input for Voltage Level V1 and V2 Susceptibility Group B		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	0	1.00
PULL WIRE IN CONDUIT	.001	1.00
PULL CORD IN CONDUIT	.02 .03 .04 .05	.10 .60 .20 .10

Table 4-3. Expert 1 Elicitation Input for Voltage Level V1 and V2 Susceptibility Group C		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	0 .001	.60 .40
PULL WIRE IN CONDUIT	.001 .01	.90 .10
PULL CORD IN CONDUIT	.10 .15 .20 .25	.10 .30 .40 .20

Table 4-4. Expert 1 Elicitation Input for Voltage Level V1 and V2 Susceptibility Group D		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	.001 .01 .10 .50	.10 .25 .40 .25
PULL WIRE IN CONDUIT	.01 .10 .20 .50	.10 .40 .25 .25
PULL CORD IN CONDUIT	.25 .40 .60 .80	.10 .50 .20 .20

Table 4-5. Expert 1 Elicitation Input for Voltage Level V1 and V2 Susceptibility Group E		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	.50 .75 .95	.40 .50 .10
PULL WIRE IN CONDUIT	.50 .75 .99	.20 .45 .35
PULL CORD IN CONDUIT	.80 .90 1.00	.15 .65 .20

Table 4-6. Expert 1 Elicitation Input for Voltage Level V1 and V2 Susceptibility Group F		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	.95 .98 1.00	.15 .60 .25
PULL WIRE IN CONDUIT	.99 1.00	.35 .65
PULL CORD IN CONDUIT	1.00	1.00

Table 4-7. Expert 1 Elicitation Input for Voltage Level V3 and V4 Susceptibility Group G		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	0	1.00
PULL WIRE IN CONDUIT	.001	1.00
PULL CORD IN CONDUIT	.01	1.00

Table 4-8. Expert 1 Elicitation Input for Voltage Level V3 and V4 Susceptibility Group H		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	0	1.00
PULL WIRE IN CONDUIT	.001	1.00
PULL CORD IN CONDUIT	.02 .03 .04 .05	.10 .60 .20 .10

Table 4-9. Expert 1 Elicitation Input for Voltage Level V3 and V4 Susceptibility Group I		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	0 .001	.85 .15
PULL WIRE IN CONDUIT	.0005 .001 .01	.20 .45 .35
PULL CORD IN CONDUIT	.04 .06 .09 .10	.15 .15 .60 .10

Table 4-10. Expert 1 Elicitation Input for Voltage Level V3 Susceptibility Group J		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	.001 .05 .20	.25 .50 .25
PULL WIRE IN CONDUIT	.01 .05 .10 .30	.10 .35 .35 .20
PULL CORD IN CONDUIT	.10 .25 .40 .50	.10 .50 .20 .20

Table 4-11. Expert 1 Elicitation Input for Voltage Level V3 Susceptibility Group K		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	.20 .50 .75 1.00	.15 .50 .25 .10
PULL WIRE IN CONDUIT	.30 .60 .80 1.00	.10 .35 .35 .20
PULL CORD IN CONDUIT	.50 .80 1.00	.10 .70 .20

Table 4-12. Expert 1 Elicitation Input for Voltage Level V4 Susceptibility Group J		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	.001 .01 .10	.25 .50 .25
PULL WIRE IN CONDUIT	.01 .05 .10 .30	.10 .35 .35 .20
PULL CORD IN CONDUIT	.10 .15 .20 .25	.10 .50 .20 .20

Table 4-13. Expert 1 Elicitation Input for Voltage Level V4 Susceptibility Group K		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	.20 .30 .60 1.00	.25 .50 .15 .10
PULL WIRE IN CONDUIT	.30 .50 .70 1.00	.10 .35 .35 .20
PULL CORD IN CONDUIT	.25 .50 .75 1.00	.10 .20 .50 .20

Table 4-14. Expert 2 Elicitation Input for Voltage Level V1 and V2 Susceptibility Group A		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	0	1.00
PULL WIRE IN CONDUIT	0	1.00
PULL CORD IN CONDUIT	0 .01 .02	.70 .15 .15

Table 4-15. Expert 2 Elicitation Input for Voltage Level V1 and V2 Susceptibility Group B		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	0 .01 .03	.80 .15 .05
PULL WIRE IN CONDUIT	0 .01 .03 .05 .10	.15 .15 .30 .30 .10
PULL CORD IN CONDUIT	.10 .15 .25 .35 .50 .60	.15 .15 .20 .20 .20 .10

Table 4-16. Expert 2 Elicitation Input for Voltage Level V1 and V2 Susceptibility Group C		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	.10 .20 .25 .30 .35 .50	.10 .25 .40 .10 .10 .05
PULL WIRE IN CONDUIT	.25 .30 .33 .40 .50 .60 .70	.10 .10 .15 .20 .25 .15 .05
PULL CORD IN CONDUIT	.25 .40 .50 .60 .70	.15 .15 .40 .20 .10

Table 4-17. Expert 2 Elicitation Input for Voltage Level V1 and V2 Susceptibility Group D		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	.60 .70 .75 .85 .90 1.00	.05 .05 .20 .40 .20 .10
PULL WIRE IN CONDUIT	.70 .75 .80 .85 .90 .95 1.00	.05 .05 .10 .10 .40 .20 .10
PULL CORD IN CONDUIT	.75 .80 .85 .93 .95 1.00	.05 .05 .20 .40 .20 .10

Table 4-18. Expert 2 Elicitation Input for Voltage Level V1 and V2 Susceptibility Group E		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	.93 .95 .97 .99 1.00	.05 .20 .35 .30 .10
PULL WIRE IN CONDUIT	.93 .95 .97 .99 1.00	.05 .05 .15 .25 .50
PULL CORD IN CONDUIT	.97 .99 .995 1.00	.05 .15 .15 .65

Table 4-19. Expert 2 Elicitation Input for Voltage Level V1 and V2 Susceptibility Group F		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	.95 .97 .99 1.00	.05 .05 .30 .60
PULL WIRE IN CONDUIT	.98 .99 1.00	.05 .05 .90
PULL CORD IN CONDUIT	1.00	1.00

Table 4-20. Expert 2 Elicitation Input for Voltage Level V3 Susceptibility Group G		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	0	1.00
PULL WIRE IN CONDUIT	0	1.00
PULL CORD IN CONDUIT	0 .01 .02 .05	.50 .20 .15 .15

Table 4-21. Expert 2 Elicitation Input for Voltage Level V3 Susceptibility Group H		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	0 .01 .02 .05	.40 .30 .25 .05
PULL WIRE IN CONDUIT	.01 .05 .10 .15 .20 .25 .30	.10 .10 .10 .40 .10 .10 .10
PULL CORD IN CONDUIT	.10 .25 .40 .50 .60 .75	.05 .15 .20 .40 .15 .05

Table 4-22. Expert 2 Elicitation Input for Voltage Level V3 Susceptibility Group I		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	.15	.05
	.25	.10
	.35	.10
	.50	.30
	.75	.30
	.85	.10
	.90	.05
PULL WIRE IN CONDUIT	.50	.10
	.65	.10
	.75	.20
	.85	.40
	.90	.10
	.95	.05
	1.00	.05
PULL CORD IN CONDUIT	.75	.05
	.80	.05
	.85	.20
	.90	.40
	.95	.15
	1.00	.15

Table 4-23. Expert 2 Elicitation Input for Voltage Level V3 Susceptibility Group J		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	.50 .67 .80 .90 .95 1.00	.05 .05 .30 .40 .15 .05
PULL WIRE IN CONDUIT	.90 .93 .95 .97 1.00	.10 .20 .40 .15 .15
PULL CORD IN CONDUIT	.90 .95 .97 .98 .99 1.00	.05 .05 .10 .40 .20 .20

Table 4-24. Expert 2 Elicitation Input for Voltage Level V3 Susceptibility Group K		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	.80 .85 .90 .95 .99 1.00	.02 .03 .05 .10 .40 .40
PULL WIRE IN CONDUIT	.90 .93 .95 .99 1.00	.02 .03 .05 .15 .75
PULL CORD IN CONDUIT	1.00	1.00

Table 4-25. Expert 2 Elicitation Input for Voltage Level V4 Susceptibility Group G		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	0 .005 .01	.85 .10 .05
PULL WIRE IN CONDUIT	N/A	
PULL CORD IN CONDUIT	N/A	

Table 4-26. Expert 2 Elicitation Input for Voltage Level V4 Susceptibility Group H		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	0 .005 .01	.85 .10 .05
PULL WIRE IN CONDUIT	N/A	
PULL CORD IN CONDUIT	N/A	

Table 4-27. Expert 2 Elicitation Input for Voltage Level V4 Susceptibility Group I		
CONDITIONS	CONDITIONAL FREQUENCY OF PULLBY DAMAGE	CONDITIONAL PROBABILITY
NO PULL WIRE OR CORD IN CONDUIT	0 .01 .05 .075 .10	.40 .45 .10 .04 .01
PULL WIRE IN CONDUIT	N/A	
PULL CORD IN CONDUIT	N/A	

Table 4-28. Expert 2 Elicitation Input for Voltage Level V4 Susceptibility Group J		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	0 .05 .10 .15 .25 .30 .33 .50	.10 .10 .10 .20 .40 .08 .01 .01
PULL WIRE IN CONDUIT	N/A	
PULL CORD IN CONDUIT	N/A	

Table 4-29. Expert 2 Elicitation Input for Voltage Level V4 Susceptibility Group K		
CONDITIONS	**CONDITIONAL FREQUENCY OF PULLBY DAMAGE**	**CONDITIONAL PROBABILITY**
NO PULL WIRE OR CORD IN CONDUIT	.15 .25 .35 .50 .65 .80 .90	.05 .10 .15 .40 .15 .10 .05
PULL WIRE IN CONDUIT	N/A	
PULL CORD IN CONDUIT	N/A	

Table 4-30 (Page 1 of 2). Combination Equations for Baseline Prior Probability Distributions

Voltage Level	Susceptibility Group	Jacket Material Impact (Note 1)	"Suspect" Crew Impact (Note 2)
V1 and V2	A	N/A	C1
V1 and V2	B	J1	C1
V1 and V2	C	J1	C2
V1 and V2	D	N/A	C3
V1 and V2	E	N/A	C3
V1 and V2	F	N/A	C3
V3 and V4	G	N/A	C1
V3 and V4	H	J1	C1
V3 and V4	I	J1	C2
V3 and V4	J	N/A	C3
V3 and V4	K	N/A	C3

Notes:

1. Approximately 55% of cables have thermoplastic jackets. "N/A" indicates jacket material impact is negligible. Distribution J1 is from Figure 4-1.
2. Approximately 36% of sampled conduits from Unit 1 have at least one cable pulled by a "suspect" crew. Distribution C1 is the solid curve; distribution C2 is the dashed curve; and distribution C3 is the dotted curve from Figure 4-2.

Table 4-30 (Page 2 of 2). Combination Equations for Baseline Prior Probability Distributions

Combination Equations

PA = (.64)(EA) + (.36)(EA)(C1)

PB = (.64)(XB) + (.36)(XB)(C1)
XB = (.45)(EB) + (.55)(EB)(J1)

PC = (.64)(XC) + (.36)(XC)(C2)
XC = (.45)(EC) + (.55)(EC)(J1)

PD = (.64)(ED) + (.36)(ED)(C3)

PE = (.64)(EE) + (.36)(EE)(C3)

PF = (.64)(EF) + (.36)(EF)(C3)

PG = (.64)(EG) + (.36)(EG)(C1)

PH = (.64)(XH) + (.36)(XH)(C1)
XH = (.45)(EH) + (.55)(EH)(J1)

PI = (.64)(XI) + (.36)(XI)(C2)
XI = (.45)(EI) + (.55)(EI)(J1)

PJ = (.64)(EJ) + (.36)(EJ)(C3)

PK = (.64)(EK) + (.36)(EK)(C3)

Notes:

1. Each equation applies to the corresponding expert prior probability distribution calculated using Equation (4.1). For example, PA1 uses EA1 calculated from Table 4-1; PA2 uses EA2 calculated from Table 4-14; etc.
2. The distributions for J1, C1, C2, and C3 are described above.
3. The multipliers of 0.55 and 0.45 account for the fact that 55% of the cables have thermoplastic jackets, and 45% do not.
4. The multipliers of 0.36 and 0.64 account for the fact that 36% of the sampled Unit 1 conduits had cables pulled by "suspect crews, and 64% did not.

Table 4-31. Final Expert Prior Probability Distribution Parameters for Voltage Levels V1 and V2

VOLTAGE LEVEL	SUSCEP-TIBILITY GROUP	EXPERT	BASELINE PROBABILITY DISTRIBUTION FOR CONDITIONAL FREQUENCY OF DAMAGE			
			5TH PERCENTILE	50TH PERCENTILE	95TH PERCENTILE	MEAN
V1 AND V2	A	1	0	.0002	.0059	.0025
		2	0	0	.025	.0052
V1 AND V2	B	1	0	.0002	.039	.0069
		2	0	.0010	.12	.022
V1 AND V2	C	1	0	.0009	.20	.036
		2	.18	.39	.61	.44
V1 AND V2	D	1	.0017	.12	.73	.27
		2	.60	.87	.99	.94
V1 AND V2	E	1	.49	.82	.90	.80
		2	.77	.93	.99	.95
V1 AND V2	F	1	.91	.95	1.00	.99
		2	.89	.95	1.00	.99

Table 4-32. Final Expert Prior Probability Distribution Parameters for Voltage Level V3.

VOLTAGE LEVEL	SUSCEP-TIBILITY GROUP	EXPERT	BASELINE PROBABILITY DISTRIBUTION FOR CONDITIONAL FREQUENCY OF DAMAGE			
			5TH PERCENTILE	50TH PERCENTILE	95TH PERCENTILE	MEAN
V3	G	1	0	.0002	.0059	.0025
		2	0	.0001	.023	.0046
V3	H	1	0	.0002	.039	.0069
		2	0	.0011	.21	.036
V3	I	1	0	.0007	.12	.022
		2	.026	.46	.94	.53
V3	J	1	.0022	.030	.40	.10
		2	.67	.88	.99	.97
V3	K	1	.24	.82	.98	.76
		2	.81	.91	.99	.95

Table 4-33. Final Expert Prior Probability Distribution Parameters for Voltage Level V4						
VOLTAGE LEVEL	SUSCEP-TIBILITY GROUP	EXPERT	BASELINE PROBABILITY DISTRIBUTION FOR CONDITIONAL FREQUENCY OF DAMAGE			
			5TH PERCENTILE	50TH PERCENTILE	95TH PERCENTILE	MEAN
V4	G	1	0	.0002	.0059	.0025
		2	0	.0001	.0085	.0027
V4	H	1	0	.0002	.039	.0069
		2	0	.0001	.0096	.0024
V4	I	1	0	.0007	.12	.022
		2	0	.0008	.13	.024
V4	J	1	.0021	.026	.30	.078
		2	0	.0015	.23	.042
V4	K	1	.28	.60	.88	.62
		2	.22	.57	.95	.61

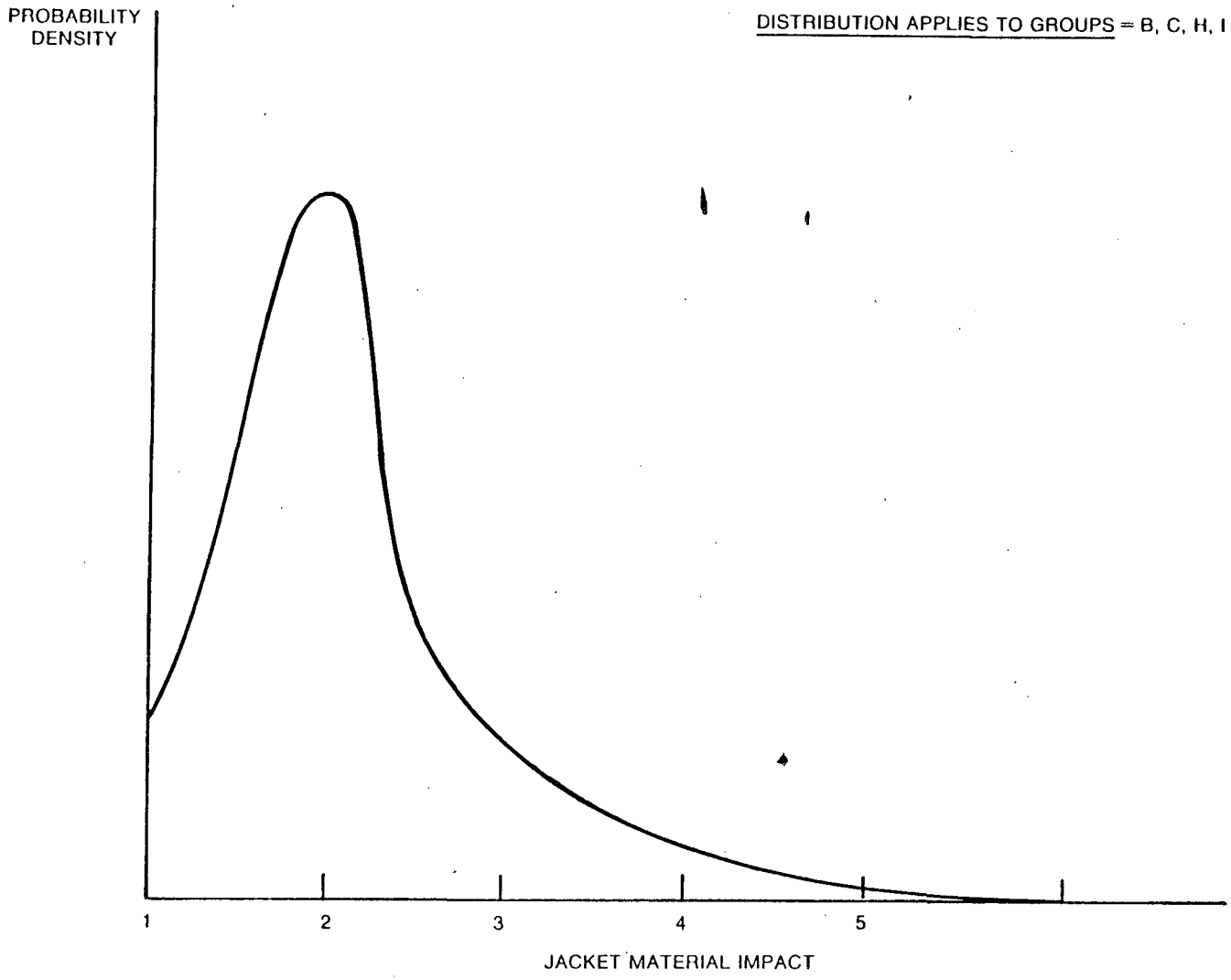

Figure 4-1. Jacket Material Effect Distribution

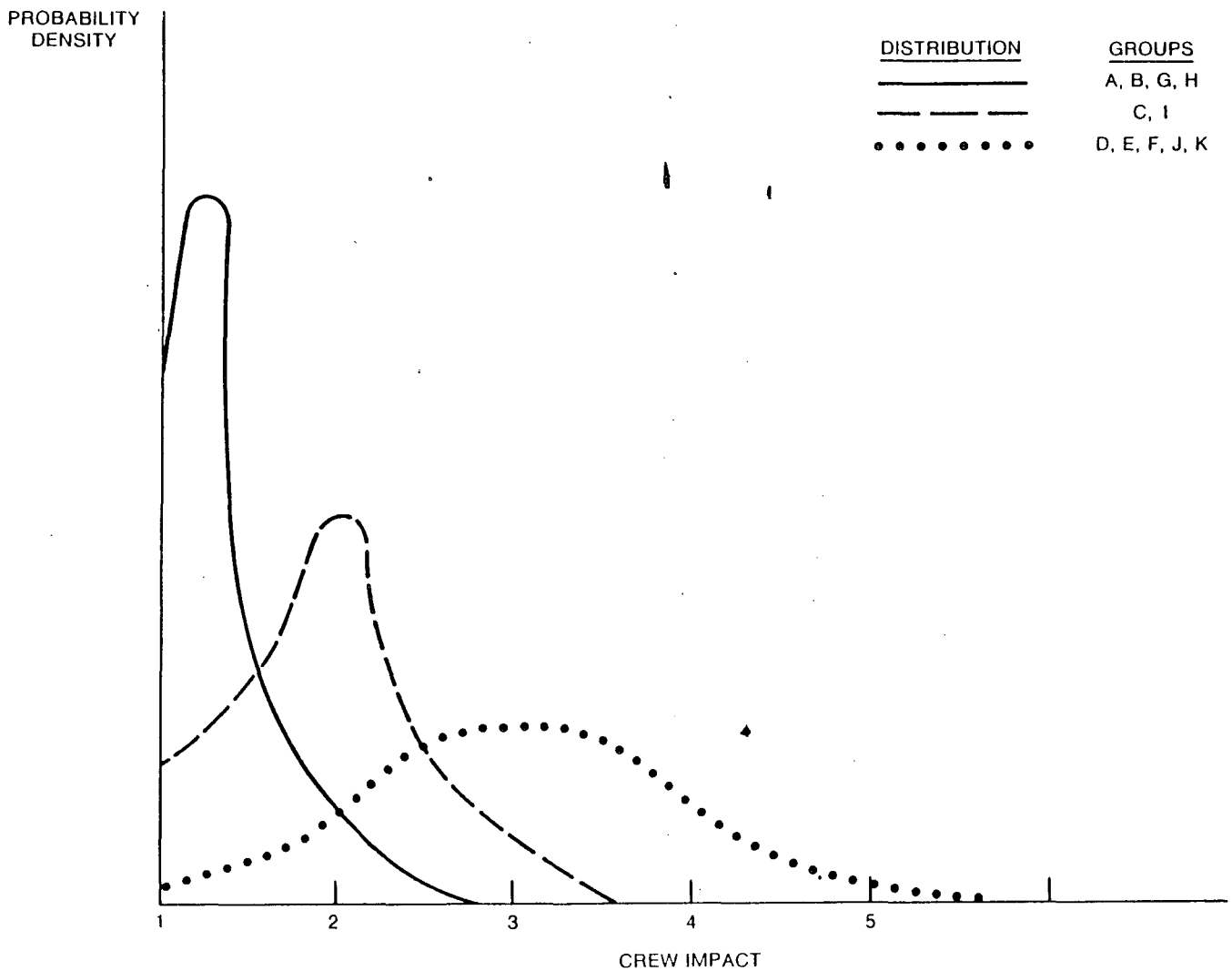

Figure 4-2. Crew Effect Distributions

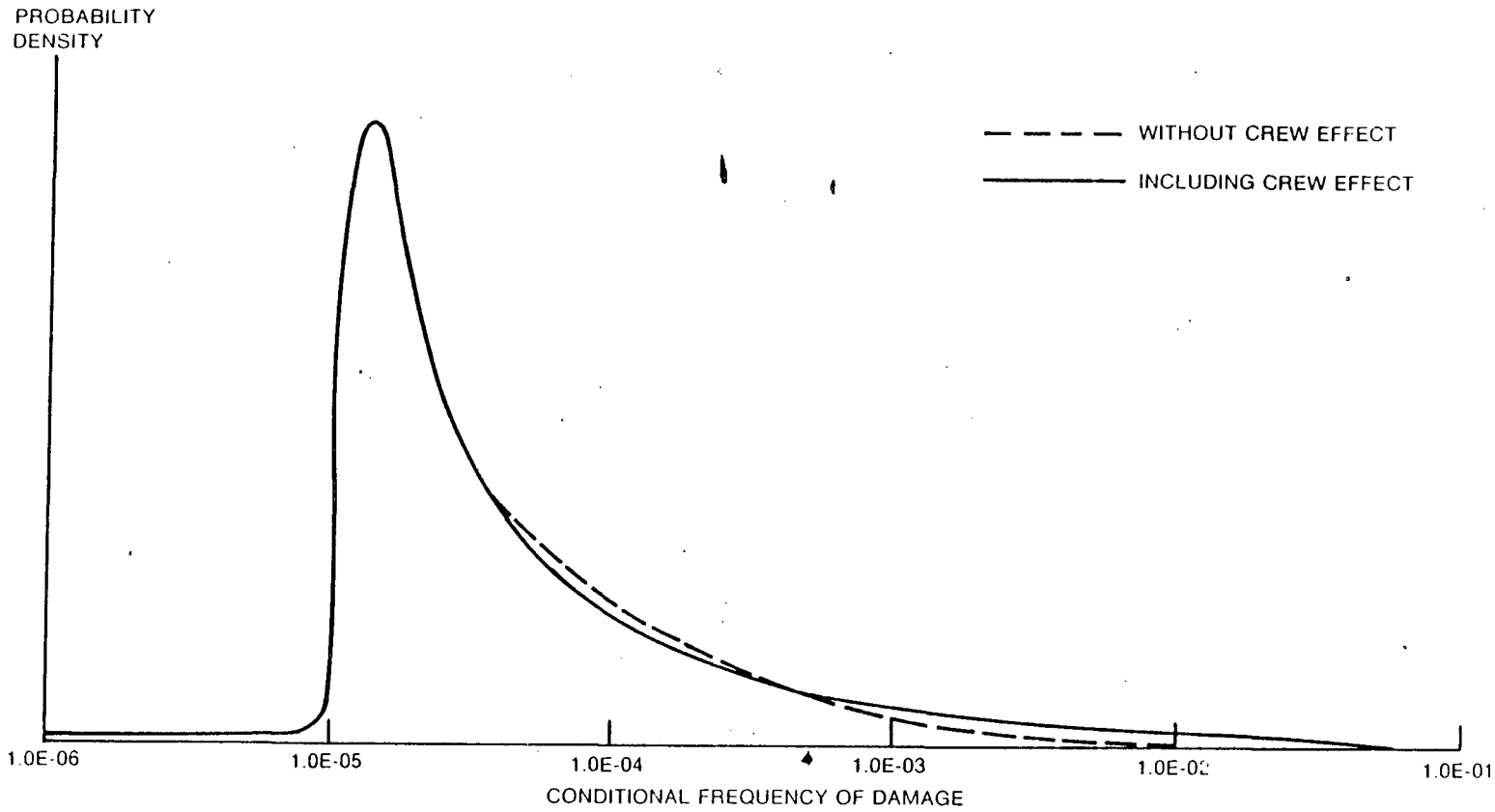

Figure 4-3. Voltage Level V1 and V2 Susceptibility Group A Expert 1 Prior Distribution

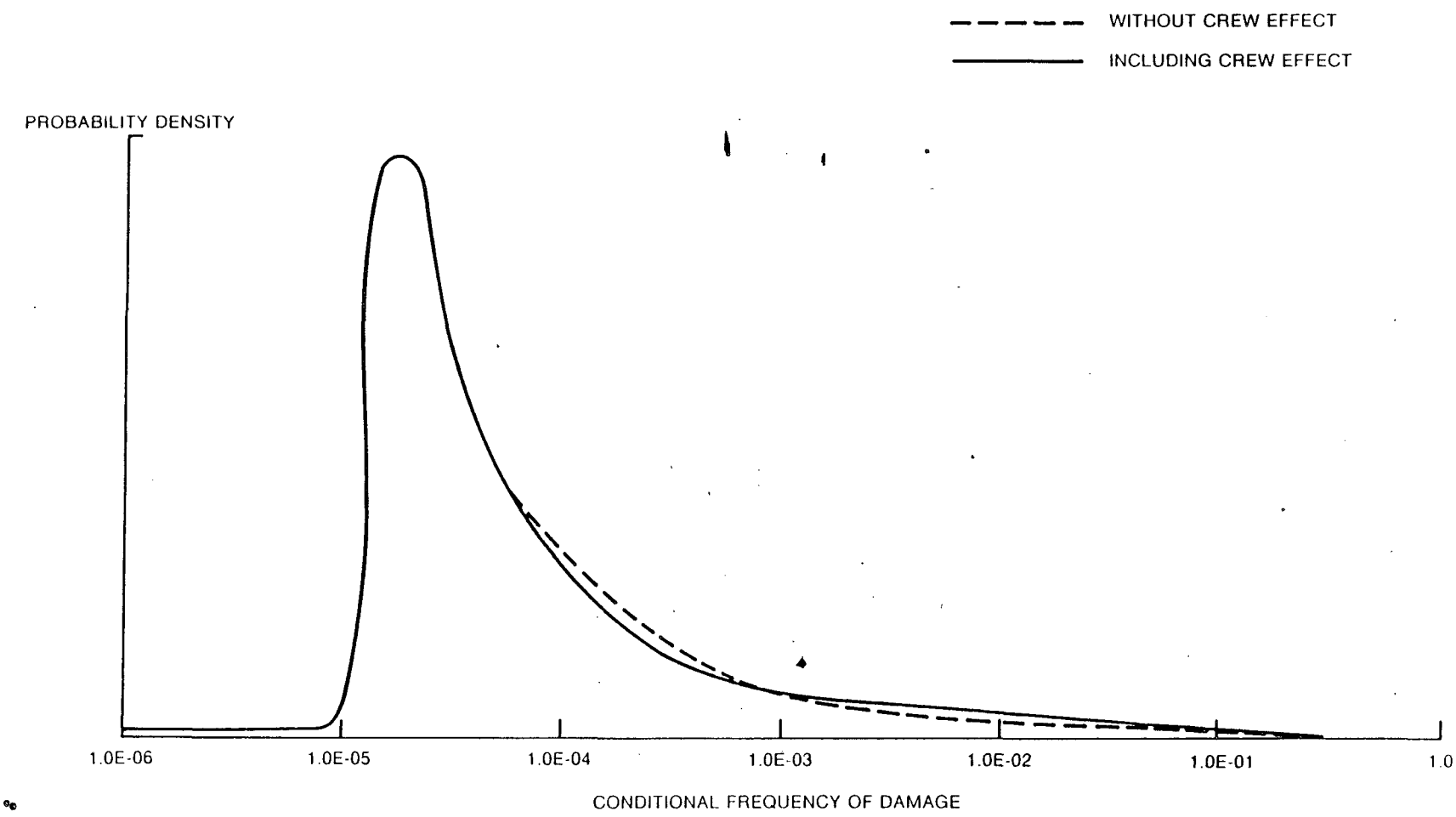

Figure 4-4. Voltage Level V1 and V2 Susceptibility Group B Expert 1 Prior Distribution

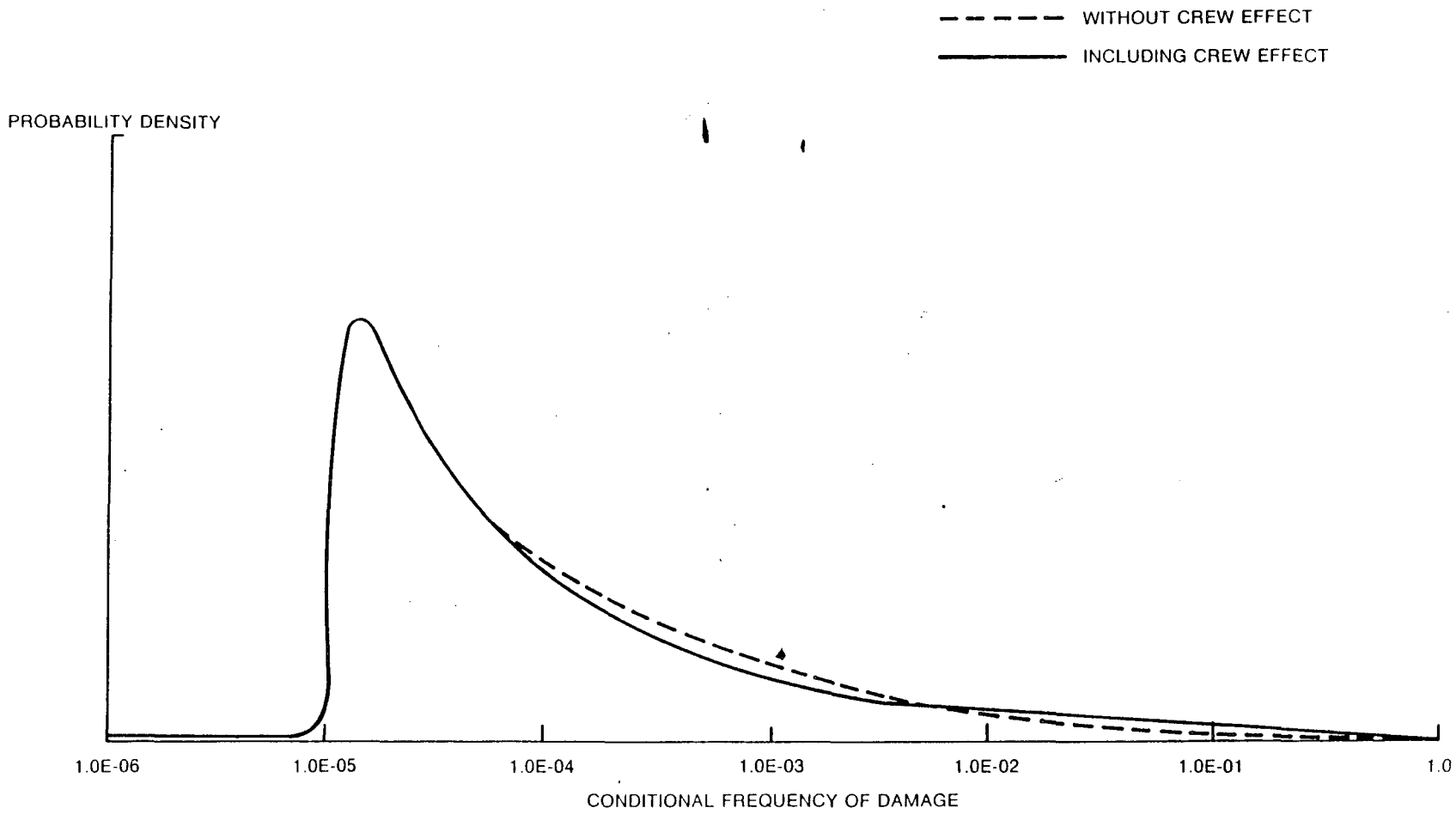

Figure 4-5. Voltage Level V1 and V2 Susceptibility Group C Expert 1 Prior Distribution

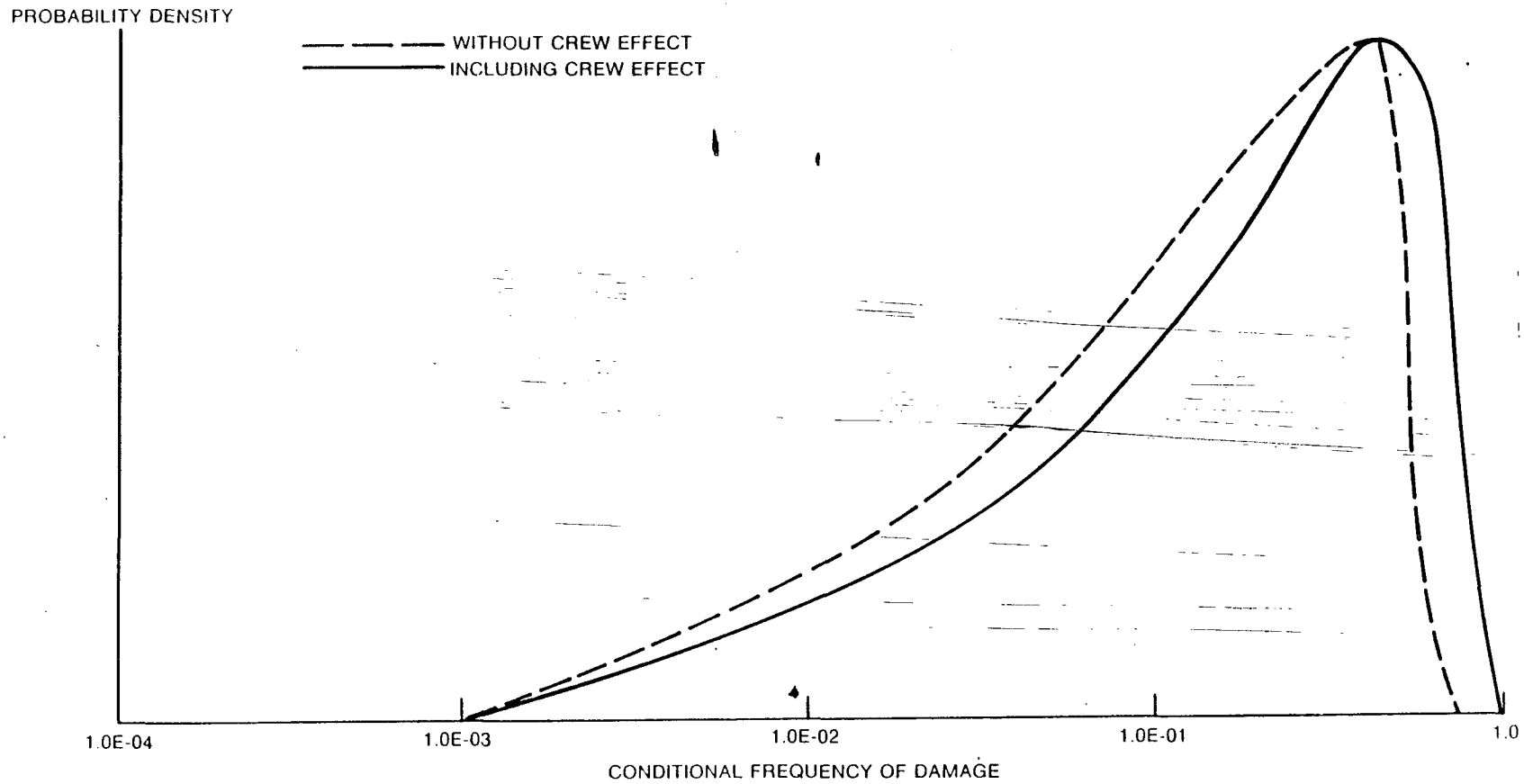

Figure 4-6. Voltage Level V1 and V2 Susceptibility Group D Expert 1 Prior Distribution

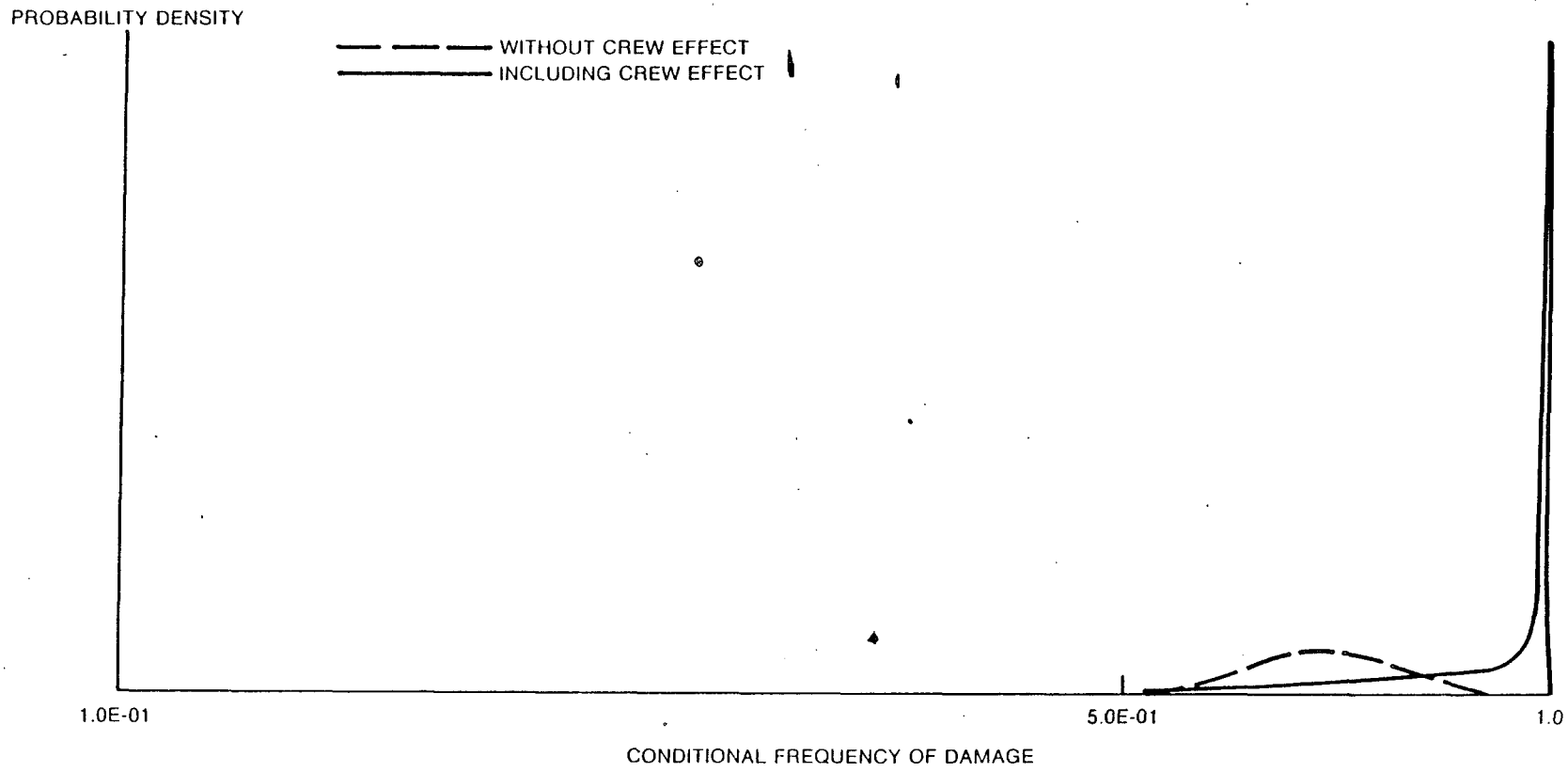

Figure 4-7. Voltage Level V1 and V2 Susceptibility Group E Expert 1 Prior Distribution

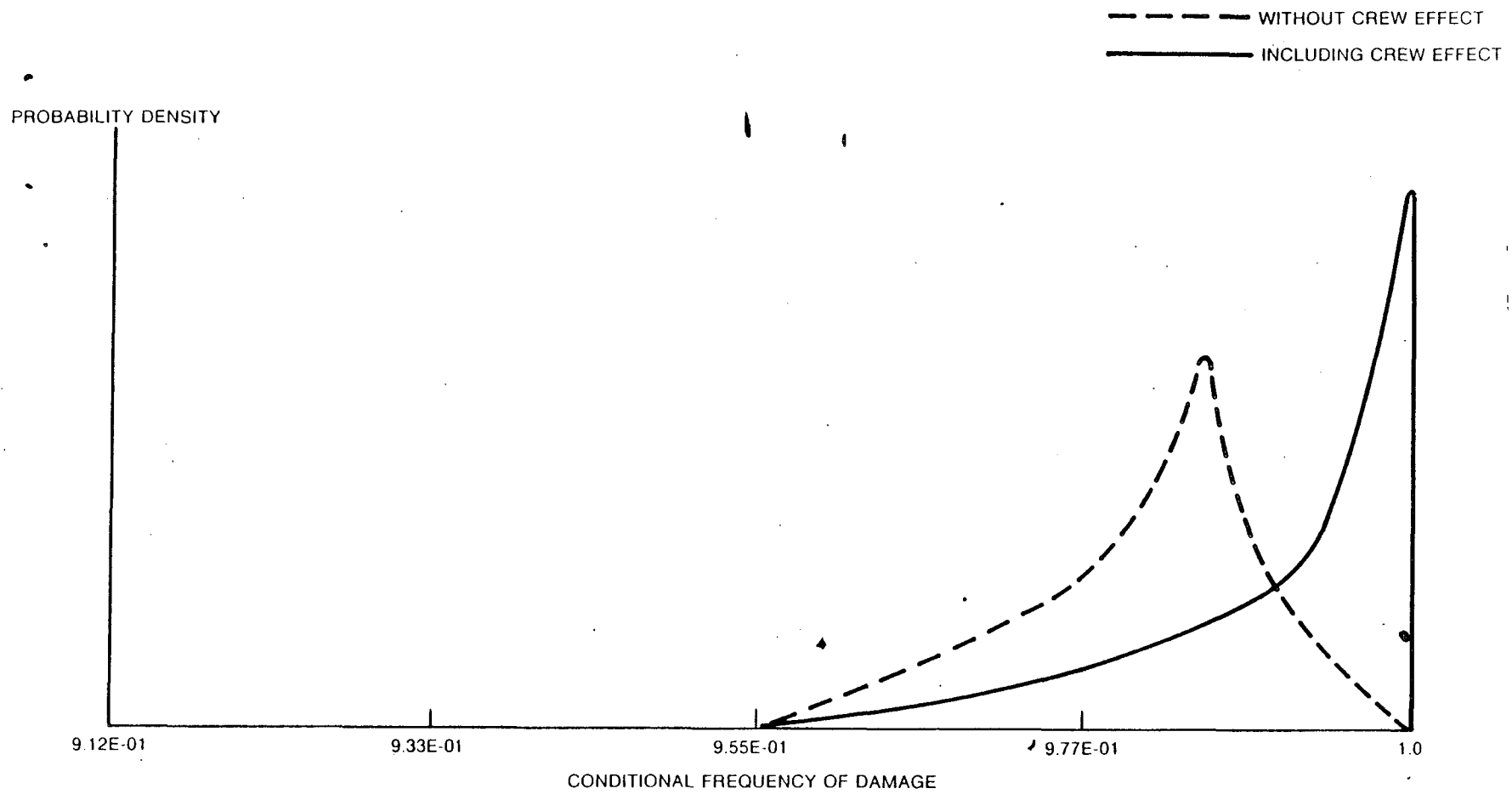

Figure 4-8. Voltage Level V1 and V2 Susceptibility Group F Expert 1 Prior Distribution

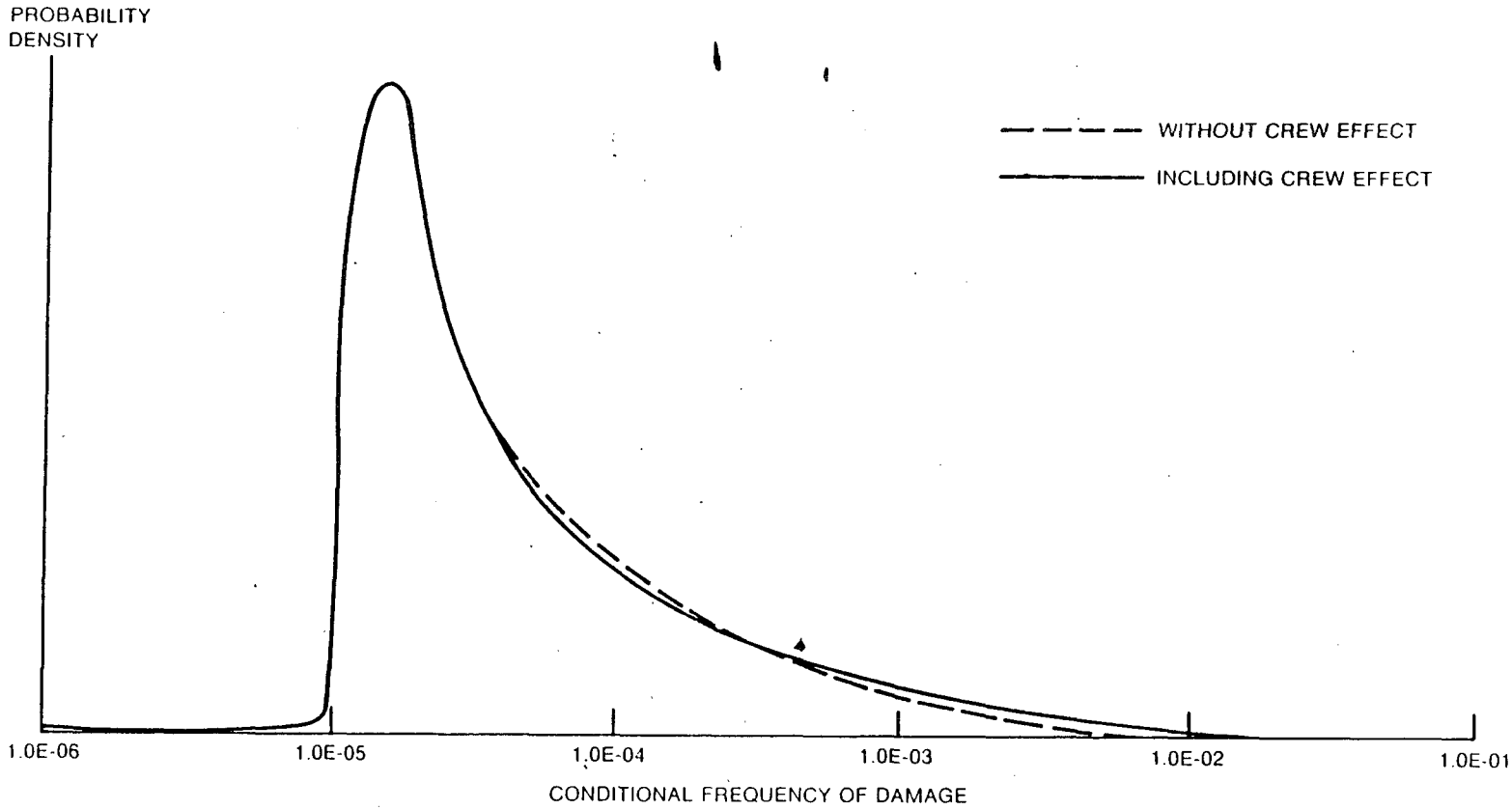

Figure 4-9. Voltage Level V3 and V4 Susceptibility Group G Expert 1 Prior Distribution

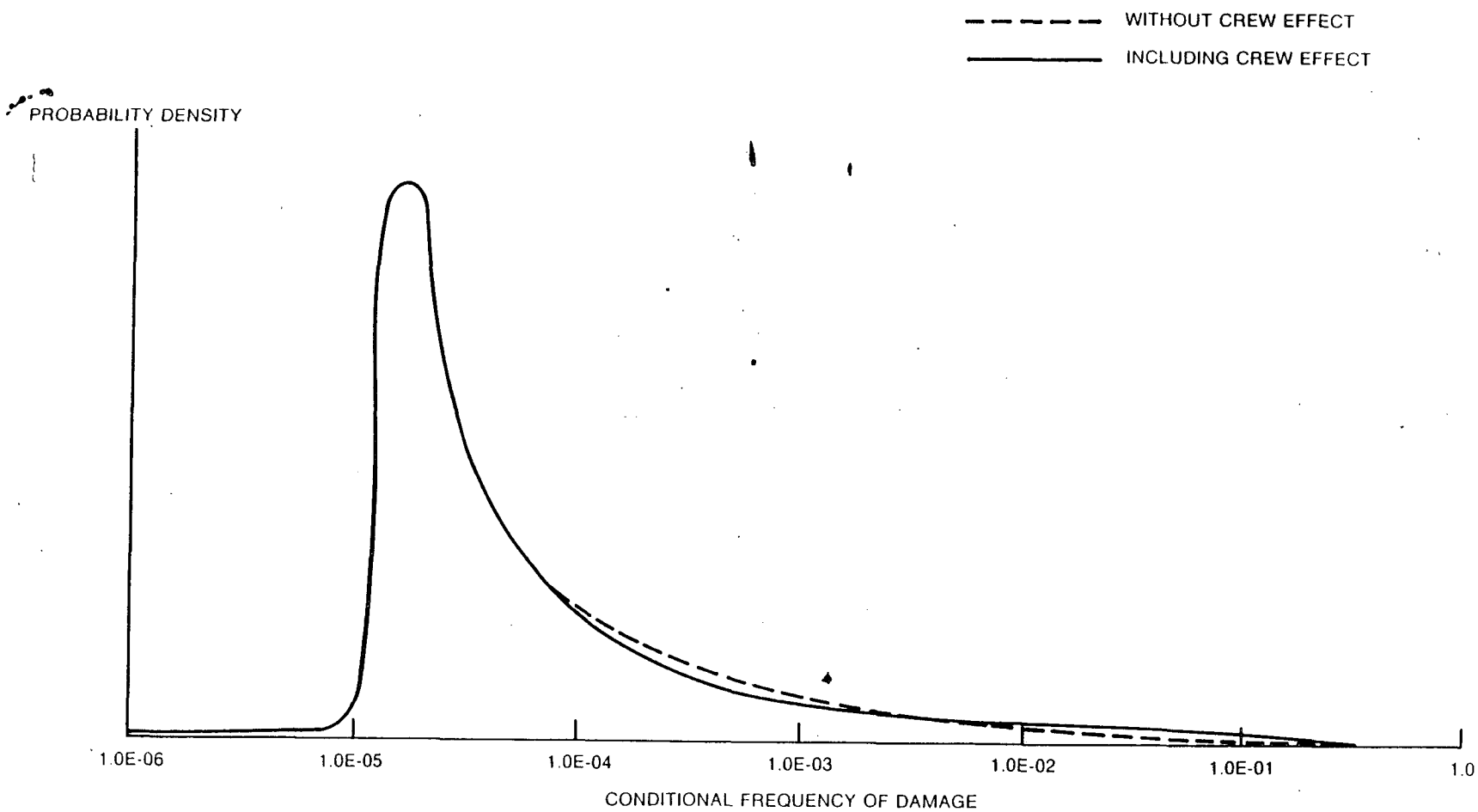

Figure 4-10. Voltage Level V3 and V4 Susceptibility Group H Expert 1 Prior Distribution

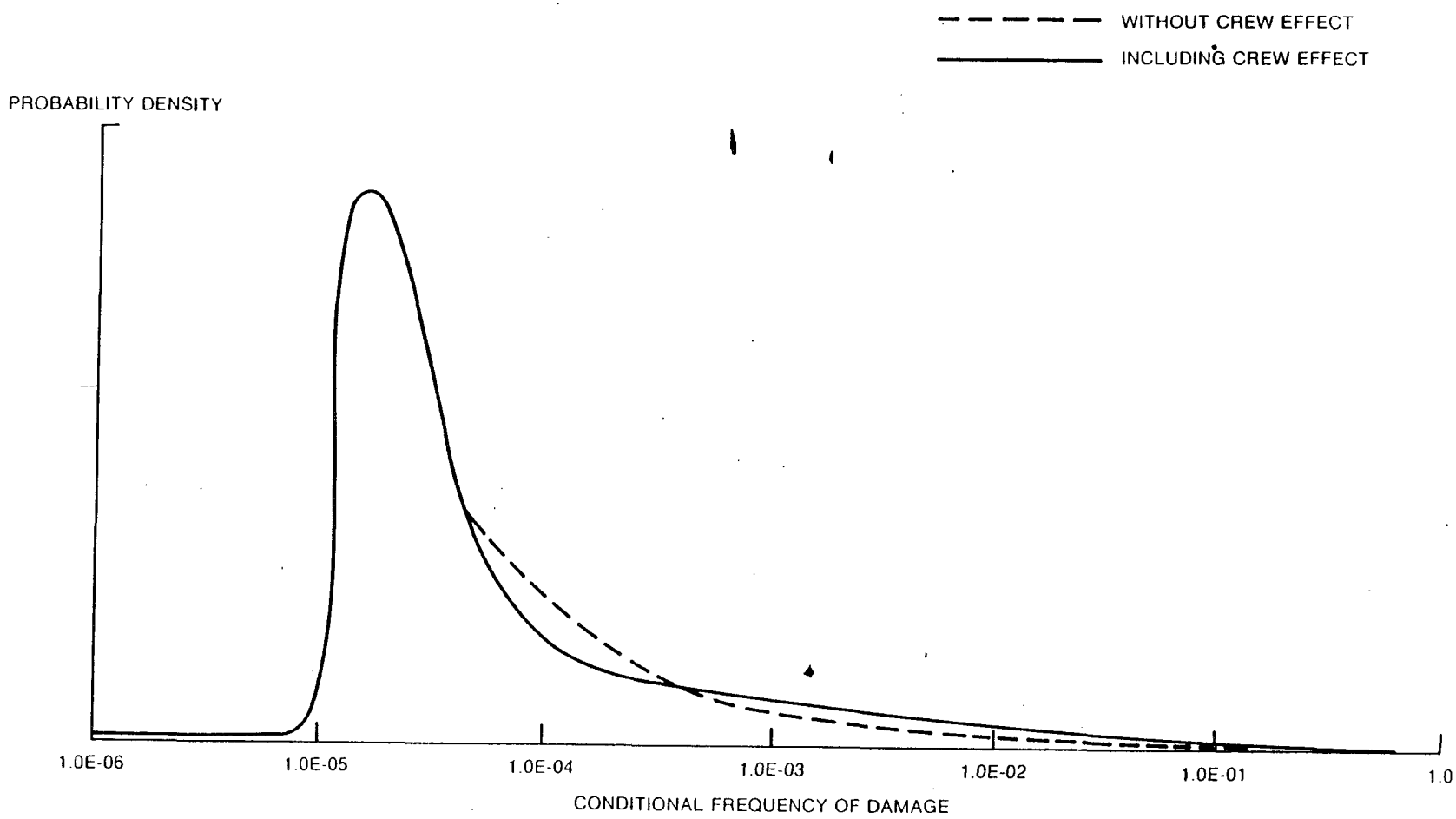

Figure 4-11. Voltage Level V3 and V4 Susceptibility Group I Expert 1 Prior Distribution

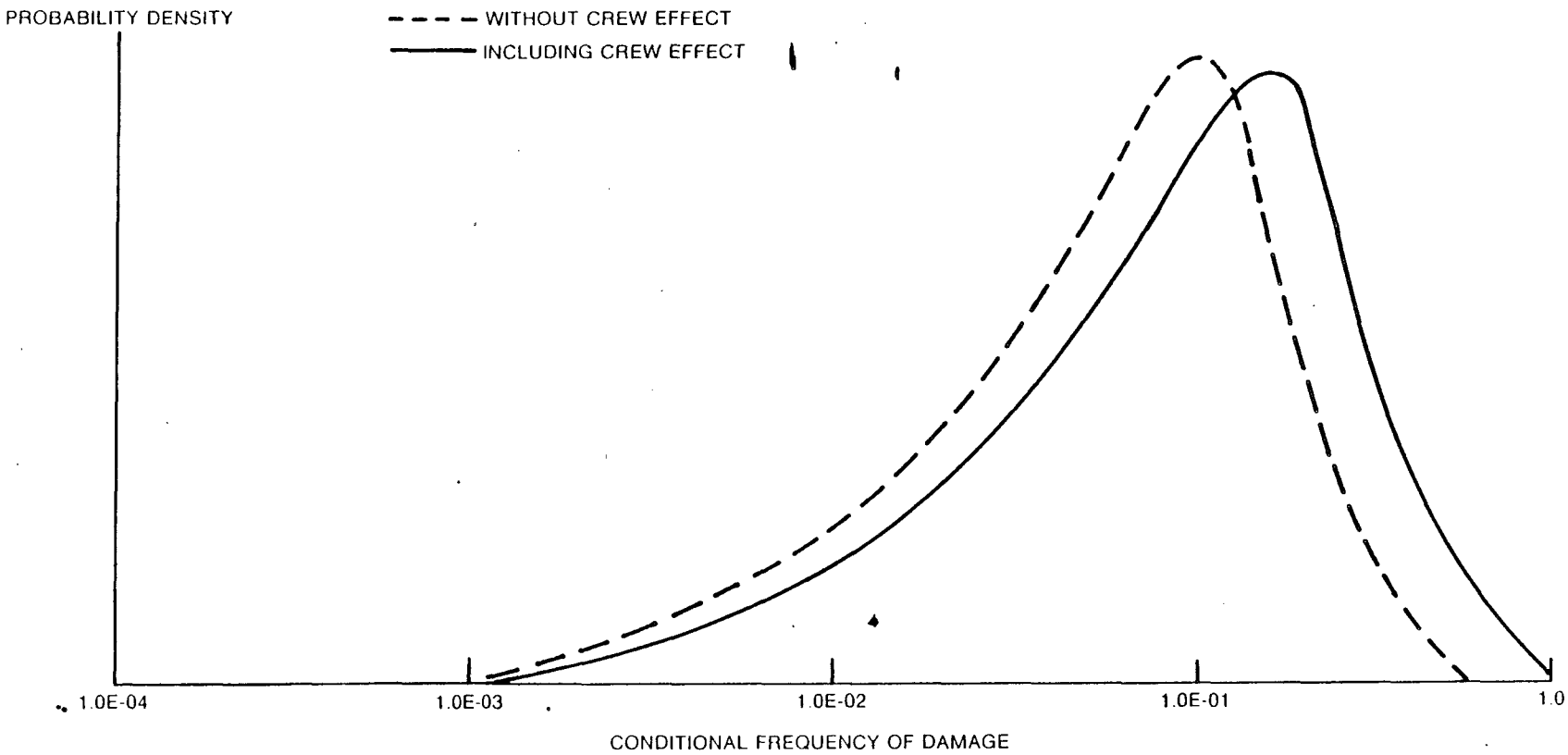

Figure 4-12. Voltage Level V3 Susceptibility Group J Expert 1 Prior Distribution

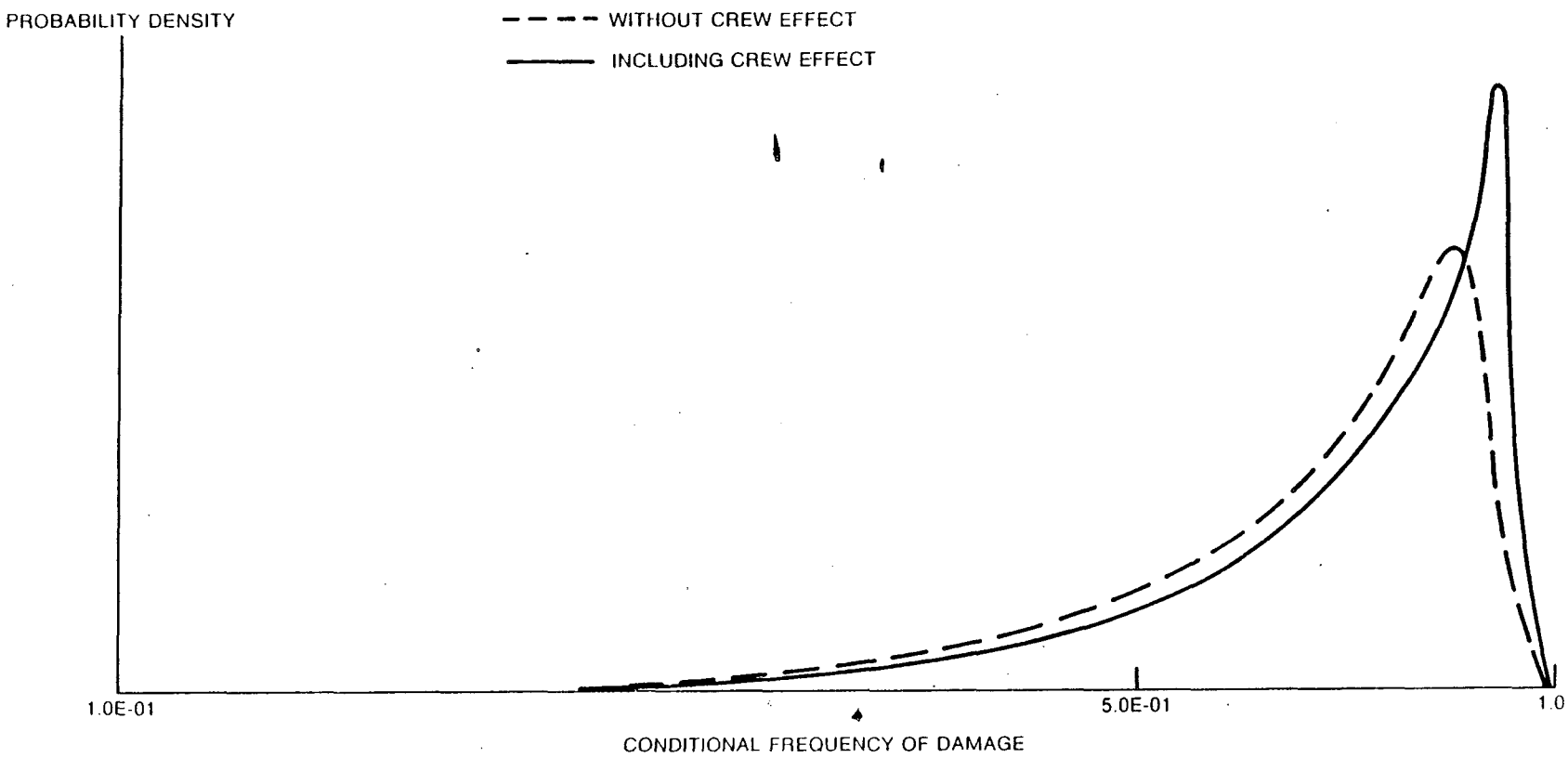

Figure 4-13. Voltage Level V4 Susceptibility Group K Expert 1 Prior Distribution

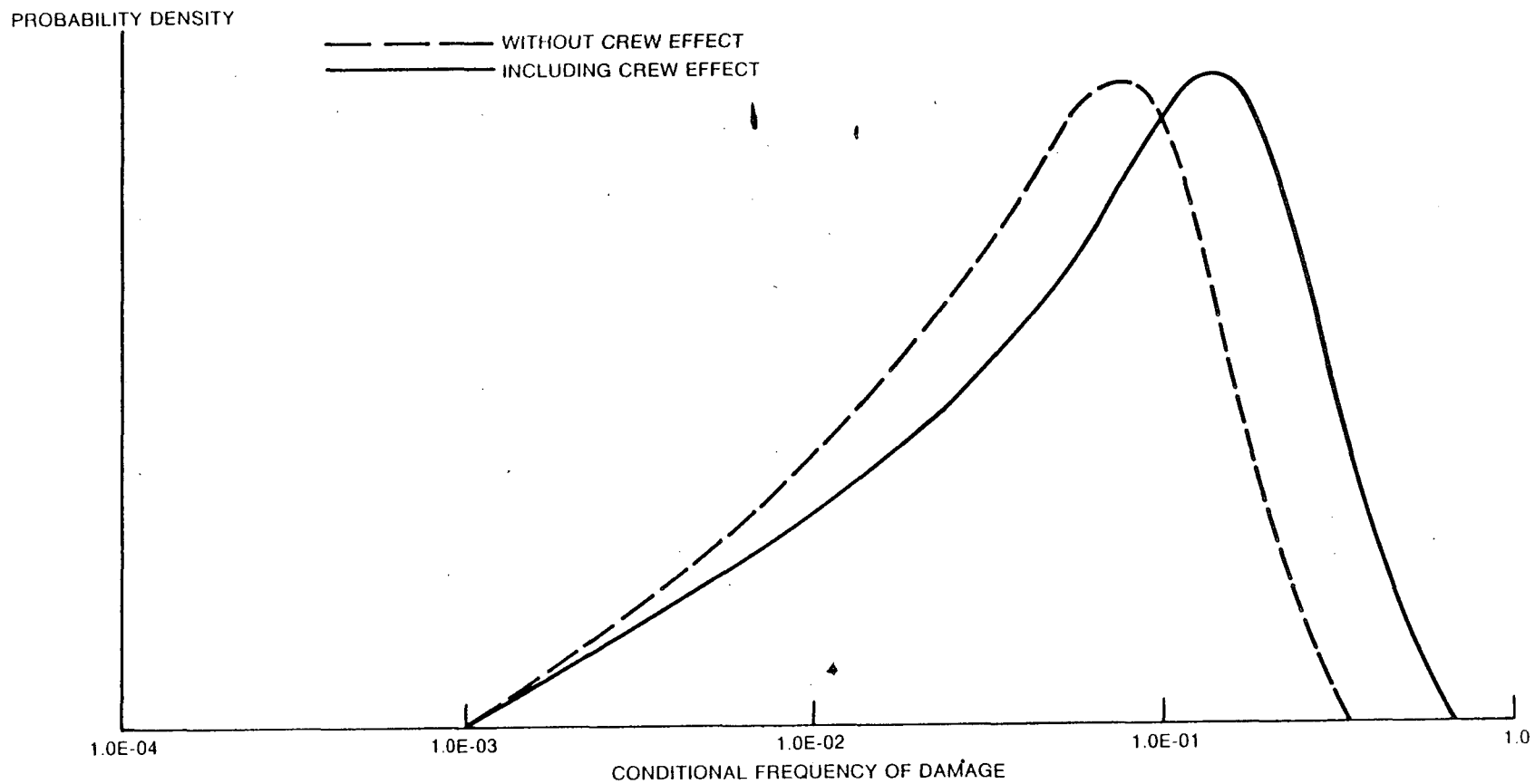

Figure 4-14. Voltage Level V3 Susceptibility Group J Expert 1 Prior Distribution

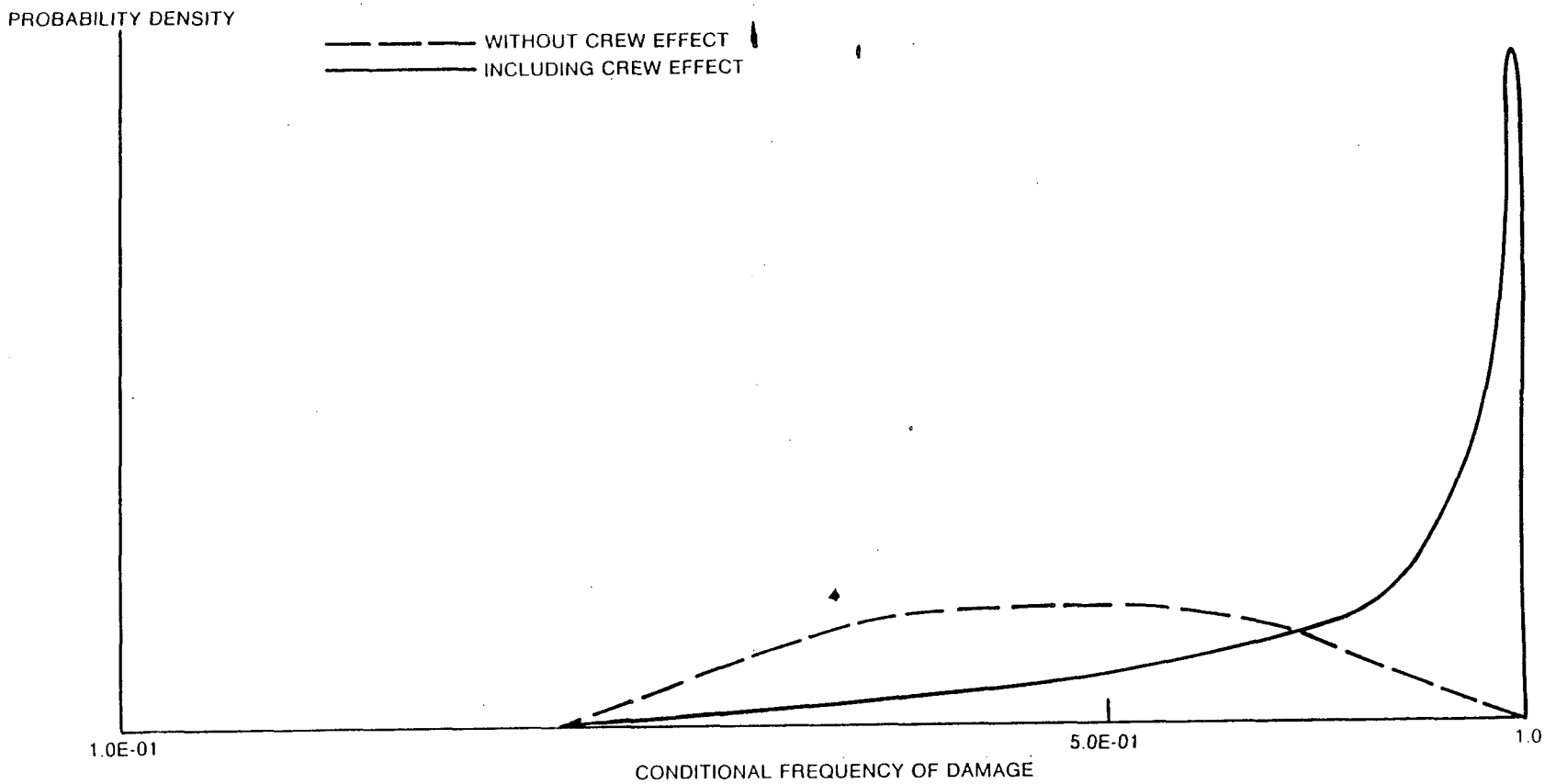

Figure 4-15. Voltage Level V4 Susceptibility Group K Expert 1 Prior Distribution

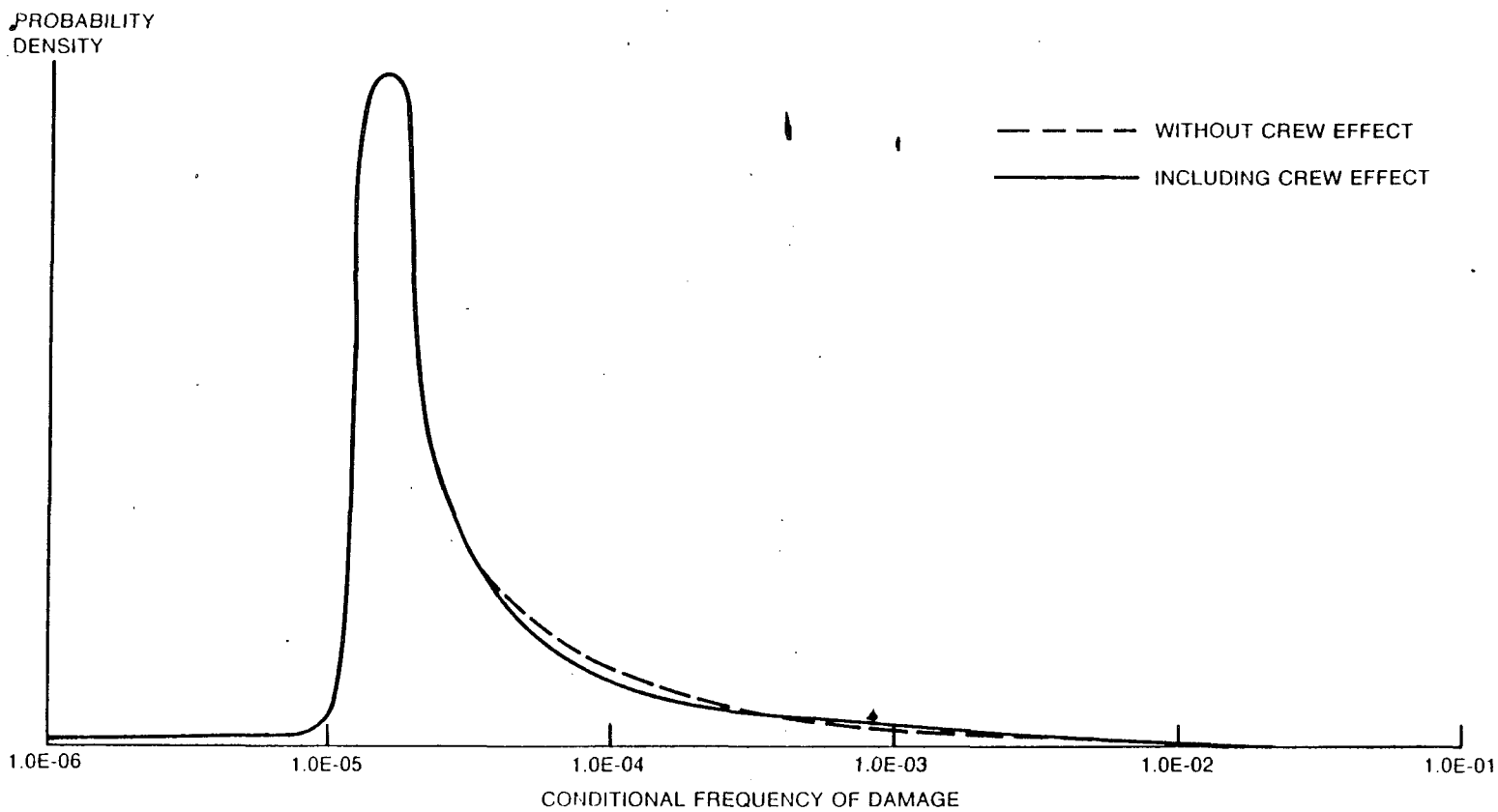

Figure 4-16. Voltage Level V1 and V2-Susceptibility Group A Expert 2 Prior Distribution

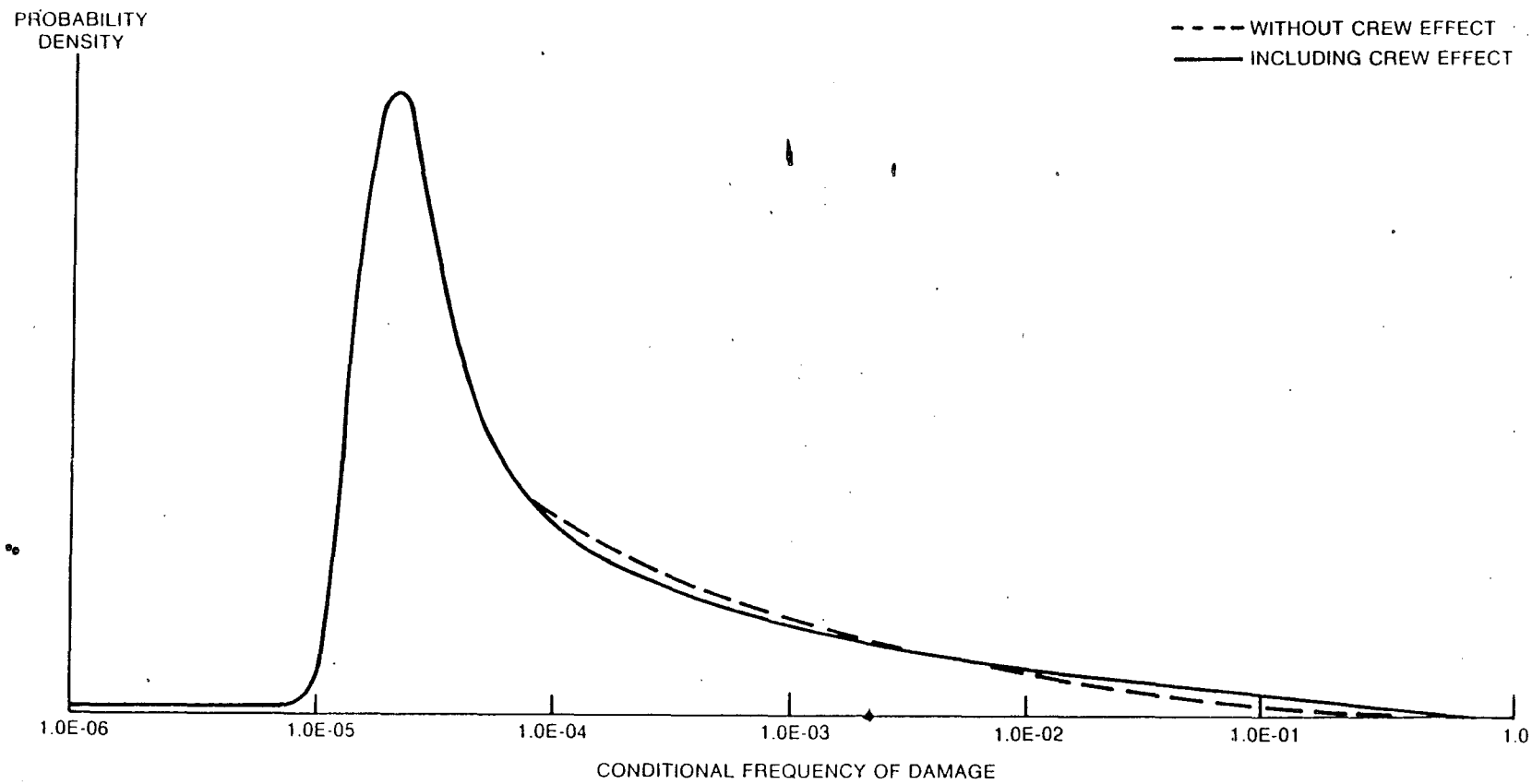

Figure 4-17. Voltage Level V1 and V2 Susceptibility Group B Expert 2 Prior Distribution

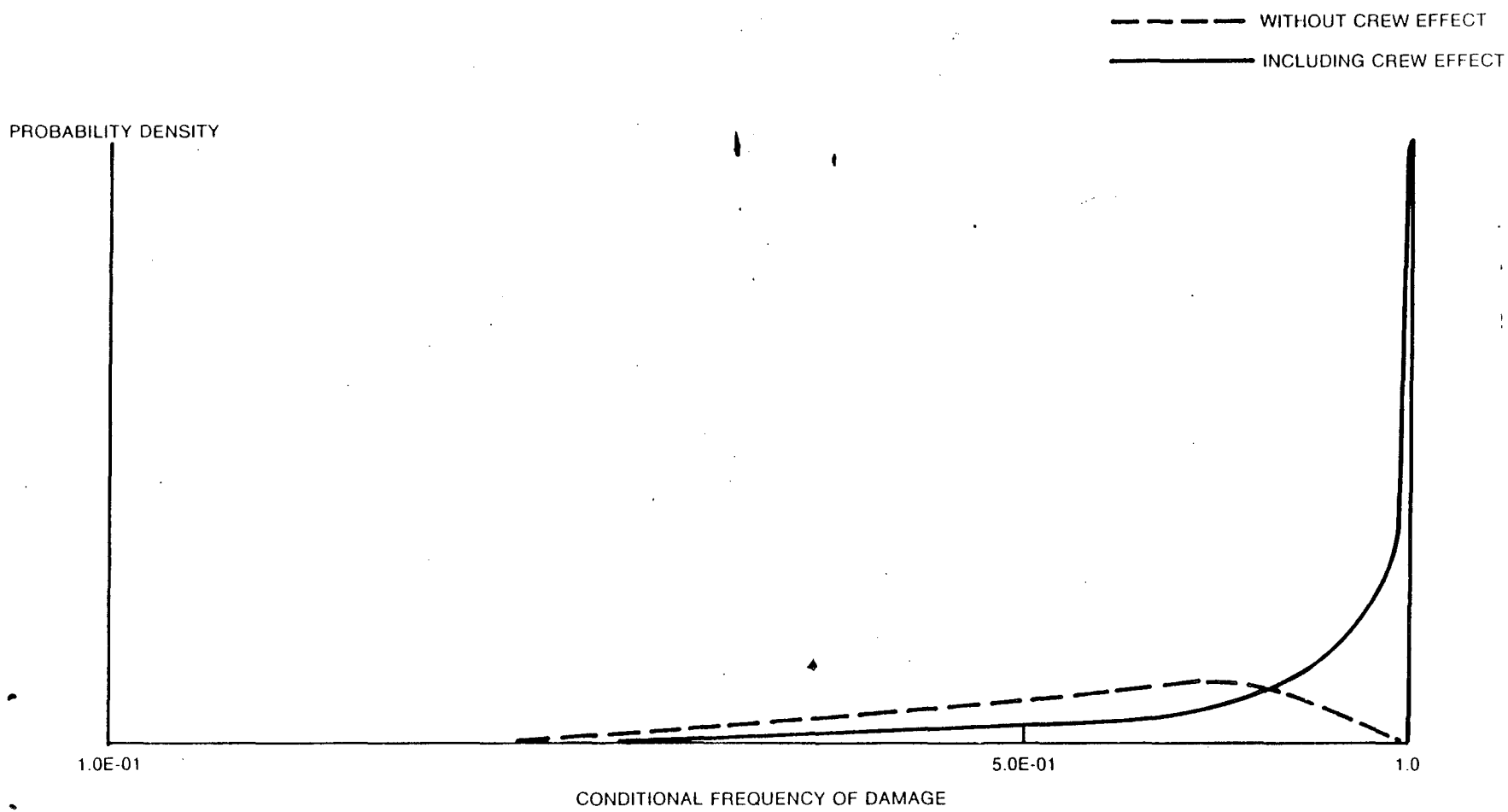

Figure 4-18. Voltage Level V1 and V2 Susceptibility Group C Expert 2 Prior Distribution

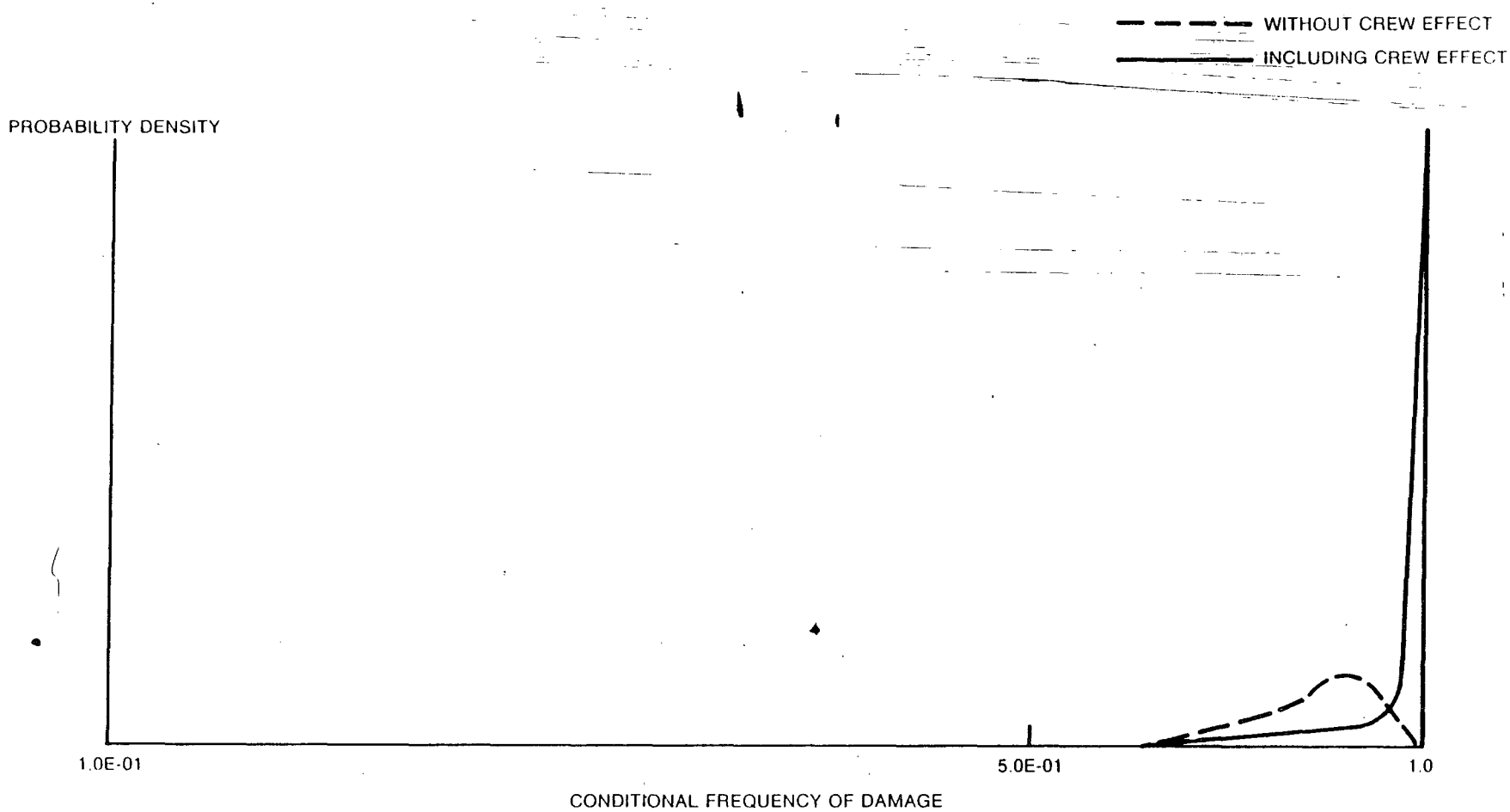

Figure 4-19. Voltage Level V1 and V2 Susceptibility Group D Expert 2 Prior Distribution

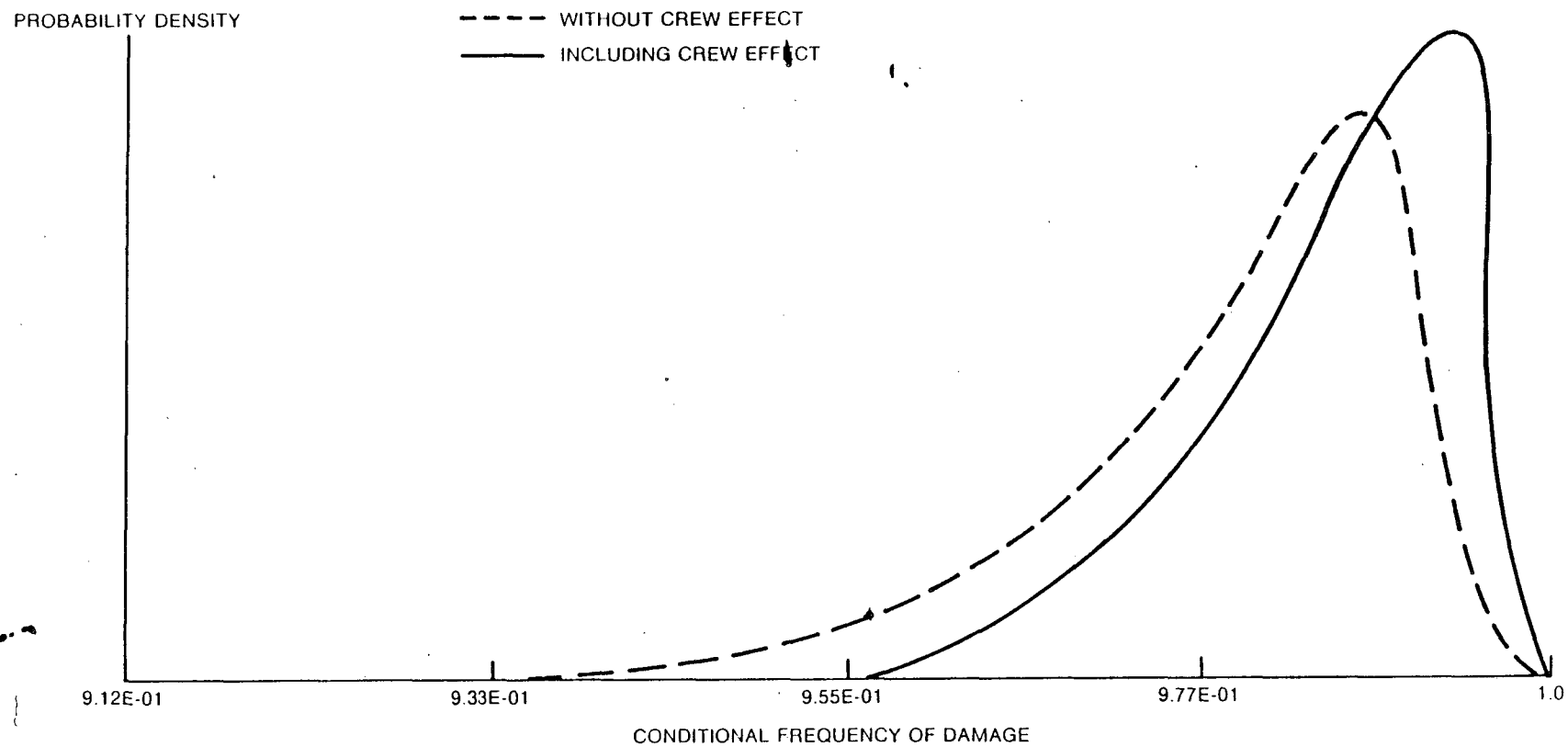

Figure 4-20. Voltage Level V1 and V2 Susceptibility Group E Expert 2 Prior Distribution

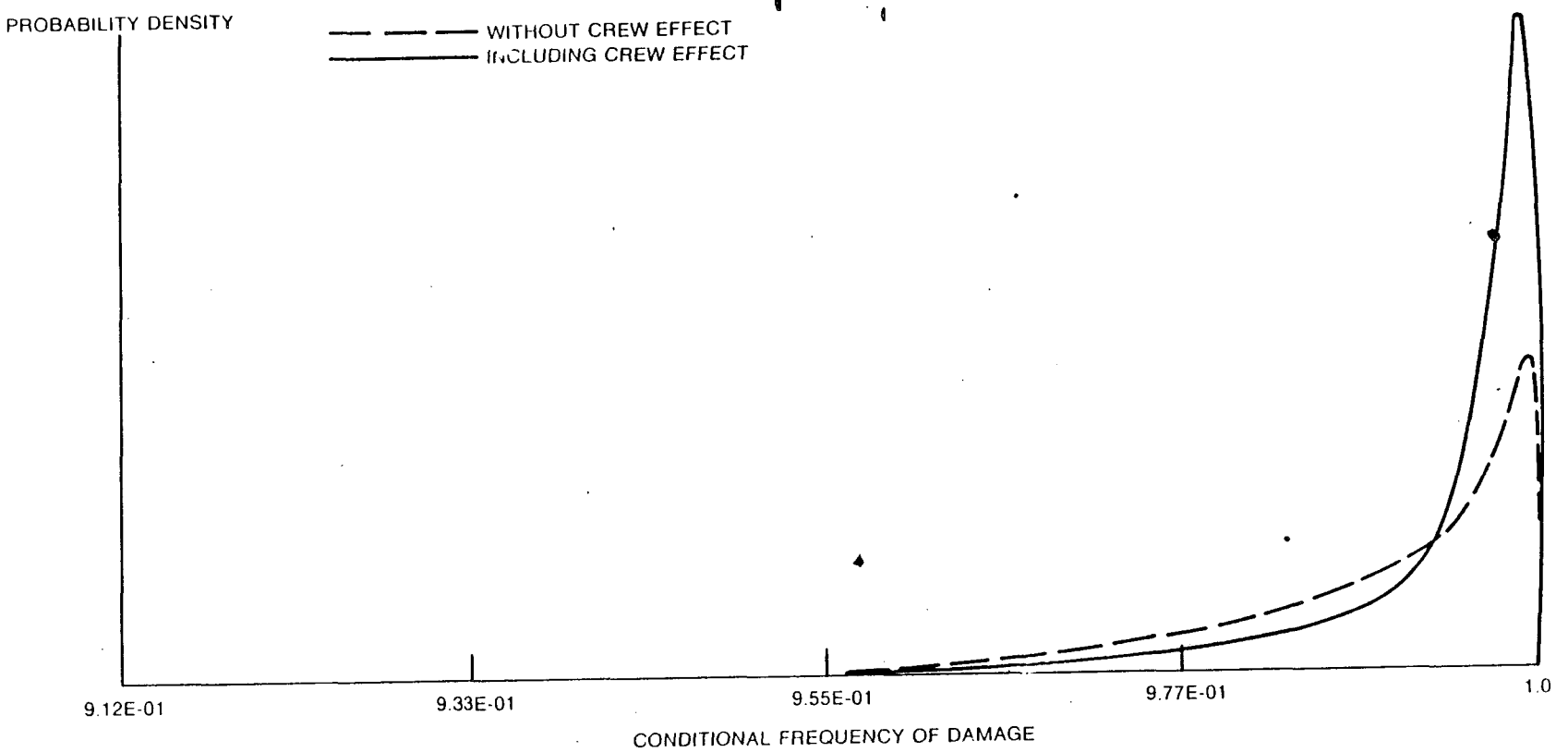

Figure 4-21. Voltage Level V1 and V2 Susceptibility Group F Expert 2 Prior Distribution

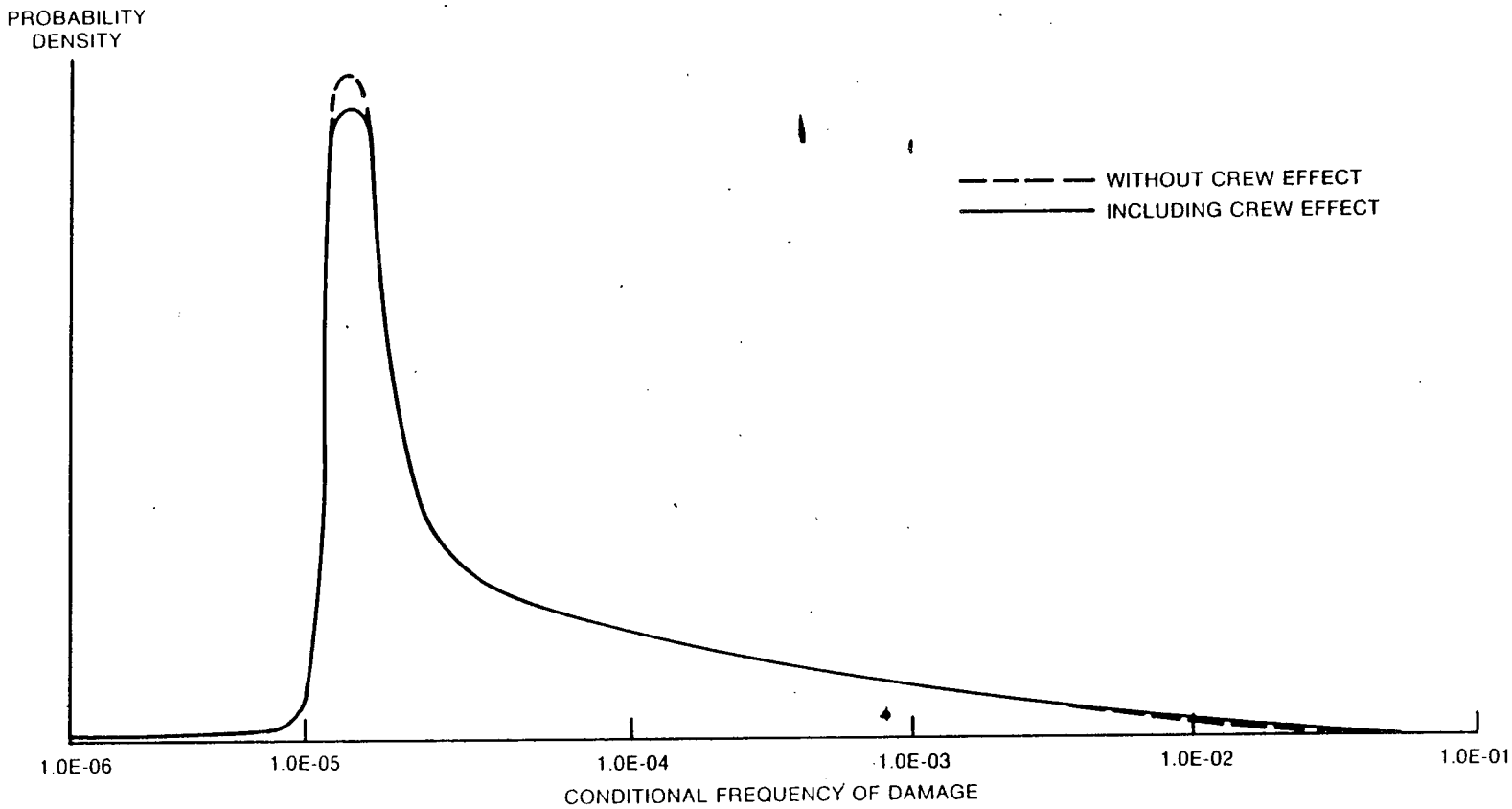

Figure 4-22. Voltage Level V3 Susceptibility Group G Expert 2 Prior Distribution

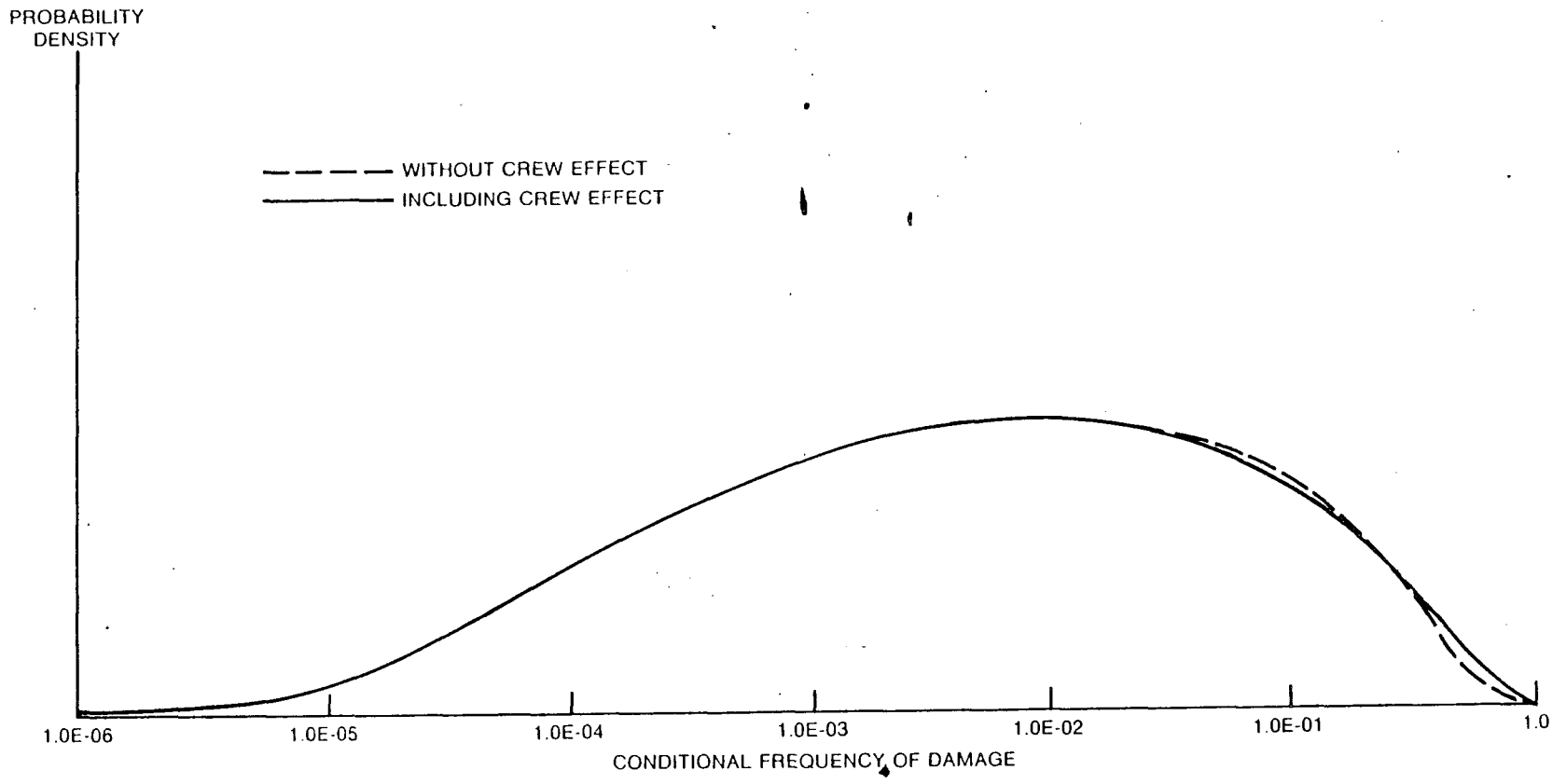

Figure 4-23. Voltage Level V3 Susceptibility Group H Expert 2 Prior Distribution

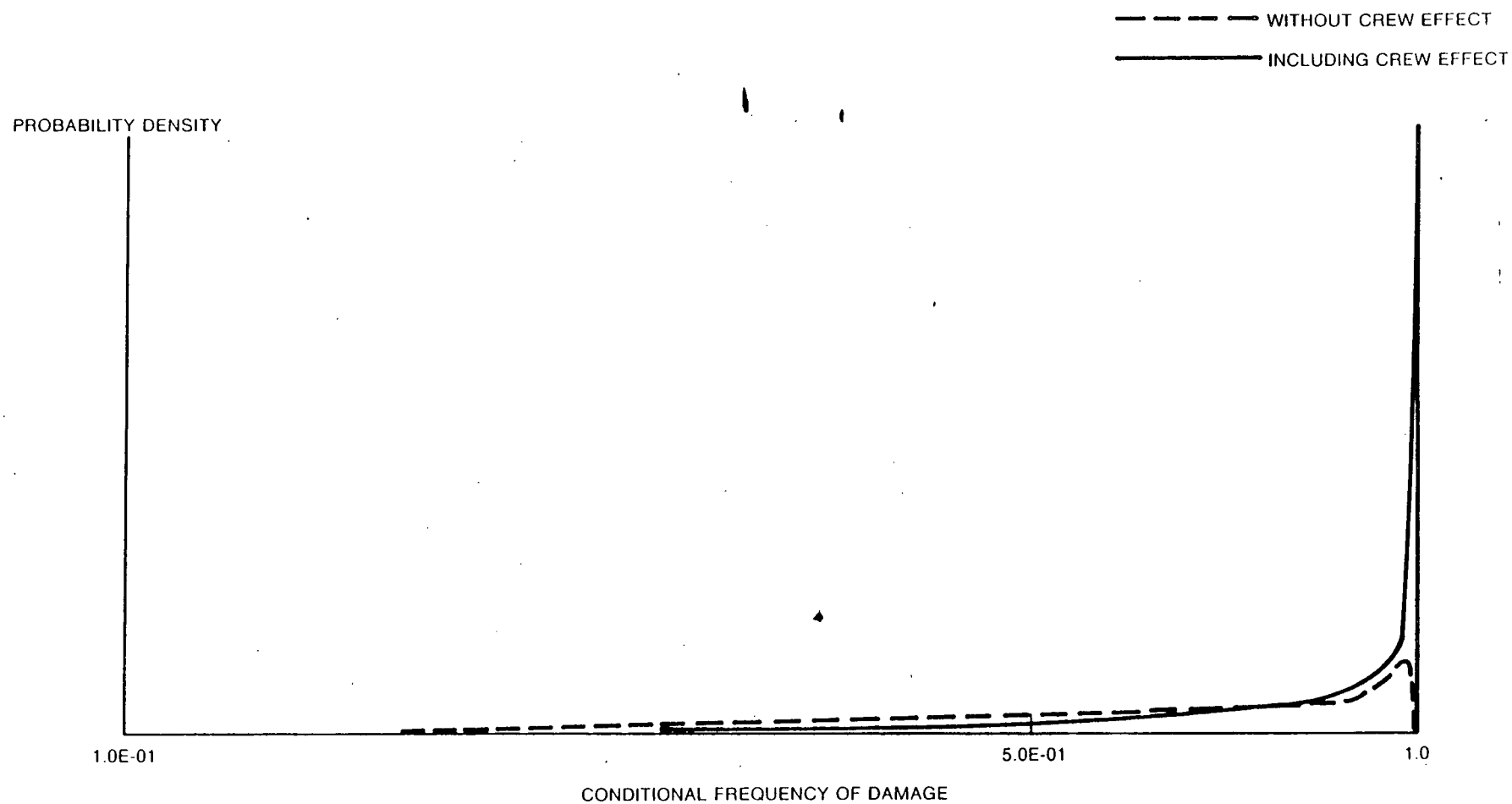

Figure 4-24. Voltage Level V3 Susceptibility Group I Expert 2 Prior Distribution

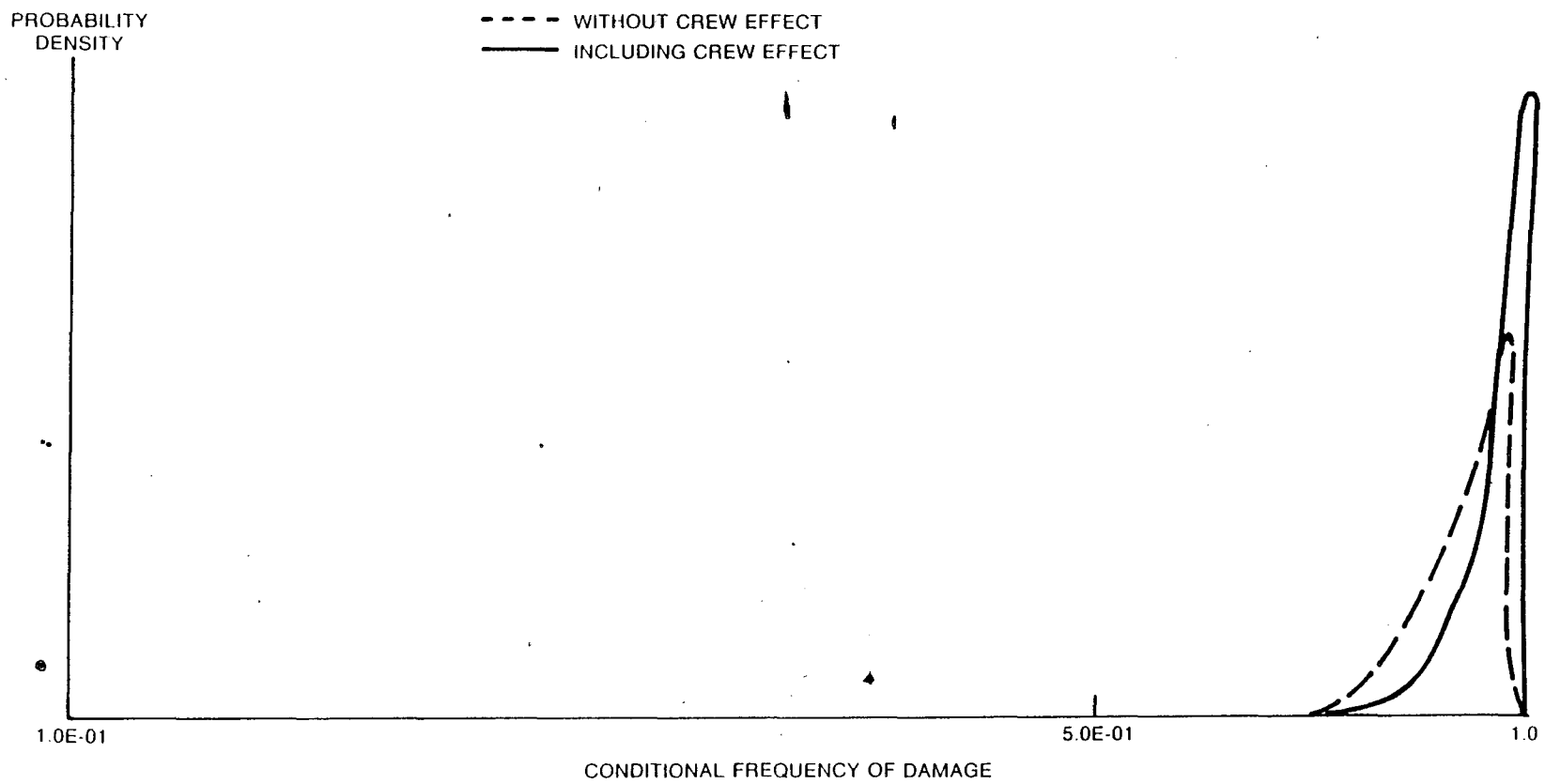

Figure 4-25. Voltage Level V3 Susceptibility Group J Expert 2 Prior Distribution

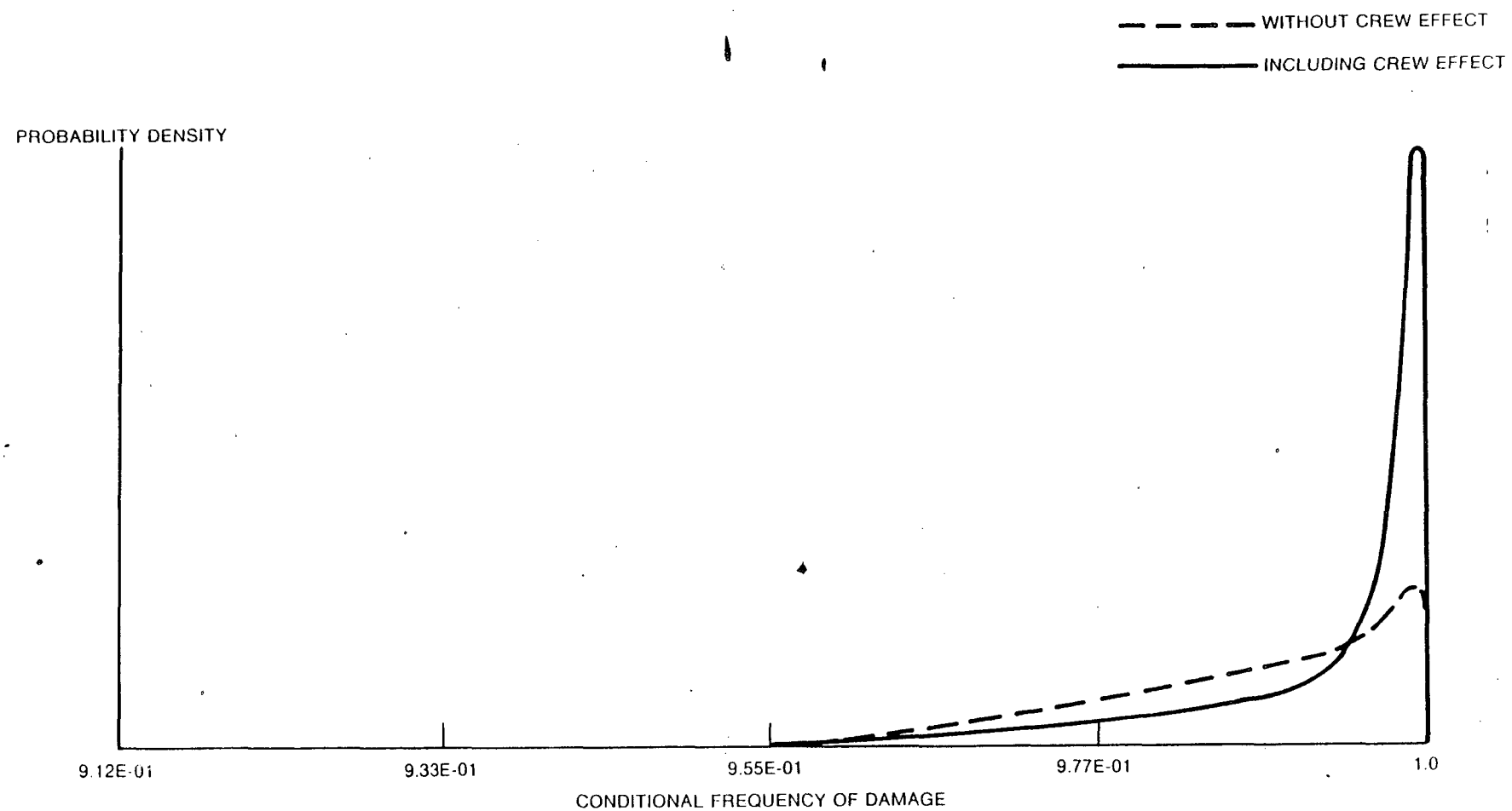

Figure 4-26. Voltage Level V3 Susceptibility Group K Expert 2 Prior Distribution

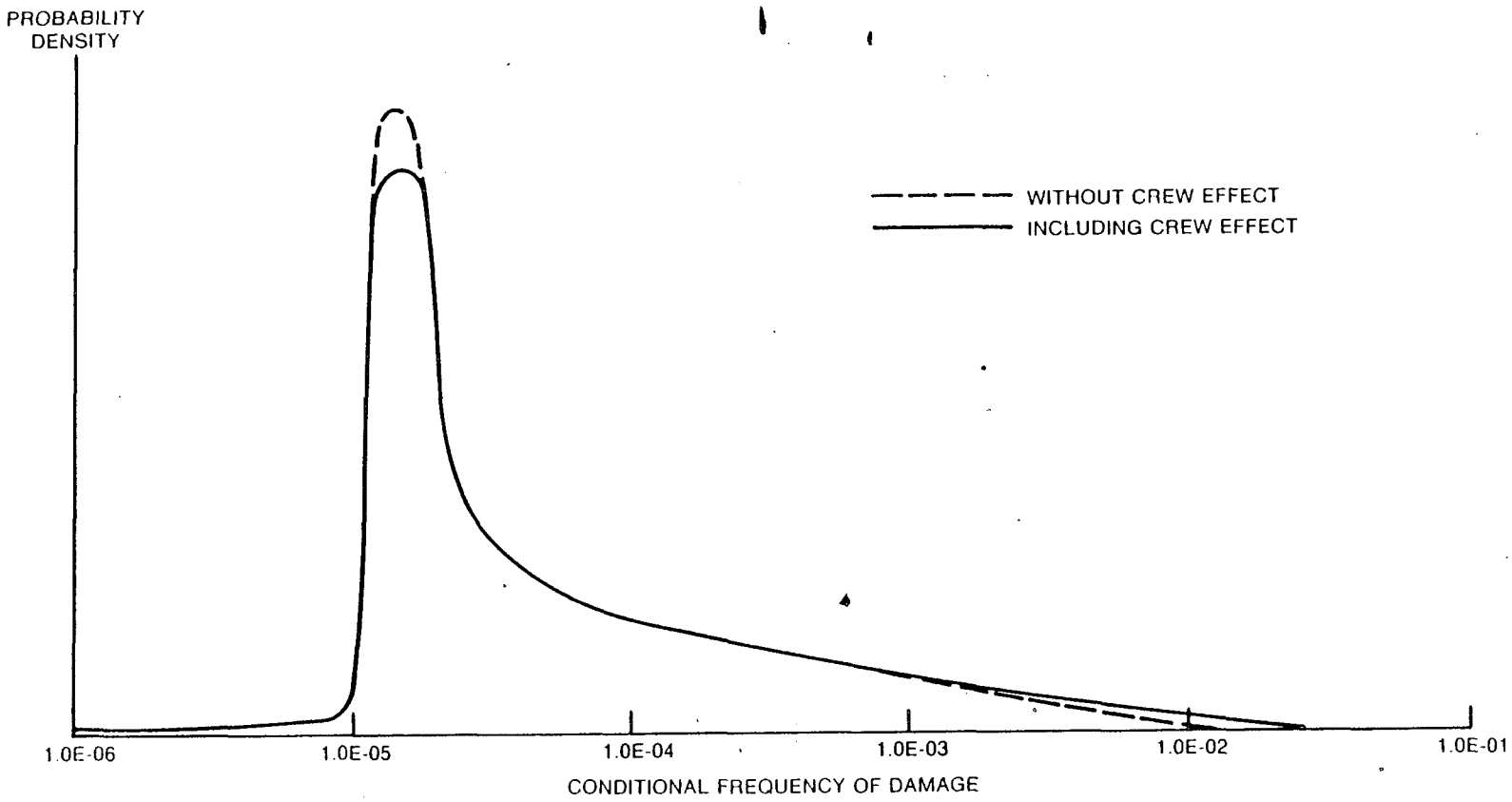

Figure 4-27. Voltage Level V4 Susceptibility Group G Expert 2 Prior Distribution

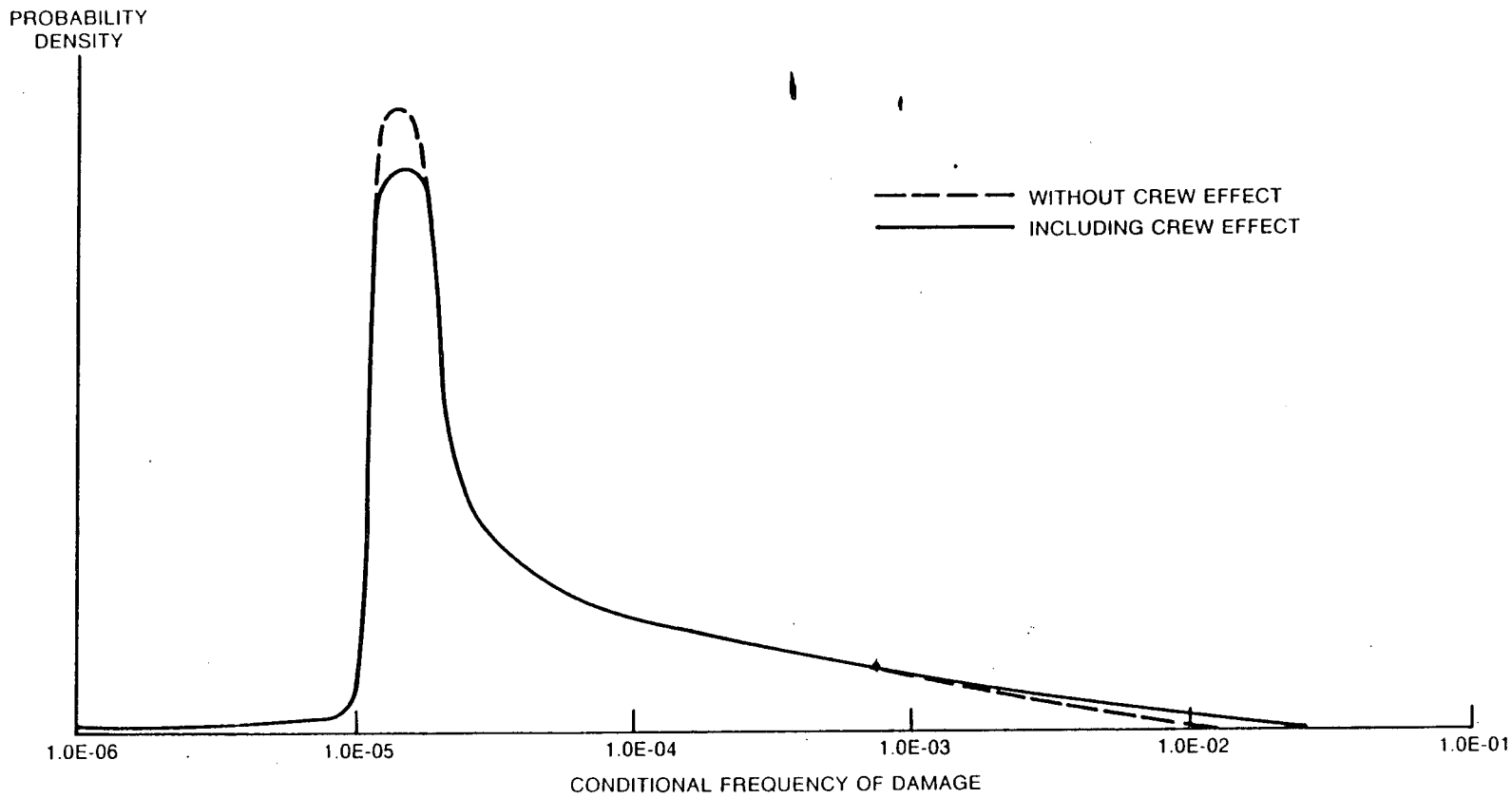

Figure 4-28. Voltage Level V4 Susceptibility Group H Expert 2 Prior Distribution

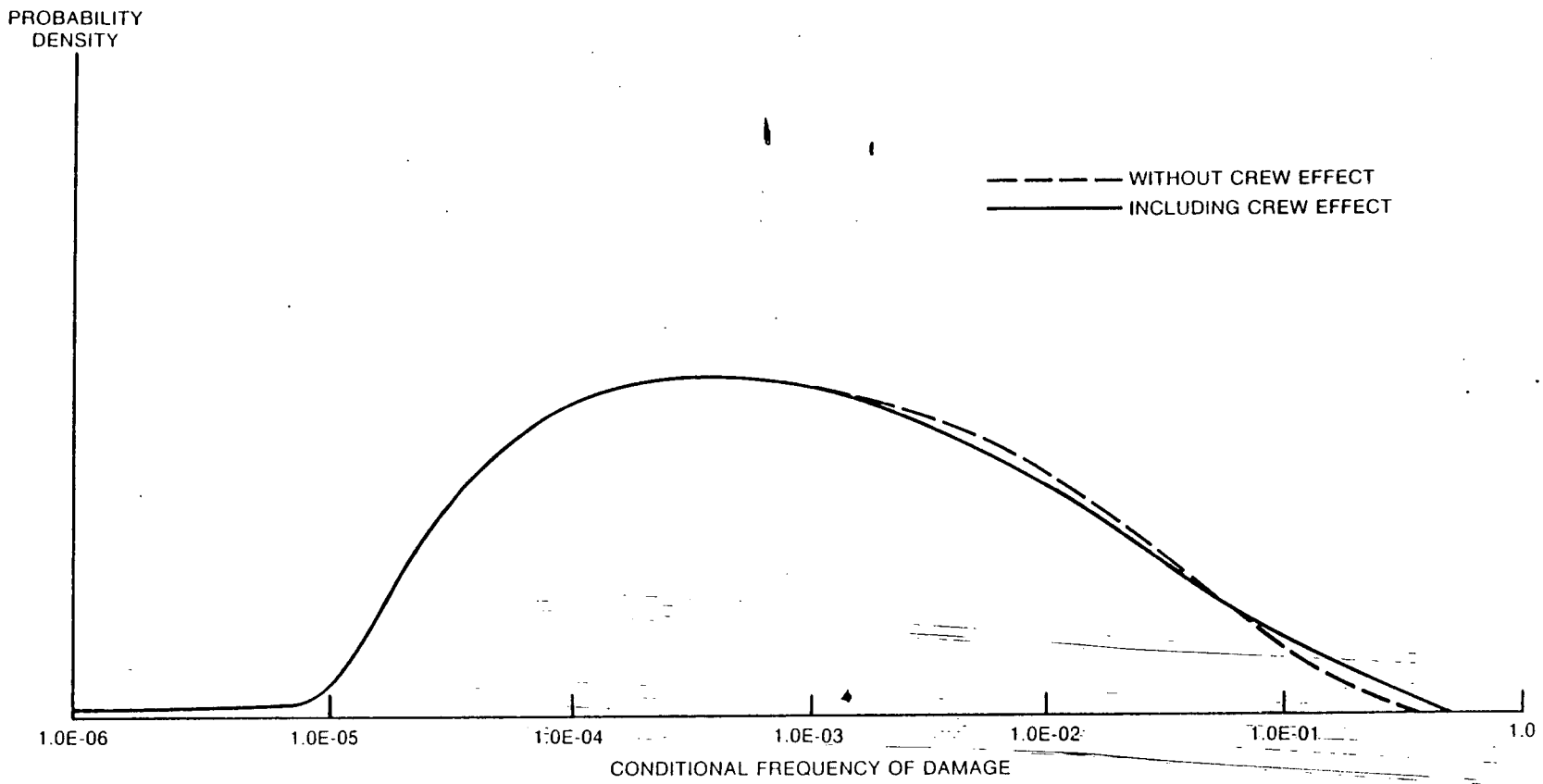

Figure 4-29. Voltage Level V4 Susceptibility Group I Expert 2 Prior Distribution

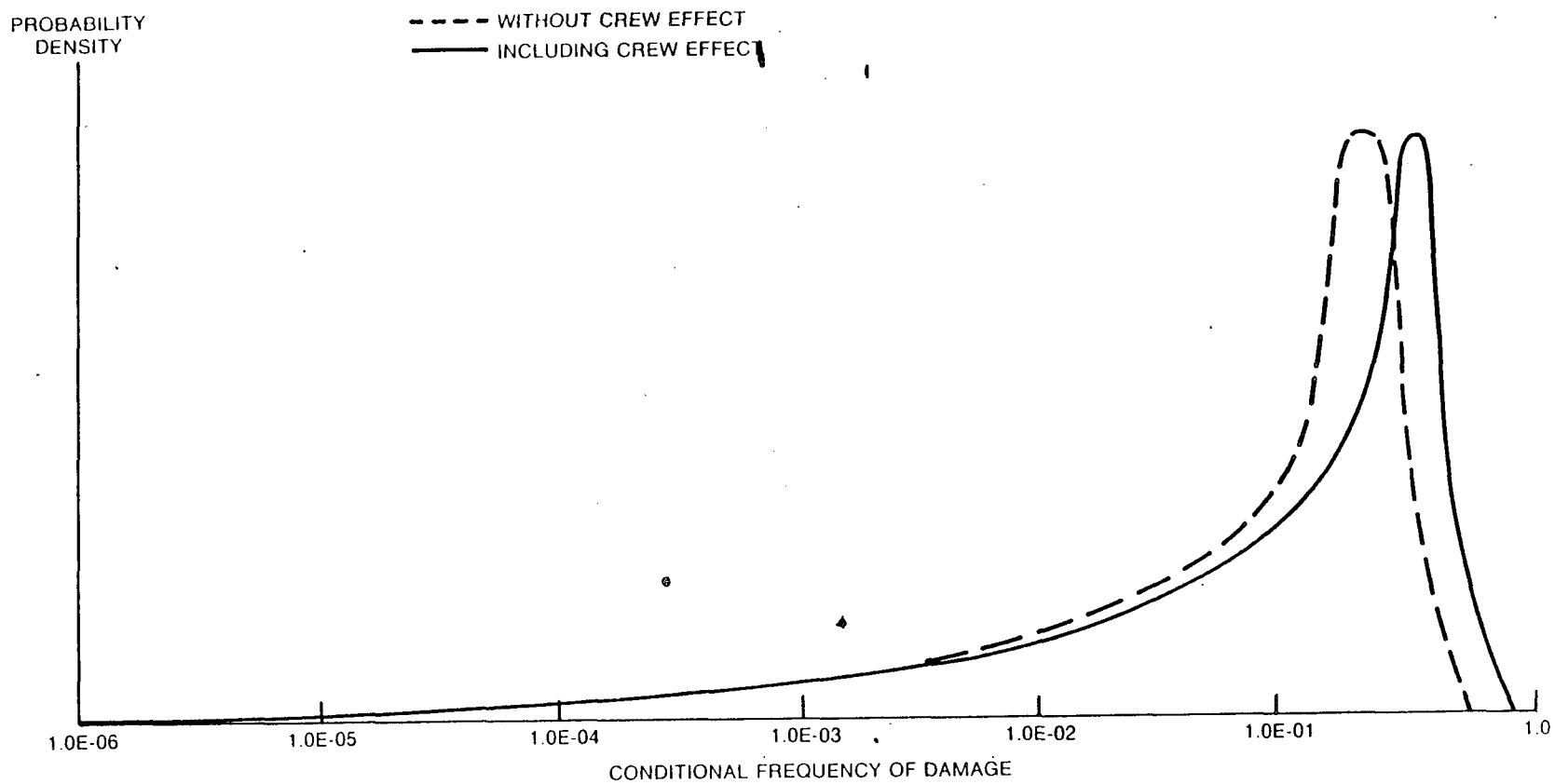

Figure 4-30. Voltage Level V4 Susceptibility Group J Expert 2 Prior Distribution

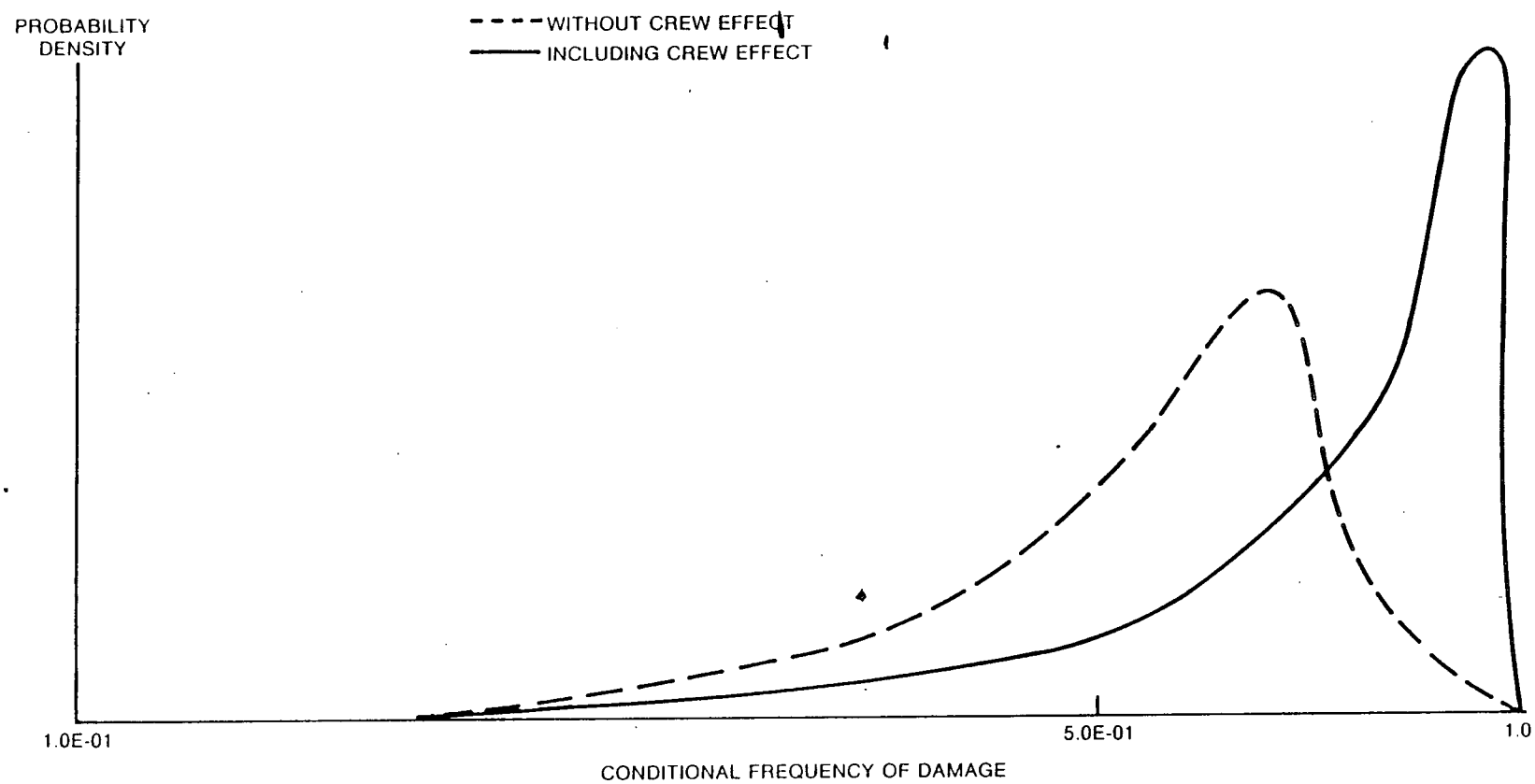

Figure 4-31. Voltage Level V4 Susceptibility Group K Expert 2 Prior Distribution

5. ANALYSIS OF SAMPLE DATA

The initial discovery of pullby damage was made during examination of a Unit 2 conduit segment for resolution of an unrelated concern. In order to fully examine the cables in this conduit segment, it was necessary to remove the cables from eight additional conduits in the same raceway. Significantly damaged cables were discovered in a total of three of these nine conduit segments. A sampling program was initiated to determine if the damage was localized or if pullby damage had also occurred in Unit 1 conduits. Preliminary assessments were made to identify candidate conduits for sampling in Unit 1. The selected conduits included 14 segments in the "sister" to the Unit 2 run where damage was found. An additional 14 conduit segments were also selected to cover the three major cable voltage levels. The selection criteria for these conduits were based on a preliminary ranking for pullby damage susceptibility that considered conduit geometry, percent fill, total number of cables, and jacket material. One damaged cable was discovered in 1 of the latter 14 conduit segments. Table 5-1 summarizes the sampling results from both units.

Section 4 briefly describes employee allegations that led to the identification of a number of "suspect" cable installation crews. The damaged Unit 2 cables were located in conduits that had been worked on by one or more of these crews. Therefore, the individual cable pull card records were carefully examined for the sampled Unit 1 conduits to identify possible correlations between cable damage and the "suspect" crews. A conduit was considered to be worked on by a "suspect" crew if the pull card records indicated that at least one cable had been installed by one of the identified crew foremen. Table 5-2 summarizes the results from this investigation. Although the Unit 1 conduit with the damaged cable had also been worked on by one of the "suspect" crews, the data in the table indicate that cable damage does not seem to be closely correlated to the activities of these crews. These data generally support the experts' assessment in Section 4 that the practices of specific crews may influence the likelihood of pullby damage, but the effect is not dominant.

Table 5-3 is a condensation of the data from Table 5-1. It summarizes the sampling results for each of the 16 damage susceptibility groups evaluated by the two experts in Section 4. This represents the plant-specific Bayesian evidence of type E_2 described in Appendix A, Sections A.1 and A.6. It was decided to combine the evidence from Unit 1 and Unit 2 for the Bayesian updating process in this study. As can be seen from the data in Table 5-3, the evidence from the Unit 2 conduits is somewhat worse than the Unit 1 experience. It is difficult to draw significant conclusions by directly comparing these results because the sample populations are quite small. However, the use of combined unit data will provide conservative estimates for the updated likelihood of damage in the target population of Unit 1, common, and Unit 2 conduits containing cables required for safe shutdown of Unit 1.

Table 5-4 compares the sample data with the final prior probability distributions obtained by merging the expert evaluations described in Section 4. The quantitative results from the formal Bayesian updates are presented in Section 6. However, a few important qualitative insights can be drawn from the data in Table 5-4. The first of these is that the actual pullby damage experience at WBNP does not contradict the expert assessments. For example, cable damage was discovered in susceptibility groups C, D, F, and K. Groups F and K represent the experts' highest assessed likelihoods for observing damage. Groups C and D are in the "transition regime" of the expert assessments where the uncertainties are quite broad. However, the observed frequency of actual damage in groups C and D is well within

the experts' uncertainty bounds. No damage was observed in high likelihood group E or group J. However, only one conduit was sampled from group E, and no samples were taken from group J. No damage was found in samples from the experts' low likelihood groups A and B. Although these limited samples are certainly not conclusive, these types of comparisons lend confidence that the expert evaluation process has not overlooked significant causative factors.

The second insight that can be drawn from Table 5-4 is that the experts may have been somewhat pessimistic in their assessments for the actual population of conduits. This is not particularly surprising since their evaluations were based on the assumption that pullby events had occurred in every conduit under rather limiting SWBP conditions. In fact, it is known that pullbys do not occur in every conduit and that the actual SWBP values cover a fairly broad range within each susceptibility group. The degree of conservatism in the assessed frequencies can be inferred from comparisons between the experience data and major parameters of the experts' distributions. Thus, although one conduit had cable damage in voltage level V3 group K, it is notable that five additional conduits sampled from this group had no damage. This evidence (17% damage) is substantially lower than the experts' evaluations, which assign 97% confidence that damage would occur in more than 33% of the conduits in this category. Similarly, although one of the two conduits sampled in group F had damage, the experts were 95% confident that more than 91% of the conduits in this category would display damage. Similar, although less dramatic, comparisons can be made for groups C and D at the experts' 50% confidence levels. It is certainly not prudent to draw sweeping conclusions from these types of comparisons because the actual sample populations are quite small. However, these selected quantitative comparisons support qualitative statements that the expert evaluation process was based on several inherent assumptions and analyses that would tend to somewhat overestimate the actual frequency of damage. None of the data in Table 5-4 indicate that the experts were optimistic in their evaluation of any susceptibility group.

The final insight that can be gained from Table 5-4 is that the experts' prior probability distributions are quite important for estimating the likelihood of damage in several of the susceptibility groups. This is obviously true for such groups as G, J, and H for voltage level V3, and K for voltage level V4, where no actual sample data were collected. However, the prior distributions will also dominate such groups as A, B, and H for voltage level V4, where the sample data are not statistically significant compared with the estimated likelihoods for observing damage. These insights do not imply that this evaluation process is statistically weak or flawed. The information in Section 4 demonstrates that the prior distributions are fundamentally based on the best engineering analyses and practical cable installation experience currently available. Care has been exercised to ensure that each expert's evaluations are internally consistent and that the final probability distributions have considered all potentially important factors that could influence pullby damage. In many cases, the experts' uncertainties about the likelihood of damage are quite broad. For those cases in which significant sample data are available, the comparisons discussed above have shown the actual experience to lie within the range of the experts' uncertainties and generally toward the lower ends of their estimates. The sparse data will not significantly reduce the uncertainties in the prior distributions for certain conduit groups. However, there is no reason to believe that these priors are any different or less valid than those for which the updated results in Section 6 display a quantitatively measurable change.

Table 5-1 (Page 1 of 2). WBNP Cable Sampling Data								
Unit	Conduit	Voltage Level	Diameter (inches)	Length (feet)	Number of Cables	Percent Fill	Susceptibility Group	Pullby Damage
1	1PM6398D	2	3.0	40	22	30	C	No
1	1PM6399D	2	3.0	40	23	30	C	No
1	1PM6420D	2	3.0	95	21	30	D	No
1	1PM6451D	2	1.0	35	1	21	A	No
1	1PM6470D	2	3.0	100	21	30	D	No
1	1PM6473D	2	3.0	80	22	32	D	No
1	1PM6474D	2	3.0	95	22	32	D	No
1	1PM6475D	2	3.0	65	26	34	C	No
1	1PM6491D	2	2.0	100	4	11	A	No
1	1PM7260D	2	3.0	60	24	33	C	No
1	1PM6222D	2	3.0	14	25	34	B	No
1	1PM6223D	2	3.0	12	24	32	B	No
1	1PS701D	2	1.5	100	4	19	B	No
1	1PS702D	2	1.5	15	5	24	A	No
1	1PLC3345B	4	3.0	50	5	30	H	No
1	1PLC2850A	4	3.0	75	5	31	I	No
1	1VC2762A	3	2.0	50	15	58	K	No
1	1VC2788A	3	3.0	65	33	46	K	No
1	1PLC235A	3	3.0	70	39	55	K	No
1	1M2988B	3	3.0	60	32	48	K	No
1	1PLC232B	3	3.0	60	27	47	K	No
1	MC400B	3	4.0	92	29	38	K	Yes
1	MC427B	3	3.0	77	17	22	I	No

Table 5-1 (Page 2 of 2). WBNP Cable Sampling Data								
Unit	Conduit	Voltage Level	Diameter (inches)	Length (feet)	Number of Cables	Percent Fill	Susceptibility Group	Pullby Damage
1	MC424B	3	3.0	78	14	18	I	No
1	1PM6645B	2	2.0	39	16	57	F	No
1	1PM6331B	2	3.0	92	31	37	E	No
1	1PM6363F	2	3.0	85	25	34	D	No
1	1PM6467A	2	3.0	30	26	30	C	No
2	2PM6398D	2	3.0	40	21	30	C	No
2	2PM6399D	2	3.0	32	21	30	C	No
2	2PM6420D	2	3.0	89	21	30	D	No
2	2PM6451D	2	1.0	20	1	10	A	No
2	2PM6470D	2	3.0	92	21	30	D	Yes
2	2PM6473D	2	3.0	47	22	31	C	Yes
2	2PM6474D	2	3.0	104	26	36	F	Yes
2	2PS701D	2	1.5	110	4	19	C	No
2	2PS702D	2	1.5	15	5	24	A	No

Table 5-2. Summary of "Suspect" Crew Activity for Unit 1 Sample Conduits				
Voltage Level	**Susceptibility Group**	**Number of Conduits Sampled**	**Number of Sample Conduits Worked on By "Suspect" Crew**	**Number of Sample Conduits With Pullby Damage**
V2	A	3	0	0
	B	3	1	0
	C	5	2	0
	D	5	0	0
	E	1	0	0
	F	1	0	0
V3	G	0	--	--
	H	0	--	--
	I	2	2	0
	J	0	--	--
	K	6	5	1
V4	G	0	--	--
	H	1	0	0
	I	1	0	0
	J	0	--	--
	K	0	--	--
	Total	28	10	1

Table 5-3. Summary of Sampling Data by Damage Susceptibility Group					
VOLTAGE LEVEL	SUSCEPTI-BILITY GROUP	CONDUITS SAMPLED		FAILURE EVIDENCE	
		UNIT 1	UNIT 2	UNIT 1	UNIT 2
V2	A	3	2	0	0
	B	3	0	0	—
	C	5	4	0	1
	D	5	2	0	1
	E	1	0	0	—
	F	1	1	0	1
V3	G	0	0	—	—
	H	0	0	—	—
	I	2	0	0	—
	J	0	0	—	—
	K	6	0	1	—
V4	G	0	0	—	—
	H	1	0	0	—
	I	1	0	0	—
	J	0	0	—	—
	K	0	0	—	—

Table 5-4. Comparison of Evidence with Prior Distributions

VOLTAGE LEVEL	SUSCEPTIBILITY GROUP	PRIOR PROBABILITY DISTRIBUTION FOR CONDITIONAL FREQUENCY OF DAMAGE				EVIDENCE		
		5TH PERCENTILE	MEDIAN	95TH PERCENTILE	MEAN	UNIT 1	UNIT 2	COMBINED
V2	A	0	.0001	.014	.0039	0/3	0/2	0/5
	B	0	.0005	.078	.015	0/3	—	0/3
	C	0	.19	.58	.24	0/5	1/4	1/9
	D	.0032	.67	.97	.60	0/5	1/2	1/7
	E	.54	.87	.99	.87	0/1	—	0/1
	F	.91	.95	1.00	.99	0/1	1/1	1/2
V3	G	0	.0001	.013	.0035	—	—	—
	H	0	.0005	.11	.022	—	—	—
	I	0	.065	.88	.28	0/2	—	0/2
	J	.0033	.58	.98	.54	—	—	—
	K	.33	.89	.99	.85	1/6	—	1/6
V4	G	0	.0001	.0072	.0026	—	—	—
	H	0	.0001	.022	.0047	0/1	—	0/1
	I	0	.0008	.12	.023	0/1	—	0/1
	J	0	.011	.27	.060	—	—	—
	K	.25	.59	.91	.61	—	—	—

6. RESULTS

Figures 6-1 through 6-16 display the final probability distributions for the likelihood of cable damage from pullby events in each WBNP conduit group. If no sample data were collected for a particular group, a single curve represents the combination of the expert prior distributions described in Section 4. Two curves are plotted for each sampled group. The dashed curve is the merged expert prior distribution, and the solid curve is the result of the Bayesian evaluation of the sample data. In every case, comparison of these curves shows that inclusion of the plant-specific evidence either has had little effect on the prior distribution or has lowered the previously estimated likelihood of damage. (Only one curve is shown for group A and for group H in voltage level V4 because the two curves for each of these groups are essentially identical.)

Figure 6-17 is a composite plot of all 16 final probability distributions. The curves have been broadly grouped into three general likelihood categories designated low, moderate, and high. The figure clearly shows the differences between the low category and the moderate and high categories. All seven distributions in the low category are characterized by best estimates that the likelihood of cable damage is very small. (It should be remembered that a numerical value of 1.00E-05 for these analyses is essentially equivalent to "no cable damage" from the original expert assessments.) These distributions have relatively long, low probability "tails" that extend to intermediate values of damage likelihood. These "tails" are dominated by the experts' unwillingness to rule out completely all possibilities that damage might occur in a small fraction of these conduits. The nine distributions in the moderate and high categories are essentially inverted forms of the low distributions. The moderate and high distributions are characterized by best estimates that the likelihood of cable damage is relatively high. In general, these best estimate values are from 100 to more than 1,000 times higher than the low distribution best estimate likelihoods. The low probability "tails" from the moderate and high distributions extend down into intermediate values of damage likelihood, but the bulk of the probabilities remain at damage frequency values above 1 in every 100 conduits.

It is relatively difficult to differentiate between the distributions in the moderate and high categories from the plots in Figure 6-17. Tables 6-1 and 6-2 summarize the major probability parameters from each of the final distributions to better illustrate the bases for these three broad categories. Table 6-1 displays the 90% confidence interval parameters, and Table 6-2 displays the 80% confidence interval. For these tables, frequency values below 5.0E-05 have been redesignated as "0" for consistency with the original expert assessments in Section 4. To interpret these tabulated values, consider the distribution for voltage level V3 group K. In Table 6-1, the 95th percentile value for the conditional frequency of damage is 0.56. This means that there is a 95% probability that damage will occur in fewer than 56 of every 100 conduits in this group. There is a 5% probability that damage will occur in more than 56 of every 100 conduits. The 50th percentile value is 0.29. This is the median value of the probability distribution. There is a 50% probability that damage will be found in fewer than 29 of every 100 conduits in this group, and a 50% probability that damage will be found in more than 29 of every 100 conduits. The 5th percentile value is 0.15. This means that there is a 5% probability that damage will occur in fewer than 15 of every 100 conduits in this group, and a 95% probability that damage will occur in more than 15 of every 100 conduits. The 90% confidence interval for the distribution lies between the 5th and 95th percentiles. In other words, there is a 90% probability that damage will occur in 15 to 56 of every 100

conduits in this group. Table 6-2 summarizes the same distributions at the 80% confidence interval. For example, in voltage level V3 group K, there is an 80% probability that damage will occur in 17 to 49 of every 100 conduits.

Comparisons of values in the 5th percentile, 10th percentile, 50th percentile, and mean columns from Tables 6-1 and 6-2 illustrate the bases for differentiation between the moderate and high likelihood categories. These differences are certainly more subtle than the obvious changes between the low and moderate categories, but they are measurable.

The dashed lines separating the major categories in Tables 6-1 and 6-2 are analgous to the "isoconcern contours" described in Section 2 and shown graphically in Figure 2-3. As intermediate results became available from the analyses described in this report, it became apparent that meaningful decisions could be made to resolve the issue of pullby damage without detailed evaluation of the plant safety or risk consequences from cable damage in each conduit group. The engineering bases for defining the initial damage likelihood groups, the prior distributions from the experts, and the reinforcement of these prior distributions from the plant-specific evidence focused concern on those groups of conduits in the moderate and high categories for damage likelihood. Therefore, the sampling plane displayed in Figure 2-3 was effectively collapsed into a set of three major levels of concern along the axis for damage likelihood, and no detailed safety consequence evaluations were required. The three damage likelihood categories (low, moderate, and high) thus defined the target groups of conduits for the final TVA cable inspection and replacement program.

Table 6-1. Pullby Damage Likelihood Categories and 90% Confidence Interval Parameters for Final Updated Probability Distributions

LIKELIHOOD OF DAMAGE	VOLTAGE LEVEL	UPDATED PROBABILITY DISTRIBUTIONS FOR CONDITIONAL FREQUENCY OF DAMAGE				
		SUSCEPTIBILITY GROUP	5TH PERCENTILE	50TH PERCENTILE	95TH PERCENTILE	MEAN
LOW	V4	G	0	.0001	.0072	.0026
	V1 AND V2	A	0	.0001	.0094	.0026
	V3	G	0	.0001	.013	.0035
	V4	H	0	.0001	.021	.0044
	V1 AND V2	B	0	.0004	.054	.010
	V4	I	0	.0007	.10	.019
	V3	H	0	.0005	.11	.022
MODERATE	V4	J	0	.011	.27	.060
	V3	I	0	.0030	.37	.073
	V1 AND V2	D	.012	.11	.38	.16
	V1 AND V2	C	.0089	.17	.38	.19
HIGH	V3	K	.15	.29	.56	.33
	V3	J	.0033	.58	.98	.54
	V4	K	.25	.59	.91	.61
	V1 AND V2	E	.44	.72	.90	.73
	V1 AND V2	F	.50	.84	.90	.82

Table 6-2. Pullby Damage Likelihood Categories and 80% Confidence Interval Parameters for Final Updated Probability Distributions

LIKELIHOOD OF DAMAGE	VOLTAGE LEVEL	UPDATED PROBABILITY DISTRIBUTIONS FOR CONDITIONAL FREQUENCY OF DAMAGE				
		SUSCEPTIBILITY GROUP	10TH PERCENTILE	50TH PERCENTILE	90TH PERCENTILE	MEAN
LOW	V4	G	0	.0001	.0035	.0026
	V1 AND V2	A	0	.0001	.0035	.0026
	V3	G	0	.0001	.0047	.0035
	V4	H	0	.0001	.0074	.0044
	V1 AND V2	B	0	.0004	.025	.010
	V4	I	0	.0007	.047	.019
	V3	H	0	.0005	.050	.022
MODERATE	V4	J	.0001	.011	.17	.060
	V3	I	0	.0030	.25	.073
	V1 AND V2	D	.022	.11	.31	.16
	V1 AND V2	C	.019	.17	.33	.19
HIGH	V3	K	.17	.29	.49	.33
	V3	J	.0064	.58	.95	.54
	V4	K	.30	.59	.87	.61
	V1 AND V2	E	.48	.72	.88	.73
	V1 AND V2	F	.59	.84	.90	.82

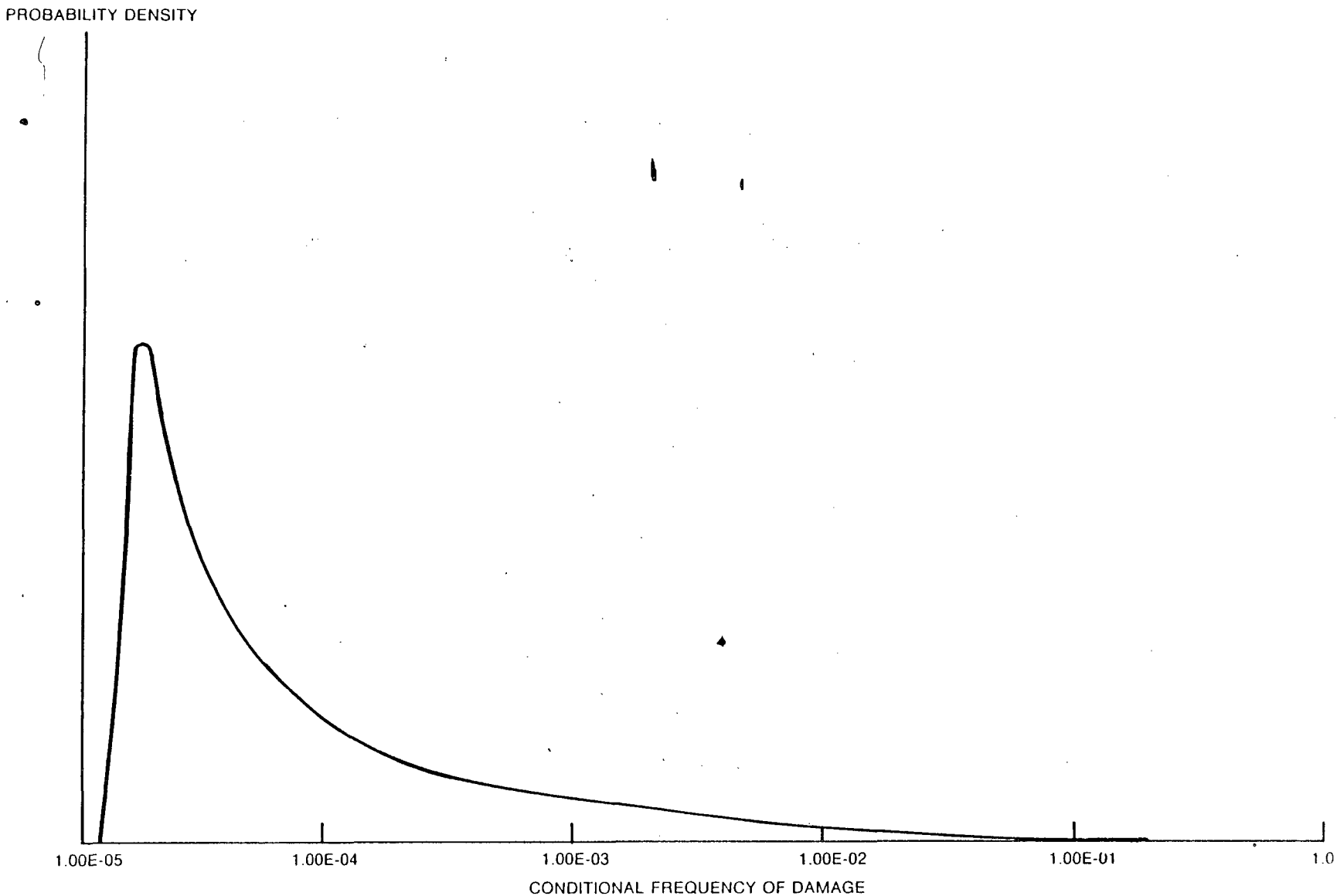

Figure 6-1. Analysis Results for Voltage Levels V1 and V2 Susceptibility Group A

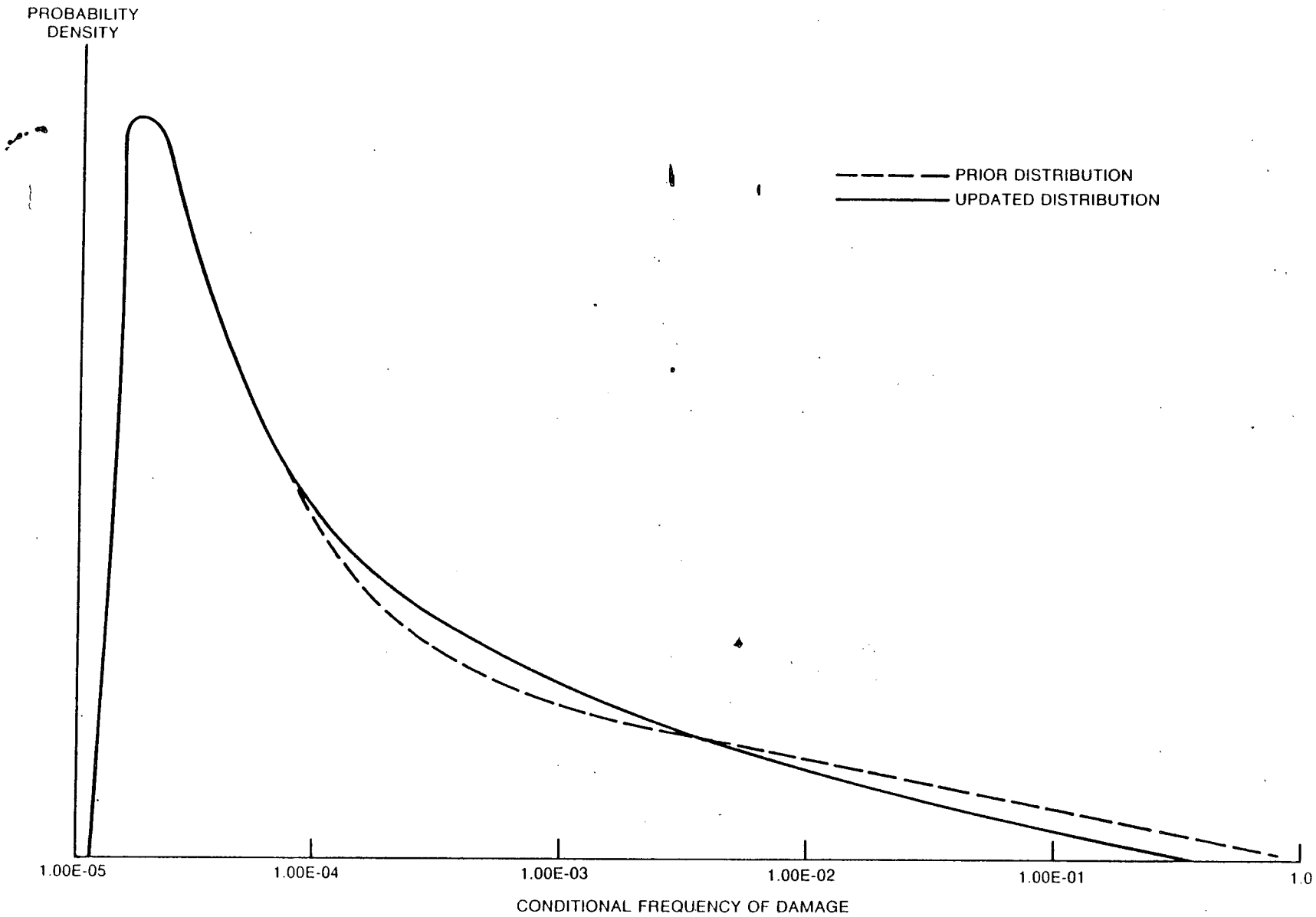

Figure 6-2. Analysis Results for Voltage Levels V1 and V2 Susceptibility Group B

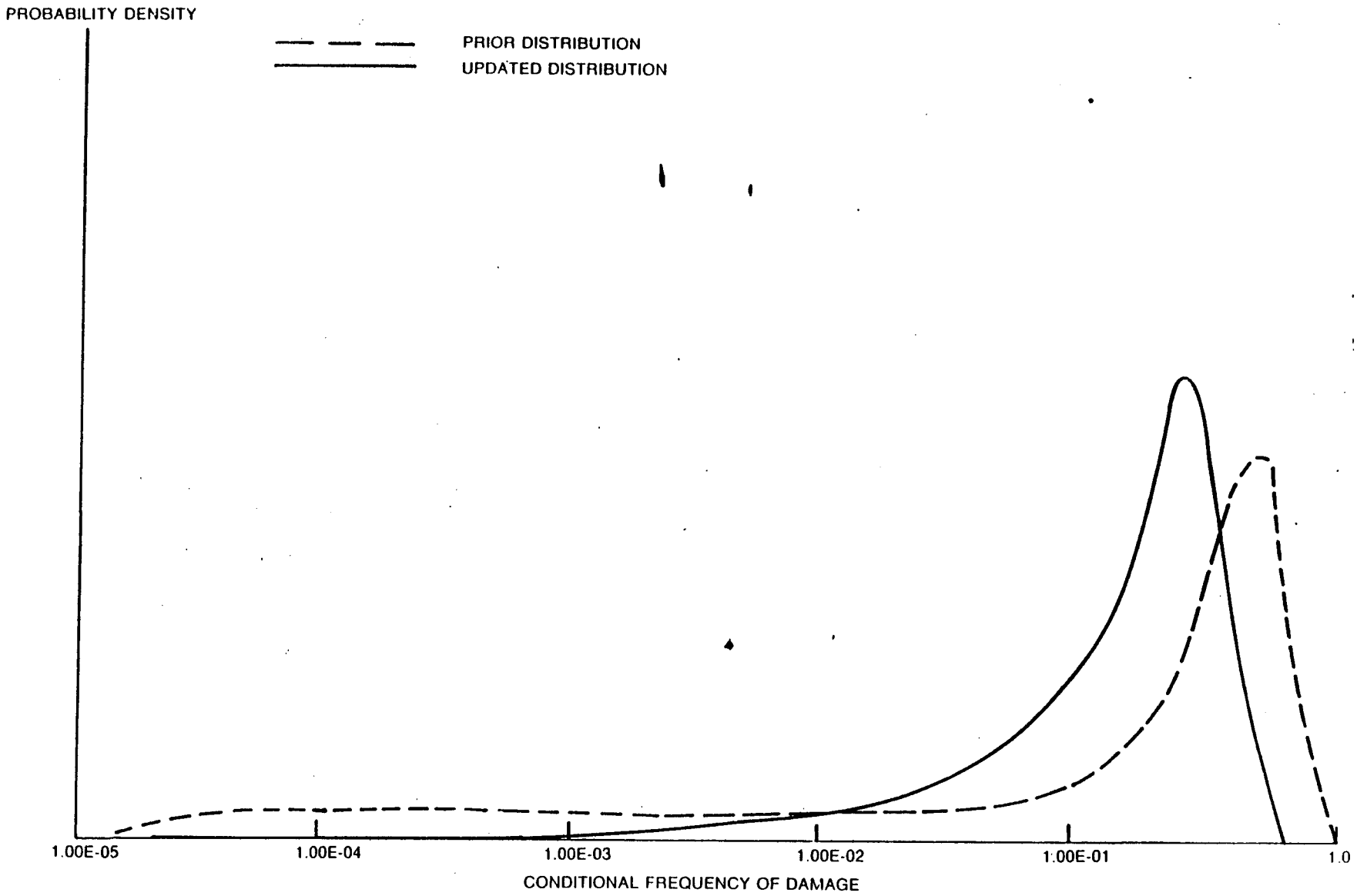

Figure 6-3. Analysis Results for Voltage Levels V1 and V2 Susceptibility Group C

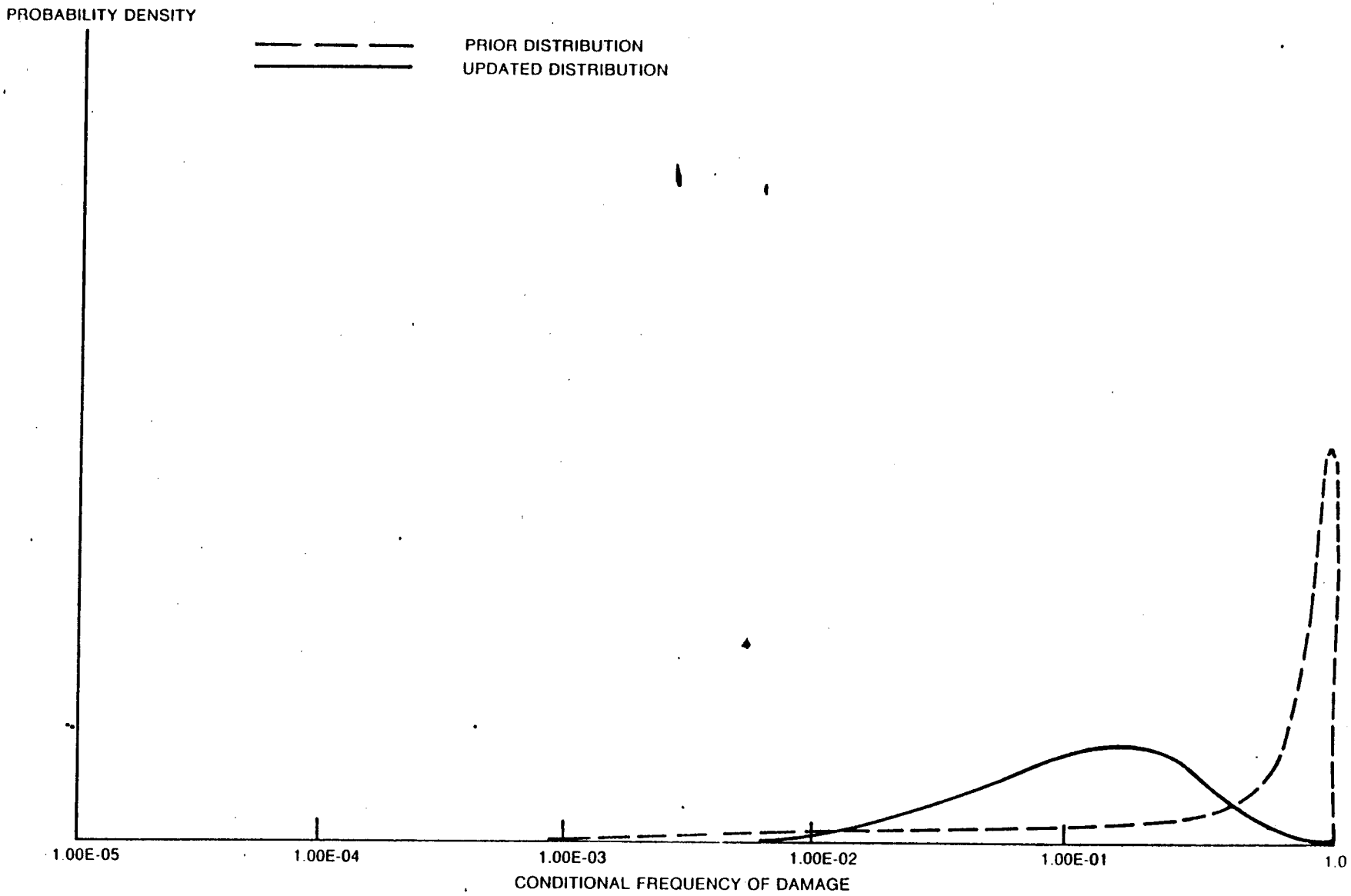

Figure 6-4. Analysis Results for Voltage Levels V1 and V2 Susceptibility Group D

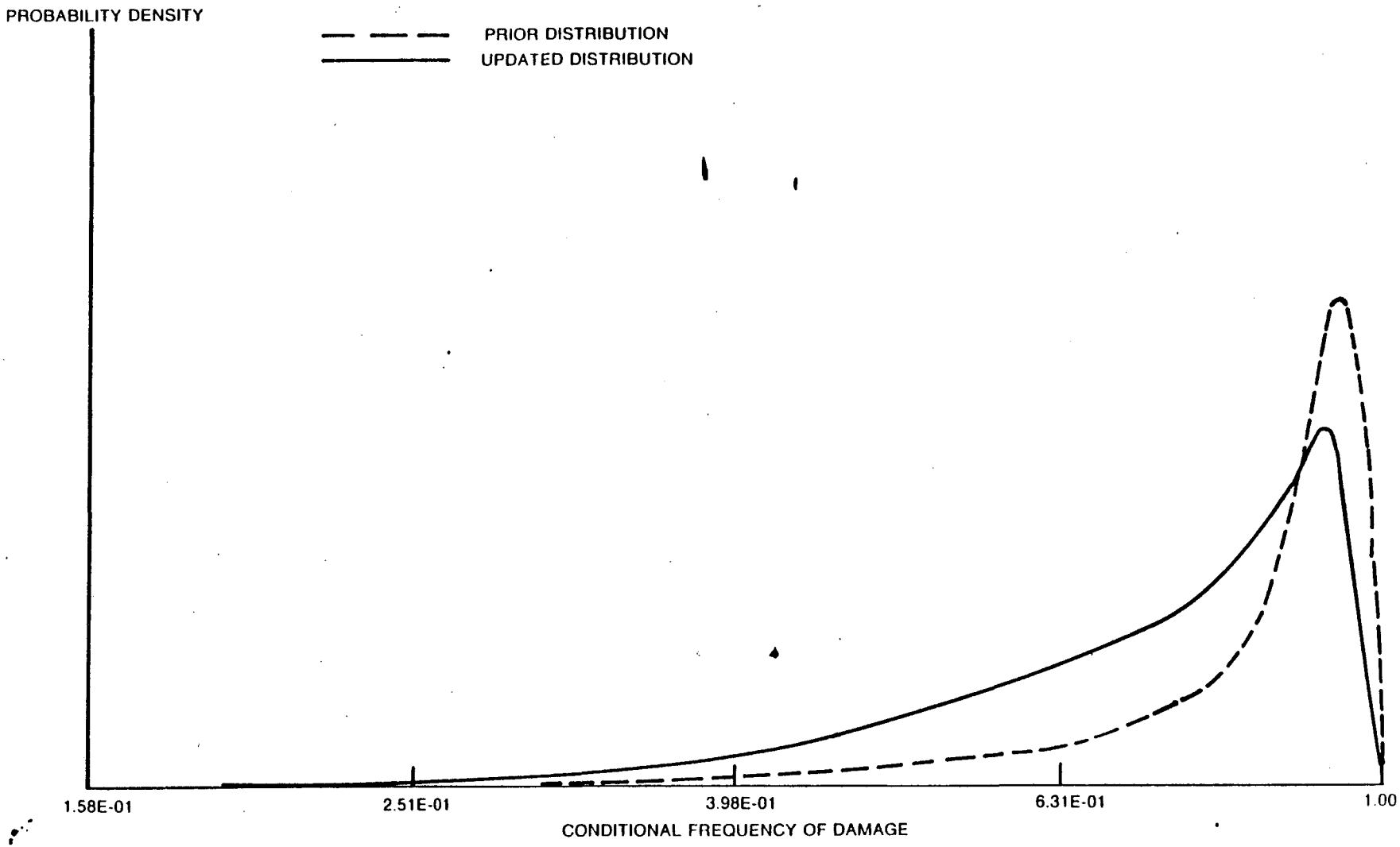

Figure 6-5. Analysis Results for Voltage Levels V1 and V2 Susceptibility Group E

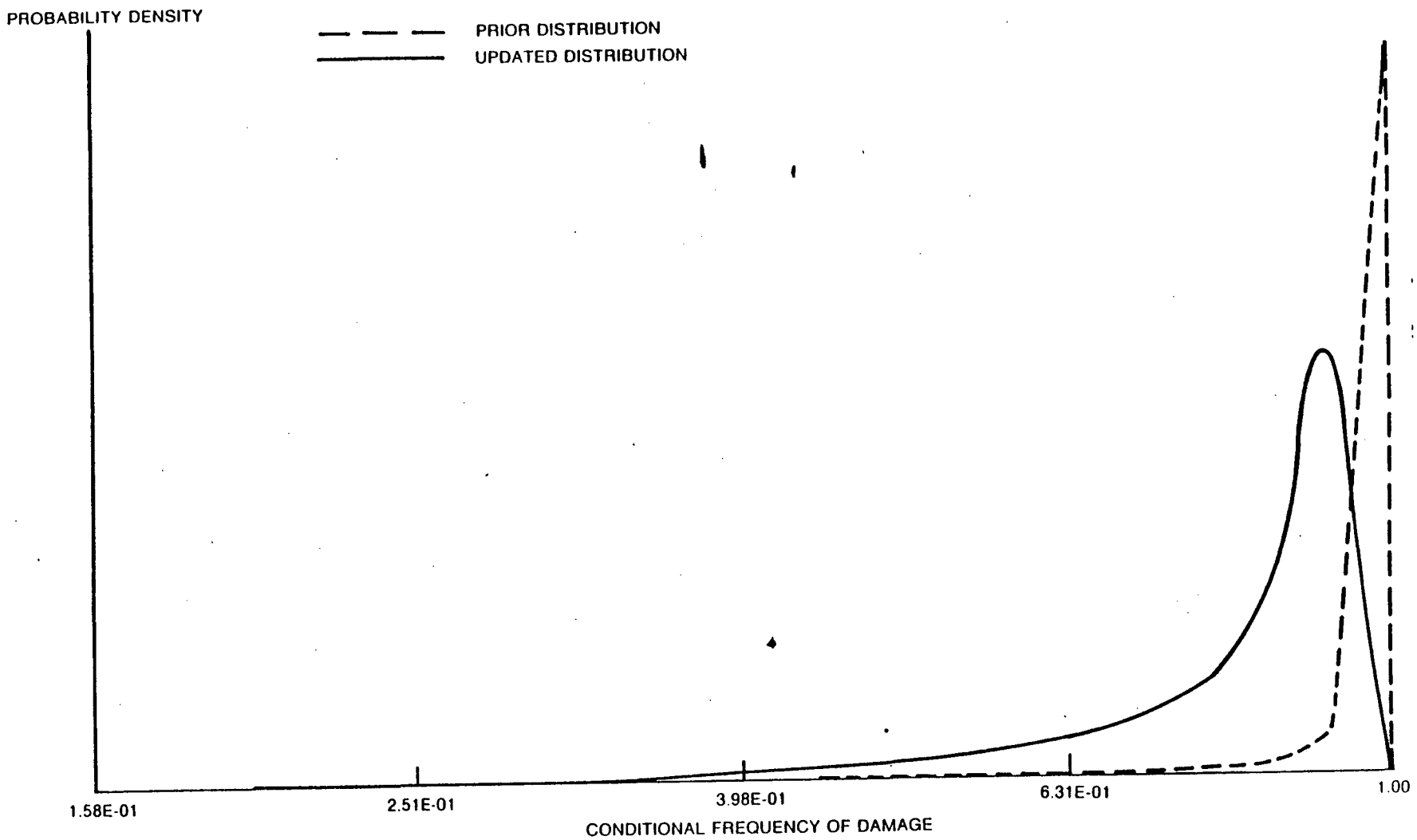

Figure 6-6. Analysis Results for Voltage Levels V1 and V2 Susceptibility Group F

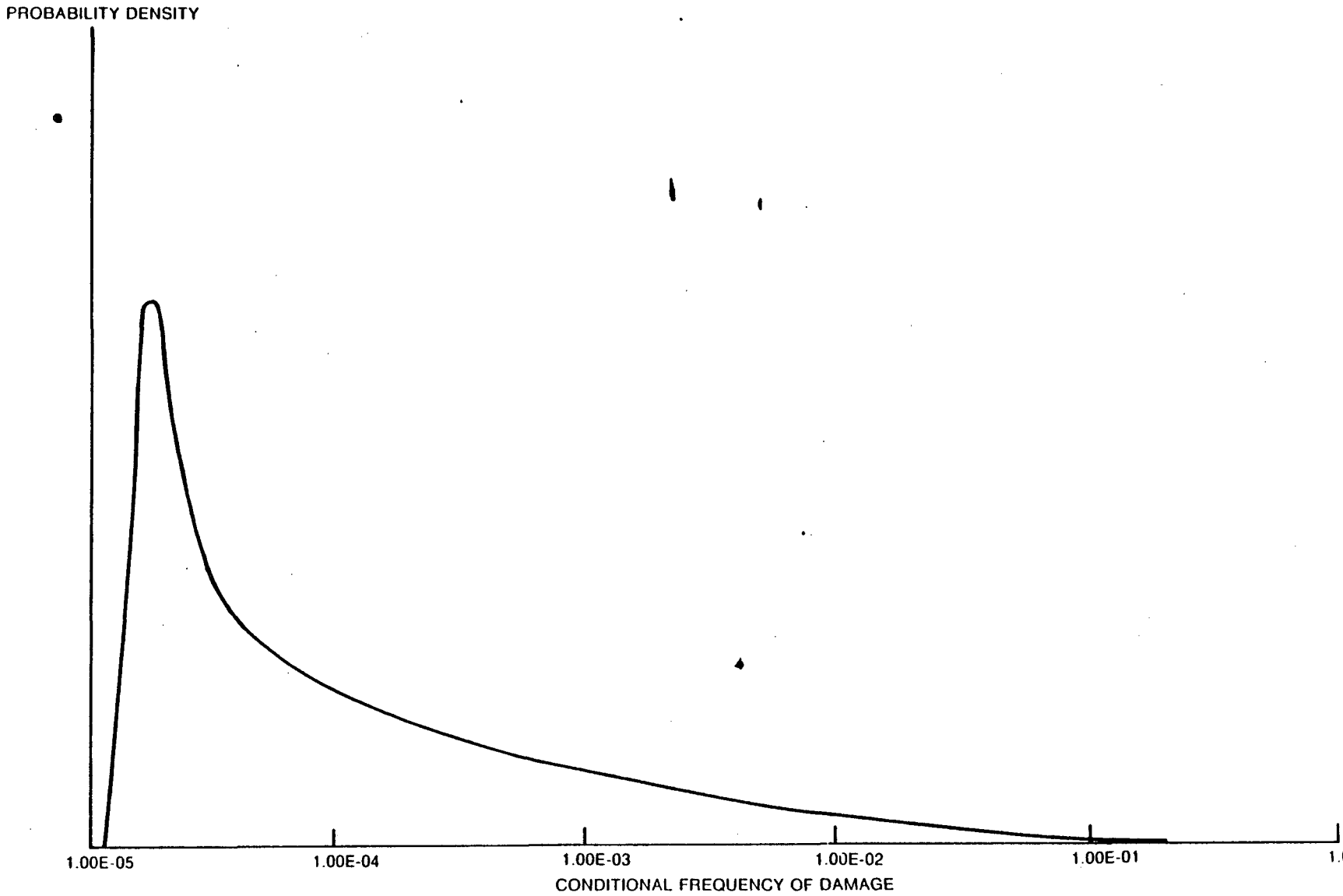

Figure 6-7. Analysis Results for Voltage Level V3 Susceptibility Group G

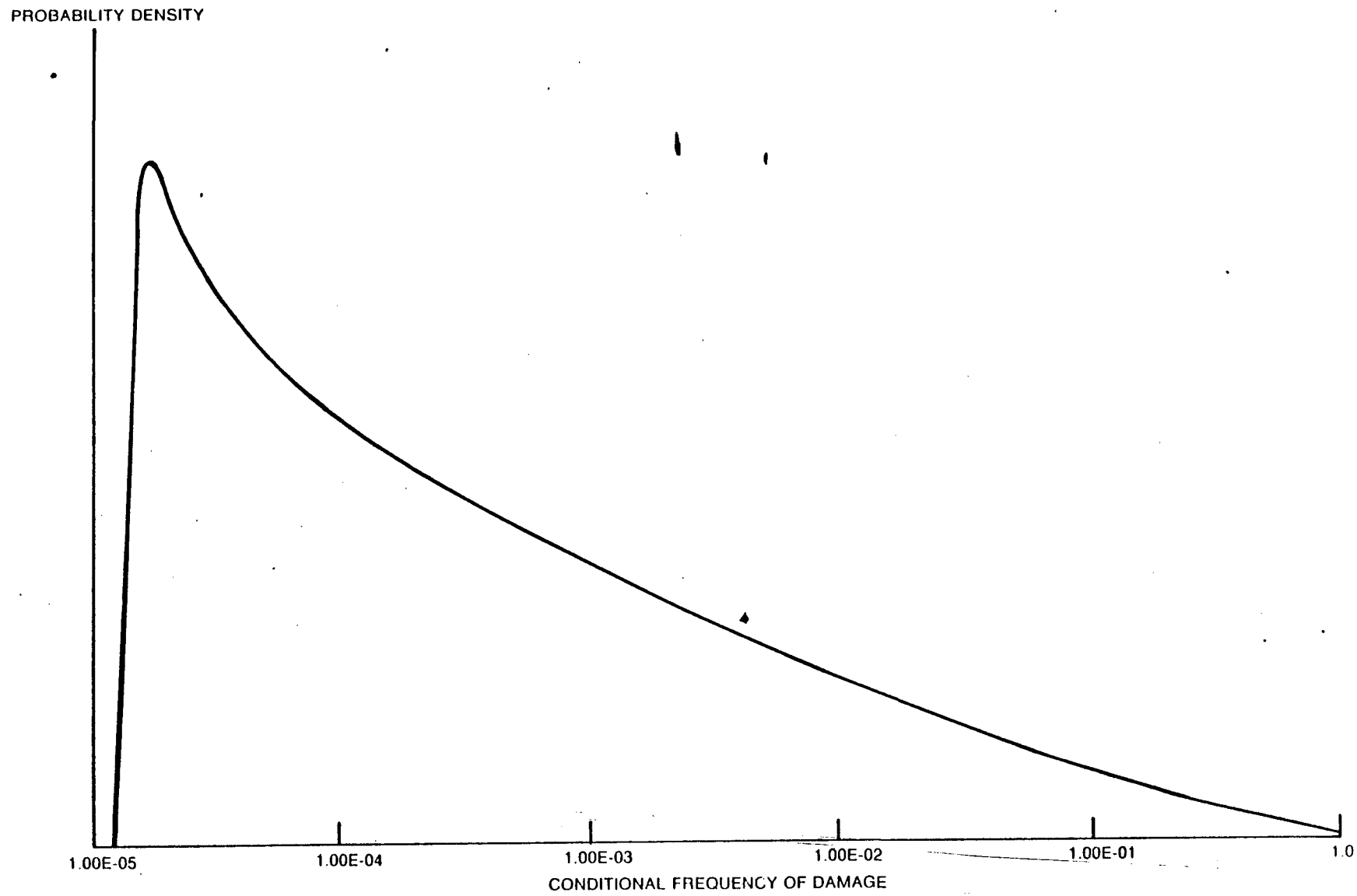

Figure 6-8. Analysis Results for Voltage Level V3 Susceptibility Group H

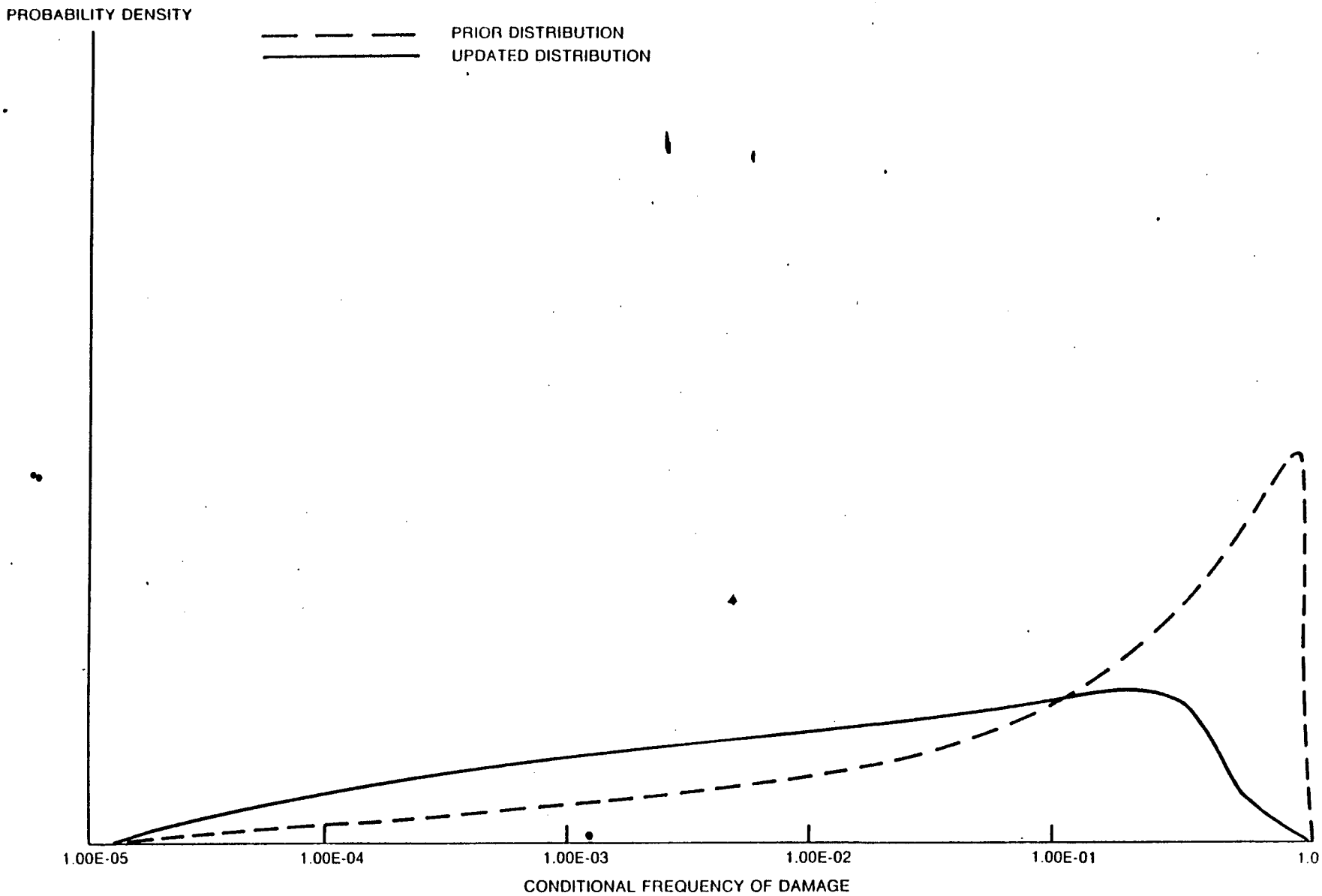

Figure 6-9. Analysis Results for Voltage Level V3 Susceptibility Group I

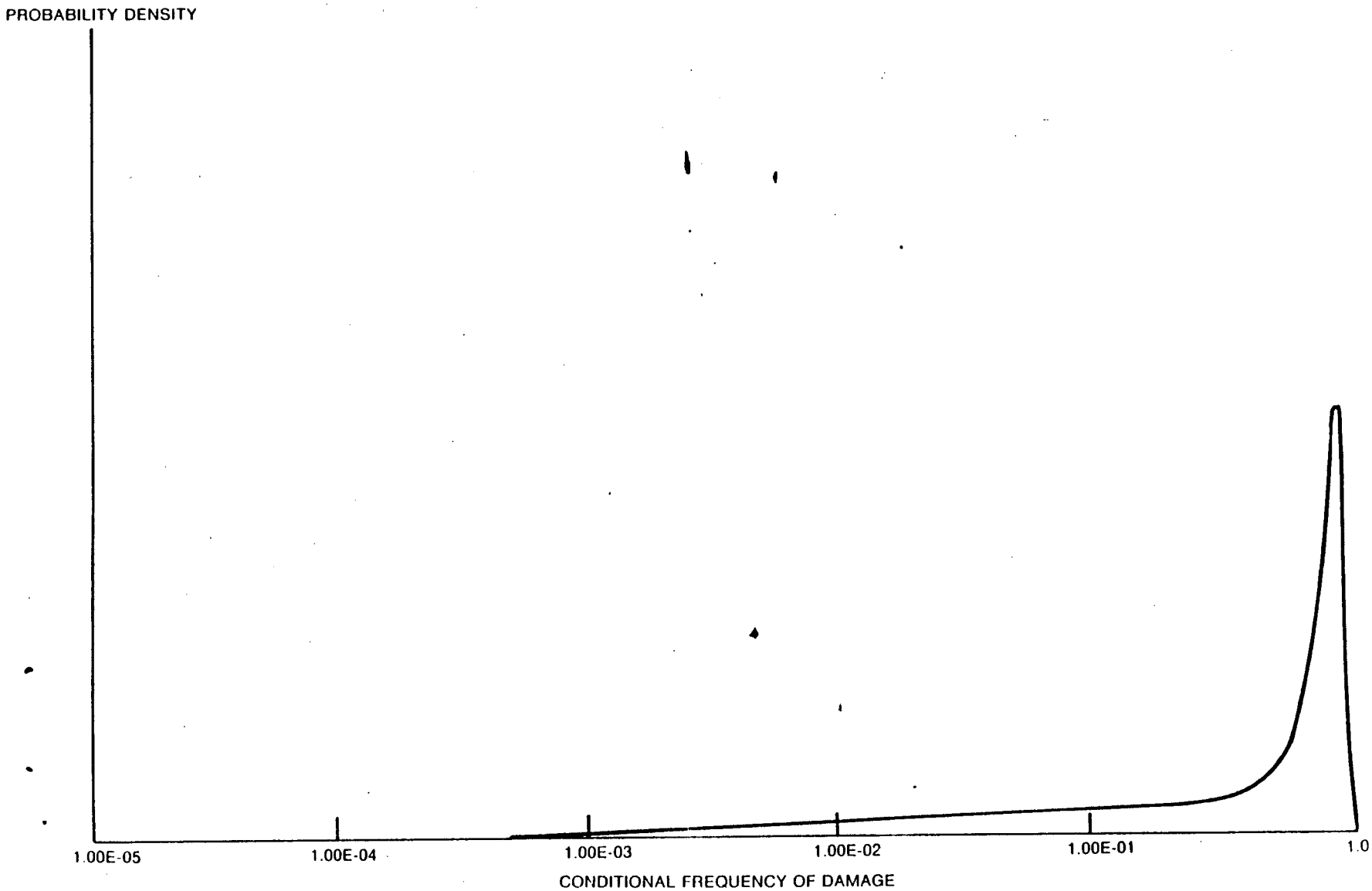

Figure 6-10. Analysis Results for Voltage Level V3 Susceptibility Group J

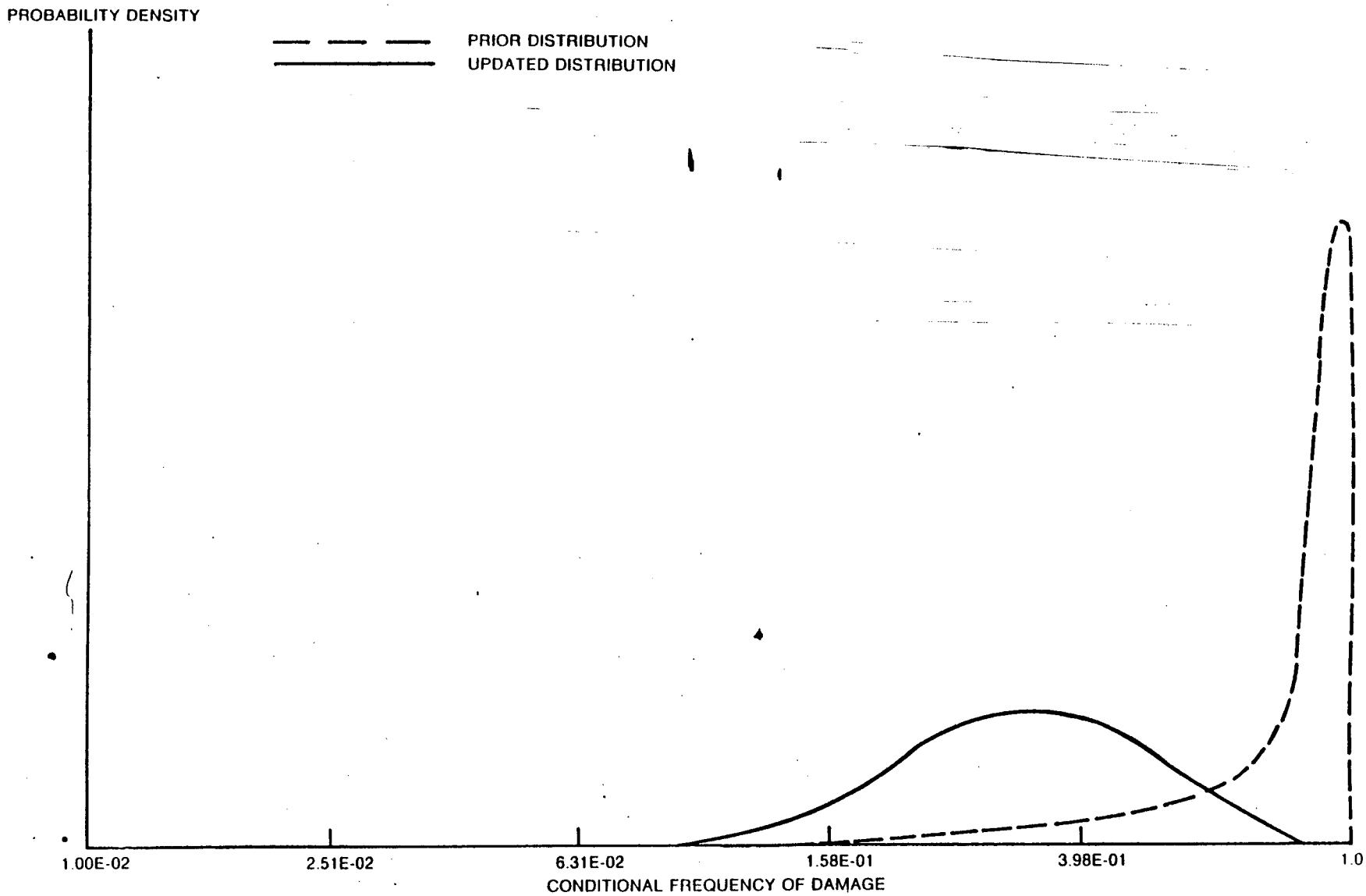

Figure 6-11. Analysis Results for Voltage Level V3 Susceptibility Group K

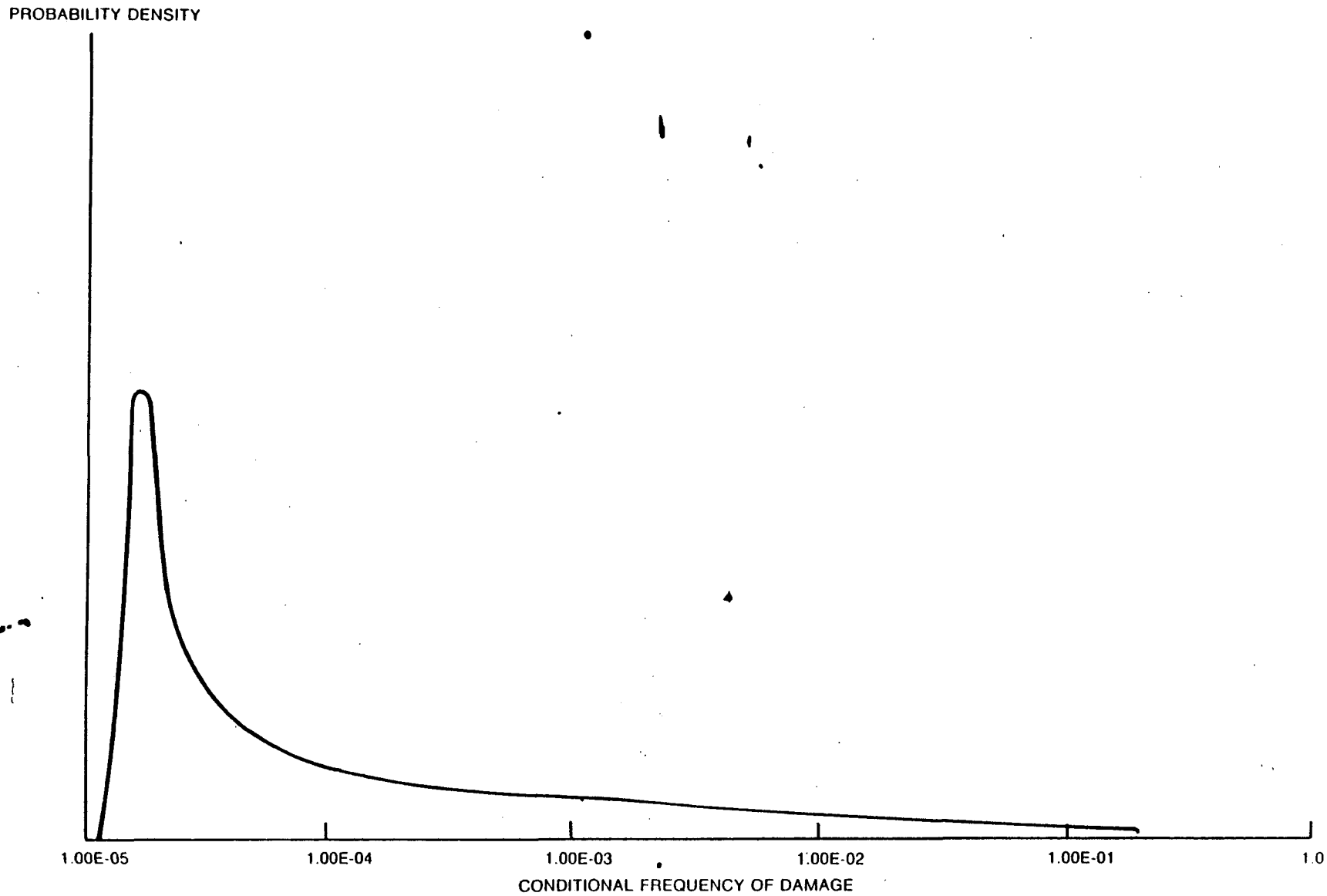

Figure 6-12. Analysis Results for Voltage Level V4 Susceptibility Group G

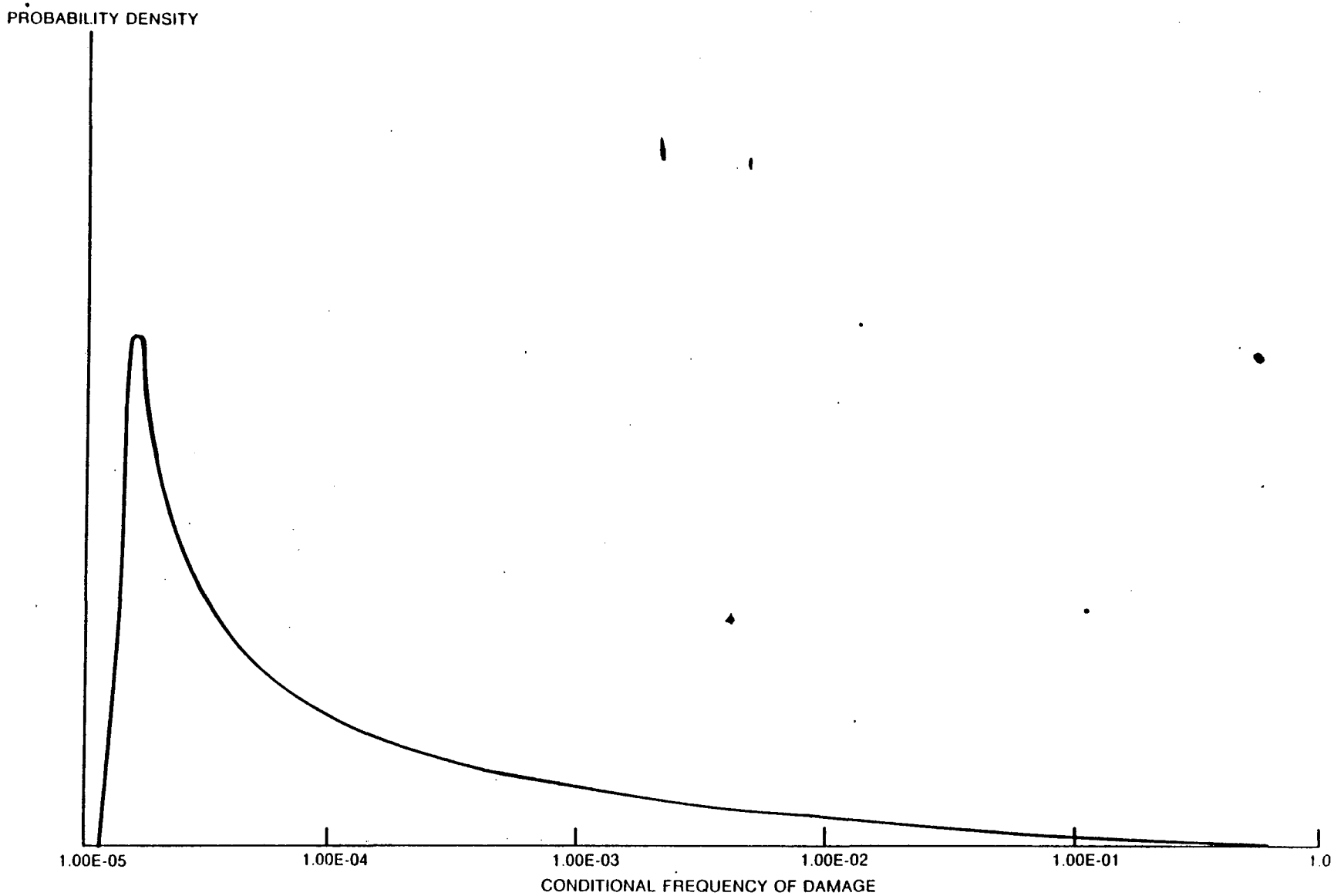

Figure 6-13. Analysis Results for Voltage Level V4 Susceptibility Group H

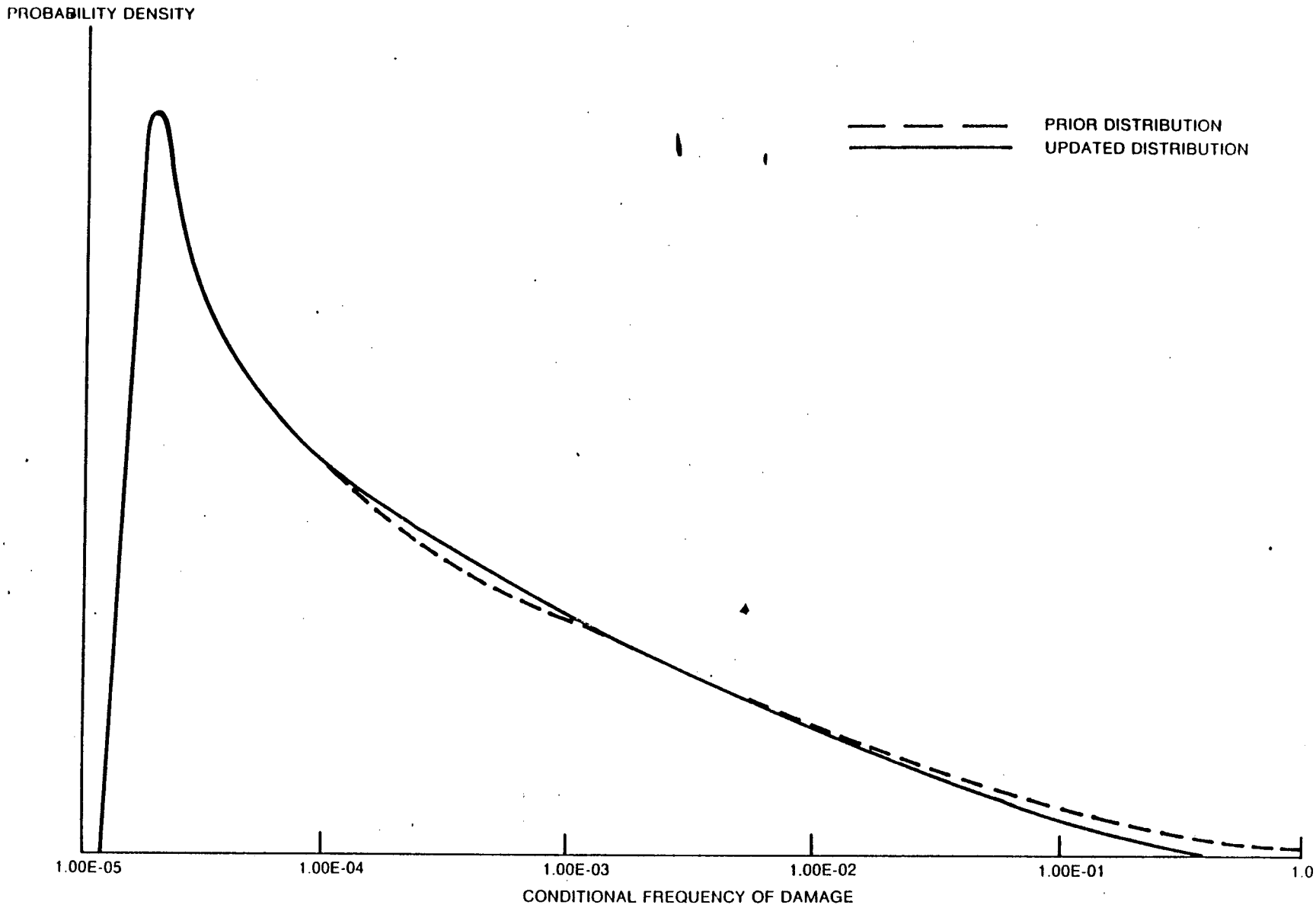

Figure 6-14. Analysis Results for Voltage Level V4 Susceptibility Group I

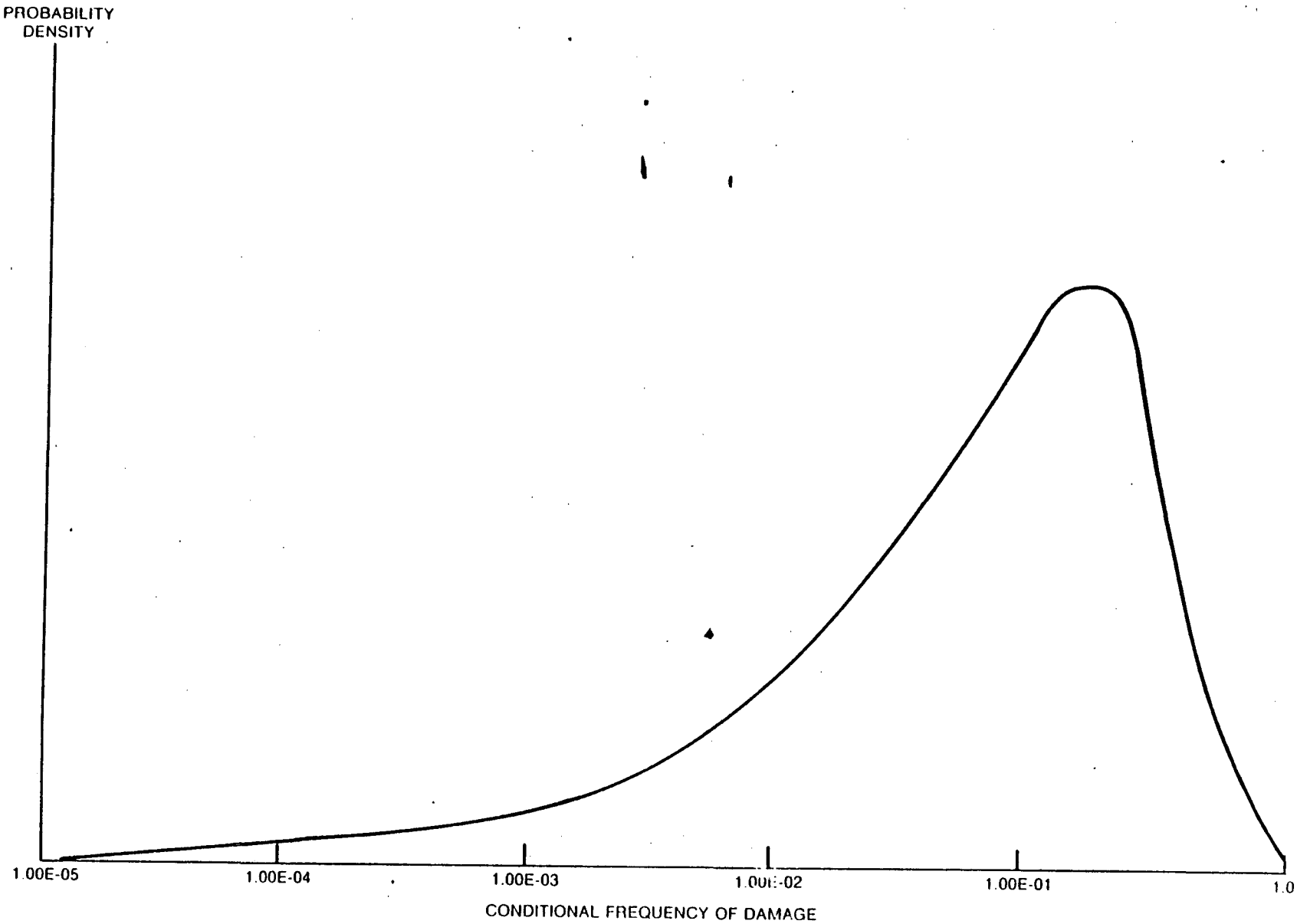

Figure 6-15. Analysis Results for Voltage Level V4 Susceptibility Group J

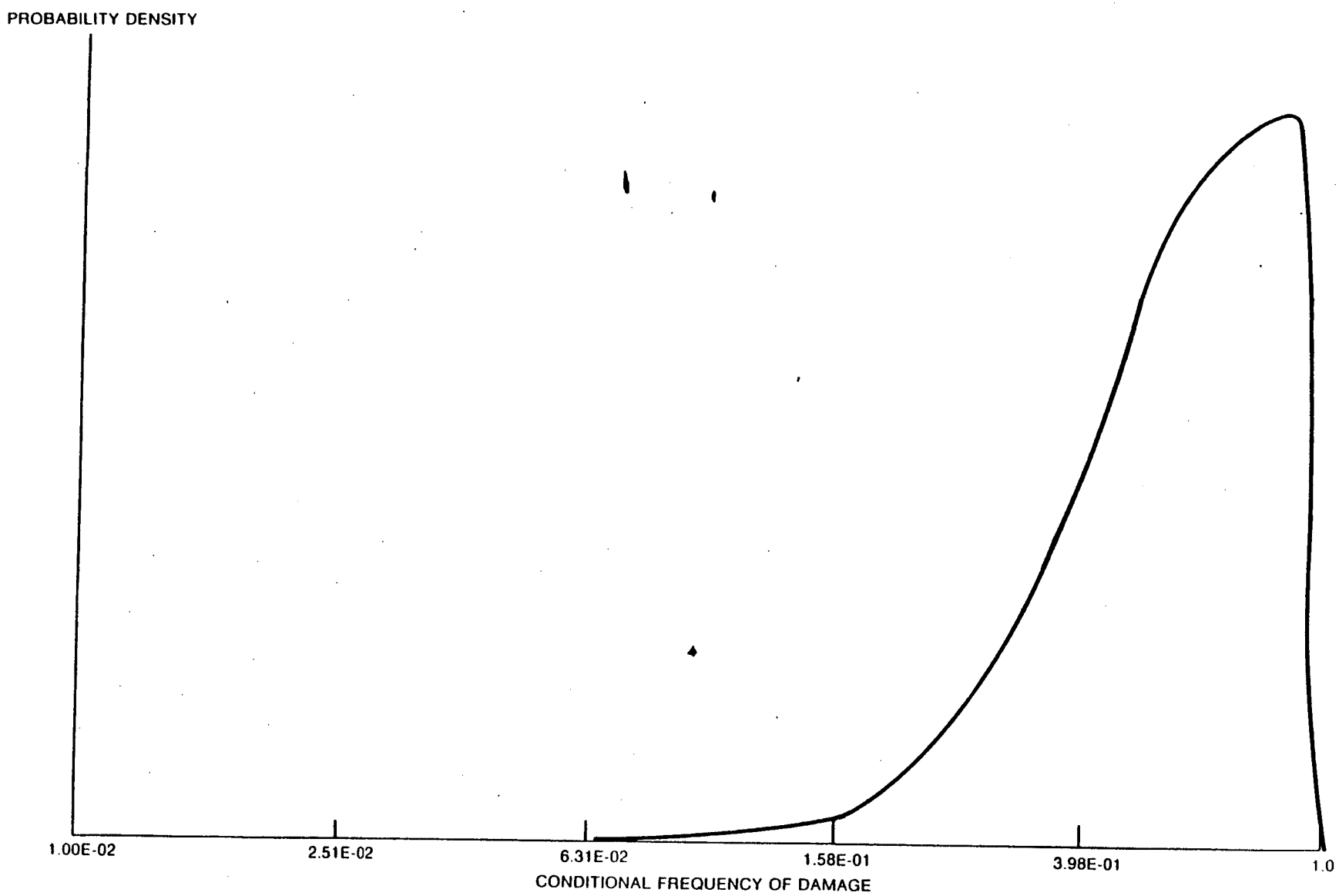

Figure 6-16. Analysis Results for Voltage Level V4 Susceptibility Group K

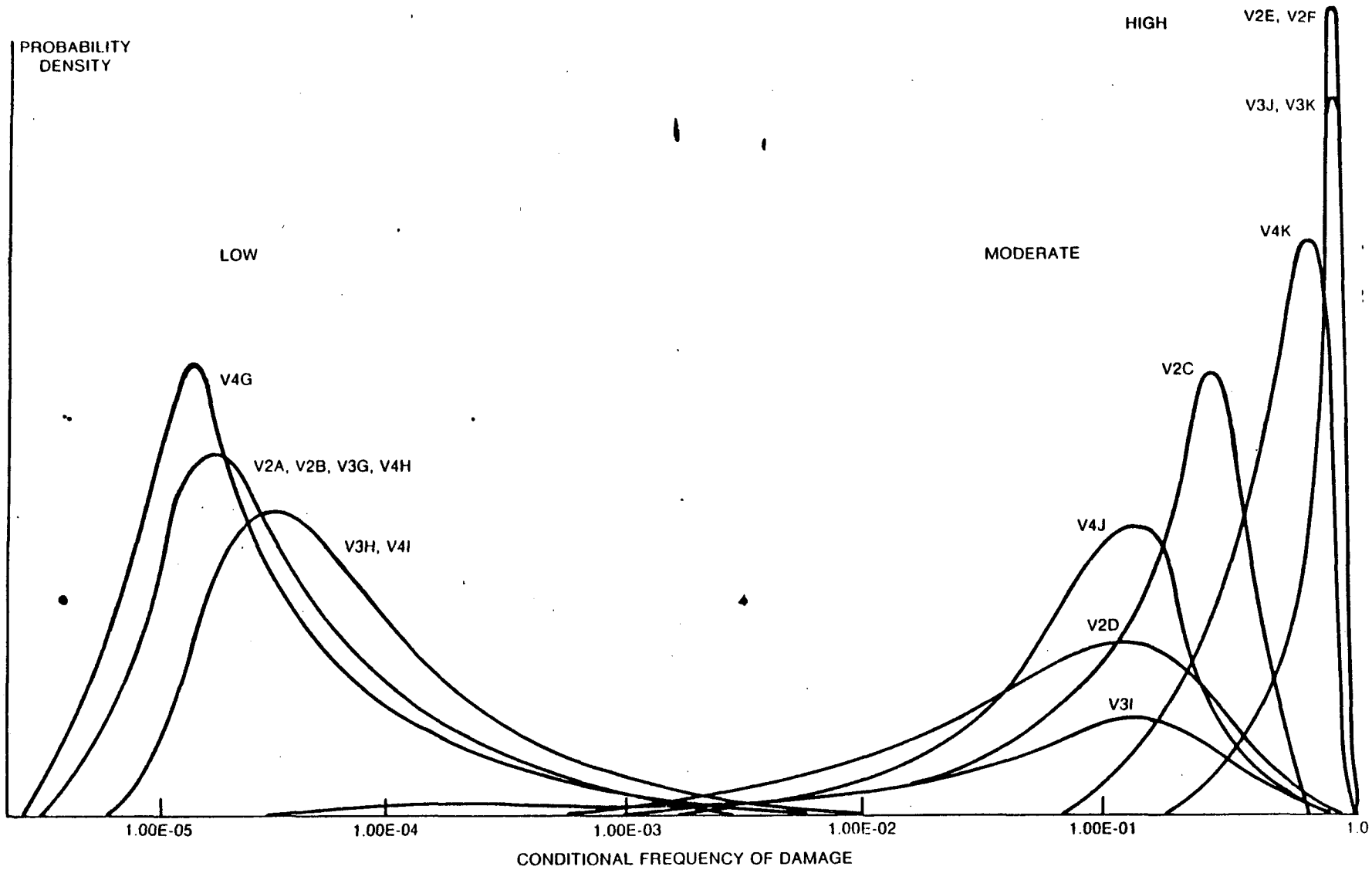

Figure 6-17. Composite Summary of Results

7. REFERENCES

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7. Wakefield, D. J., and K. N. Fleming, "STADIC4 Computer Code Users Manual," PLG-0438, Pickard, Lowe and Garrick, Inc. October 1985.

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APPENDIX A. BAYESIAN METHODS

A.1 BASIC CONCEPTS

The methodology used to develop estimates for the likelihood of cable damage in this study is based on the Bayesian interpretation of probability and the concept of "probability of frequency" (Reference 1). In this context, event frequencies are treated as measurable quantities for which uncertainty is dependent on the state of knowledge of the investigator. The state of knowledge is presented in the form of a probability distribution over the range of possible values of that quantity. The probability that is associated with a particular numerical value of an uncertain quantity indicates the likelihood that the numerical value is the correct one.

A key issue in developing state-of-knowledge distributions for the parameters of probabilistic models is to ensure that the information regarding each parameter, its relevance, and its value as viewed by the analyst is presented correctly, and that the various pieces of information are integrated coherently. Coherence is preserved if the final outcome of the process is consistent with every piece of information used and all assumptions made. This is done by using the fundamental tool of probabilistic inference; i.e., Bayes' theorem (Reference 2). Mathematically, Bayes' theorem is written as

$$P(x \mid E, E_0) = k^{-1} \; L(E \mid x, E_0) P(x \mid E_0) \qquad (A.1.1)$$

where

$P(x \mid E, E_0)$ ≡ probability of x being the true value of an unknown quantity in light of the new evidence, E, and the prior body of knowledge, E_0.

$L(E \mid x, E_0)$ ≡ likelihood of the new evidence, E, assuming that the true value of the unknown quantity is x.

$P(x \mid E_0)$ ≡ probability of x being the true value of the unknown quantity based on the state of knowledge, E_0, prior to receiving the evidence E.

Finally, k is a normalizing factor which is defined according to

$$k \equiv \int_{\text{all } x} L(E \mid x, E_0) P(x \mid E_0) dx \qquad (A.1.2)$$

In the context of a plant-specific analysis, three types of information are available for the frequencies of elemental events:

E_0 = general engineering knowledge, such as knowledge about the design and manufacture of equipment.

E_1 = historical information from other similar plants.

E_2 = past experience of the specific plant being studied.

The information of types E_0 and E_1 together constitute the "generic" information, and E_2 is the "plant-specific" or "item-specific" information.

The following section describes the Bayesian approach to data analysis in more detail. Evidence in the form of either actual experience or expert estimates is addressed. Most of this discussion is in terms of component failure rates. However, the discussion is equally applicable to the analysis of many other types of data.

A.2 GENERIC FAILURE RATE DISTRIBUTIONS

To discuss the way in which generic event frequency distributions are developed based on different types of information, we consider the following cases:

- **Type 1.** Data from operating experience at various nuclear power plants.
- **Type 2.** Estimates or distributions contained in various industry compendia, such as WASH-1400 (Reference 3) and IEEE-500 (Reference 4).

By type 1 information, we mean data that were collected from the performance of similar equipment in various power plants. (Reference 5, for example, provides a detailed list of reported valve failures at various U.S. commercial nuclear power plants for a 2-year period. Also given in this reference are the number of demands and the total operating time for the valves at each power plant.)

Type 2 information, which could be called processed data, consists of estimates based on information ranging from the opinion of experts with engineering knowledge about the design and manufacture of the equipment in question, on the one hand, to the observed performance of that equipment in various applications, on the other. (For instance, Reference 4 provides failure estimates based on the opinions of several experts. The estimates of Reference 5, on the other hand, are based on recorded failures of equipment at various nuclear power plants.)

Normally, type 2 data are in the form of either a point estimate (usually referred to as the "best estimate"), or a range of values centered about a best estimate. In some cases, a distribution is provided covering a range of values for the event frequency in question, with the mean or median representing the best estimate of that source. For instance, IEEE-500 provides low, high, and recommended values for component failure rates under normal conditions, and a maximum value for extreme environments. WASH-1400, on the other hand, assesses a probability distribution for each component failure rate to represent the variability of the available data from source to source. Such distributions are normally centered around a median value judged to be most representative of the equipment in question for nuclear applications.

The methodology used to develop this generic database uses both types of information to generate generic probability distributions. Such distributions represent the variability of the assessed quantities from source to source (for type 2 information) and/or from plant to plant (for type 1 information). In the absence of plant-specific information, these population variability distributions are also, in fact, our state-of-knowledge curves. The following discussion helps to clarify this distinction.

Let us suppose that we have 100 plants, and that for each plant, the exact value of the failure rate of a particular type of pump is known. Let λ_i be the failure rate of the pump at the ith plant. Suppose further that the λ_i's can be grouped into a limited number of discrete values, say λ_1^*, through λ_5^*, with 20 of the λ_i's being equal to λ_1^*, 35 equal to λ_2^*, 25 equal to λ_3^*, 15 equal to λ_4^*, and finally, 5 equal to λ_5^*. The frequency distribution of the λ_i's is then given by the histogram shown in Figure A.2-1.

This histogram represents the population variability of the λ_i's because it shows how the failure rate of the particular type of pump under consideration varies from plant to plant. It is thus an exact and true representation of the variability of the failure rate at the 100 plants in

the population, and does not include any uncertainty or ambiguity because the distribution is presumed to be based on perfectly known failure rates at each and every plant.

Now consider the case where only estimates, not the exact values, of the failure rates are available, and for only some, not all, of the 100 plants in the population. With this state of knowledge, we are not able to know the exact population variability distribution (Figure A.2-1). The questions then are how one can use this more limited information to estimate the population variability curve, and how close this estimate will be to the true distribution, as given in Figure A.2-1.

To answer these questions, note first that the desired population variability distribution is a member of the set of all possible histograms. Because of our limited information, however, we are uncertain as to which member of that set is, in fact, the true distribution. This situation can be represented by a probability distribution over the set of all possible histograms expressing our state of knowledge about the nature of the true histogram.

For instance, if the entire space, H, of all possible histograms is composed of only n histograms,

$$H \equiv \{h_1, h_2, \ldots, h_n\}$$

where h_i represents the ith histogram, then the evidence regarding the pump failure rates at different power plants can be used to assess a probability distribution over H as follows:

$$P(H) = \{p_1, p_2, \ldots, p_n\} \quad \text{with} \sum_{i=1}^{n} p_i = 1 \tag{A.2.1}$$

where p_i is the chance that h_i is the true histogram. (Figure A.2-2 depicts the situation in which the variable λ is considered to be continuous, and the desired distribution is a density function instead of a histogram.)

With a perfect state of knowledge, we would be able to say in which of the histograms h_i is the true distribution; consequently, the corresponding p_i would be equal to 1, and all others would be equal to 0. However, based on the state of knowledge expressed by Equation (A.2.1), our estimate of the true histogram is

$$\bar{h} = \sum_{i=1}^{n} p_i \; h_i \tag{A.2.2}$$

This is called the "expected distribution." Another histogram of interest has the highest chance of being the true histogram. We call this one the "most likely distribution," h_m, and it has probability

$$p_m = \max \{p_i; \; i = 1, \ldots, n\} \tag{A.2.3}$$

More generally, the problem of obtaining P, as defined by Equation (A.2.1), is formulated in the Bayesian context as follows

$$P(h_i | E) = k^{-1} \; L(E | h_i) P_0(h_i) \tag{A.2.4}$$

where $P_0(h_i)$ is the prior state of knowledge regarding the set H as defined by Equation (A.2.1), and $P(h_i | E)$ is the posterior state of knowledge in light of the evidence E [see Equation (A.1.1)]. The evidence is incorporated via the likelihood term, $L(E | h_i)$, which is the probability of observing the evidence given that the true histogram is h. Finally, k is a normalizing factor defined as

$$k = \sum_{i=1}^{n} L(E | h_i) P_0(h_i) \tag{A.2.5}$$

In this context [see Equation (A.1.2)], the expected distribution, Equation (A.2.2), is our estimate of the true population variability of the desired quantity. It shows, for example, how the failure rates of similar pumps are distributed among the plants in the population. Now, if all we know about a specific pump before we have any experience with it is that it is one member of the population, the population variability curve also becomes our state-of-knowledge distribution for the failure rate of that specific pump. In other words, generic distributions representing population variability can also be used to predict the expected behavior of any member of the population, if no other information is available.

The following sections describe how types 1 and 2 information can be used to develop generic distributions.

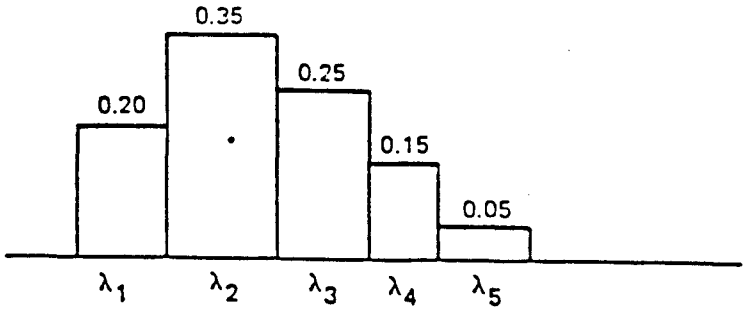

Figure A.2-1. Population Variability of the Failure Rate

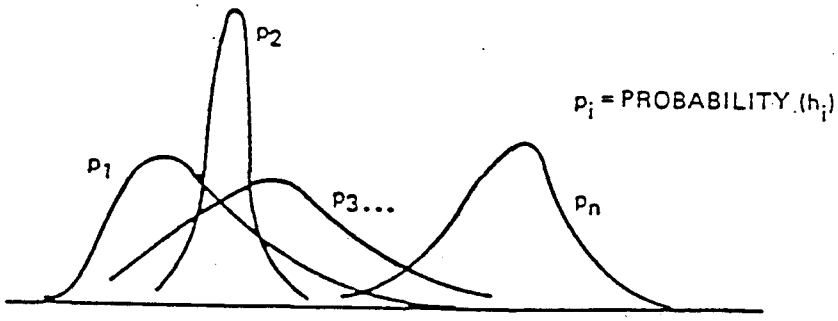

Figure A.2-2. State-of-Knowledge Distribution over the Set of Frequency Distributions

A.3 DEVELOPING GENERIC DISTRIBUTIONS BASED ON ACTUAL PERFORMANCE RECORDS (TYPE 1)

The following discussion is based on the method presented in Reference 6. Consider the case where the following information is available about the performance of a generic component in N plants:

$$I_1 = \{ < k_i, T_i > ; \quad i = 1, \ldots, N\} \tag{A.3.1}$$

where k_i is the number of failures of the component in the ith plant during a specific period of time, T_i.

The desired information is $\phi(\lambda)$, the distribution of the component failure rate, λ, in light of the evidence I_1. This distribution represents the variation of λ from one plant to another, and is analogous to Figure A.2-1.

Following our discussion above, we would like to determine our posterior state of knowledge about the true nature of the function $\phi(\lambda)$. To make matters practical, we will assume that $\phi(\lambda)$ belongs to a particular family of m-parameter distributions, and will let θ be the set of m parameters of $\phi(\lambda)$:

$$\theta = \{\theta_1, \ldots, \theta_m\} \tag{A.3.2}$$

Thus, for each value of the vector variable θ, there exists a unique distribution $\phi(\lambda \mid \theta)$, and vice versa. Therefore, the state-of-knowledge distribution over the space of all possible $\phi(\lambda \mid \theta)$'s is equivalent to the state-of-knowledge distribution over all possible values of θ.

In this case, Bayes' theorem can be written as

$$P(\theta \mid I_0, I_1) = k^{-1} \; L(I_1 \mid \theta, I_0) P_0(\theta \mid I_0) \qquad \text{[See Equation (A.2.4)]} \tag{A.3.3}$$

where

$P(\theta \mid I_0, I_1)$ = the posterior state of knowledge about θ in light of the evidence I_1 and prior information I_0.

$L(I_1 \mid \theta, I_0)$ = the likelihood of observing the evidence I_1 given that the actual set of parameters of $\phi(\lambda)$ is θ.

$P_0(\theta \mid I_0)$ = the prior state of knowledge about θ based on general engineering knowledge I_0.

Finally, k is a normalizing factor given by

$$k = \int_\theta L(I_1 \mid \theta, I_0) P_0(\theta \mid I_0) d\theta$$

In this formulation, the likelihood term is the conditional probability of observing the evidence, I_1, given that the data are based on an underlying population variability curve

$\phi(\lambda \mid \theta)$ with θ as the value of its parameters. In other words, since the evidence I_1 is in the form of N sets of component failures, K_i, and operating hours, T_i, we can express the likelihood as

$$L(I_1 \mid \theta, I_0) = P(< k_i, T_i >; \quad i = 1, \ldots, N \mid \theta, I_0) \tag{A.3.4}$$

Note that the likelihood function is conditional on the prior state of knowledge I_0.

If we now assume that the numbers of operating hours, T_i, at the different plants are independent of one another and that the observed failures, k_i, are also independent (since, according to our model, each k_i is based on a different underlying failure rate), the joint probability distribution given by Equation (A.3.4) can be reduced simply to the product of the marginal distributions as follows:

$$L(I_1 \mid \theta, I_0) = \prod_{i=1}^{N} P_i(k_i, T_i \mid \theta, I_0) \tag{A.3.5}$$

where $P_i(k_i, T_i \mid \theta, I_0)$ is the probability of observing k_i failures of the equipment in question during the period T_i at the ith plant, assuming that the set of parameters of the underlying population variability curve is given by θ.

If the failure rate, λ_i, at the ith plant is known exactly, the likelihood of observing k_i failures in T_i hours can then be calculated using a Poisson model according to

$$P(k_i, T_i \mid \lambda_i) = \frac{(\lambda_i T_i)^{k_i}}{k_i!} \exp(-\lambda_i T_i) \tag{A.3.6}$$

However, λ_i is not known. All we know is that λ_i is one of many possible values of the variable λ. In addition, according to our model, λ is distributed according to $\phi(\lambda \mid \theta)$, with θ being unknown. For this reason, we calculate the probability of observing the evidence $< k_i, T_i >$, by allowing the failure rate to assume all possible values. This is achieved by averaging Equation (A.3.6) over the distribution of λ as follows:

$$\begin{aligned} P(k_i, T_i \mid \theta, I_0) &= \int_0^\infty P(k_i, T_i \mid \lambda)\phi(\lambda \mid \theta)d\lambda \\ &= \int_0^\infty \frac{(\lambda T_i)^{k_i} e^{-\lambda T_i}}{k_i!} \phi(\lambda \mid \theta)d\lambda \end{aligned} \tag{A.3.7}$$

Depending on the parametric family chosen to represent $\phi(\lambda \mid \theta)$, the integration in Equation (A.3.7) can be carried out either analytically or by numerical techniques. For example, if $\phi(\lambda \mid \theta)$ is assumed to be a gamma distribution, which has the following form:

$$\phi(\lambda \mid \alpha, \beta) = \frac{\beta^\alpha}{\Gamma(\alpha)} \lambda^{\alpha-1} e^{-\beta\lambda} \tag{A.3.8}$$

with α and β (both nonnegative), as its parameters, then the desired integral can be evaluated analytically, resulting in (Reference 7)

$$P(k_i, T_i \mid \alpha, \beta) = \frac{T_i^{k_i}}{k_i!} \frac{\beta^\alpha}{\Gamma(\alpha)} \frac{\Gamma(\alpha + k_i)}{(\beta + T_i)^{\alpha + k_i}} \tag{A.3.9}$$

In developing failure rate distributions, however, $\phi(\lambda \mid \theta)$ is more commonly assumed to be lognormal with μ and σ as its parameters:

$$\phi(\lambda \mid \mu, \sigma) = \frac{1}{\sqrt{2\pi}\,\sigma\lambda} \exp\left\{-\frac{1}{2}\left(\frac{\ell n\lambda - \ell n\mu}{\sigma}\right)^2\right\} \tag{A.3.10}$$

In this case, Equation (A.3.7) can be evaluated numerically. The total likelihood for all N plants can now be found by substituting Equation (A.3.7) into Equation (A.3.5):

$$L(I_1 \mid \theta, I_0) = \prod_{i=1}^{N} \left\{\int_0^\infty \frac{(\lambda T_i)^{k_i}}{k_i!} \exp\,(-\lambda T_i)\phi(\lambda \mid \theta)d\lambda\right\} \tag{A.3.11}$$

The posterior distribution that results from using the likelihood of Equation (A.3.11) in Bayes' theorem, Equation (A.3.3), is a probability distribution over the m-dimensional space of the vector of parameters θ. Any specific point, θ, in this space has a one-to-one correspondence with a distribution, $\phi(\lambda \mid \theta)$, in the space of possible distributions. Figure A.3-1 is an example of $P(\theta \mid I_0, I_1)$ for $\theta = \{\alpha, \beta\}$, the two parameters of gamma distribution, based on pump data from all U.S. nuclear power plants (Reference 7).

The expected distribution is obtained from

$$\bar{\phi}(\lambda) = \int_\theta \phi(\lambda \mid \theta)P(\theta \mid I_0, I_1)d\theta \qquad \text{[See Equation (A.2.2)]} \tag{A.3.12}$$

In this equation, the quantity $\bar{\phi}(\lambda)$ "summarizes" the information about λ; it is used as the generic failure distribution.

Sometimes, it is also useful to obtain the most likely distribution [see Equation (A.2.3)]. According to the definition, the most probable distribution of λ is the one whose parameters maximize $P(\theta \mid I_0, I_1)$. These parameters are therefore the solution of the following system of m equations:

$$\frac{\partial P(\theta \mid I_0, I_1)}{\partial \theta_i} \Big|_{\theta_{i,\,max}} = 0; \qquad i = 1, \ldots, m \tag{A.3.13}$$

The methodology discussed above also applies to demand failure data, where the evidence is of the form

$$I_1 = \{ < k_i, D_i > ,\ i = 1, \ldots, N\} \tag{A.3.14}$$

Here, k_i and D_i are the numbers of failures and demands, respectively, in the ith plant. To use data of this type, the Poisson distribution used in Equation (A.3.7) is simply replaced by the binomial distribution

$$P(k_i, D_i \mid \lambda) = \frac{D_i!}{k_i!(D_i-k_i)!} \lambda^{k_i} (1-\lambda)^{D_i-k_i} \qquad \text{(A.3.15)}$$

Example

For motor-operated valve failures to start on demand, the following data from six plants were available:

Plant (i)	Number of Failures (k_i)	Number of Demands (D_i)
1	10	$1.65 \times 10^{+4}$
2	14	$1.13 \times 10^{+4}$
3	7	$1.73 \times 10^{+3}$
4	42	$6.72 \times 10^{+3}$
5	3	$1.26 \times 10^{+3}$
6	31	$9.72 \times 10^{+3}$

These data (which form a set of type 1 information, I_1) were used in model 1 of the computer code BEST (Reference 8), which calculates Equations (A.3.7) and (A.3.11) and generates $\phi(\lambda)$ based on Equation (A.3.12). The result was a 20-bin discrete probability distribution with the following characteristics:

- 5th Percentile: 6.10×10^{-4}
- 50th Percentile: 1.05×10^{-3}
- Mean: 2.26×10^{-3}
- 95th Percentile: 3.19×10^{-3}

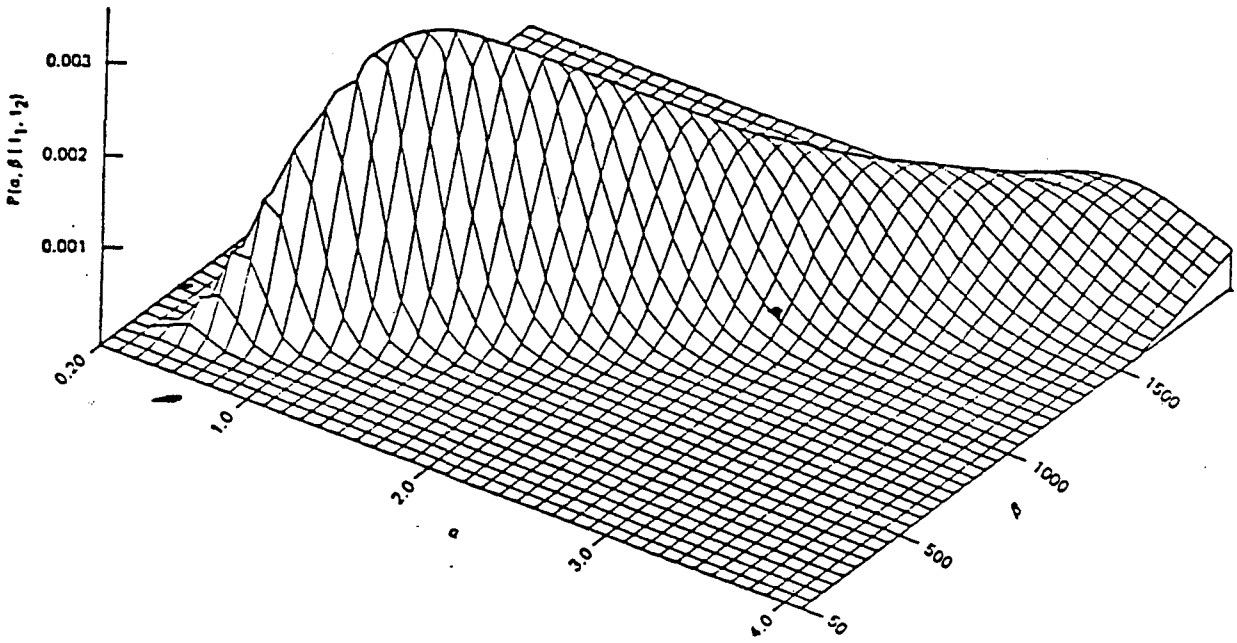

Figure A.3-1. Posterior Distribution for the Parameters of the Distribution of Pump Failure-to-Start-on-Demand Rates

A.4 DEVELOPING GENERIC DISTRIBUTIONS USING ESTIMATES FROM AVAILABLE SOURCES OF GENERIC DATA (TYPE 2)

As mentioned earlier, generic data frequently are not in the form of raw data as given by Equations (A.3.1) and (A.3.14). Rather, most sources report point or interval estimates, or even distributions for failure rates (type 2 information). These estimates are either judgmental (i.e., expert opinion), or are based on standard estimation techniques used by the analysts to translate raw data into point or interval estimates (or sometimes into a full distribution).

An example of such an estimation technique is the well-known maximum likelihood estimator, given by

$$\lambda_M = \frac{k}{T} \tag{A.4.1}$$

where k is the total number of failures in T units of operating time. Many data sources report only λ_M, and not k and T.

To develop a model for constructing generic distributions using this type of data, two cases are considered, as described in the following sections.

A.4.1 Estimating an Unknown Quantity Having a Single True Value

The following method is adopted from Reference 9. Suppose that there are M sources of data, each providing its own estimate of the quantity λ, which has a single true (but unknown) value, λ_t. An example is the failure rate of a particular component at a given plant. The true value of that failure rate, λ_t, can only be known with an infinite amount of experience. Before then, however, the failure rate may be estimated by one or more experts who is familiar with the performance of the component. Let

$$I_2^* = \{\lambda_i^*; i = 1, \ldots, M\} \tag{A.4.2}$$

be the set of such estimates, where λ_i^* is the estimate of λ_t given by the ith expert.

The objective is to use the information I_2^* to obtain a state-of-knowledge distribution for λ_t. Obviously, when everything is known about λ_t, such a state-of-knowledge distribution would simply be a delta function centered at λ_t:

$$P(\lambda \mid \text{perfect knowledge}) = \delta(\lambda - \lambda_t) \tag{A.4.3}$$

[Note that in Equation (A.4.3), λ is used as a variable representing the unknown failure rate.]

Now, if we assume a prior state of knowledge, $P_0(\lambda)$, about the quantity λ, Bayes' theorem can be used to incorporate the information I_2^* into the prior distribution to obtain an "updated" state of knowledge about λ:

$$P(\lambda \mid \lambda_1^*, \ldots, \lambda_N^*) = k^{-1}\ L(\lambda_1^*, \ldots, \lambda_N^* \mid \lambda) P_0(\lambda) \tag{A.4.4}$$

For N independent sources of information, the likelihood term $L(\lambda_1^*, \ldots, \lambda_N^* | \lambda)$ can be written as

$$L(\lambda_1^*, \ldots, \lambda_N^* | \lambda) = \prod_{i=1}^{N} P_i(\lambda_i^* | \lambda) \tag{A.4.5}$$

where $P_i(\lambda_i^* | \lambda)$ is the probability that the estimate of the ith source will be λ_i^*, when the true value of the unknown quantity is λ. (The case of dependent sources of information is discussed in Reference 9.)

Obviously, if the ith source is a perfect one, then we have

$$P_i(\lambda_i^* | \lambda) = \delta(\lambda_i^* - \lambda_t) \tag{A.4.6}$$

which means that the estimate, λ_i^*, is equal to the true value, λ_t. The posterior, $P(\lambda | \lambda_1^*, \ldots, \lambda_N^*)$, in this case, will be determined entirely by the estimate of this source:

$$P(\lambda | \lambda_1^*, \ldots, \lambda_N^*) = \delta(\lambda - \lambda_i^*) \tag{A.4.7}$$

At the other extreme, when it is believed that the source is totally unreliable, we then have

$$P_i(\lambda_i^* | \lambda) = C \tag{A.4.8}$$

where C is a constant. This means that even if the true value is λ, the estimate of the ith source can take on any value. Using a likelihood of this form in Equation (A.4.5) will have no effect on the posterior state of knowledge, as expected.

In this approach, the likelihood term is the most crucial element. It reflects the analyst's degree of confidence in the various sources of information, their accuracy, and the applicability of their estimates to the particular case of interest. As can be seen, the subjective nature of evaluating and "weighting" the evidence from different sources fits very well in the above formulation. This becomes clearer in discussing possible models for the likelihood functions in Equation (A.4.5).

Suppose that in estimating the true value of λ_t, the ith source makes an error of magnitude E. Two simple models are available for the relationships among the quantities λ_t, E, and λ_t^*:

$$\lambda_i^* = \lambda_t + E \tag{A.4.9}$$

$$\lambda_i^* = \lambda_t \times E \tag{A.4.10}$$

In the model of Equation (A.4.9), if a normal distribution is assumed for the error term of the estimate of each source, the likelihood function will itself be a normal distribution with a mean of $\lambda_t + b_i$, where b_i is the expected error or "bias" about which the error of the ith source is distributed.

Using this model, we have

$$P(\lambda_i^* | \lambda_t) = \frac{1}{\sqrt{2\pi}\,\sigma_i} \exp\left\{-\frac{1}{2}\left(\frac{\lambda_i^* - (\lambda_t + b_i)}{\sigma_i}\right)^2\right\} \tag{A.4.11}$$

In this formulation, the variance of the likelihood, σ_i^2, is simply equal to the variance of the error distribution. The values of b_i and σ_i must be subjectively assessed by the data analyst, and should reflect the credibility and accuracy of the source as viewed by the data analyst. Sometimes, information provided by the source itself, such as uncertainty bounds for the estimate, can be used to assess σ_i.

If, in addition to a normal likelihood function, a normal prior distribution is assumed for λ_t, with mean λ_0 and variance σ_0^2, the posterior distribution in Equation (A.4.4) will also be normal, with a mean given by

$$\lambda_p = \sum_{i=1}^{N} w_i(\lambda_i^* - b_i) \tag{A.4.12}$$

and a variance of

$$\sigma_p^2 = \left(\sum_{i=1}^{N} \frac{1}{\sigma_i^2}\right)^{-1} \tag{A.4.13}$$

where w_i, the weight given to the ith source, is defined as

$$w_i = \left(\frac{\sigma_p}{\sigma_i}\right)^2 \tag{A.4.14}$$

Note that

$$\sum_{i=1}^{N} w_i = 1 \tag{A.4.15}$$

The mean therefore is a weighted average of the individual estimates after correcting for their expected biases. Also, as can be seen from Equation (A.4.14), smaller values of σ_i result in higher weights. In other words, a source that is believed to make errors of smaller magnitudes (σ_i being the standard deviation of E) is assigned a higher weight, as intuitively expected. Extreme cases are when $\sigma_i = 0$ (highest possible degree of confidence in the ith estimate), for which $w_i = 1$, and when $\sigma_i = \infty$ (no confidence at all), for which $w_i = 0$.

If, instead of Equation (A.4.9), the model of Equation (A.4.10) is instead applied, and the logarithm of the error is assumed to be normally distributed, then the likelihood function for the ith source becomes a lognormal distribution:

$$P_i(\lambda_i^* \mid \lambda_t) = \frac{1}{\sqrt{2\pi}\,\sigma_i \lambda_i^*} \exp\left\{-\frac{1}{2}\left(\frac{\ell n\lambda_i^* - (\ell n\lambda_t + \ell n b_i)}{\sigma_i}\right)^2\right\} \tag{A.4.16}$$

where $\ell n b_i$ is the logarithmic mean error about the logarithm of the true value, $\ell n\lambda_t$, and σ_i is the multiplicative standard deviation. Again, $P_i(\lambda_i^* \mid \lambda_t)$ is the probability that the estimate of the ith source will be equal to λ_i^* when the true value of the failure rate is λ_t. Some evidence in support of the lognormality of $P_i(\lambda_i^* \mid \lambda_t)$ is provided in References 9 and 10.

If we use the model of Equation (A.4.16) for individual likelihoods in Bayes' theorem [i.e., Equation (A.4.4)], and assume a lognormal prior distribution for λ_t, the posterior state of knowledge will also be lognormal, with a median of

$$\lambda_{50,p} = \prod_{i=1}^{N} \left(\frac{\lambda_i^*}{b_i}\right)^{w_i} \tag{A.4.17}$$

where w_i is defined by Equation (A.4.14). The median, then, is a weighted geometric average of the individual estimates, after correcting for their multiplicative biases.

Note that the usual arithmetic and geometric average methods frequently used in the literature are special cases of these Bayesian normal and lognormal models. For instance, Reference 4 uses the geometric average of the estimates provided by several experts:

$$\bar{\lambda} = \left(\prod_{i=1}^{N} \lambda_i\right)^{1/N} \tag{A.4.18}$$

assuming equal weights (i.e., $w_i = 1/N$), no bias ($b_i = 1$), and no prior information. In addition, Reference 4 does not show any uncertainty about the resulting value.

Example

Reference 5 provides a point estimate of $\lambda_1^* = 5.60 \times 10^{-3}$ for the demand failure rate of motor-operated valves (MOV). We would like to use this estimate to obtain a state-of-knowledge distribution for the MOV failure rate. To do this, we first use the lognormal model of Equation (A.4.16) to express our confidence in the estimated value λ_1^*:

$$P(\lambda_i^* \mid \lambda_t) = \frac{1}{\sqrt{2\pi}\,\sigma_1 \lambda_1^*} \exp\left\{-\frac{1}{2}\left(\frac{\ell n\lambda_1^* - (\ell n\lambda_t + \ell n b_1)}{\sigma_1}\right)^2\right\} \tag{A.4.19}$$

where λ_1^* is the estimate (5.60×10^{-3}) and λ_t is the assumed true value of the failure rate (which remains an unknown variable at this point). In this model, our subjective judgment about the magnitude of the error in this data source is expressed by assigning numerical values to the multiplicative bias term, b_1, and the logarithmic standard deviation σ_1.

In this example, we assume that there is no systematic bias (i.e., $b_1 = 1$); we will estimate σ_1 based on the range factor, which is a more understandable quantity. The range factor here is

defined as the ratio of the 95th to the 50th percentiles of the lognormal distribution. Therefore, given a range factor, the value of σ_1 can be obtained from the following equation:

$$\sigma_1 = \frac{\ell n RF}{1.645} \tag{A.4.20}$$

For our example, we assume a range factor of 3. Such a range factor represents a relatively high degree of confidence; it implies that the source's estimate will be no more than a factor of 3 higher or lower than the true failure rate with 90% confidence. Using this range factor in Equation (A.4.20) results in a value of 0.67 for σ_1.

If we now use the likelihood of Equation (A.4.19) in Bayes' theorem [Equation (A.4.4)] and assume a flat prior distribution, $P_0(\lambda_t)$, then posterior distribution will be

$$P(\lambda \mid \lambda_1^* = 5.6 \times 10^{-3}) = 106.65 \exp\left\{ -\frac{1}{2}\left(\frac{\ell n\lambda - \ell n(5.6 \times 10^{-3})}{0.67} \right)^2 \right\} \tag{A.4.21}$$

This distribution has the following characteristics:

- 5th Percentile: 1.87×10^{-3}
- 50th Percentile: 5.60×10^{-3}
- Mean: 7.01×10^{-3}
- 95th Percentile: 1.68×10^{-2}

A.4.2 Estimating Distributions Using Point Estimates from Various Sources

We now go back to our original problem, which was to estimate the generic failure rate distribution $\phi(\lambda \mid \theta)$. This time, however, we assume that, instead of the $< k_i, T_i >$ defined in Equation (A.3.1) from various plants, we are given one estimate, λ_i^*, for each plant; that is, the evidence is of the form

$$I_2 = \{\lambda_i^*; i = 1, \ldots, N\} \tag{A.4.22}$$

The model to be used is a combination of the methods presented in Sections A.3 and A.4.1, and is fully discussed in References 7 and 11. A particular family of parametric distributions, $\phi(\lambda \mid \theta)$, is assumed for λ, and the information I_2 is used in Bayes' theorem to obtain a posterior distribution over the entire set of possible values of θ, and consequently over all possible distributions $\phi(\lambda \mid \theta)$. Formally, we have

$$P(\theta \mid I_2, I_0) = k^{-1}\ L(I_2 \mid \theta, I_0) P_0(\theta \mid I_0) \tag{A.4.23}$$

[See the set of definitions immediately following Equation (A.3.3) for the interpretations of the terms in Equation (A.4.23).]

The total likelihood function when the λ_i's are independently estimated can be written as

$$L(I_2 | \theta, I_0) = \prod_{i=1}^{N} P_i(\lambda_i^* | \theta, I_0) \qquad \text{[See Equation (A.3.5)]} \tag{A.4.24}$$

where

$P_i(\lambda_i^* | \theta, I_0)$ ≡ the probability that the estimate provided for the ith plant is is λ_i^* given that the population variability distribution of the failure rates has parameter θ. (A.4.25)

To make matters clearer, note that we are assuming that the ith source of data is providing an estimate for the failure rate at a particular plant, and all we know is that failure rates vary from plant to plant, according to the population distribution variability $\phi(\lambda | \theta)$. Each λ_i therefore is an estimate of one point in that distribution. As a result, there are two sources of variability in the estimates. First, the estimates of the individual sources are not necessarily perfect; i.e., they could involve errors and biases, as discussed in Section A.4.1. Second, even if all of the sources were perfect, the estimates would still be different due to the actual variation of the failure rate from plant to plant.

Based on our discussion in the previous section, our confidence in the accuracy of the estimate λ_i^* for the failure rate at the ith plant can be modeled by a lognormal distribution [see Equation (A.4.16)]. Assuming no bias, we have

$$P_i(\lambda_i^* | \lambda_i) = \frac{1}{\sqrt{2\pi}\,\sigma_i \lambda_i^*} \exp\left\{-\frac{1}{2}\left(\frac{\ell n\lambda_i^* - \ell n\lambda_i}{\sigma_i}\right)^2\right\} \tag{A.4.26}$$

where λ_i is the true value of the failure rate at the ith plant. Again, we do not know λ_i, but we assume that it belongs to $\phi(\lambda | \theta)$, the distribution representing the variability of the λ_i's from plant to plant. The relationship between $P_i(\lambda_i^* | \theta, I_0)$ and $\phi(\lambda | \theta)$ is shown in Figure A.4-1.

Therefore, as in Equation (A.3.7), we can write

$$P_i(\lambda_i^* | \theta, I_0) = \int_0^\infty P_i(\lambda_i^* | \lambda_i)\phi(\lambda_i | \theta) d\lambda_i \tag{A.4.27}$$

As mentioned earlier, in developing failure rate distributions, $\phi(\lambda_i | \theta)$ is assumed to be lognormal, as defined by Equation (A.3.10). With this assumption, the integration in Equation (A.4.27) can be done analytically, yielding

$$P_i(\lambda_i^* | \theta, I_0) = \frac{1}{\sqrt{2\pi}\,\sqrt{\sigma_i^2 + \sigma^2}\;\lambda_i^*} \exp\left\{-\frac{1}{2}\frac{(\ell n\lambda_i^* - \ell n\mu)^2}{\sigma_i^2 + \sigma^2}\right\} \tag{A.4.28}$$

Equation (A.4.23), Bayes' theorem, can now be written as:

$$P(\theta | \lambda_i^*, \ldots, \lambda_N^*) = k^{-1} \prod_{i=1}^{N} P_i(\lambda_i^* | \theta, I_0) P_0(\theta | I_0) \tag{A.4.29}$$

The most probable and expected distributions of λ can be found in the same way as was discussed in Section A.4.1. In particular, the expected distribution is calculated by substituting the result of Equation (A.4.26) in Equation (A.3.12). The parameters of the most likely distribution can be shown to be the solutions of the following system of equations (Reference 11):

$$\ell n\mu = \sum_{i=1}^{N} \frac{(\sigma_i^{\,2} + \sigma^2)^{-1}}{\sum_{i=1}^{N} (\sigma_i^{\,2} + \sigma^2)^{-1}} \ell n\lambda_i^{\bullet} \tag{A.4.30}$$

$$\sum_{i=1}^{N} \left[\frac{1}{\sigma_i^{\,2} + \sigma^2} - \left(\frac{(\ell n\lambda_i^{\bullet} - \ell n\mu)}{\sigma_i^{\,2} + \sigma^2} \right)^2 \right] = 0 \tag{A.4.31}$$

For perfect sources of information (i.e., $\sigma_i = 0$), the above equations result in the following simplified solution:

$$m = \left(\prod_{i=1}^{N} \lambda_i^{\bullet} \right)^{\frac{1}{N}} \tag{A.4.32}$$

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (\ell n\lambda_i^{\bullet} - \ell n\mu)^2 \tag{A.4.33}$$

Note that Equations (A.4.32) and (A.4.33) are similar to the conventional results for fitting a lognormal distribution to a set of estimates. It should also be mentioned that the results of this section apply to any set of event frequency estimates from various sources in which a true variability is suspected to exist among the actual values being estimated by the sources. For instance, if several generic sources of data all provide estimates for the failure rate of a particular type of equipment and it is known or suspected that each source's estimate is based on a different subset of the population, the methods of this section can be applied to obtain a generic distribution representing the "source to source" variability of the failure rate.

Example

The following estimates are available for the demand failure rate of MOVs:

Source	Estimate
WASH-1400 (Reference 3)	1.00×10^{-3}
NUREG/CR-1363 (Reference 5)	5.60×10^{-3}
GCR (Reference 12)	1.00×10^{-3}

To use the model of this section, we must assign range factors to each source, as a measure of our confidence in the estimate provided by that source. We can then determine $P_i(\lambda_i^* | \lambda_i)$ for each source using Equation (A.4.26).

Following our discussion in the example of Section A.4.1, we will assign a range factor of 3 to the estimate from NUREG/CR-1363. For the estimate of WASH-1400, we assign a range factor of 5, which results in a broader likelihood function, $P_i(\lambda_i^* | \lambda_i)$, for that source and represents less confidence than for NUREG/CR-1363. This is because the estimate of NUREG/CR-1363 appears to be based on a larger sample of MOV failures in nuclear applications than the estimate of WASH-1400. WASH-1400 provides a range factor of 3 for the lognormal distribution whose median (1.00×10^{-3}) we have taken as the estimate. Assigning a range factor of 5 rather than 3 implies that we believe WASH-1400 has overstated its confidence in the estimated median value. Similarly, we assign a range factor of 10 for the GCR estimate. This reflects a lower degree of confidence in the estimate of Reference 12.

The idea of broadening some WASH-1400 distributions when used in developing generic distributions was introduced in an early site-specific PRA study (References 13 and 14) in which the WASH-1400 curves (as given) were used as generic prior distributions. It was then found that several posterior distributions, reflecting the evidence of the specific plant being analyzed, lay in the tail regions of the prior distributions (on the high side). These results led to the conclusion that the generic curves should be broadened to reflect greater uncertainty.

References 15 and 16 provide further support to our decision. For example, in Reference 15, the authors reviewed experimental results on the adequacy of probability assessments, and concluded that "the overwhelming evidence from research on uncertain quantities is that people's probability distributions tend to be too tight. The assessment of extreme fractiles is particularly prone to bias." Referring to WASH-1400 in particular, they state that "the research reviewed here suggests that distributions built from assessments of the 0.05 and 0.95 fractiles may be grossly biased."

Similarly, commenting on judgmental biases in risk perception, Reference 16 states:

> *A typical task in estimating uncertain quantities like failure rates is to set upper and lower bounds such that there is a 98% chance that the true value lies between them. Experiments with diverse groups of people making many different kinds of judgments have shown that, rather than 2% of true values falling outside the 98% confidence bounds, 20 to 50% do so (Reference 15). Thus, people think that they can estimate such values with much greater precision than is actually the case.*

The numerical effect of using a larger range factor is illustrated in the following table:

Distribution	5th Percentile	Median	Mean	95th Percentile	Range Factor
WASH-1400	3.3×10^{-4}	1.0×10^{-3}	1.2×10^{-3}	3.0×10^{-3}	3
Broadened Distribution	2.0×10^{-4}	1.0×10^{-3}	1.6×10^{-3}	5.0×10^{-3}	5

We see here that the medians remain the same, while the mean value increases slightly, reflecting the extended upper tail of the distribution.

For the cases in which WASH-1400 was the only source used for a failure rate, the above methodology was used to generate a broader generic curve from the distribution of WASH-1400. The applied range factor, however, was not necessarily the same for each case.

These range factors can be used to obtain the corresponding σ_i values by using Equation (A.4.20). The results are $\sigma_1 = 0.67$, $\sigma_2 = 0.98$, and $\sigma_3 = 1.40$, for WASH-1400, NUREG/CR-1363, and GCR, respectively. These values as well as the estimates from the three sources were used as input to mode 2 of the computer code, BEST, which evaluates Equations (A.4.26) through (A.4.29) and obtains an expected distribution based on an integration similar to Equation (A.3.12).

The resulting histogram has the following characteristics:

- 5th Percentile: 8.4×10^{-4}
- 50th Percentile: 1.5×10^{-3}
- Mean: 2.0×10^{-3}
- 95th Percentile: 7.4×10^{-3}

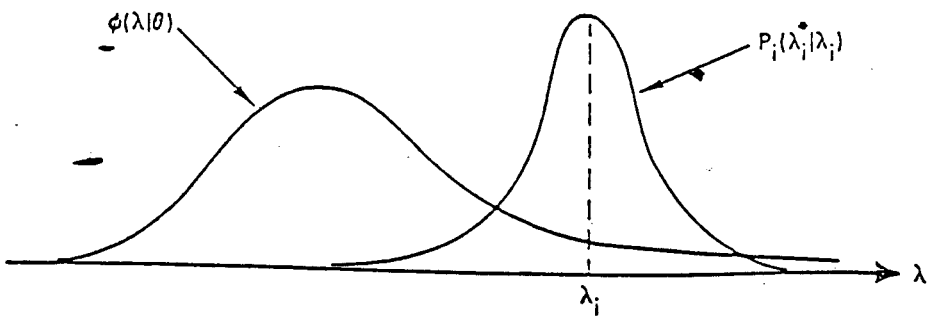

Figure A.4-1. The Relation between the Population Variability Curve and Uncertainty about Individual Estimates

A.5 DEVELOPING GENERIC DISTRIBUTIONS BASED ON A MIXTURE OF TYPE 1 AND TYPE 2 DATA

An obvious extension of the situations discussed in Sections A.3 and A.4.2 is the case in which a mixture of I_2 and I_1 type information is available. In this case, the equivalent of Equations (A.3.3) and (A.4.23) is

$$P(\theta \mid I_2, I_1, I_0) = k^{-1}\ L(I_2, I_1 \mid \theta, I_0) P_0(\theta \mid I_0) \tag{A.5.1}$$

If I_1 and I_2 are independent pieces of information, then we can rewrite the likelihood as

$$L(I_2, I_1 \mid \theta, I_0) = L(I_2 \mid \theta, I_0) L(I_1 \mid \theta, I_0) \tag{A.5.2}$$

where the terms on the right-hand side of the equation are defined by Equations (A.3.5) and (A.4.24), respectively.

The expected distribution of λ can now be found from

$$\overline{\phi}(\lambda) = \int_0^\infty \phi(\lambda \mid \theta) P(\theta \mid I_2, I_1, I_0) d\theta \tag{A.5.3}$$

Example

As an example, we will use the combined data given in the examples in Sections A.3 and A.4.2. This information was used as the main input to mode 3 of the computer code, BEST, which evaluates Equations (A.5.1) through (A.5.3). The resulting discretized distribution has the following characteristics:

- 5th Percentile: 7.49×10^{-4}
- 50th Percentile: 2.84×10^{-3}
- Mean: 4.30×10^{-3}
- 95th Percentile: 1.05×10^{-2}

A.6 DATA SPECIALIZATION

When plant-specific data are available, plant-specific distributions can be developed by applying Bayes' theorem as follows:

$$P(\lambda | E_2) = k^{-1} \; L(E_2 | \lambda) P_0(\lambda) \tag{A.6.1}$$

where $P(\lambda | E_2)$ is the plant-specific distribution reflecting the operating experience E_2 (see Section A.1), and the generic distribution $P_0(\lambda)$ is the prior state of knowledge about the frequency of the event in question. When λ is a frequency per unit time and the evidence E_2 is k events in T time units, the likelihood term, $L(E_2 | \lambda)$, takes the form of a Poisson distribution:

$$P(k, T | \lambda) = \frac{(\lambda T)^k}{k!} e^{-\lambda T} \tag{A.6.2}$$

Similarly, if λ is a demand frequency and E_2 is k events in D demands, then $L(E_2 | \lambda)$ is a binomial distribution:

$$P(k, D | \lambda) = \frac{D!}{(D-k)! \; k!} (1-\lambda)^{D-k} \; \lambda^k \tag{A.6.3}$$

The effect of adding plant-specific data depends on the relative strength of the data compared with the prior level of confidence (as expressed by the spread of the prior distribution). Typically, both the location and the spread of the posterior or updated distribution are affected by the plant-specific evidence. In general, the mean value of the updated distribution could be either higher or lower than the mean of the generic prior, but adding plant-specific data will normally reduce the spread of the distribution, as shown in the following example. In this case, the generic distribution for the MOV demand failure frequency presented in the example of Section A.5 was updated with evidence of 15 failures in 5,315 demands. The calculations were performed using mode 4 of the BEST computer code. The following table compares some of the basic characteristics of the generic prior and updated distributions. As can be seen from this table, the updated posterior distribution is substantially more narrow than the prior, with a higher 5th percentile and a lower 95th percentile.

Distribution	5th Percentile	Median	Mean	95th Percentile
Generic	7.49×10^{-4}	2.84×10^{-3}	4.30×10^{-3}	1.05×10^{-2}
Updated	1.57×10^{-3}	2.57×10^{-3}	2.87×10^{-3}	3.85×10^{-3}

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ENCLOSURE 2

COMMITMENT*

TVA will implement the comprehensive program described in Enclosure 1 to ensure the adequacy of the safety-related cable systems. These programs will be completed by fuel load for Units 1 and 2 respectively.

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*See also the 10 CFR 50.55(e) final report on this issue (Reference 2).

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