Further Development of the Weibull Distribution Method for Evaluating ALARA Performance

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Abstract – Performance indicators developed from Weibull distribution analysis of individual workers' radiation doses have been proposed as complementary to current performance indicators for evaluating the effectiveness of As Low as Reasonably Achievable (ALARA) implementation at nuclear facilities. The Weibull-based indicators provide insights based on objective supplemental information. The purpose of this work is to investigate additional topics related to the implementation of this methodology. This paper is a follow-on to a paper presented in October 2009 at the ISOE ALARA Symposium but contains only new analyses and techniques developed since that time, including goodness of fit and the influence of transient workers and experienced workers on site results. A Chi-squared goodness of fit test and goodness of fit plots based on the hazard function are described, and guidelines are proposed for their use. Sensitivity analyses involving the effects of experienced workers on Weibull results are presented from both a statistical and a practical perspective. Additional applications of the Weibull approach are provided, including the effect on the Weibull distribution of accumulating transient workers' doses from all reactors.

Key words: ALARA, Weibull distribution, statistical modeling, goodness of fit, hazard function

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1.0 INTRODUCTION

The As Low As Reasonably Achievable (ALARA) radiation safety principle was developed to safeguard workers who are occupationally exposed to radiation. It has been adopted by numerous international agencies, including the United States Department of Energy (DOE) and Nuclear Regulatory Commission (NRC). This principal has two complementary purposes: to reduce the collective exposure as low as can be reasonably achieved and to maintain dose to individual workers as far below the permissible exposure limits as possible by using all practical, cost-effective methods. Traditionally, performance indicators based on collective dose have been employed to evaluate ALARA implementation at a site. Recently, supplemental performance indicators based on dose distribution among workers receiving dose have been developed to promote the second aspect of the ALARA principle. These indicators are based on site-specific Weibull distribution parameter values derived by fitting a statistical model to individual doses from the site. The Weibull distribution methods are described in detail (Frome et al., 2009). As in the 2009 work, statistical models in this study use distributions of annual individual doses above the minimum inclusion threshold (MIT) of 0.1 mSv, and x is defined as follows: x = [Total Effective Dose Equivalent (TEDE) – MIT].

Whenever statistical models are utilized, the question arises as to how well the data fit the proposed model. In the context of model-based performance indicators that may be used to evaluate sites with respect to ALARA, the issue of goodness of fit has two distinct facets. These two components are the formal evaluation of goodness of fit based on a statistical test and the legitimate use of the performance indicators to evaluate ALARA. All statistical analyses and graphs in this report were obtained using the R (R Development Core Team, 2010) environment for statistical computing. Detailed documentation can be found on the R home page at http://www.r-project.org.

2.0 MATERIALS AND METHODS FOR GOODNESS OF FIT

2.1 Formal Assessment of Goodness of Fit

Goodness of fit is commonly evaluated by a Chi-squared test that has a null hypothesis that the data fit the specified distribution. The data are separated into *k* bins, and the test statistic is defined as the sum over all bins of the squares of the residuals, i.e. (observed – expected) / sqrt(expected). Because an expected frequency of at least five is required for the Chi-squared approximation to be valid, bins are combined where necessary to meet this restriction. Because two parameters are estimated in the Weibull model, the number of degrees of freedom (df) for the Chi-squared test is $k - 2$.

For each site, a p-value is determined based on the Chi-squared statistic, X^2, and the appropriate degrees of freedom. Goodness of fit is assessed independently with a p-value for each site in the group. Although for each site there is a 5% chance of erroneously rejecting a Weibull model, this chance increases depending upon the number of sites tested. To maintain an overall significance level of at most 0.05, each site can be compared with an adjusted critical p-value based on the number of sites in the group. Appendix A contains details of the formal goodness of fit assessment, and *Table A-1* gives the adjusted critical value for 2-100 simultaneous tests Any site having a p-value smaller than the critical value is concluded to have statistically significant lack of fit to the Weibull model and requires further evaluation. Although consensus has not been reached among statisticians as to the best method of adjusting for multiple simultaneous hypothesis tests, there appears to be agreement that adjustment is needed (Benjamin and Yekutieli, 2005).

A more conservative approach to determining which sites have statistically significant lack of fit would be to select a fixed critical value. A p-value below the fixed critical level would indicate lack of fit, and further evaluation of patterns of lack of fit would be required. More details of this approach appear in Appendix A.

2.2 Creating Customized Goodness of Fit Plots

One visual indication of how well site data fit a Weibull distribution is how close the points fall to the Weibull survival (exceedance) function fit line in the custom probability plots (Frome et al., 2009). To provide a complementary perspective, the goodness of fit plots are based on the Weibull hazard function (Johnson et al., 2004). The hazard function with shape parameter α and scale parameter β is specified as

$$h(x) = \alpha/\beta\ [x/\beta]^{\alpha-1}. \qquad (1)$$

When $\alpha = 1$, the Weibull distribution simplifies to a negative exponential distribution, which has a constant hazard function (horizontal line). All but a few sites have $\alpha < 1$, which produces a hazard that is monotonically decreasing with increasing dose as the corresponding Weibull hazard line drops from upper left to lower right. If $\alpha > 1$, then the hazard is monotonically increasing with increasing dose. It has been noted (Frome et al., 2009) that, as a rule-of-thumb, the value of α should be examined and a site should be considered as not effectively implementing ALARA if $\alpha > 1$. An exception to this rule is a site having $\alpha > 1$, a very small 99^{th} percentile, and a percent exceedance near zero.

In the goodness of fit plots, the Weibull hazard function is represented by a solid green line. To construct this line, equation (1) is transformed into the equation of a line (see equation A1 in Appendix A). The resulting Weibull line is composed of ordered pairs $(\ln(v_i),\ln[h(v_i)])$ where $\ln(v_i)$ are natural logarithms of the ordered midpoints of the dose intervals (bins) and $\ln[h(v_i)]$ is given in equation A1. The Nelson-Aalen (N-A) hazard estimate for v_i is the number of doses in its interval divided by the number of doses larger than the lower bound of that interval (Lawless, 2003). The open circles on the plot represent ordered pairs where the first coordinate is $\ln(v_i)$ and the second coordinate is ln(N-A estimate for v_i).

Goodness of fit can be examined visually in these plots by noting whether the open circles fall near the green Weibull hazard fit line. To identify intervals with statistically significant lack of fit, any interval whose residual has a value greater than two, including intervals with no observed doses, has its open circle enclosed in a red diamond. A non-parametric smoother (Friedman, 1984 and Everitt and Hothorn, 2010) shown with a solid blue curve, is applied to the points for all intervals. Rising areas of this curve indicate that the hazard is increasing faster than the Weibull, which means that doses are falling into lower intervals than predicted by the Weibull distribution. When a rising blue curve covers dose intervals around values such as 10 mSv, it is possible that administrative criteria were applied to pull individuals out of jobs with exposure potential when their dose for the year approached this predetermined criterion value. Although such practices may maintain worker health, this approach is not optimum for ALARA and could affect the goodness of fit of the site's doses to any statistical distribution. More effective ALARA practices entail actively maintaining each worker's dose as low as reasonably achievable throughout the year, rather than imposing an upper limit for the year.

2.3 Understanding Customized Weibull Plots

In conjunction with the statistical modeling and testing, two types of plots have been developed to provide the ability to visually compare distributions over time and/or among sites and to visually examine patterns of goodness of fit. *Table 1* summarizes important attributes of the customized Weibull probability plots and corresponding goodness of fit plots. Examined together, these two plots provide much complementary information for assessing the goodness of fit of the site's dose distribution to the Weibull model.

As an example, *Figure 1* is the goodness of fit plot for the DOE Hanford site in 2009. The Weibull hazard line falls from upper left to lower right, and so $\alpha < 1$. Results of the formal Chi-squared test appearing at the bottom of the plot in green text show a p-value 0.150, indicating there is not statistical evidence to reject the null hypothesis (i.e., H_0: the Weibull distribution fits these data). Although there are several intervals near 1 mSv that have residuals greater than two, as indicated by the red diamonds, points generally straddle the line. The blue non-parametric smoother shows that the hazard is somewhat below Weibull in higher doses, which is the area of greatest interest. *Figure 2* is the corresponding probability plot. Probability plots have been described in detail (Frome et al., 2009); emphasis here is on their use in examining goodness of fit. Points, by and large, fall quite close to the Weibull line with the heaviest concentration between 1 mSv and 5 mSv. Whenever a probability plot shows "survival" in a dose range being above-Weibull, the hazard in that range will be below-Weibull. This correspondence can be seen at the higher dose end of the goodness of fit plot. In particular, of the 1,274 doses in the distribution, six values in the probability plot are above 5 mSv and correspond to points noticeably above the Weibull fit line. These six dose values are included in the last interval of the goodness of fit plot, where points correspond to intervals rather than distinct doses.

3.0 RESULTS FOR GOODNESS OF FIT

3.1 Statistical Results

Table 2 and *Table 3* show Weibull-based statistical results based on 2009 dose distributions for DOE and NRC sites, respectively, where the columns are defined as follows:

α	B	99th percentile	99th percentile ucl	% exceedance	nx	X^2	df
Weibull shape parameter	Weibull scale parameter	fitted 99th percentile	99th percentile upper confidence limit	percent exceedance*	Number of doses > MIT	Chi-squared statistic	degrees of freedom

**Percent exceedance is calculated for 2.5 mSv for the DOE sites and 3 mSv for the NRC sites.*

Table 1: Comparing Attributes of Customized Weibull Probability Plots and Goodness of Fit Plots

Attribute	Probability Plots	Goodness of Fit Plots
Weibull line		
starting point	maximum likelihood site-specific values of α and β from Weibull fit	maximum likelihood site-specific values of α and β from Weibull fit
derived from	S(x) = 1 – F(x): exceedance (also called survival) function; -S(x) represented	h(x): hazard function
line	solid black from upper left to lower right	solid green: upper left to lower right if α < 1
x-“axis”/ x-axis	$\ln(u_i)$: u_i are ordered distinct values of x; labels adjusted to doses before MIT subtracted; intersects Weibull line at fitted 99th percentile	$\ln(v_i)$: v_i are ordered interval midpoints of x; labels adjusted to match doses with MIT subtracted
y-axis	$\ln(\beta)*\alpha - \alpha* \ln(u_i)$: labels adjusted to values of exceedance function in %	$\{\ln(\alpha)-\alpha \ln(\beta)\}+(\alpha-1)[\ln(v_i)]$: labels adjusted to values of hazard function
Points		
symbol	open circle	open circle
basis	one for each distinct value of x	one for each interval in Chi-squared
x-coordinate	$\ln(u_i)$	$\ln(v_i)$
y-coordinate	$-\ln(-\ln(S_{emp}(u_i)))$, where $S_{emp}(u_i) = [n/(n+1)]*[1–F_{emp}(u_i)]$, where F_{emp} is the empirical cdf	$\ln(h_{N-A}(v_i))$, where h_{N-A} is Nelson-Aalen hazard estimate
Added line		
reference line	dashed green line from upper left to lower right: Weibull line for –slope = 1 and 99% of doses < 1 rem	blue curve: non-parametric smoother that shows change in hazard over dose range

Figure 1: Sample Customized Goodness of Fit Plot

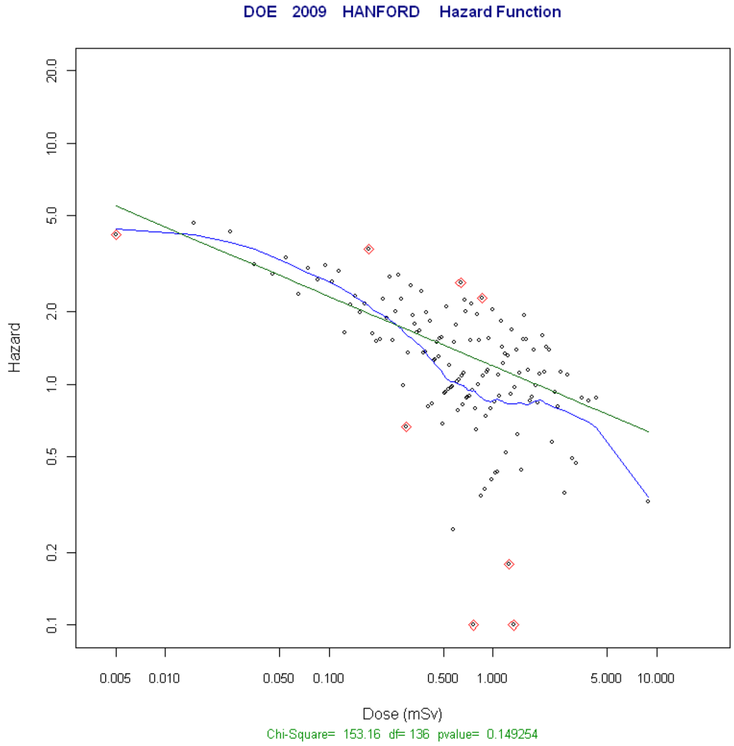
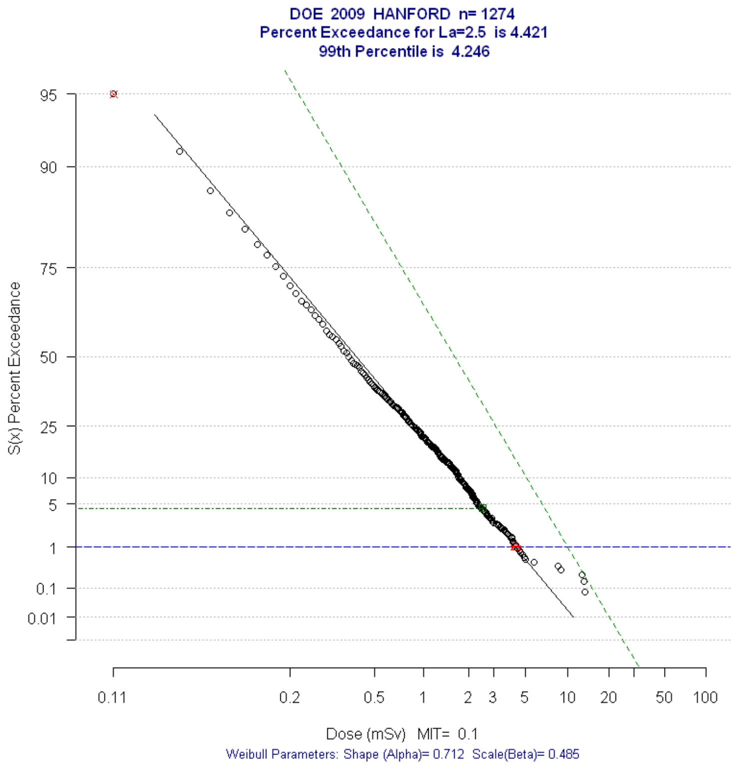


Figure 2: Corresponding Customized Weibull Probability Plot



Sites in *Table 2* and *Table 3* are ranked by the fitted Weibull 99th percentile, where sites from lowest to highest quartiles are color-coded in blue, green, purple, and red, respectively. Ranking sites by upper confidence limit (UCL) of their 99th percentiles, rather than by the percentiles themselves, takes into account uncertainties in the estimates of the parameters used to calculates the percentiles. For DOE, only 2 of 22 sites would change quartiles if ranking were done by the UCLs rather than the 99th percentiles; Sandia National Laboratory would move from Q2 to Q3, while Hanford would switch from Q3 to Q2. One might question whether partitioning into quartiles would be prudent for the DOE sites because there is a distinct gap between the 99th percentile of Pantex (5.141), the first site in the highest quartile, and Los Alamos National Laboratory (8.058), the second site in that quartile.

An alternative to ranking sites by quartiles could be to use the performance indicators to identify clusters of sites. The most important subset would be those sites that do not appear to be implementing ARARA effectively. A second subset would be those sites that are a bridge between the first subset and the remainder of the sites that appear to implement ALARA effectively. Values for LANL, West Valley, Argonne National Laboratory, and Lawrence Livermore National Laboratory (LLNL) are presented in bold font in *Table 2* to emphasize this subset of notably high 99th percentiles. Values for the bridge sites, Oak Ridge National Laboratory and Pantex, are underlined. Percent exceedance confirms the cluster of the four highest and two bridge sites and suggests adding Fermi Lab to the bridge sites.

Among the 64 NRC sites, those that practice good ALARA are readily identified by exhibiting the lowest values of 99th percentile, UCL, and percent exceedance. Because the 99th percentiles and related statistics show no clear gaps between one quartile and the next, partitioning into quartiles may not make fullest use of the information obtained from the Weibull approach. The alternative use of Weibull performance indicators to identify the subset with notably high performance indicators and the subset of bridge sites reveals that Vermont Yankee, Palisades, and Perry are set apart by their high 99th percentiles and UCLs. Palisades and Perry each have over 30% of their doses exceeding 3 mSv, substantially exceeding any of the other sites. Bridge sites include Cooper Station, Pilgrim, Columbia Generating, Millstone, Waterford, and Nine Mile Point. Furthermore, Surry and Browns Ferry show percent exceedance above 15% and should be encouraged to examine their ALARA practices for possible enhancements.

3.2 Utilizing Customized Weibull Plots to Assess Goodness of Fit

The first step in assessing goodness of fit to the Weibull model is to compare the p-value of the site to the critical value for the group. The p-value column of *Table 2* reveals that there is statistically significant lack of fit for the DOE sites of Idaho National Laboratory, LLNL, Pantex, and Waste Isolation Pilot Project (WIPP). Therefore, the pairs of Weibull plots for these four sites must be examined for patterns of the lack of fit to decide if it is substantive. When a site has statistically significant lack of fit, management must weigh in on the decision of whether to evaluate the site's ALARA based on its Weibull performance. Customized Weibull goodness of fit and probability plots based on 2009 data for 22 DOE sites and 64 NRC sites appear in Appendix B and Appendix C, respectively, and provide complementary, critical information for making such administrative decisions.

Of the four DOE sites with statistically significant lack of fit, WIPP is most easily resolved. The dose distribution for WIPP comprises only 33 individuals. With the Chi-squared restriction of at least five expected doses in each interval, the goodness of fit plot shows only four dose intervals, one of which contains no observed doses. The statistical lack of fit in this situation is not surprising. In the probability plot, the points are fairly close to the Weibull line, and the highest dose is about 0.5 mSv. *Table 2* gives the percent exceedance of zero for 2.5 mSv. WIPP appears to have implemented ALARA very effectively and to have warranted its low ranking.

Table 2: DOE Sites Ranked by 2009 Fitted Weibull 99th Percentiles in mSv

Site	α	β	99th percentile	99th percentile -ucl	% exceedance	nx	X^2	df	p-value
Waste Isolation Pilot Plant	0.871	0.060	0.453	0.655	0.000	33	15.866	3	*0.001
Princeton Plasma Physics Laboratory	1.154	0.100	0.479	0.656	0.000	25	4.007	3	0.261
Ames Laboratory	1.338	0.196	0.717	0.983	0.000	24	0.972	2	0.615
Oak Ridge – East Tennessee Technology Park	0.992	0.211	1.091	1.550	0.002	35	6.579	5	0.254
Uranium Mill Tailings Remediation Action Project	0.958	0.283	1.500	1.875	0.044	92	20.309	16	0.207
Paducah / Portsmouth Gaseous Diffusion Plant	0.777	0.275	2.072	2.976	0.467	57	8.655	9	0.470
Brookhaven National Laboratory	0.863	0.374	2.301	2.956	0.699	91	17.697	16	0.342
Nevada Test Site	0.919	0.514	2.815	3.591	1.638	86	20.358	15	0.159
Sandia National Laboratory	0.571	0.226	3.381	5.035	2.125	83	10.880	12	0.539
Oak Ridge – Y-12 National Security Complex	0.795	0.496	3.494	3.814	3.035	876	111.198	111	0.477
Savannah River Site	0.780	0.500	3.649	3.906	3.364	1,517	182.819	149	0.031
Hanford – Office of River Protection	0.628	0.343	4.002	4.787	3.367	333	66.654	49	0.047
Fermi National Accelerator Laboratory	0.929	0.789	4.187	4.906	6.046	198	29.739	18	0.040
Hanford Site	0.712	0.485	4.246	4.606	4.421	1,274	153.159	136	0.149

Site	α	β	99th percentile	99th percentile -ucl	% exceedance	nx	X^2	df	p-value
Hanford – Pacific Northwest National Laboratory	0.651	0.406	4.337	5.361	4.164	223	62.430	36	0.004
Idaho National Laboratory	0.628	0.378	4.415	4.789	4.140	1,700	211.360	146	*0.000
Oak Ridge – Oak Ridge National Laboratory	0.711	0.572	5.009	5.681	6.283	562	99.458	87	0.170
Pantex Plant	0.785	0.720	5.141	6.055	7.659	265	91.934	49	*0.000
Los Alamos National Laboratory	0.633	0.713	**8.058**	**8.954**	**11.603**	1,007	171.662	137	0.024
West Valley Demonstration Project	0.785	1.340	**9.479**	**11.428**	**20.651**	227	42.306	43	0.501
Argonne National Laboratory	0.585	0.769	**10.560**	**14.523**	**14.308**	134	15.597	22	0.835
Lawrence Livermore National Laboratory	0.550	0.724	**11.756**	**15.596**	**14.515**	174	109.627	29	*0.000

**Below critical value of 0.0023; statistically significant evidence of lack of fit at the overall 0.05 level of significance based on 22 sites.*
Ranking by 99th percentile, 99th percentile-ucl, and percent exceedance, Quantiles 1-4 are color-coded blue, green, purple, and red, respectively.
Values of 99th percentile, 99the percentile-ucl, and percent exceedance are shown in bold font or underlined to indicate association with less effective ALARA or bridging toward less effective ALARA, respectively.

Table 3: NRC Sites Ranked by 2009 Fitted Weibull 99th Percentiles in mSv

Site	α	β	99th percentile	99th percentile -ucl	% exceedance	nx	X^2	df	p-value
Callaway	0.969	0.199	1.066	1.258	0.000	154	29.962	25	0.2257
Davis-Besse	0.778	0.190	1.458	1.875	0.024	111	18.097	18	0.4493
Farley	0.934	0.522	2.783	3.037	0.707	648	86.015	96	0.7576
Cook	0.827	0.434	2.860	3.153	0.825	680	81.552	91	0.7506
Harris	0.850	0.459	2.874	3.157	0.837	673	74.173	92	0.9131
Robinson	0.756	0.384	3.002	3.886	1.003	117	14.911	20	0.7815
Palo Verde	0.795	0.475	3.348	3.584	1.487	1,459	141.875	141	0.4635
Mcguire	0.843	0.538	3.395	3.652	1.600	1,145	152.671	133	0.1167
Ginna	0.857	0.608	3.718	4.139	2.218	539	129.389	89	0.0034
Summer	0.846	0.617	3.859	4.236	2.479	712	140.035	108	0.0207
Comanche Peak	0.769	0.555	4.144	4.612	2.832	654	91.547	97	0.6372
Grand Gulf	0.827	0.652	4.242	4.844	3.244	354	82.137	64	0.0630
Watts Bar	0.778	0.587	4.279	4.711	3.131	811	138.405	114	0.0597
Vogtle	0.854	0.703	4.308	4.678	3.509	918	128.943	133	0.5833
Indian Point	0.828	0.687	4.450	4.851	3.724	896	118.022	130	0.7659
Wolf Creek	0.818	0.684	4.532	4.959	3.860	818	151.911	122	0.0344
Byron	0.804	0.666	4.556	4.962	3.844	975	149.906	135	0.1798
Prairie Island	0.873	0.805	4.737	5.252	4.708	553	101.097	99	0.4226
Kewaunee	0.832	0.815	5.209	5.802	5.656	557	110.739	99	0.1976
Oconee	0.818	0.799	5.273	5.601	5.692	1,802	209.714	205	0.3959
Seabrook	0.805	0.791	5.385	5.888	5.845	856	180.214	133	0.0040
Arkansas	0.834	0.864	5.501	5.976	6.458	961	125.321	149	0.9211
North Anna	0.824	0.851	5.539	6.084	6.447	740	144.229	124	0.1034
Braidwood	0.800	0.813	5.586	6.001	6.306	1,383	181.900	180	0.4464
South Texas	0.624	0.475	5.590	6.222	4.550	996	158.457	118	0.0077
Clinton	0.844	0.920	5.731	6.476	7.213	432	74.696	81	0.6758
Fermi	0.806	0.858	5.814	6.248	6.963	1,383	195.073	184	0.2741
Three Mile Island	0.867	1.018	6.026	6.364	8.407	2,014	234.346	244	0.6601
Oyster Creek	0.668	0.604	6.037	7.068	5.779	409	103.939	67	0.0026
San Onofre	0.828	0.948	6.105	6.524	8.053	1,546	212.960	205	0.3369
St. Lucie	0.846	0.988	6.112	6.588	8.344	1,120	182.447	174	0.3152
Calvert Cliffs	0.774	0.870	6.370	7.002	7.931	855	155.688	136	0.1189
Ft Calhoun	0.866	1.140	6.749	7.351	10.619	830	144.170	148	0.5737
Point Beach	0.799	0.993	6.818	7.516	9.526	757	144.392	130	0.1834
Catawba	0.794	0.986	6.851	7.362	9.517	1,371	246.029	195	0.0077
Fitzpatrick	0.663	0.683	6.945	8.290	7.394	336	68.290	58	0.1672
Dresden	0.771	0.948	6.972	7.427	9.389	1,911	273.812	232	0.0310
Sequoyah	0.750	0.922	7.171	7.739	9.460	1,376	195.887	189	0.3504
Susquehanna	0.778	0.996	7.193	7.631	10.084	2,103	293.314	249	0.0282
Diablo Canyon	0.876	1.272	7.378	7.765	12.808	2,296	282.899	292	0.6379
Quad Cities	0.813	1.120	7.433	7.849	11.486	2,338	340.258	278	0.0063
Turkey Point	0.735	0.922	7.461	8.066	9.833	1,342	223.272	186	0.0321
Crystal River	0.802	1.128	7.682	8.212	11.897	1,602	200.418	226	0.8888
Hatch	0.810	1.203	8.039	8.668	13.059	1,283	223.179	201	0.1355
Brunswick	0.777	1.132	8.191	8.657	12.575	2,449	372.734	287	*0.0005
Limerick	0.795	1.204	8.325	8.915	13.415	1,598	264.963	231	0.0619
Beaver Valley	0.799	1.230	8.424	9.028	13.789	1,493	234.036	223	0.2927
River Bend	0.715	1.001	8.570	9.236	11.791	1,615	279.160	215	0.0021

Site	α	β	99th percentile	99th percentile -ucl	% exceedance	nx	X^2	df	p-value
Salem	0.730	1.045	8.574	9.170	12.202	1,917	244.146	243	0.4673
Peach Bottom	0.761	1.169	8.788	9.337	13.597	2,075	295.819	267	0.1087
Surry	0.785	1.282	9.077	9.812	15.026	1,224	209.641	198	0.2718
Duane Arnold	0.701	1.073	9.593	10.584	13.471	947	167.933	152	0.1784
Monticello	0.669	0.975	9.650	10.561	12.589	1,221	265.755	176	*0.0000
Lasalle	0.698	1.097	9.886	10.593	13.960	1,977	337.452	252	*0.0003
Browns Ferry	0.753	1.292	9.911	10.546	15.933	2,127	263.420	281	0.7671
Nine Mile Point	0.720	1.287	10.830	11.734	16.645	1,409	247.904	215	0.0613
Waterford	0.801	1.608	10.924	11.767	**20.158**	1,322	217.605	225	0.6259
Millstone	0.668	1.135	11.284	12.492	15.434	969	238.123	154	*0.0000
Columbia Gen.	0.698	1.263	11.379	12.247	16.804	1,788	320.948	248	0.0012
Pilgrim	0.865	2.049	12.090	13.025	25.972	1,141	210.383	216	0.5950
Cooper Station	0.645	1.162	12.519	13.644	16.508	1,443	281.602	207	*0.0004
Vermont Yankee	0.569	0.985	**14.526**	**17.736**	15.774	370	95.890	63	0.0048
Palisades	0.768	2.275	**16.732**	**18.324**	**30.024**	970	211.108	183	0.0757
Perry	0.853	3.084	**18.583**	**19.773**	**38.775**	1,796	423.532	337	0.0009

**Below critical value of 0.000801; statistically significant evidence of lack of fit at the overall 0.05 level of significance.*
Ranking by 99th percentile, 99percentile-ucl, and %exceedance, Quantiles 1-4 are color-coded blue, green, purple, and red, respectively.
Values of 99th percentile, 99percentile-ucl, and %exceedance are shown in bold font or underlined to indicate association with less effective ALARA or bridging toward less effective ALARA, respectively.

Both plots for LLNL reveal clear lack of fit throughout the dose range. The goodness of fit plot shows that 10 of the 31 intervals have statistically significant lack of fit, and 6 of these 10 are below 0.5 mSv. Although intervals in this low dose range are not of major interest for ALARA, here, they make a strong contribution to the statistical lack of fit. The non-parametric smoother reveals that within the range of about 1-5 mSv, the hazard is less than Weibull and is decreasing. This section of the graph reflects a situation in which individuals are readily accumulating dose and moving on to higher dose levels. In contrast, the interval for 10 mSv and above contains a statistically significant increase in observed doses than expected by the Weibull model. The probability plot shows a substantial number of dose values above the reference line, as well as numerous dose values above 10 mSv. For doses above 10 mSv, there is a precipitous drop in "survival" in the probability plot corresponding to the increase in hazard in the goodness of fit plot. It appears that a concerted effort was made to ensure that individuals receiving 10 mSv would not accumulate more dose. Without this effort, a larger proportion of individuals would likely have received higher doses, whose points may have fallen closer to the line. Although a Weibull model does not fit the LLNL data, it appears to be the case that ALARA implementation for LLNL is among the least effective of DOE sites.

The goodness of fit plot or Pantex reveals that six of the seven dose intervals having statistical lack of fit occur in the very low dose range. The Friedman smoother shows a hazard less than Weibull for the dose range below 5 mSv, although there is a rising trend beginning at about 2 mSv. In the probability plot, most points are fairly close to the Weibull line at doses above 0.4 mSv. If the Weibull fit were better in the low dose range, it appears that the 99th percentile might be slightly smaller because the Weibull line would have a steeper slope. Pantex is the first site in the highest quartile ranked by fitted 99th percentile. However, since the fitted 99th percentile may be slightly inflated by lack of fit in the low dose range, the alternative interpretation seems particularly appropriate (i.e., Pantex and Oak Ridge National Laboratory form a bridge between the sites that do not appear to be implementing ALARA effectively and those that do).

The probability plot for Idaho shows most points fairly close to the Weibull line for doses in the range of approximately 0.5 mSv to 3.5 mSv. Below 0.5 mSv, the smaller the dose, the farther the point is below the Weibull line, indicating an excessive number of doses in the very low range. Above 3.5

mSv, the “survival” into higher doses is less than predicted by the Weibull. There is only one dose value above 5 mSv, which suggests that an administrative limit may have been applied. The fitted 99th percentile would likely be larger if individuals with doses above about 3.5 mSv were permitted to receive the annual doses toward which they were heading. The Friedman smoothed curve in the goodness of fit plot shows the hazard close to or below Weibull for dose intervals between about 0.5 mSv and 3.5 mSv. However, at about 1 mSv, the hazard begins rising and exceeds Weibull expectation at about 3.5 mSv. A cluster of intervals between about 2mSv and 4 mSv has significantly higher observed than expected numbers of doses, as shown by the red diamonds. This cluster suggests that some individuals are being pulled out of areas or tasks that would lead them to accumulate 5 mSv of dose. It does not appear that optimal ALARA practices are being applied to maintain each individual’s dose as low as reasonably possible. Because the patterns in the lack of fit indicate that the fitted 99th percentile may have been decreased because of a 5 mSv individual limit, a reasonable management decision may be to include Idaho with the bridge sites Pantex and Oak Ridge National Laboratory.

The p-values for NRC sites in *Table 3* indicate statistically significant lack of fit for Brunswick, Cooper Station, LaSalle, Millstone, and Monticello using a critical value based on 64 sites in the group. The pairs of Weibull plots for these five sites, found in Appendix C, should be examined for patterns in the lack of fit. This examination is particularly important for Cooper Station and Millstone because they have been identified by Weibull-based performance indicators as belonging to the transition sites between effective and less effective ALARA implementation.

In the probability plot for Cooper Station, points are fairly close to, but generally above, the Weibull line for doses larger than about 1 mSv. However, above 15 mSv, doses begin dropping below the line, which suggests that individuals may have been pulled out of jobs with exposure potential to prevent their reaching 20 mSv. The fitted 99th percentile may have been even higher if the points in the lower dose range were not pulling the slope toward being steeper. The goodness of fit plot reveals a cluster of intervals with significant lack of fit in the range between 0.1 mSv and 0.5 mSv. Although the majority of the diamond-circled points occur below 1 mSv, there are several such intervals above this value. Confirming that doses from about 0.5 mSv are in higher intervals than predicted by the Weibull is the fact that the non-parametric smoother is below the Weibull hazard line. Although the Weibull distribution has significant lack of fit for Copper Station, the ranking position for this site based on Weibull performance indicators appears to be reasonable and even conservative.

The Millstone probability plot reveals an obvious lack of fit to the Weibull at the high doses. It is likely that an administrative rule prescribes that individuals whose doses reach a certain level are to be removed from tasks that have the potential of allowing their doses to reach 20 mSv. The Friedman smoother in the goodness of fit plot confirms this observation. Intervals generally have fewer observed than expected doses in the range of about 0.4 mSv to 5 mSv. However, at 5 mSv, the smoother takes a sharp turn upward, reflecting the influence of the intervals in the highest doses range that are significantly above the Weibull hazard. Also contributing to the Chi-squared for significant lack of fit are various intervals scattered throughout the dose range to about 2 mSv; these intervals generally have more observed than expected doses in an area where the trend is fewer observed than expected. Considering the Millstone dose distribution that might occur without the likely administrative intervention, it appears that the doses would be much closer to the Weibull line on the probability plot.

4.0 INVESTIGATING THE EFFECTS OF TRANSIENT AND EXPERIENCED WORKERS

4.1 Transient Workers at Nuclear Power Plants

Certain job tasks, such as nuclear reactor refueling, are done periodically rather than on a routine basis. Individuals who carry out such tasks do not perform their job duties at one site but instead are transients who work wherever their services are required and go from one site to another during the year. Because doses are reported by site, the annual dose for a transient worker is partitioned into separate records, one record for each site of employment during the year. This method of reporting is appropriate for assigning to a site the amount of dose that was accrued by individuals working there. However, when records for all NRC sites are combined for analysis, the doses of transient workers remain in their separate records. Therefore, an additional analysis was carried out for all NRC sites combined in which dose records for each individual who had worked at more than one site were replaced with one record containing the combined dose received by that person at all reactors during the year. *Figure 3* is the probability plot for all NRC sites with transient workers' doses separated by site, while *Figure 4* is the corresponding plot with each transient worker's doses combined into one record. *Table 4* summarizes the results for these two ways of analyzing transient worker dose.

Table 4: Comparing Weibull Results with Two Methods of Accruing Transient Worker Dose

	Dose Separated by Site of Accrual	Dose Combined into One Record
Number of Records	74,667	60,487
Fitted 99th Percentile	8.102 mSv	10.694 mSv
% Exceedance for 3 mSv	11.41%	15.86%
-Slope	0.740	0.707

When transients' doses are accumulated over sites, an additional 4.5% of the dose records exceed 3 mSv, and the 99th percentile increases by about 2.6 mSv, or over 30%. Also, there was an increase in dose values above 20 mSv; however, no individuals approached an annual dose of 50 mSv. The slope of the Weibull line is somewhat less steep because of the influence of the higher doses from the transient workers that pull the line farther to the right, and the higher doses fall fairly close to the Weibull fit line. Examining the high-dose end of the plot in which transient doses are partitioned by site, it is clear that the separate sites each enforced an annual upper bound of 20 mSv on individual dose accumulation because dose values drop nearly vertically rather than falling near the Weibull line. Goodness of fit plots are not presented here because they are not meaningful for datasets of this size.

Figure 3: Weibull Probability Plot for All NRC Sites 2009 – Transients' Doses Separated by Site of Accrual

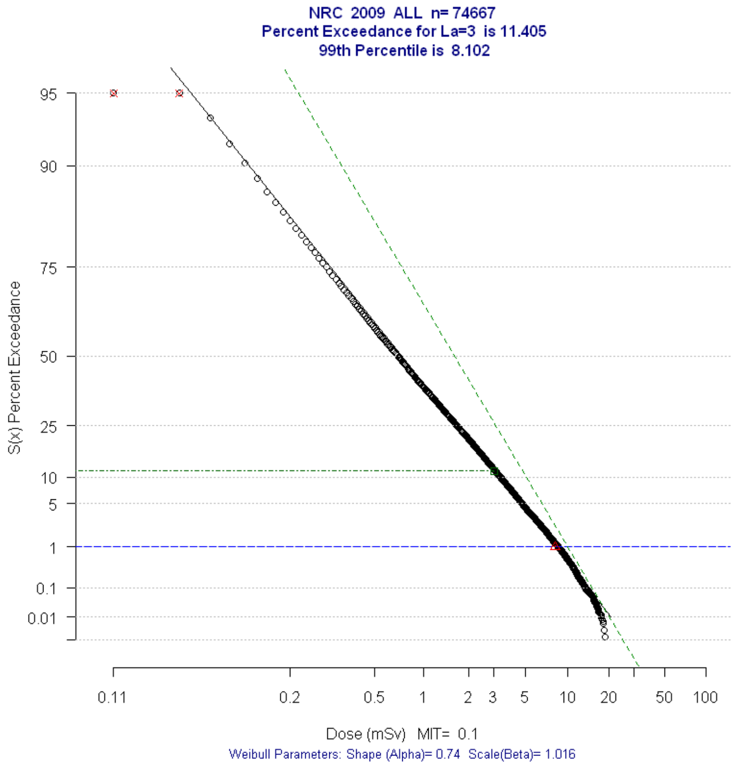
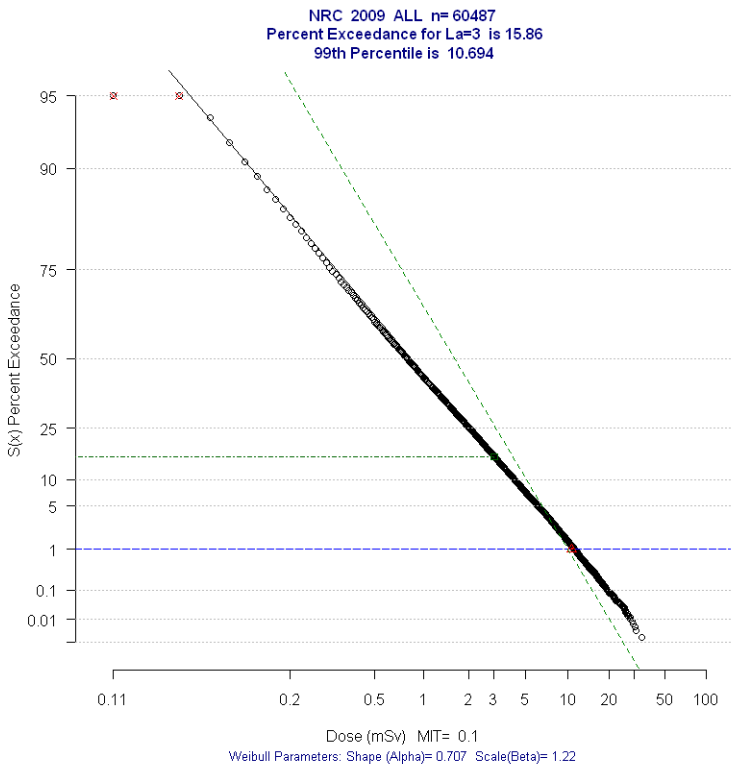


Figure 4: Weibull Probability Plot for All NRC Sites 2009 – Transients' Doses Accumulated into One Record per Person



4.2 Sensitivity Analysis of Experienced Worker Effect at a Nuclear Power Plant

Specialists are commonly trained to perform job tasks that involve potentially high exposure to occupational radiation. Using experienced workers among these specialists can promote safety and result in the lowest accumulation of collective dose at a site. With historical emphasis on the first aspect of ALARA (i.e., maintaining the collective dose as low as reasonably achievable), having these experienced individuals carry out such tasks can be seen as an acceptable approach for supporting ALARA. The purpose of this analysis is to investigate how the Weibull methodology, and particularly the 99th percentile indicator, is affected by this ALARA approach where an experienced worker may receive a higher individual dose while the collective dose for the task is reduced.

To investigate the experienced worker effect on the Weibull approach, several scenarios were developed and an informal sensitivity analysis was carried out to examine changes in the parameter values and performance indicators. *Table 5* describes the three scenarios based on the 2009 Crystal River dose distribution. Column definitions are identical to columns in *Tables 2* and *3*. Customized probability plots for scenarios 1-3 appear in *Figures 5-7*. Weibull-based results for each scenario are condensed in *Table 6*.

Table 5: Description of Scenarios for Sensitivity Analysis of Experienced Worker Effect

Scenario	Description
1	The actual dose distribution as reported by the nuclear power plant.
2	The actual distribution is modified by reducing or eliminating the dose received by one individual in the higher dose ranges and distributing this dose among two or three workers in the lower dose ranges. The effect that is being modeled here is that an experienced worker can get a task done more quickly with less dose compared with two or three workers that may take somewhat less time but would be less efficient and would end up increasing the collective dose for the task. Using an experienced worker that receives a higher individual dose but reduces the collective dose for a task is an acceptable implementation of the ALARA principle. Scenario 2 involved less than 10 individual dose modifications. It should be noted that this effect is only appropriate for individuals in the higher dose ranges in a distribution as the tasks for these individuals would provide opportunities for such ALARA optimization.
3	In scenario 3, the same modifications were performed as in scenario 2 but with 12 additional modifications simulating the use of less experienced workers that received less individual dose, but a higher collective dose for the assigned task.

Table 6: Results of Scenarios for Sensitivity Analysis of Experienced Worker Effect

Scenario	A	β	99th percentile	99th %tile- ucl	% exceedance	nx	X^2	df	p-value
1	0.802	1.128	7.682	8.212	11.897	1602	200.42	226	0.8888
2	0.801	1.143	7.803	8.345	11.148	1595	209.10	227	0.7972
3	0.802	1.156	7.864	8.410	12.386	1595	212.48	228	0.7620

As can be seen in Table 6, each successive scenario experienced an increase in the 99th percentile. This would indicate that when less experienced workers are used for a task, the effect on the 99th percentile of the Weibull plot would show this to be a less effective ALARA practice. This analysis assumes; 1) that the use of an experienced worker would reduce the collective dose for a task while the experienced individual would receive a higher dose and, 2) that two or three inexperienced workers would increase the collective dose for the task while individually received lower doses.

The observed impact on the 99th percentile shows that even with a large workforce at a reactor of over 1500 individuals with measurable dose, the strategic use of a relatively small number of experienced workers (< 20) that reduce collective dose for a task will have a positive impact on the 99th percentile ALARA performance indicator.

Figure 11: Weibull Probability Plot for Crystal River 2009 – Scenario 1

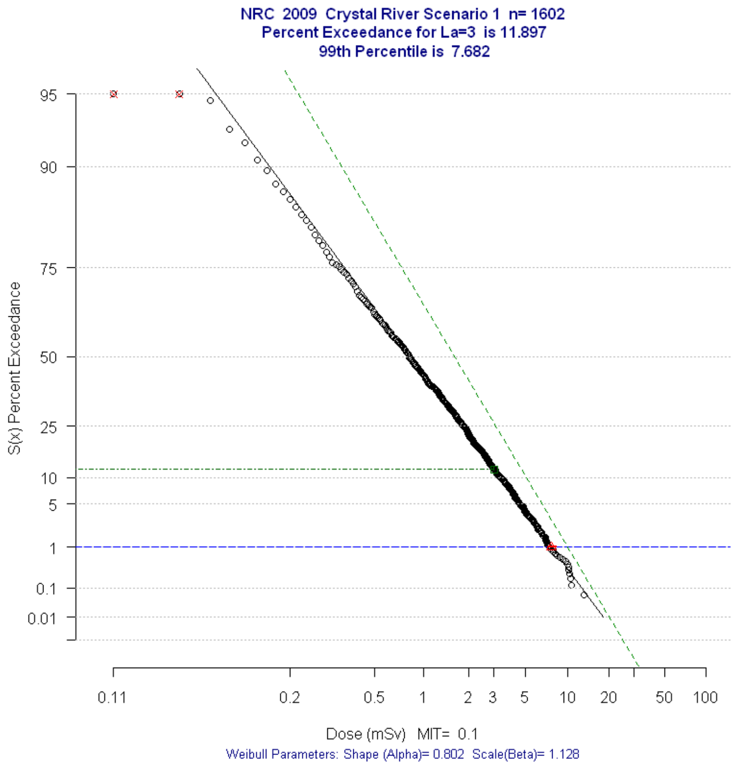


Figure 12: Weibull Probability Plot for Crystal River 2009 – Scenario 2

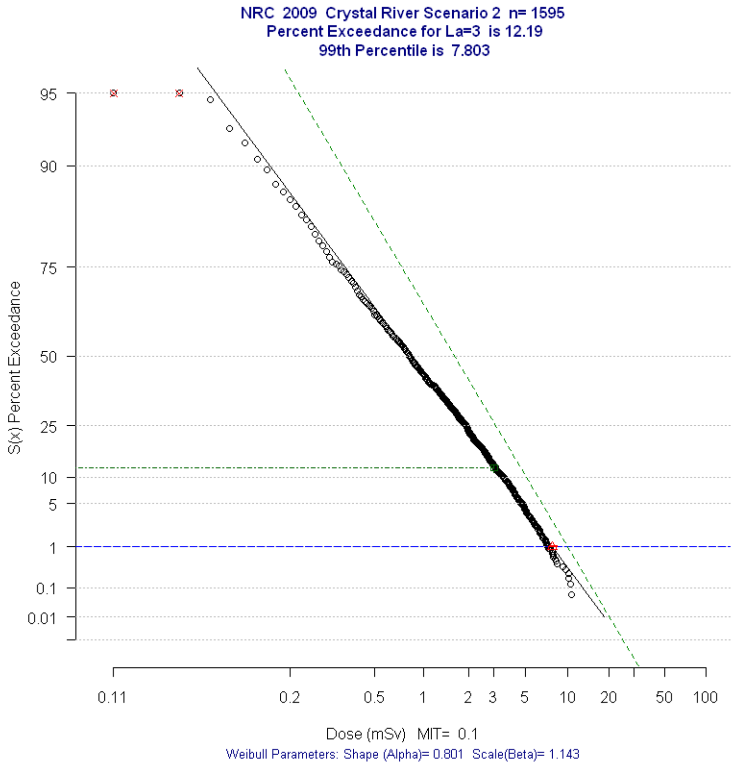
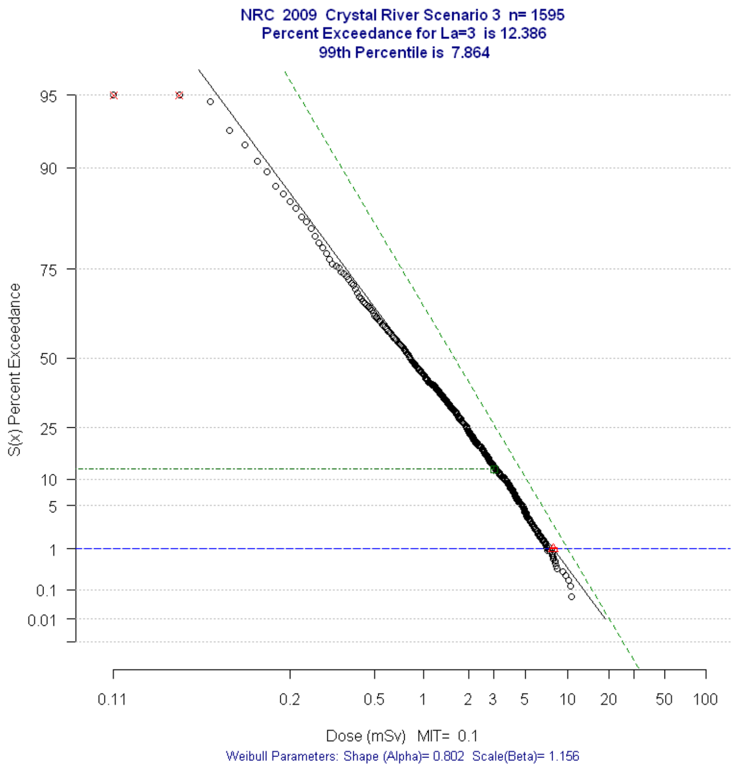


Figure 13: Weibull Probability Plot for Crystal River 2009 – Scenario 3



5.0 CONCLUSIONS

The Weibull-based methods for creating and utilizing performance indicators to evaluate ALARA involve these features:

- using maximum likelihood methods to estimate the shape and scale parameter values of a Weibull distribution for each site in the group
- using the site-specific parameters to calculate the fitted 99th percentile for each site as a performance indicator and the percent exceedance (e.g., for 2.5 mSv for DOE sites and 3 mSv for NRC sites) as an alternative performance indicator
- performing Chi-squared goodness of fit tests to identify sites in the group with statistically significant lack of fit to a Weibull distribution
- reviewing customized probability and goodness of fit plots for each site with statistical lack of fit to decide whether it appears to be reasonable to use its Weibull-based performance indicators

Weibull-based performance indicators can be used to detect those sites in the group that do not appear to be implementing ALARA effectively and to find additional sites that bridge between effective and less effective ALARA implementation. Once these sites are identified, management at each of the sites should be consulted to determine whether any operational issues transpired during the year that affected the dose distribution. Also, Weibull-based performance indicators for an identified site should be compared with the site's values for previous years to see whether the current set of results is an anomaly.

One might argue whether it is justifiable to use the fitted 99th percentile and percent exceedance to evaluate ALARA for sites that have statistically significant lack of fit to the Weibull model. However, when a data set contains hundreds or even thousands of doses, it would not be surprising that a two-parameter model would have statistical lack of fit. To determine whether the lack of fit is substantial enough for the Weibull-based performance indicators to be rejected, further investigation of the patterns of lack of fit should be carried out. A managerial decision to use these indicators may be reasonable for certain dose distributions with lack of fit. Examples of such distributions include those where the lack of fit contributions to the Chi-squared statistic are concentrated in intervals from the very low dose range or from intervals around values that appear to have been set administratively as an upper bound for an individual's dose. The customized Weibull probability and goodness of fit plots provide abundant complementary information and allow visual inspection for patterns of lack of fit that can be useful when making such a decision. Although utilizing a boundary dose may ensure that no individuals at a site receive unacceptably high radiation exposure, ALARA is better served by actively ensuring throughout the year that each worker's dose remains as low as reasonable achievable. In addition, imposing an individual upper limit for the year affects the goodness of fit of the site's doses to the Weibull or any other statistical distribution because patterns in the dose distribution are administratively manipulated by imposing such a limit.

As can be seen in the analysis of transient and experienced workers, the Weibull methodology reflects the expected impact of these effects on the ALARA performance indicators. In the case of transient workers, these individuals actually receive higher doses from their work at multiple facilities during the year. Therefore one would anticipate an effect on the Weibull indicators to show less effective ALARA performance when these individuals are correctly reflected in the worker dose distribution. This was observed when the Weibull method was applied to the transient worker distribution. The effect of experienced workers in the dose distribution indicate that an individual worker that receives a higher individual dose, but who contributes to a lower collective dose due to experience, has a impact on the Weibull ALARA performance indicator that supports this practice as a proper ALARA technique.

6.0 REFERENCES

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APPENDIX A: Statistical Details

A.1 Derivation of the Equation of the Weibull Hazard Line

The Weibull hazard function for shape parameter α and scale parameter β is given by:

$h(v) = \alpha/\beta\ [v/\beta]^{\alpha-1}$
$\ln [h(v)] = \ln(\alpha) - \ln(\beta) + (\alpha\text{-}1)[\ln(v) - \ln(\beta)]$
$\ln [h(v)] = \{ \ln(\alpha) - \ln(\beta) - (\alpha\text{-}1) \ln(\beta) \} + (\alpha\text{-}1)[\ln(v)]$
$\ln [h(v)] = \{ \ln(\alpha) - \ln(\beta) - \alpha^* \ln(\beta) + \ln(\beta) \} + (\alpha\text{-}1)[\ln(v)]$
$\ln [h(v)] = \{ \ln(\alpha) - \alpha \ln(\beta) \} + (\alpha\text{-}1)[\ln(v)]$ (A1)

The line for ln(v) on x-axis and ln [h(v)] on y-axis has y-intercept $[\ln(\alpha) - \alpha \ln(\beta)]$ and slope $(\alpha\text{-}1)$.

A.2 Details of Formal Assessment of Goodness of Fit

Goodness of fit is commonly evaluated with a Chi-squared test having a null hypothesis that the data follow the specified distribution. The data are separated into *k* bins, and the test statistic is defined as the sum over all bins of the squares of the residuals, where a residual is calculated as (observed – expected) / sqrt(expected). That is, $X^2 = \sum (O_i - E_i)^2 / E_i$, where the sum over i goes from 1 to *k*. To obtain the bins for the Weibull goodness of fit test for a site, the range of the site's dose distribution is divided into intervals that are determined by quantiles of the Weibull distribution having the site-specific shape and scale parameters. In each interval, the expected number of doses is based on the Weibull cumulative distribution function and *n*, which is the total number of doses that exceed the MIT. Specifically, $E_i = n(F(X_u) - F(X_l))$, where X_u and X_l are the upper and lower limits, respectively of the doses in interval i. The cumulative distribution function for a Weibull distribution with shape parameter α and scale parameter β is specified as follows:

$P[X \leq x] = F(x) = 1 - \exp(-[x/\beta]^{\alpha})\ , \alpha > 0, \beta > 0.$ (A2)

Because an expected frequency of at least five is required for the Chi-squared approximation to be valid, intervals determined by the quantiles are combined where necessary to meet this restriction. In addition, no interval can have width smaller than 0.01 mSv since doses are not recorded in smaller units. Because two parameters are estimated, the number of degrees of freedom (df) for the Chi-squared test is $k - 2$.

For each site a p-value is determined based on the sum of the squared residuals, X^2, and the appropriate degrees of freedom. The p-value is the probability of observing a X^2 value that is greater than or equal to the calculated value for the given site. At the 0.05 level of significance, the null hypothesis expressed in terms of p-values is this: H_0: p-value ≥ 0.05. If the null hypothesis is true, then there is a probability of 0.05 that a Type I error (rejecting the null hypothesis when it is true) will occur, and there is a probability of 0.95 of not rejecting the null hypothesis and coming to a "not evidence for significant lack of fit" conclusion. Goodness of fit is assessed independently with a p-value for each site in the group, and each site may be considered as a subgroup of a larger group. The statistical question to be answered is which sites in the group have significant lack of fit to the Weibull model. Although for each individual site there is a 5% chance of erroneously rejecting a Weibull model when it does indeed fit, this chance increases depending upon the number of sites being tested simultaneously. For a group of 20 sites that each fit a Weibull model the expected number of erroneous rejections of the null hypothesis is 20*0.05 = 1. The probability that none of the tests is significant is $0.95^{20} = 0.36$, and the probability of getting at least one significant result by chance is 1 – 0.36, which equals 0.64 or 64%. When testing 50 sites simultaneously the probability of obtaining one or more p-values < 0.05 by chance is $(1\text{-}\ 0.95^{50})$, which equals 0.92 or 92%. To maintain an overall significance level of at most 0.05, each site is compared to an adjusted critical p-value based on the number of sites in the group. Using *nsites* to designate the number of sites in the group, the adjusted critical value against which each site's p-value is calculated by $1 - [0.95^{(1/nsites)}]$. *Table A-1* gives the adjusted critical value for each number of simultaneous tests from 2-100.

An alternative, more conservative approach to determining which sites have statistically significant lack of fit is to select a fixed critical value, such as 0.01 or 0.05. Any site having a p-value below the fixed critical level would be further evaluation for lack of fit based on the observed and expected values in each bin and the hazard function estimate for each interval. Tables of observed, expected, and estimated hazard could be examined and goodness of fit graphs based on the hazard function would present these values visually. If the resulting evaluation indicated that the Weibull model was reasonable, then estimated variance of the Weibull parameters would be multiplied by the heterogeneity factor $\Phi = X^2$ / df as is done in biological assays and other areas of data analysis (Finney, 1984). These adjusted variances would be used in the calculation of confidence intervals.

Table A-1: Adjusted critical value for n simultaneous hypothesis tests to maintain overall significance level of 0.05

nsites	probability of p-value < 0.05 by chance (in %)	adjusted cutpoint $1-(0.95^{1/nsites})$	nsites	probability of p-value < 0.05 by chance (in %)	adjusted cutpoint $1-(0.95^{1/nsites})$
2	9.75	0.025321	31	79.61	0.001653
3	14.26	0.016952	32	80.63	0.001602
4	18.55	0.012741	33	81.60	0.001553
5	22.62	0.010206	34	82.52	0.001507
6	26.49	0.008512	35	83.39	0.001464
7	30.17	0.007301	36	84.22	0.001424
8	33.66	0.006391	37	85.01	0.001385
9	36.98	0.005683	38	85.76	0.001349
10	40.13	0.005116	39	86.47	0.001314
11	43.12	0.004652	40	87.15	0.001282
12	45.96	0.004265	41	87.79	0.001250
13	48.67	0.003938	42	88.40	0.001221
14	51.23	0.003657	43	88.98	0.001192
15	53.67	0.003414	44	89.53	0.001165
16	55.99	0.003201	45	90.06	0.001139
17	58.19	0.003013	46	90.55	0.001114
18	60.28	0.002846	47	91.03	0.001091
19	62.26	0.002696	48	91.47	0.001068
20	64.15	0.002561	49	91.90	0.001046
21	65.94	0.002440	50	92.31	0.001025
22	67.65	0.002329	51	92.69	0.001005
23	69.26	0.002228	52	93.06	0.000986
24	70.80	0.002135	53	93.40	0.000967
25	72.26	0.002050	54	93.73	0.000949
26	73.65	0.001971	55	94.05	0.000932
27	74.97	0.001898	56	94.34	0.000916
28	76.22	0.001830	57	94.63	0.000899
29	77.41	0.001767	58	94.90	0.000884
30	78.54	0.001708	59	95.15	0.000869

nsites	probability of p-value < 0.05 by chance (in %)	adjusted cutpoint $1-(0.95^{1/nsites})$
60	95.39	0.000855
61	95.62	0.000841
62	95.84	0.000827
63	96.05	0.000814
64	96.25	0.000801
65	96.44	0.000789
66	96.61	0.000777
67	96.78	0.000765
68	96.94	0.000754
69	97.1	0.000743
70	97.24	0.000732
71	97.38	0.000722
72	97.51	0.000712
73	97.64	0.000702
74	97.75	0.000693
75	97.87	0.000684
76	97.97	0.000675
77	98.07	0.000666
78	98.17	0.000657
79	98.26	0.000649
80	98.35	0.000641
81	98.43	0.000633
82	98.51	0.000625
83	98.58	0.000618
84	98.65	0.000610
85	98.72	0.000603
86	98.79	0.000596
87	98.85	0.000589
88	98.90	0.000583
89	98.96	0.000576
90	99.01	0.000570
91	99.06	0.000564
92	99.11	0.000557
93	99.15	0.000551
94	99.19	0.000546
95	99.23	0.000540
96	99.27	0.000534
97	99.31	0.000529
98	99.34	0.000523
99	99.38	0.000518
100	99.41	0.000513

APPENDIX B: Customized Weibull Probability Plots By Site For Doe 2009

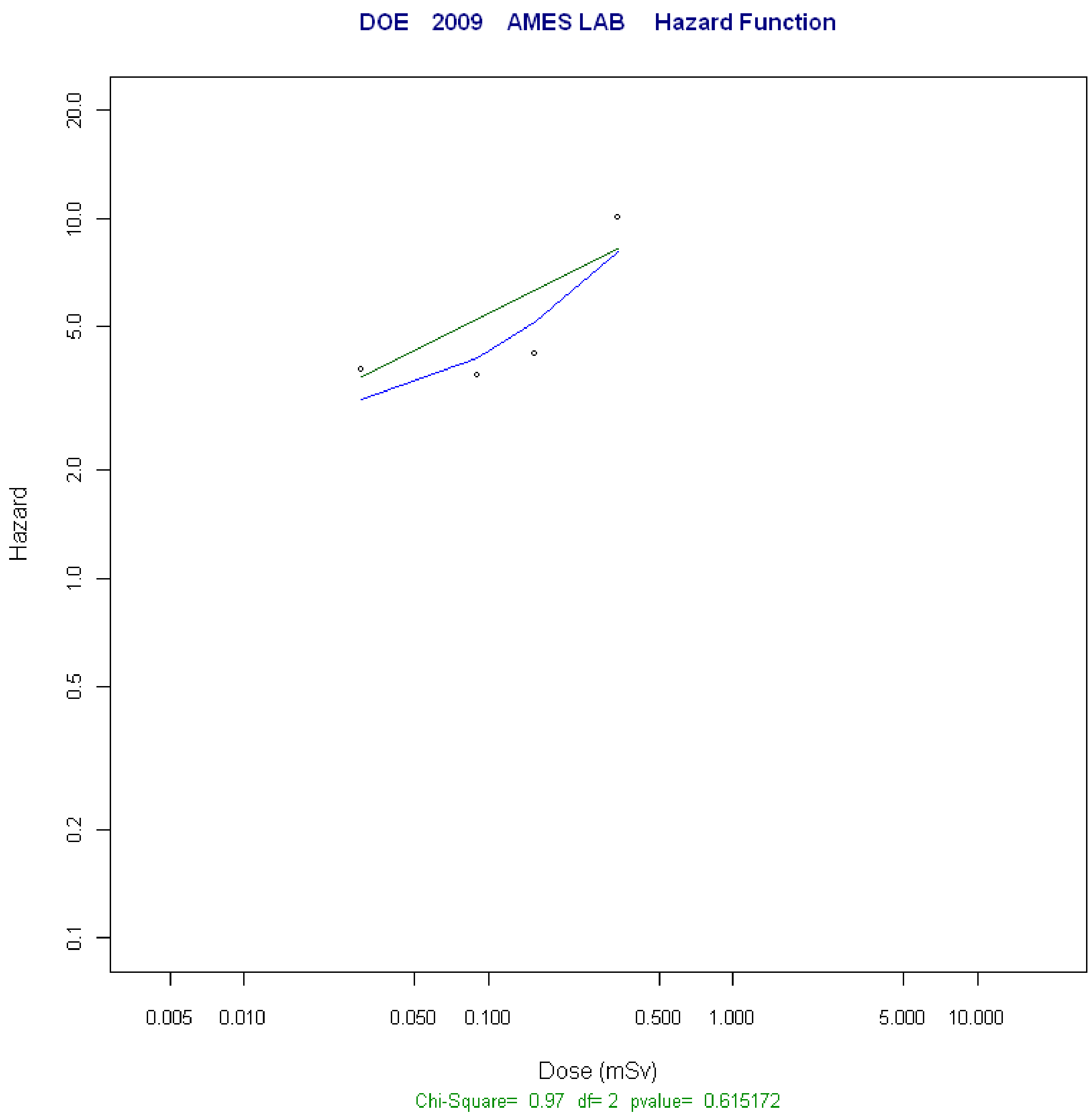

Figure B1: Weibull Goodness of Fit Plot for Ames Laboratory.

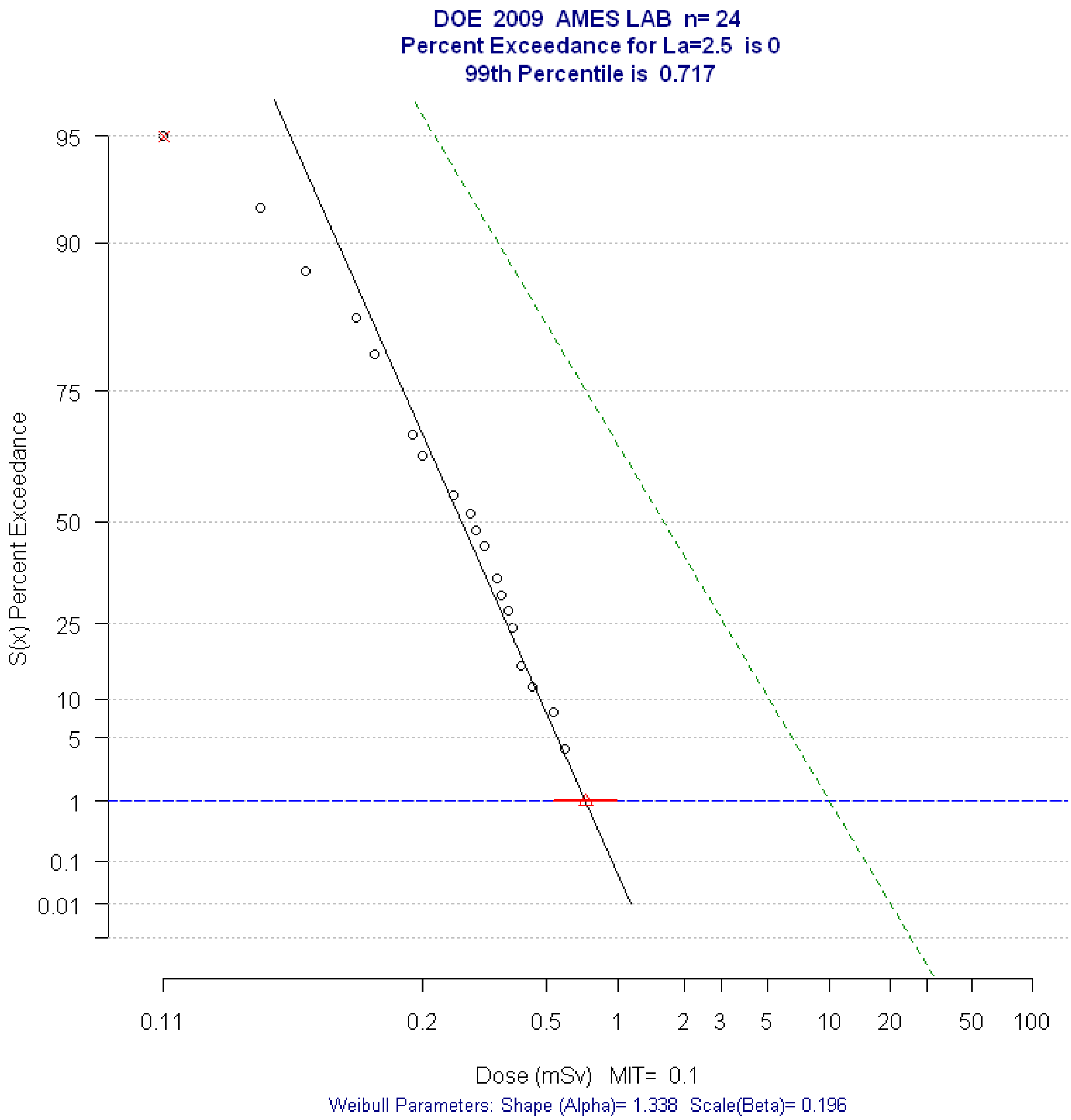

Figure B2: Weibull Probability Plot for Ames Laboratory.

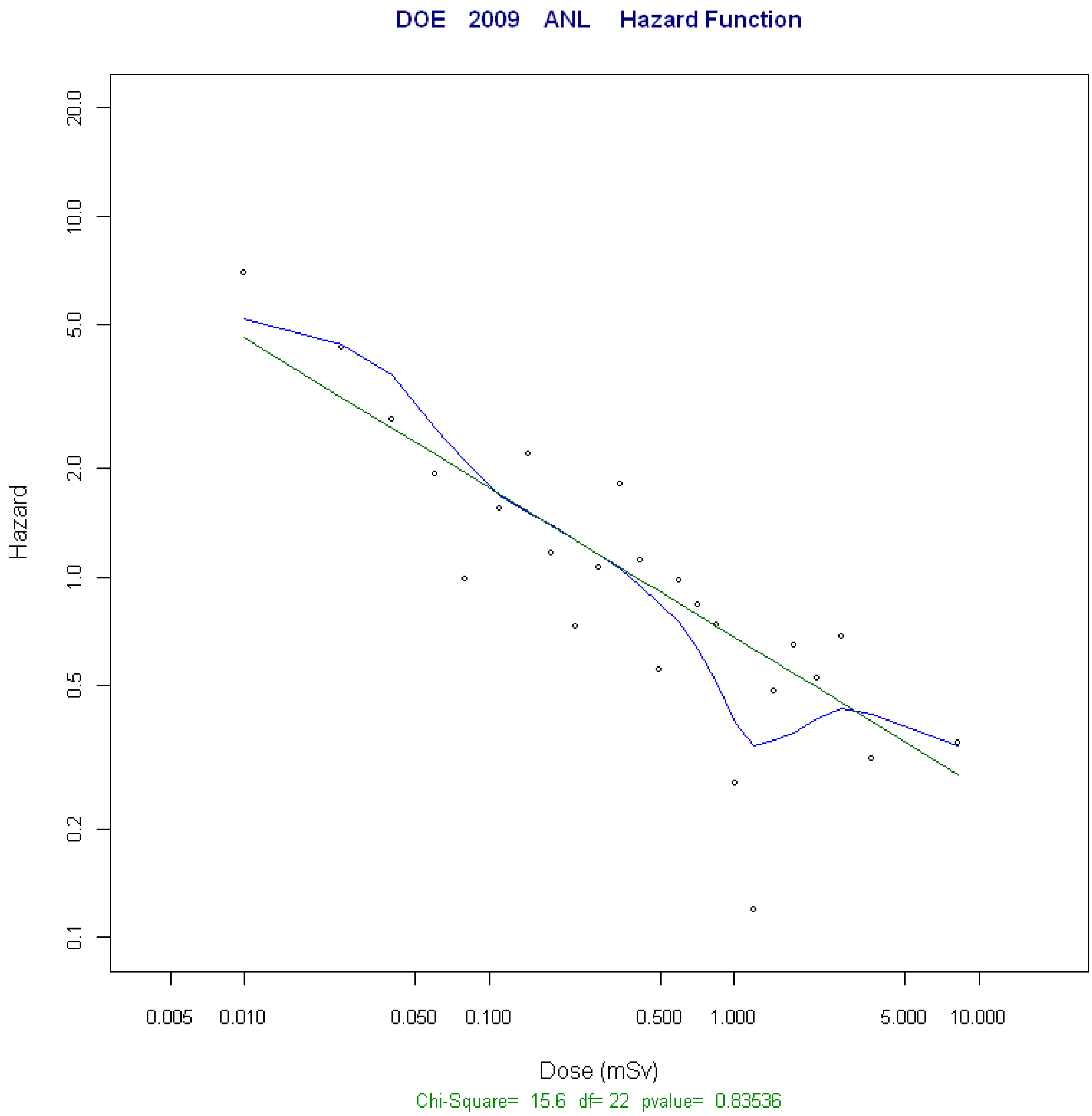

Figure B3: Weibull Goodness of Fit Plot for Argonne National Laboratory.

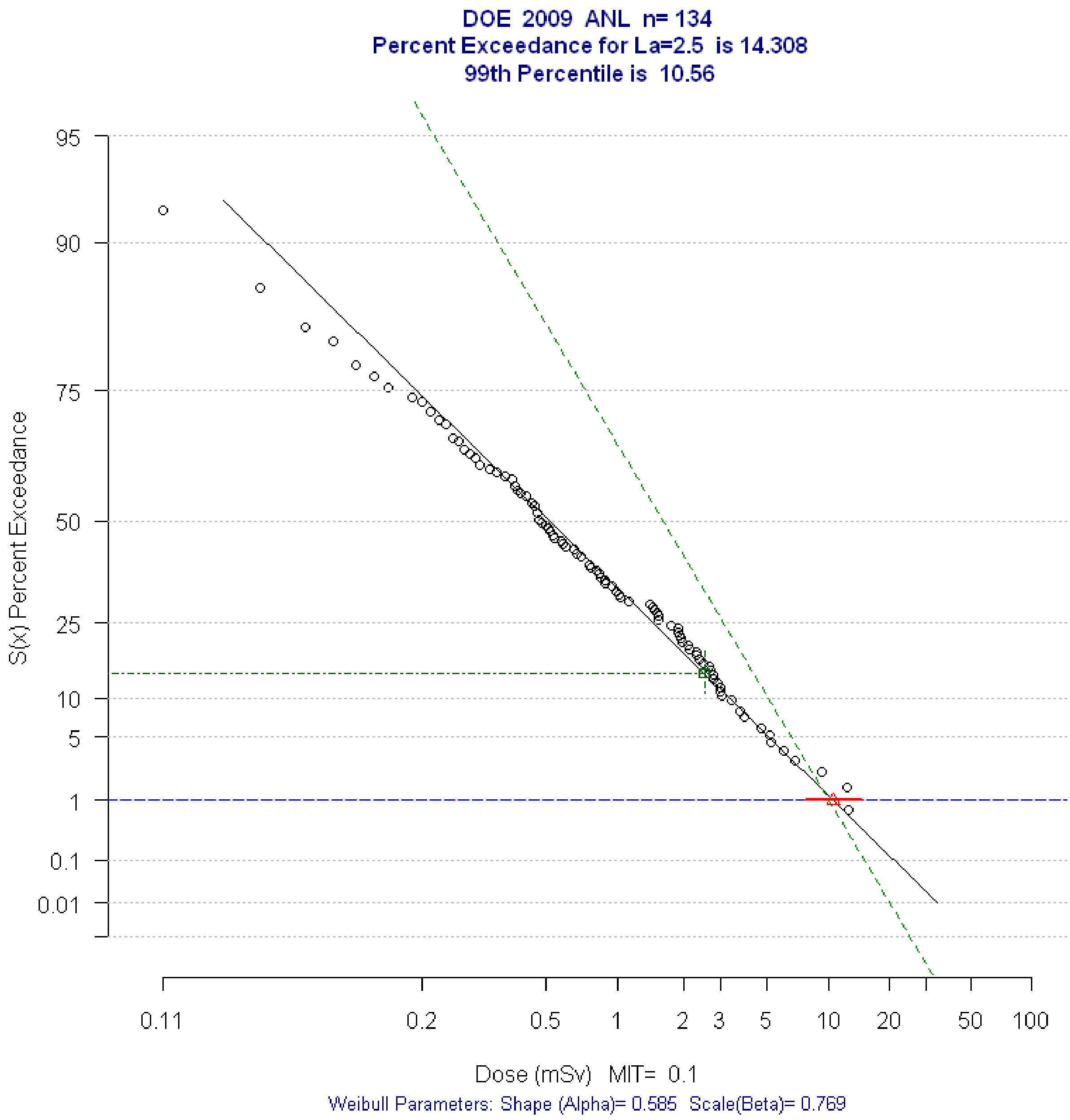

Figure B4: Weibull Probability Plot for Argonne National Laboratory.

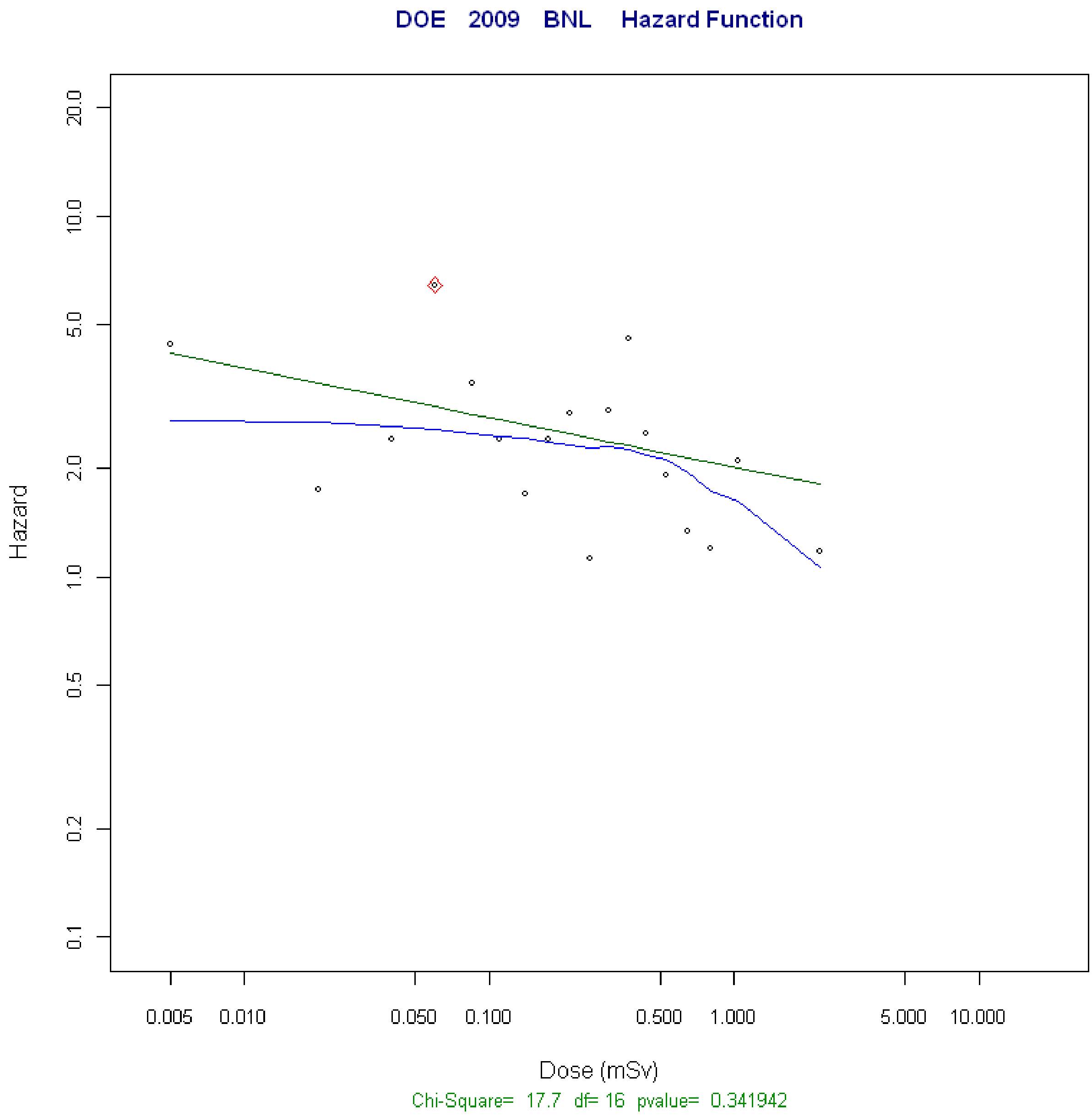

Figure B5: Weibull Goodness of Fit Plot for Brookhaven National Laboratory.

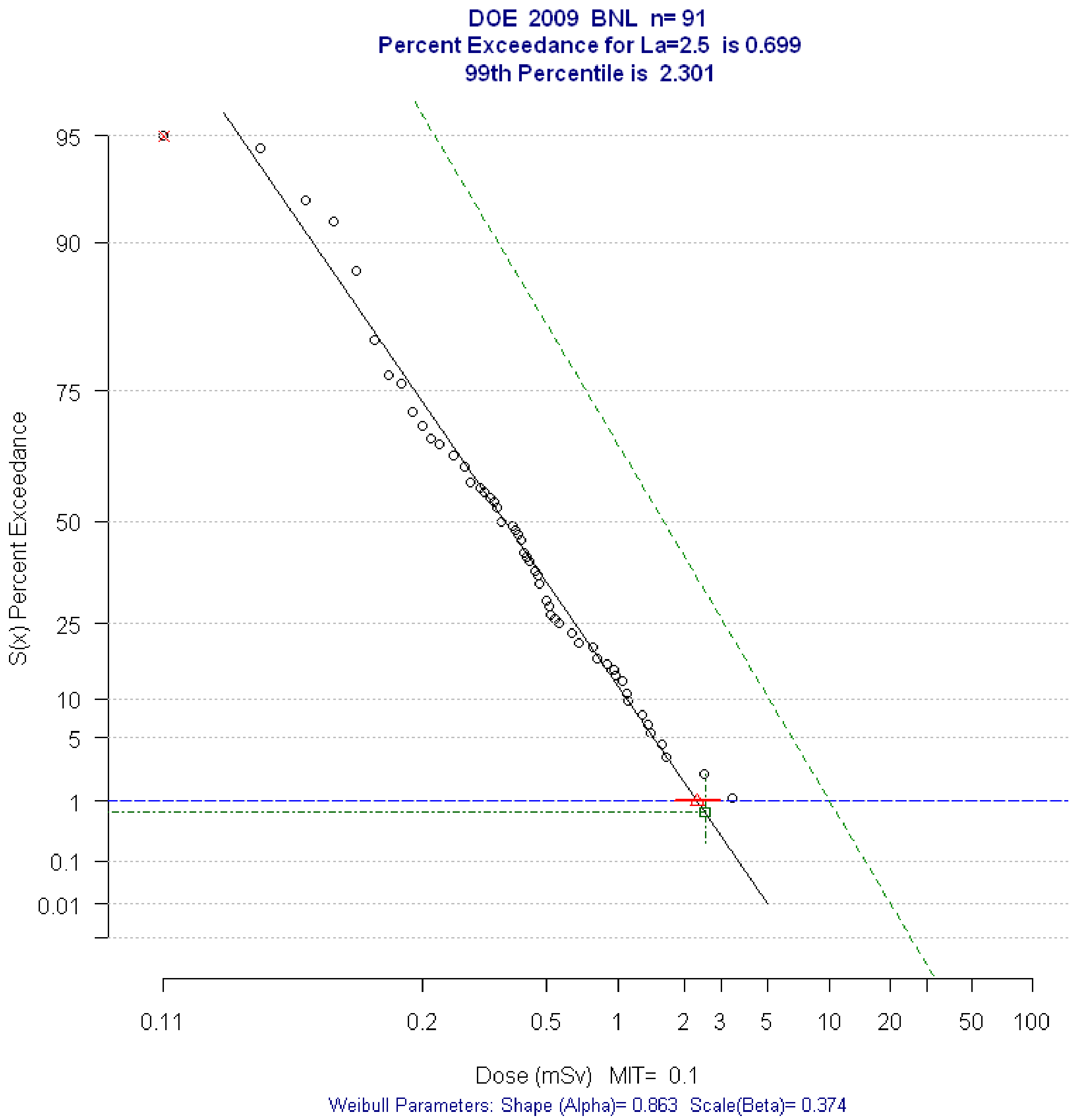

Figure B6: Weibull Probability Plot for Brookhaven National Laboratory.

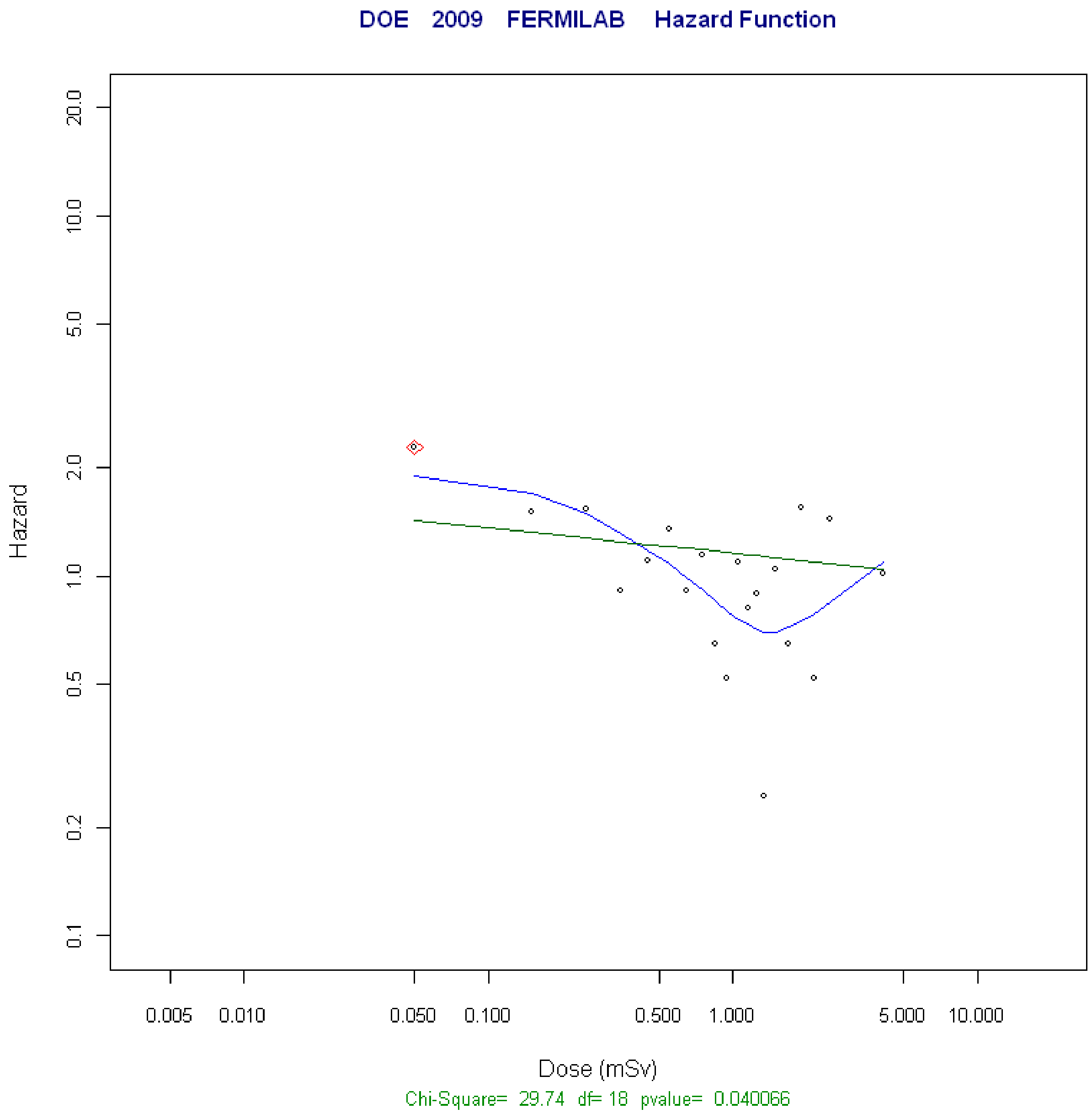

Figure B7: Weibull Goodness of Fit Plot for Fermilab.

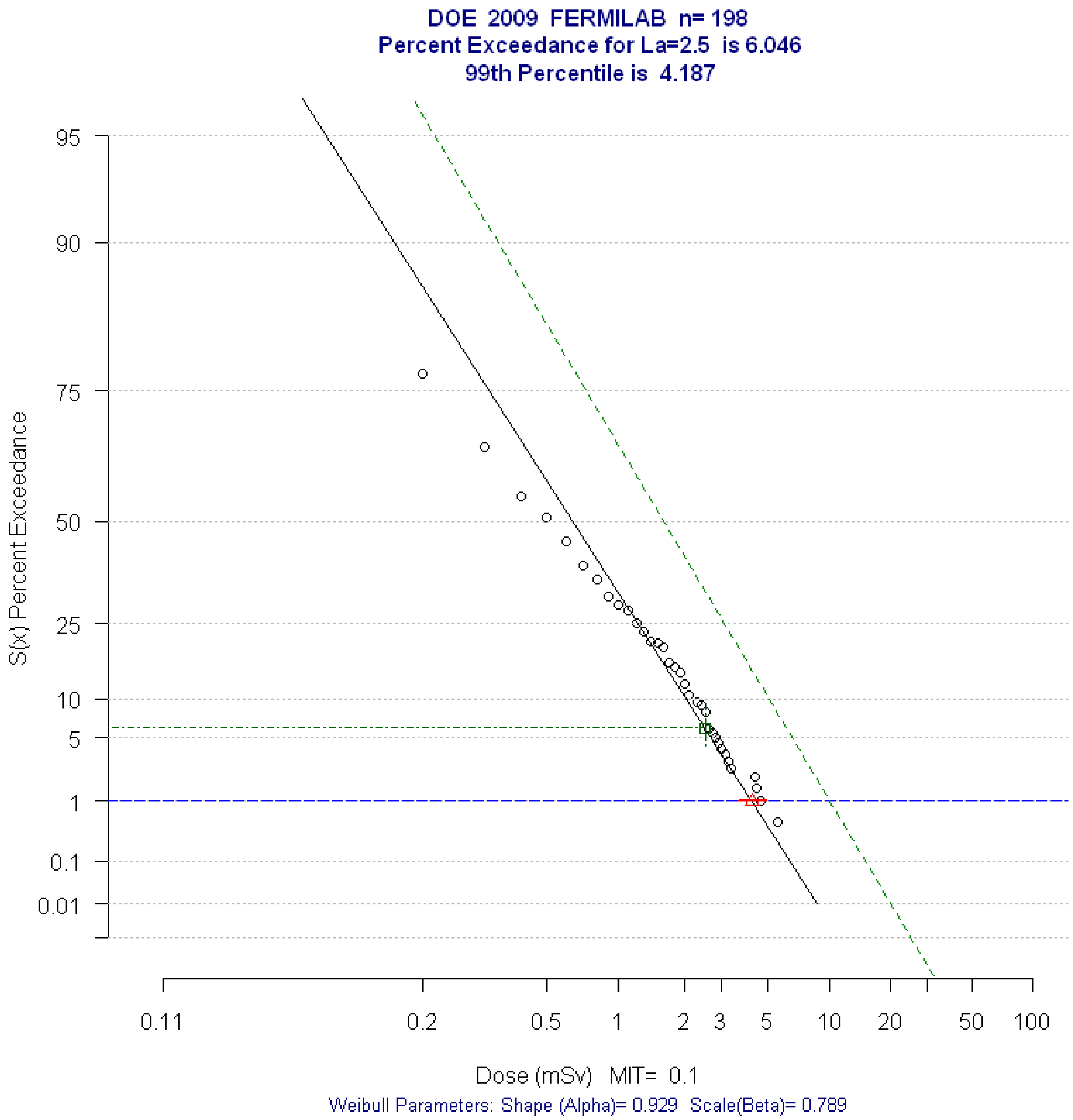

Figure B8: Weibull Probability Plot for Fermilab.

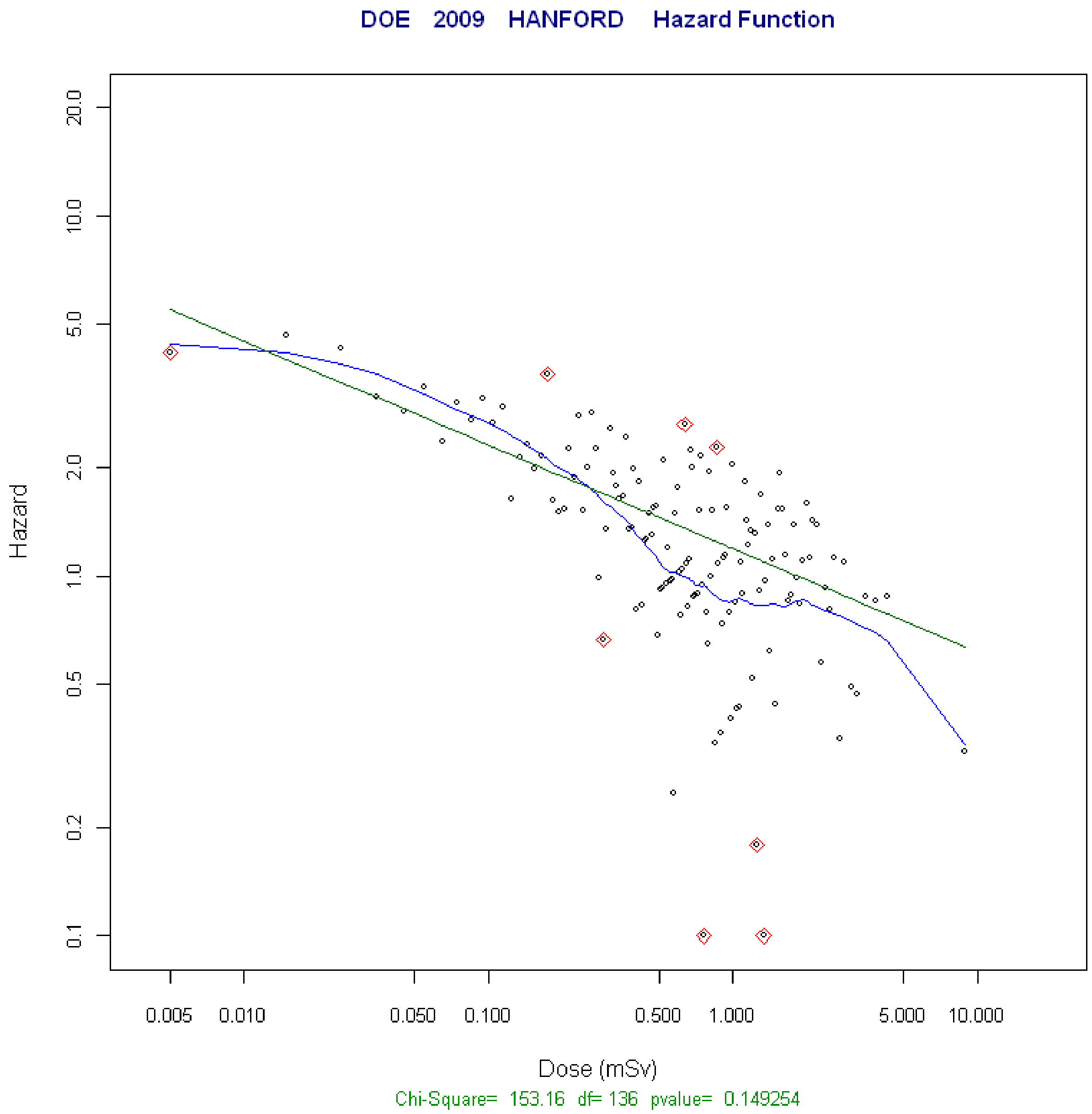

Figure B9: Weibull Goodness of Fit Plot for Hanford.

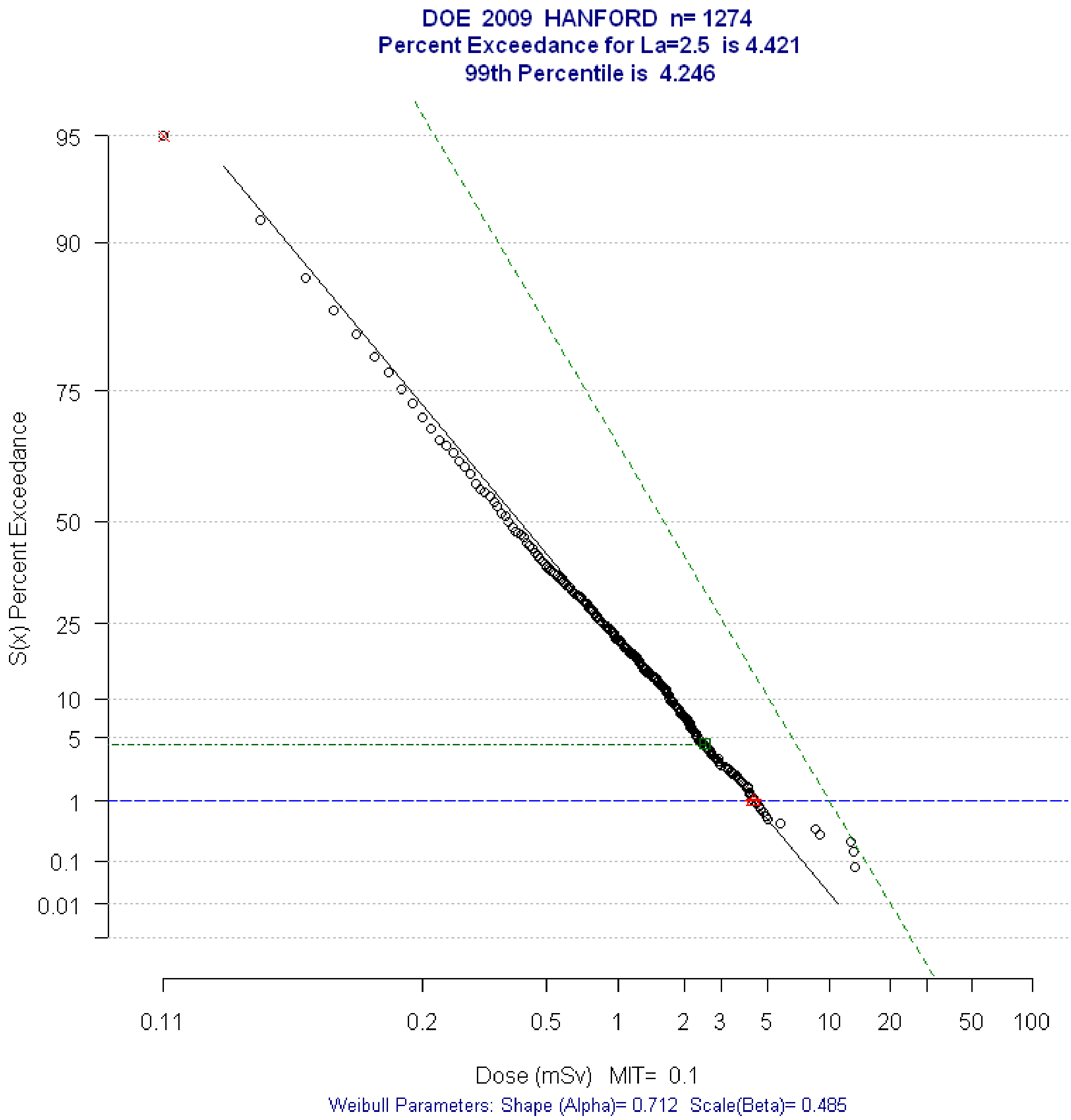

Figure B10: Weibull Probability Plot for Hanford.

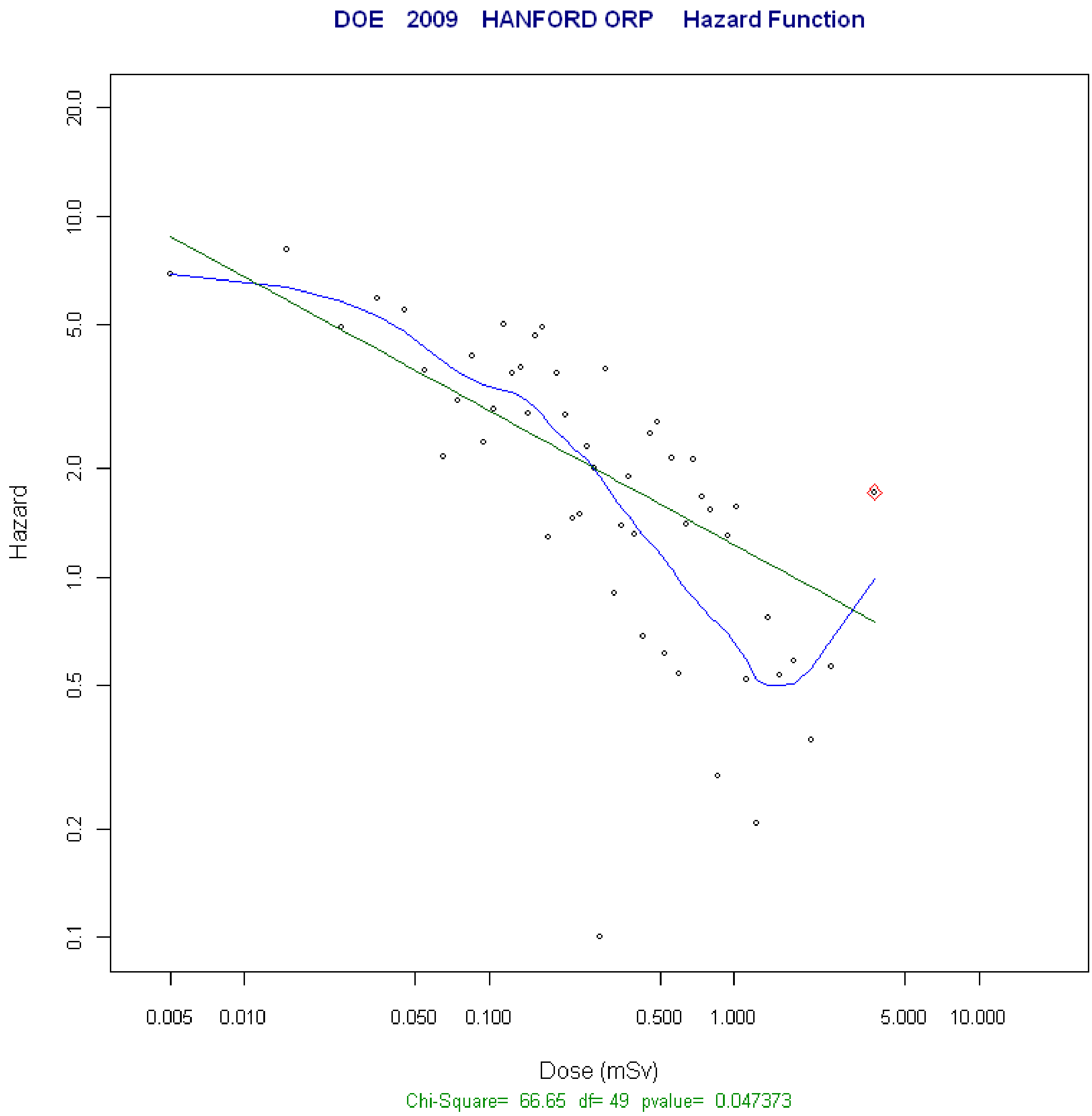

Figure B11: Weibull Goodness of Fit Plot for Hanford Office of River Protection.

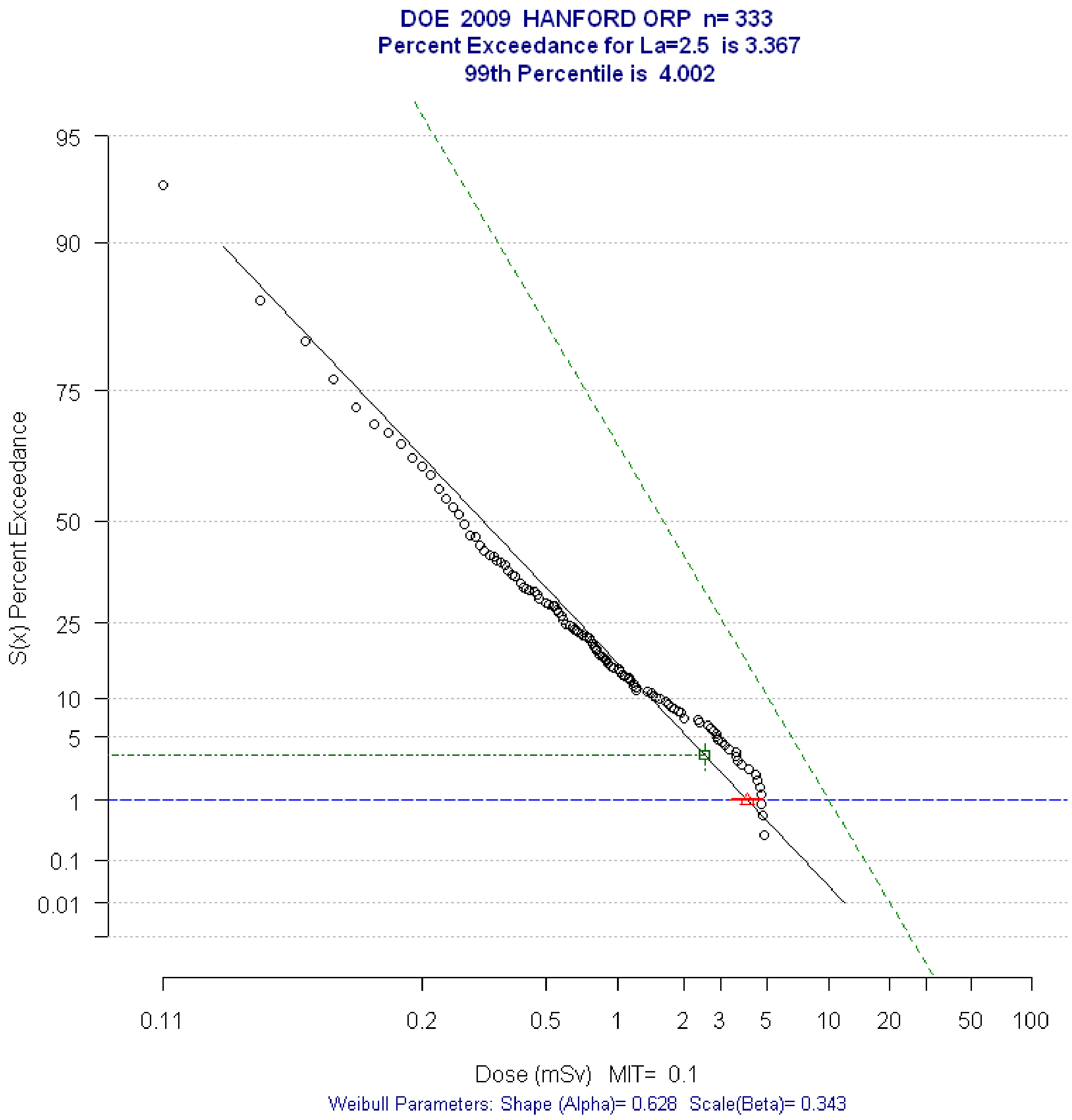

Figure B12: Weibull Probability Plot for Hanford Office of River Protection.

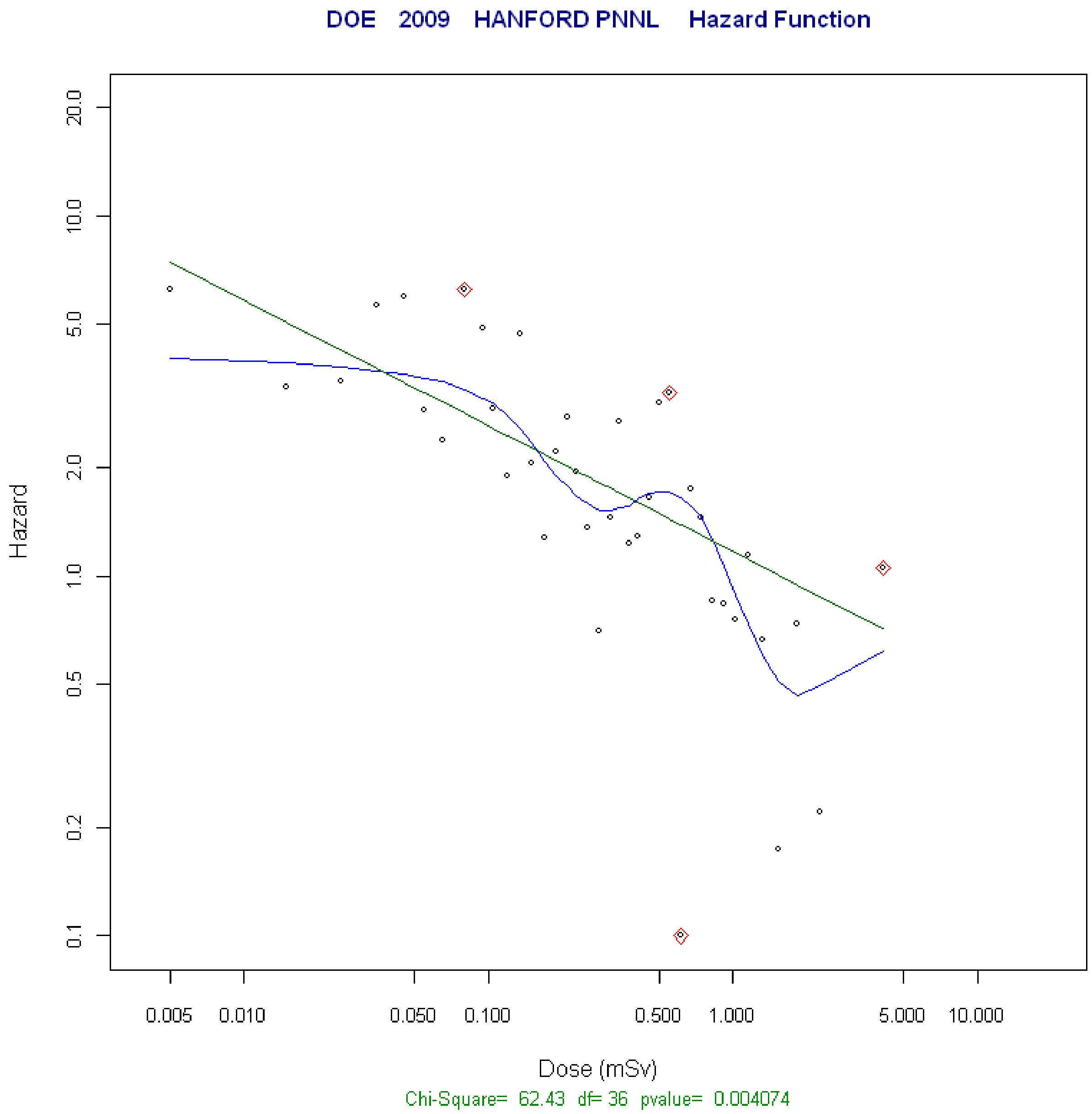

Figure B13: Weibull Goodness of Fit Plot for Hanford Pacific Northwest National Laboratory.

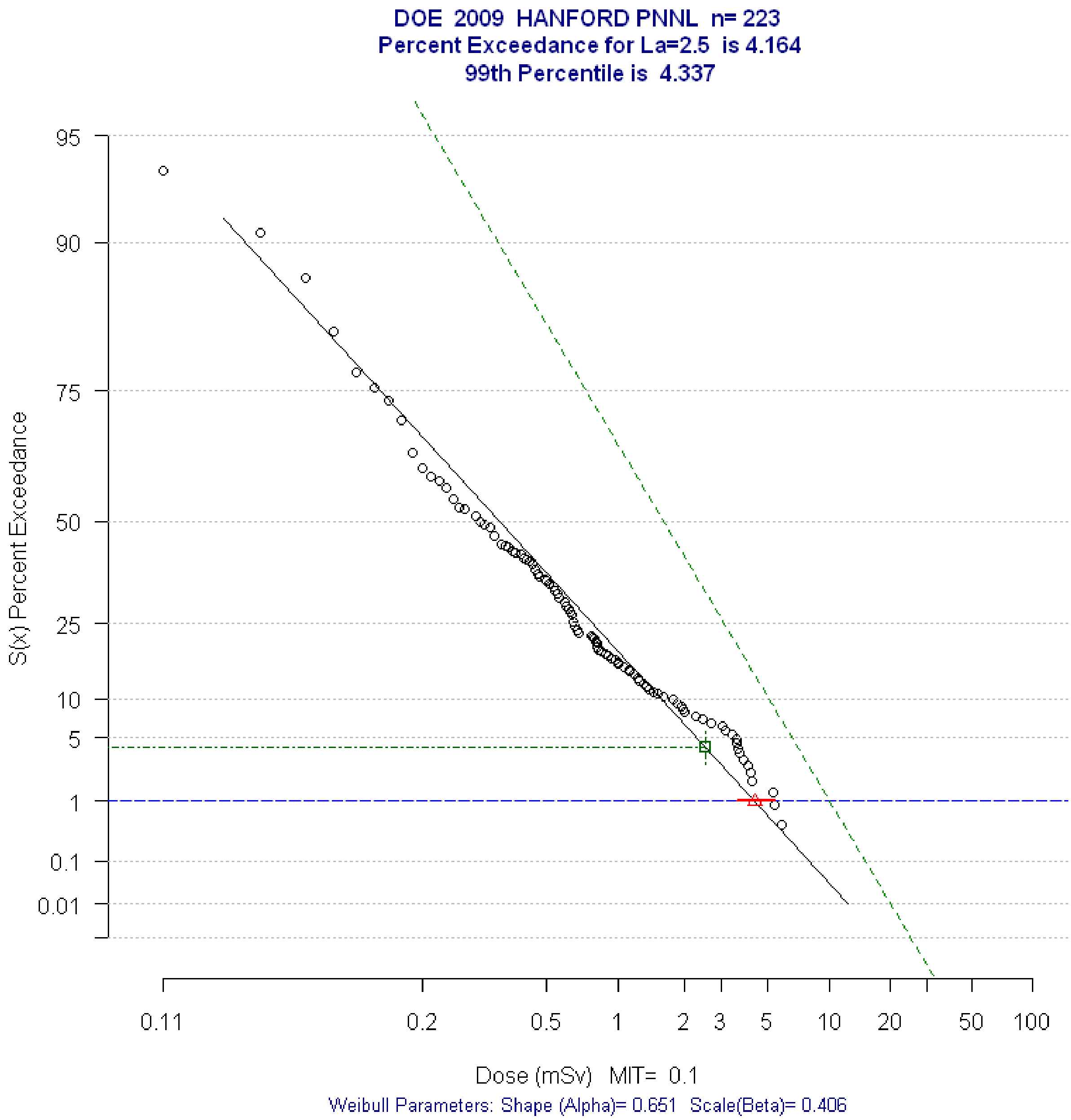

Figure B14: Weibull Probability Plot for Hanford Pacific Northwest National Laboratory.

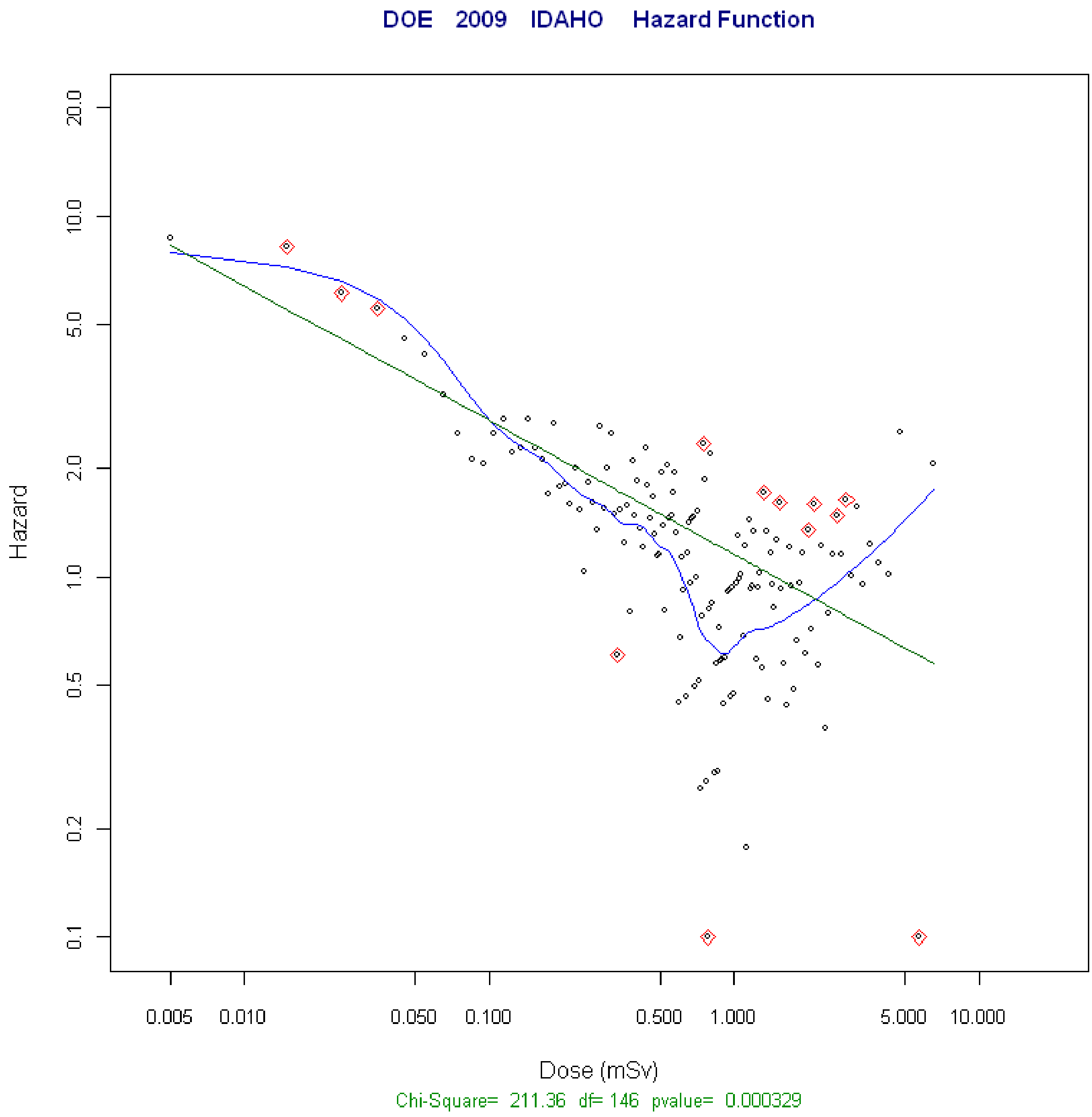

Figure B15: Weibull Goodness of Fit Plot for Idaho National Laboratory.

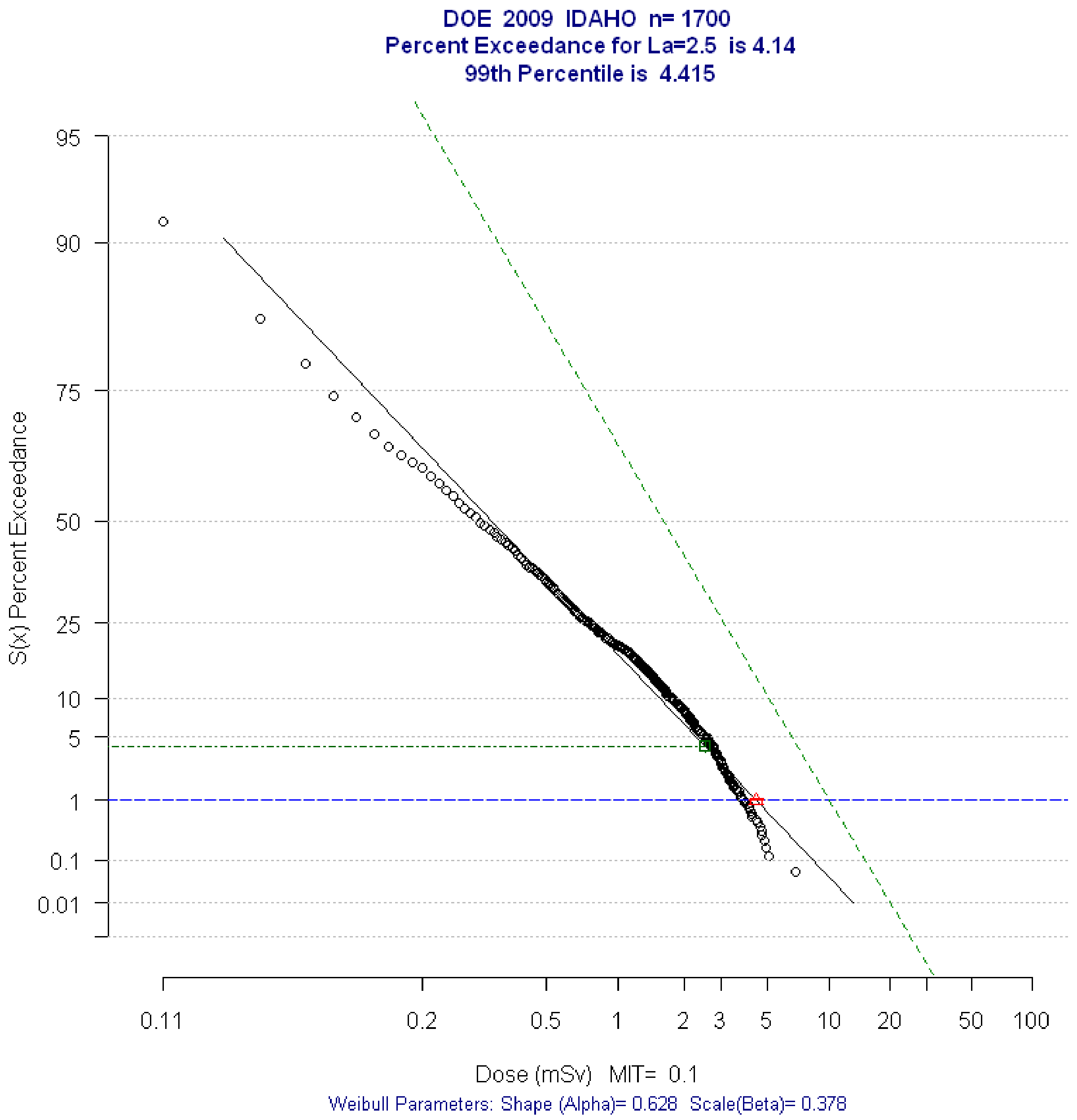

Figure B16: Weibull Probability Plot for Idaho National Laboratory.

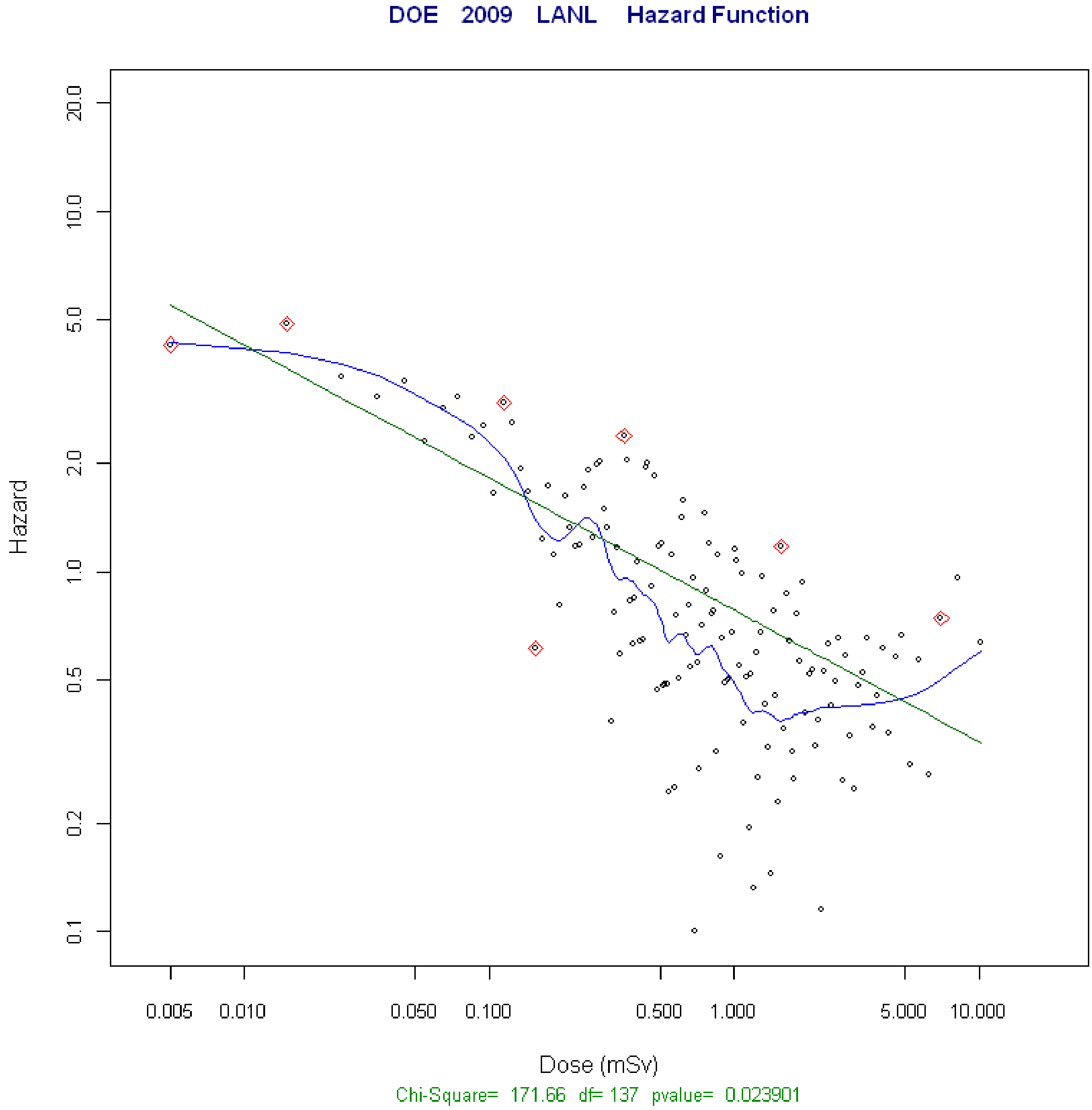

Figure B17: Weibull Goodness of Fit Plot for Los Alamos National Laboratory.

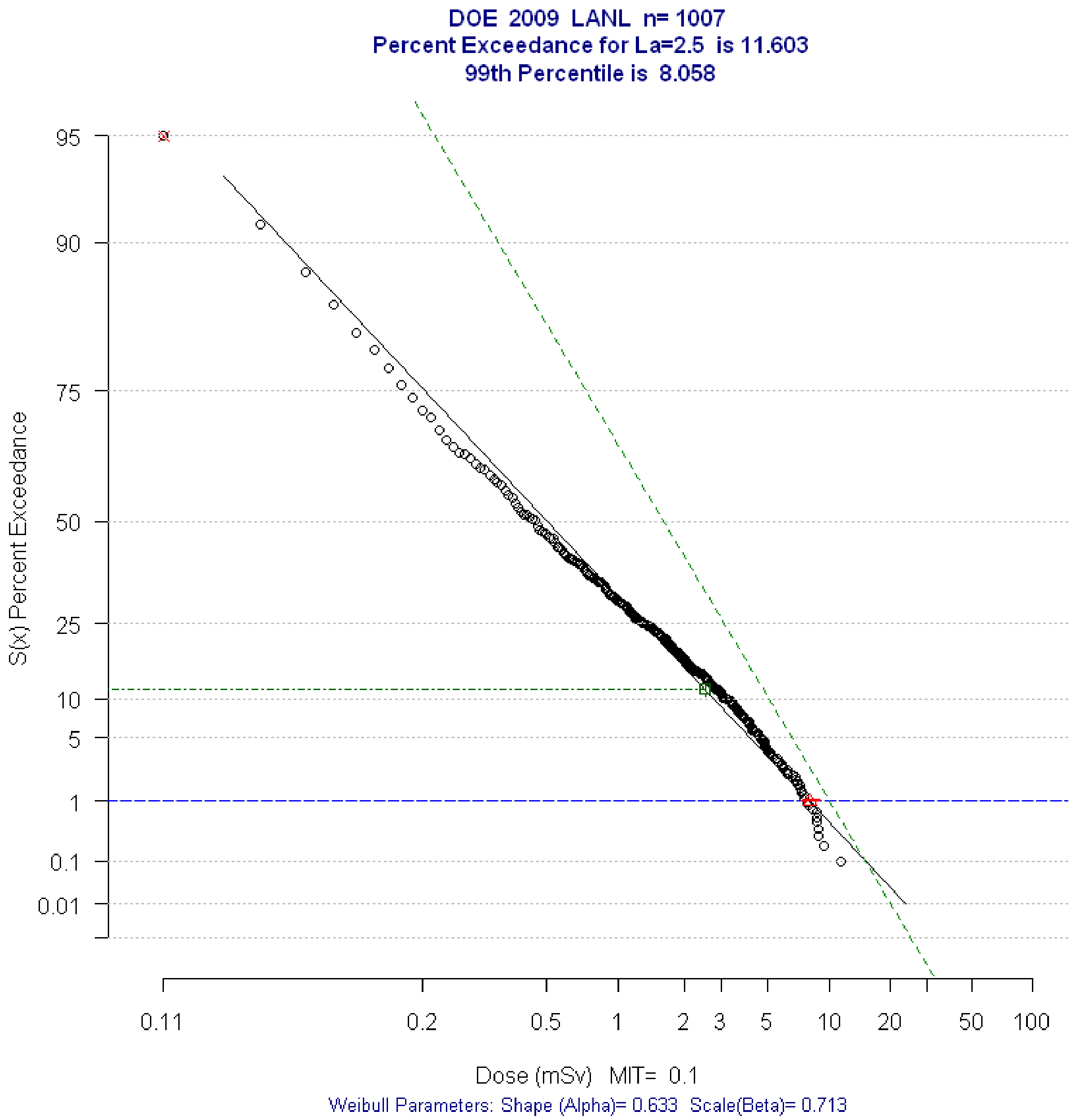

Figure B18: Weibull Probability Plot for Los Alamos National Laboratory.

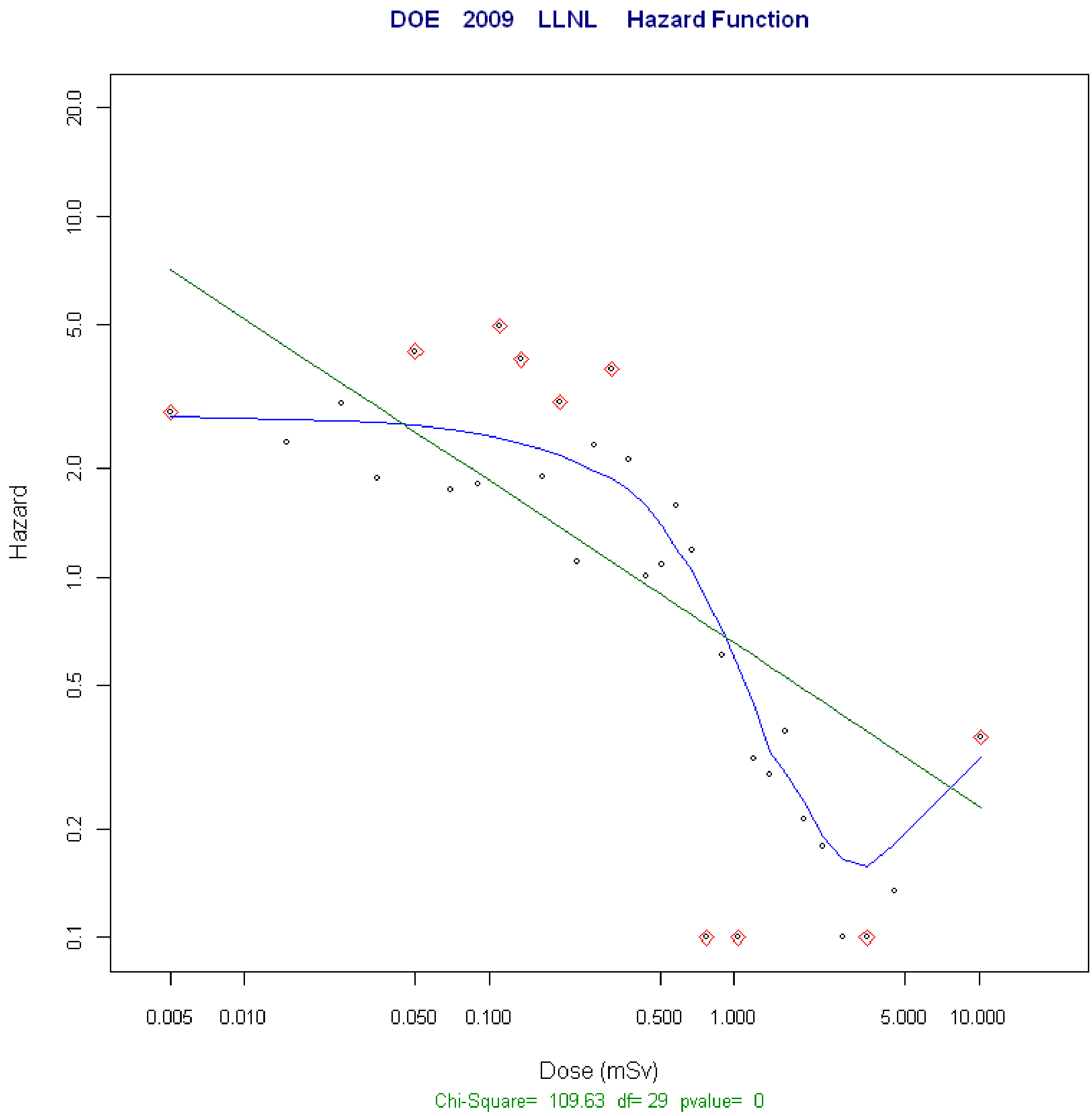

Figure B19: Weibull Goodness of Fit Plot for Lawrence Livermore National Laboratory.

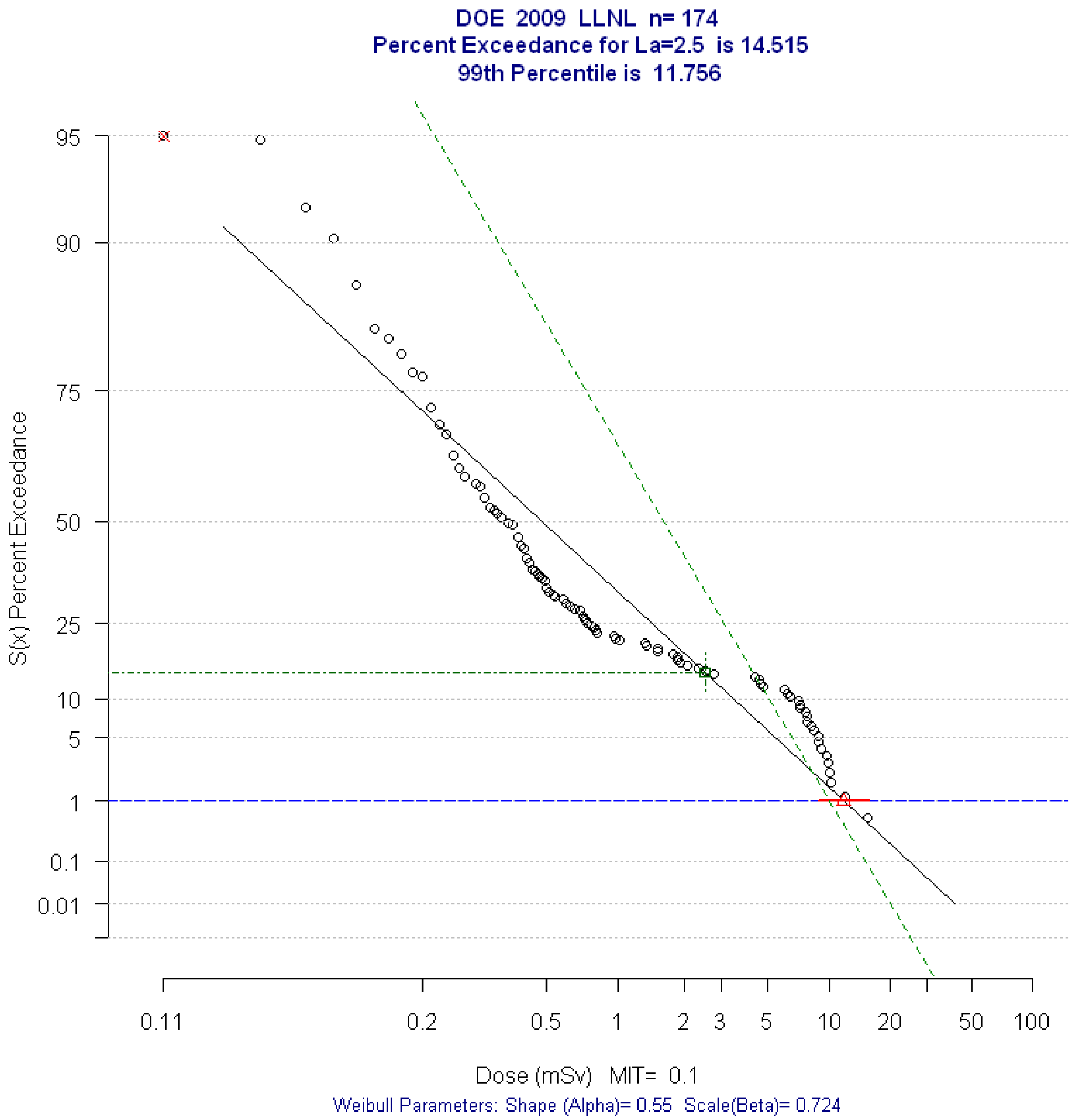

Figure B20: Weibull Probability Plot for Lawerence Livermore National Laboratory.

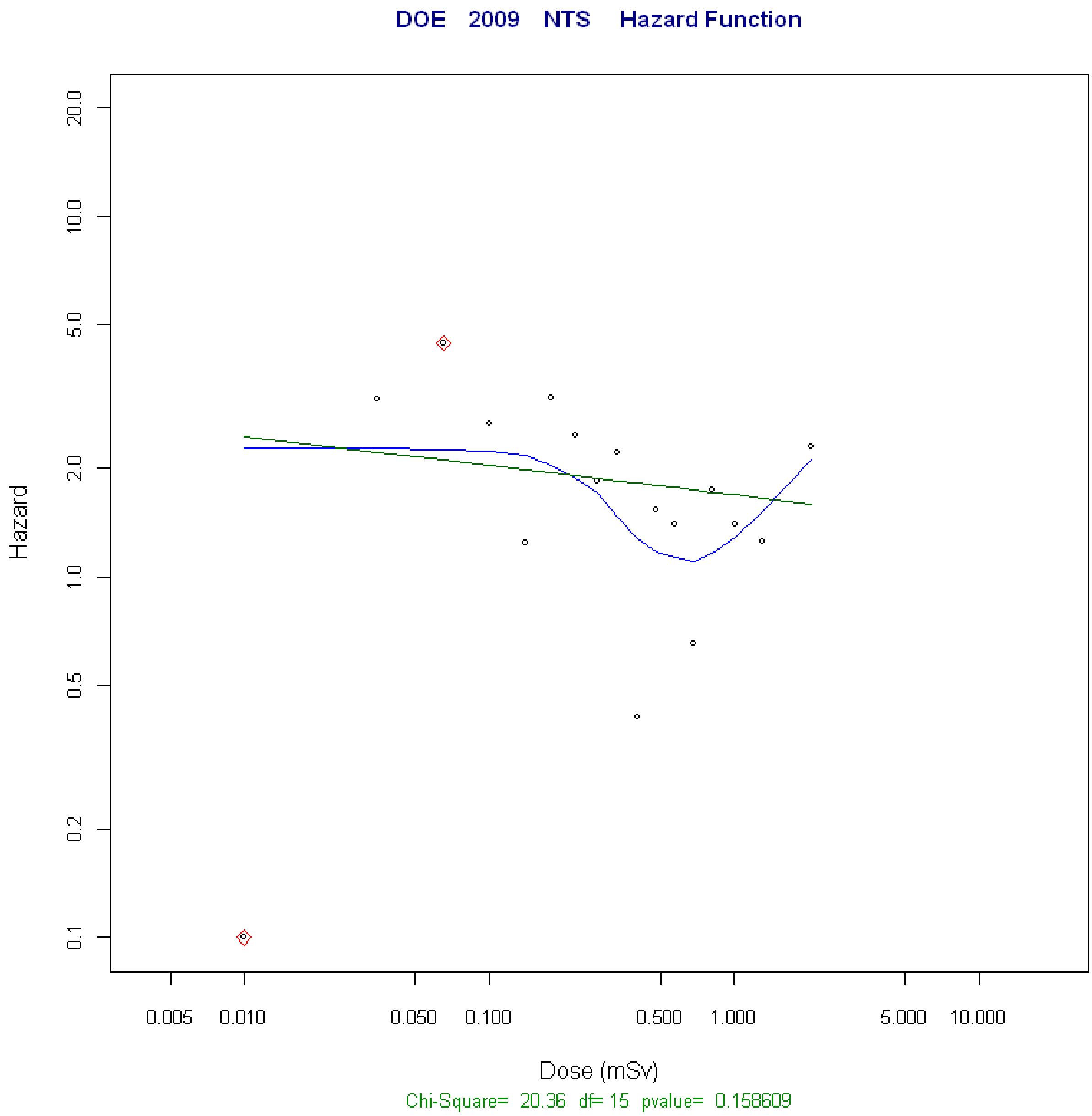

Figure B21: Weibull Goodness of Fit Plot for Nevada Test Site.

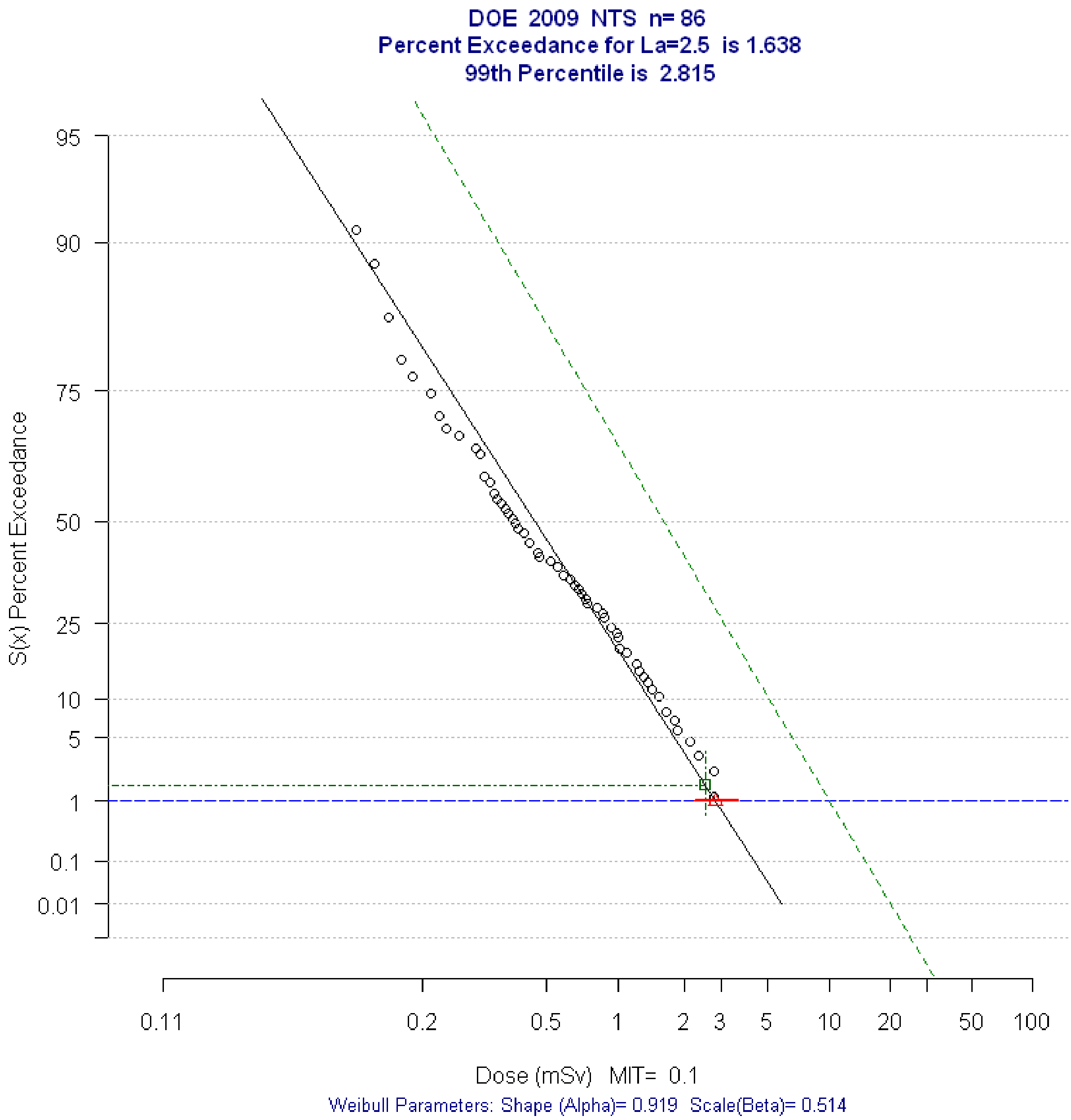

Figure B22: Weibull Probability Plot for Nevada Test Site.

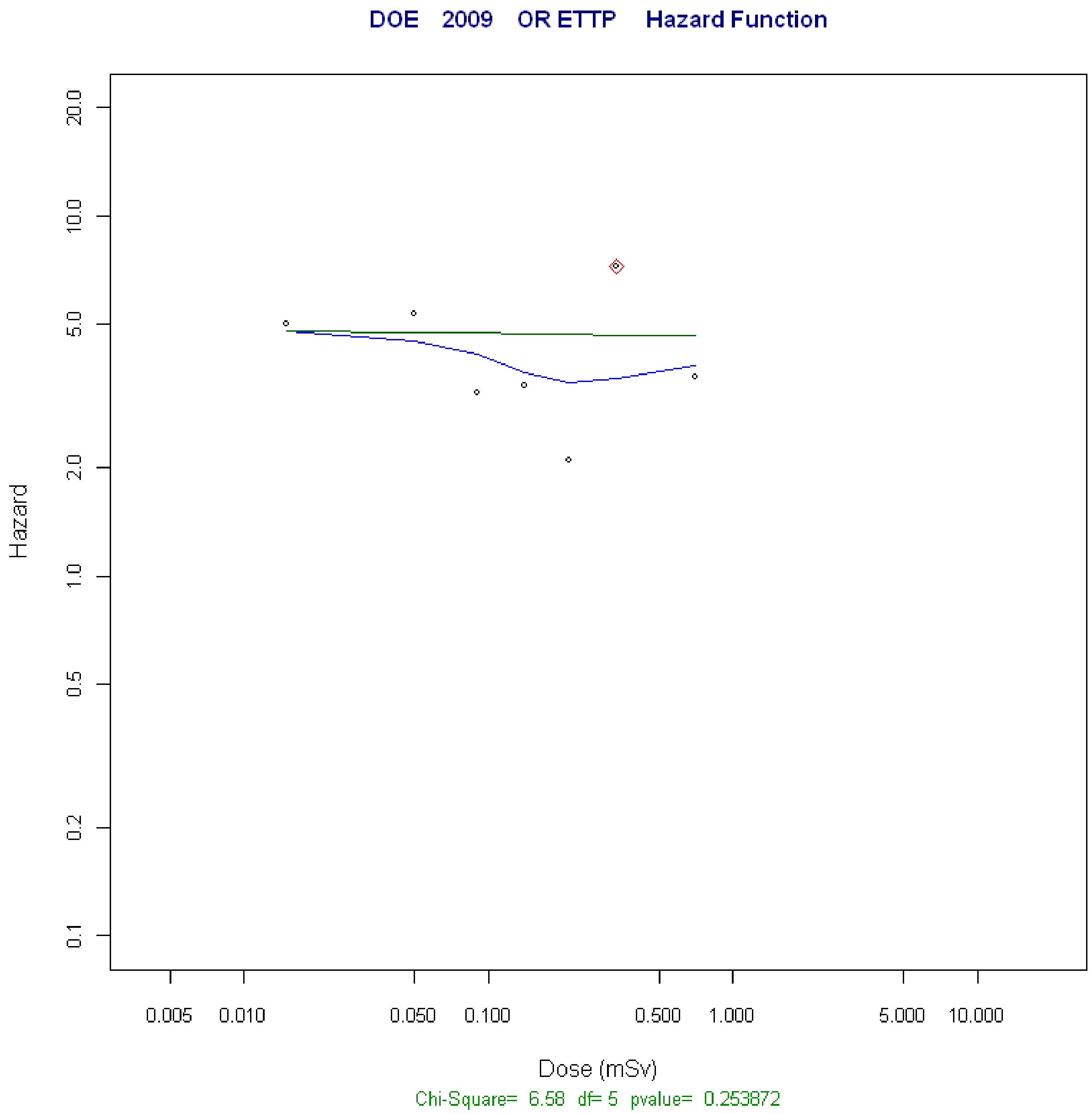

Figure B23: Weibull Goodness of Fit Plot for Oak Ridge – East Tennessee Technology Park.

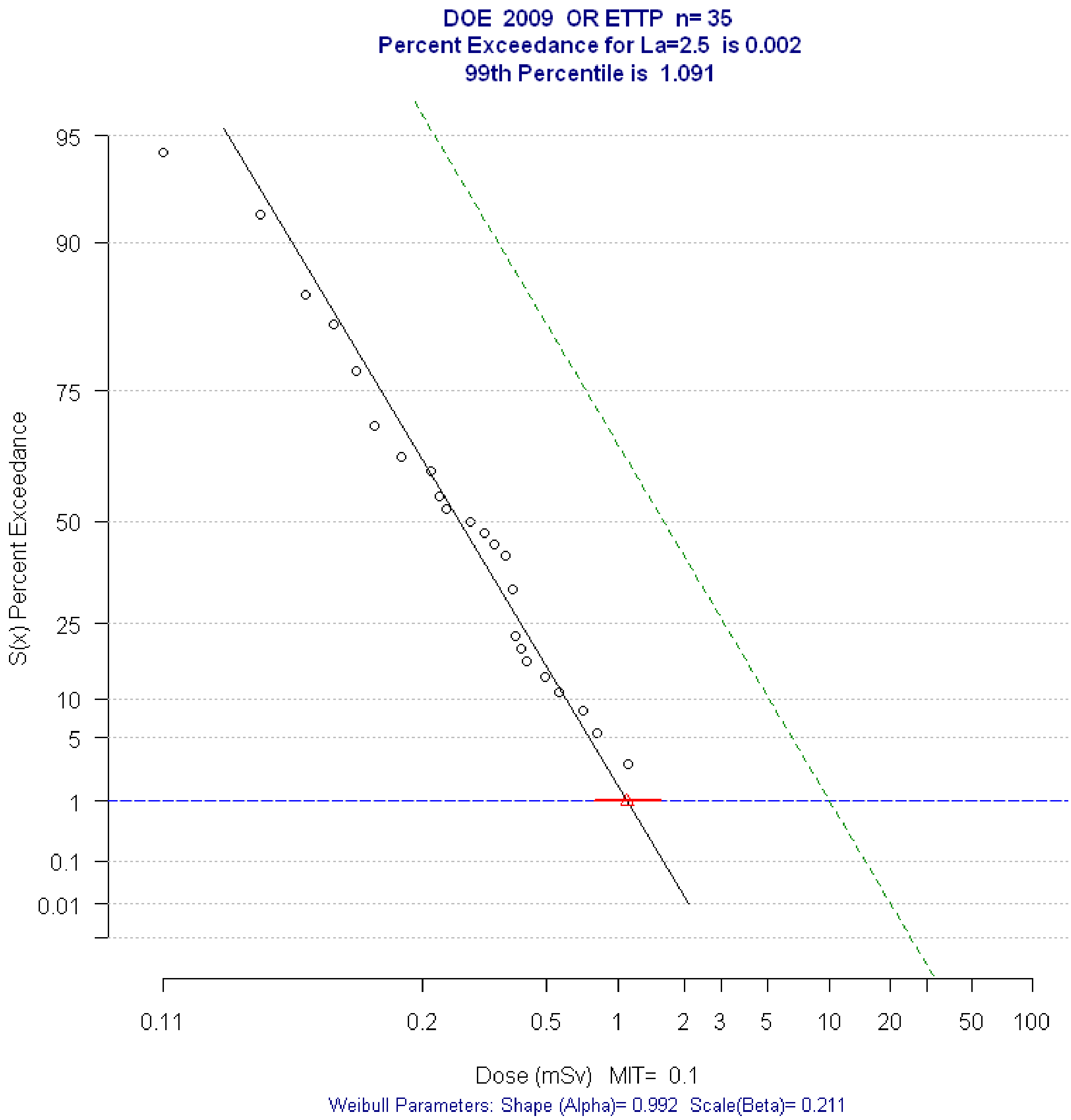

Figure B24: Weibull Probability Plot for Oak Ridge – East Tennessee Technology Park.

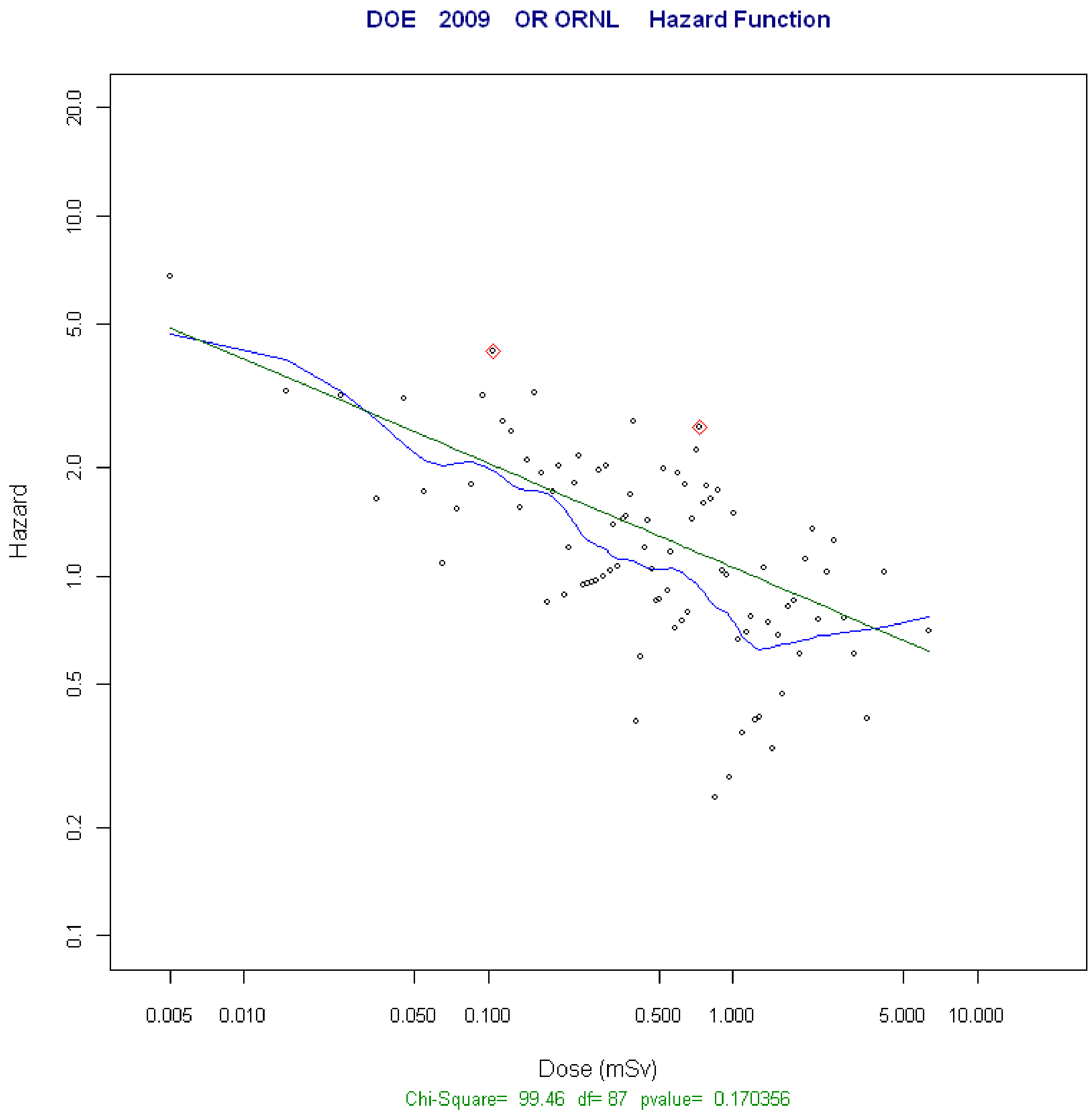

Figure B25: Weibull Goodness of Fit Plot for Oak Ridge – Oak Ridge National Laboratory.

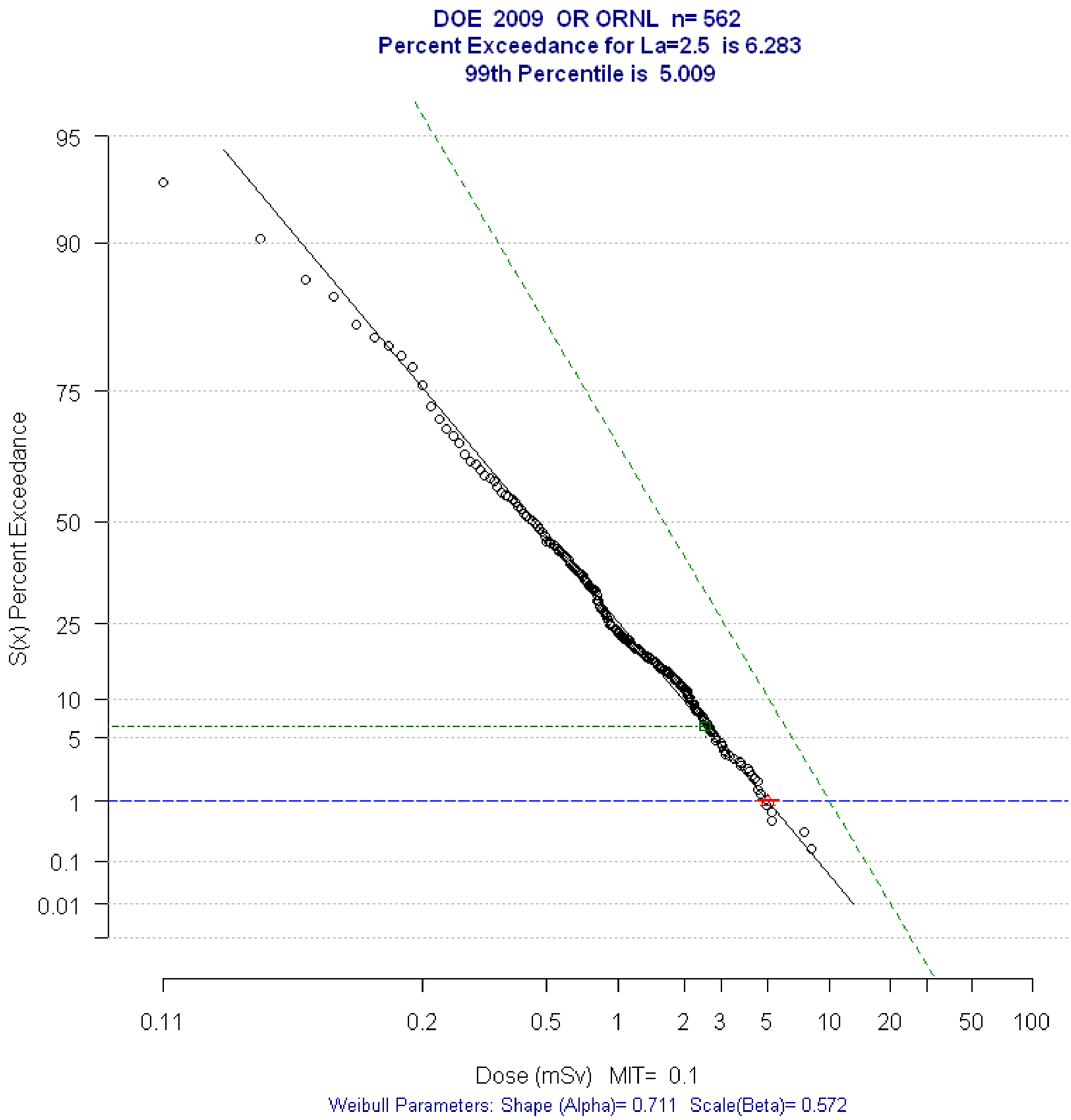

Figure B26: Weibull Probability Plot for Oak Ridge – Oak Ridge National Laboratory.

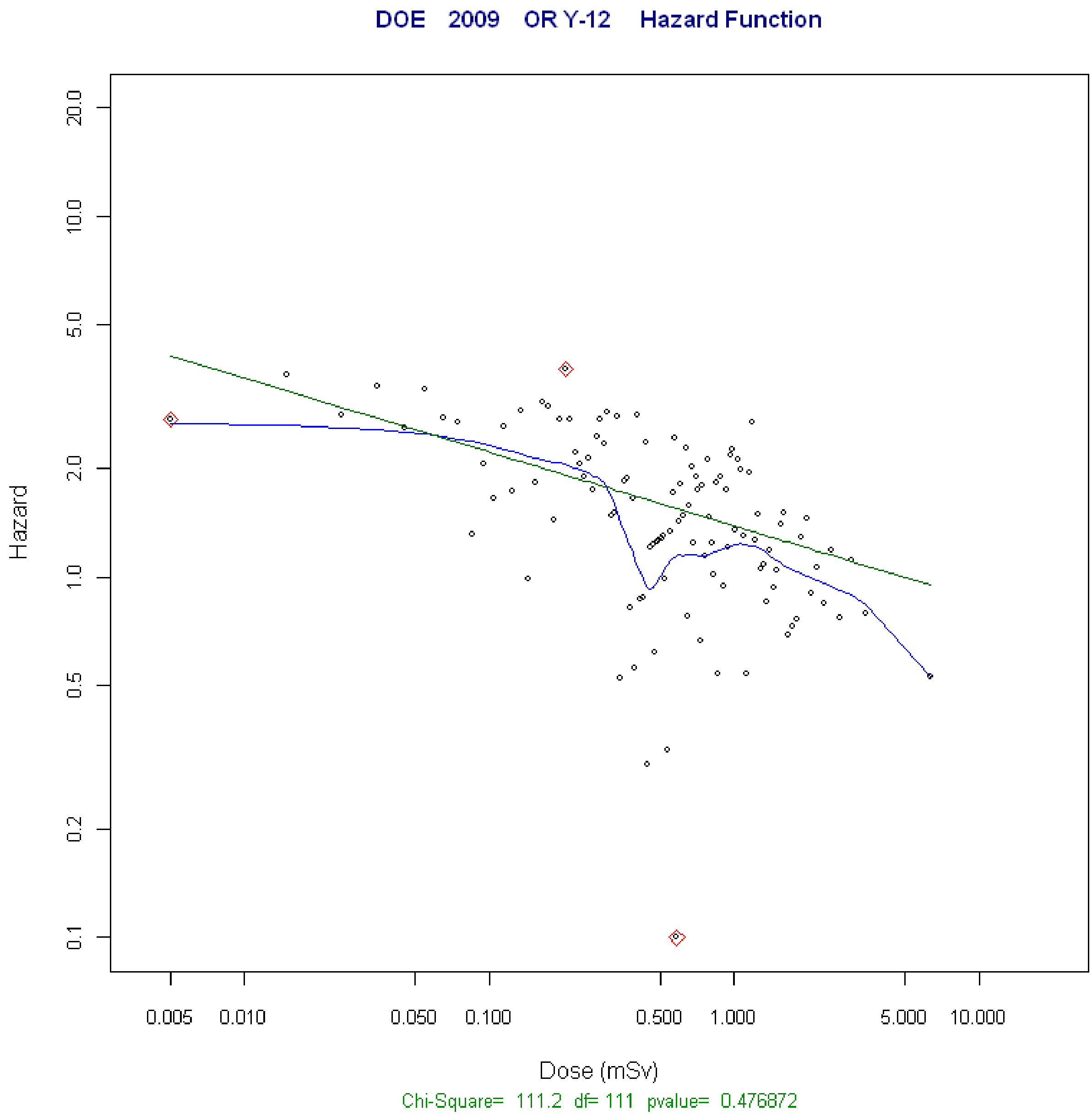

Figure B27: Weibull Goodness of Fit Plot for Oak Ridge – Y-12 National Security Complex.

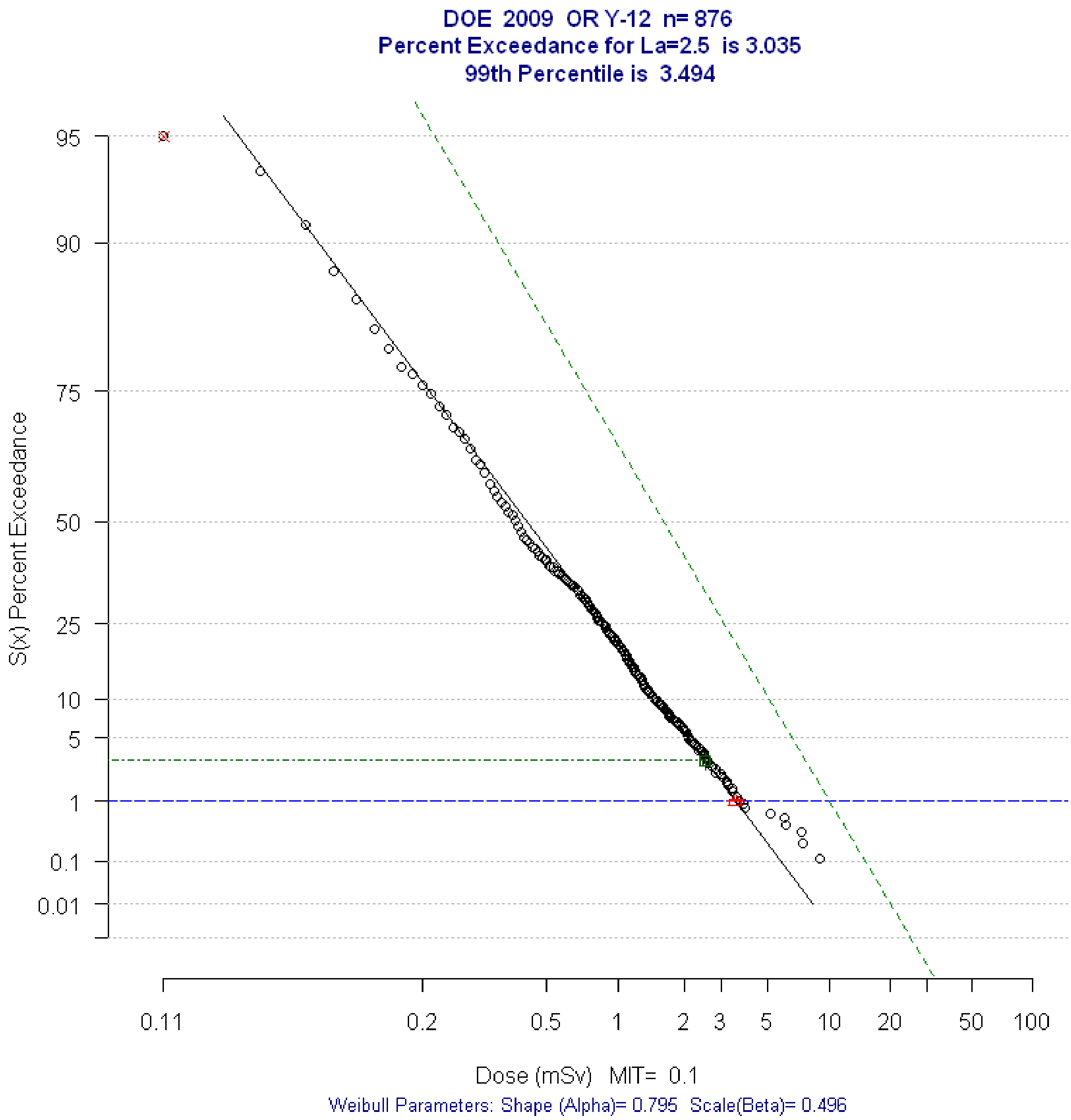

Figure B28: Weibull Probability Plot for Oak Ridge – Y-12 National Security Complex.

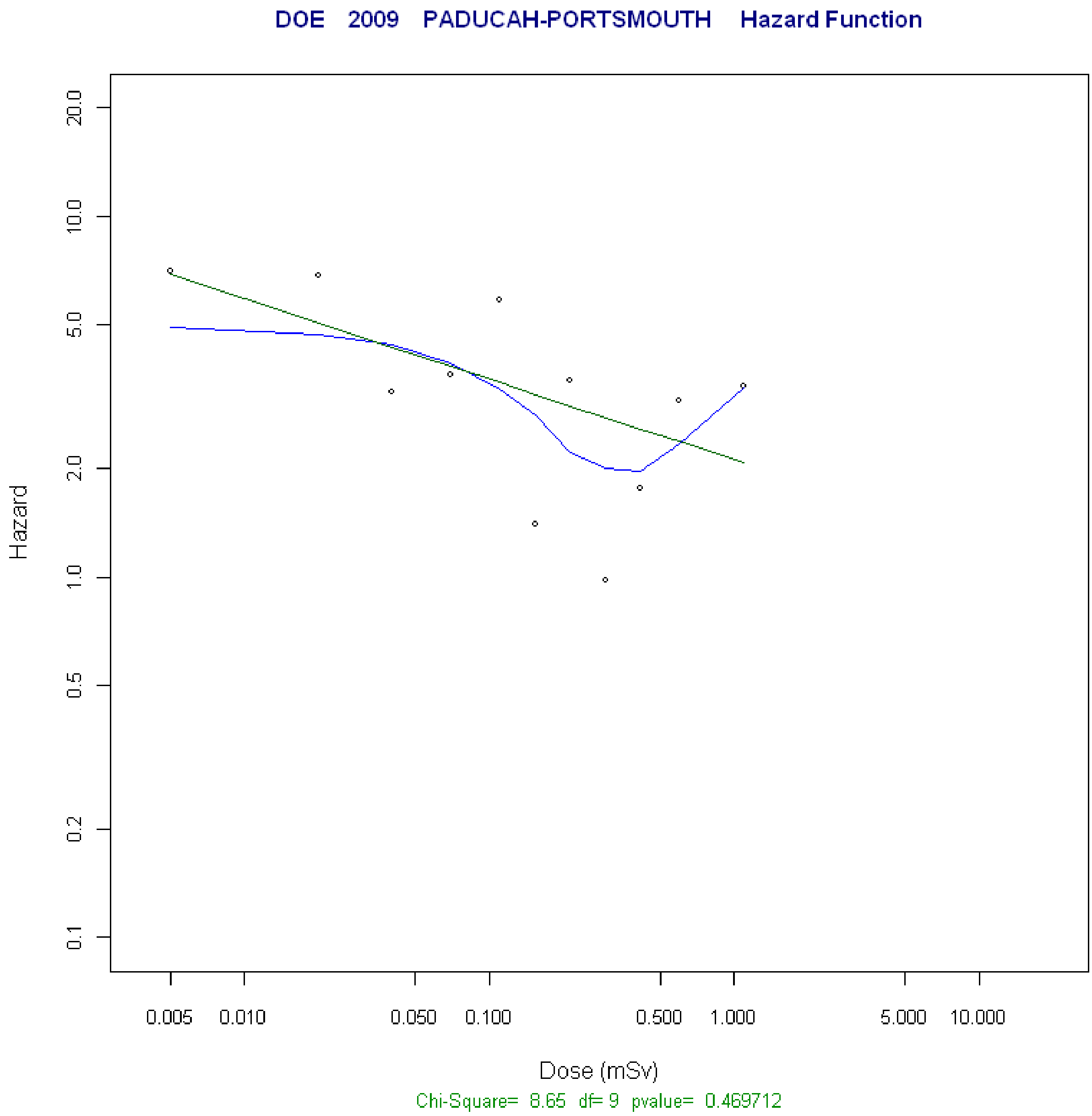

Figure B29: Weibull Goodness of Fit Plot for Paducah-Portsmouth.

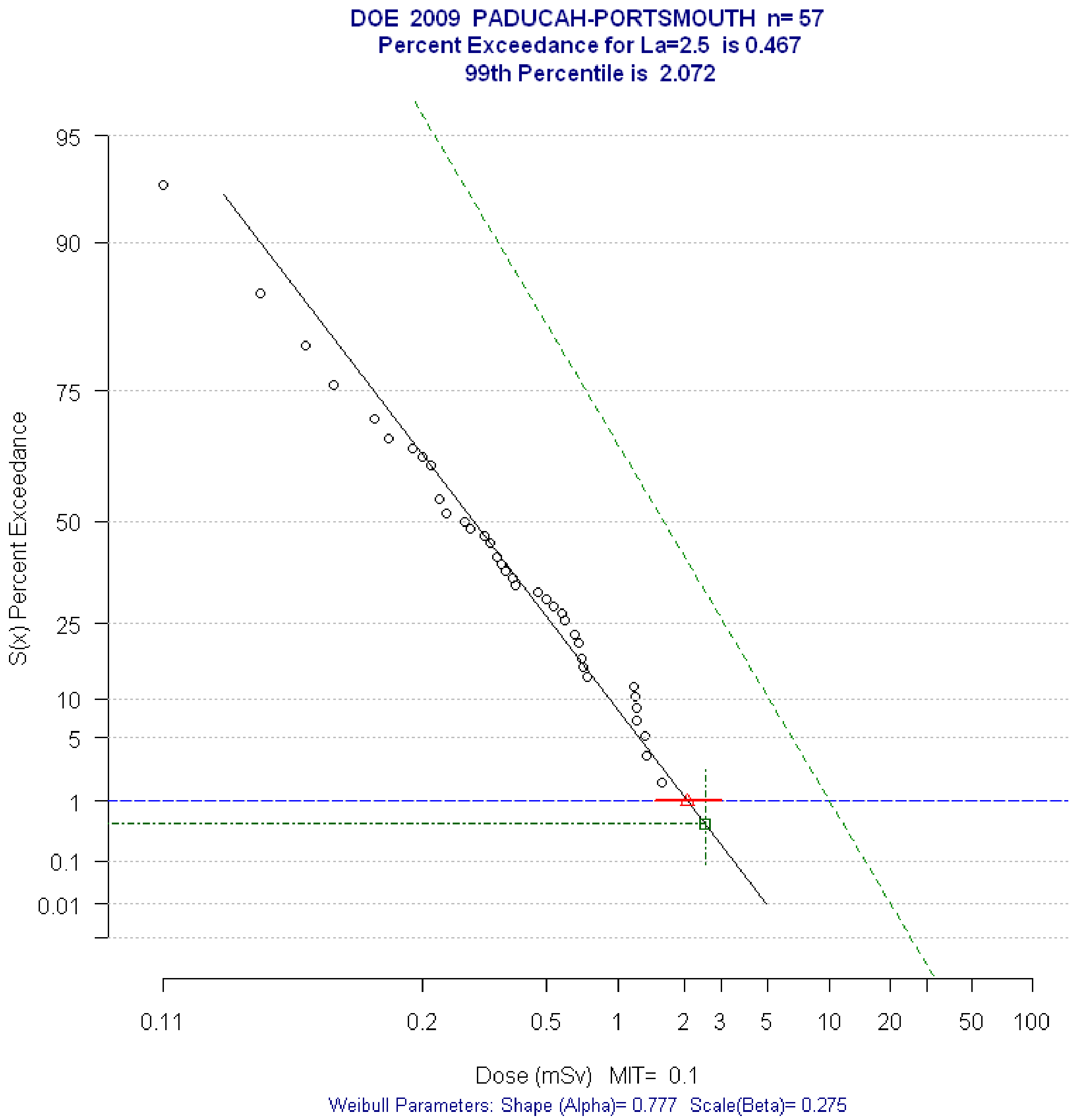

Figure B30: Weibull Probability Plot for Paducah-Portsmouth.

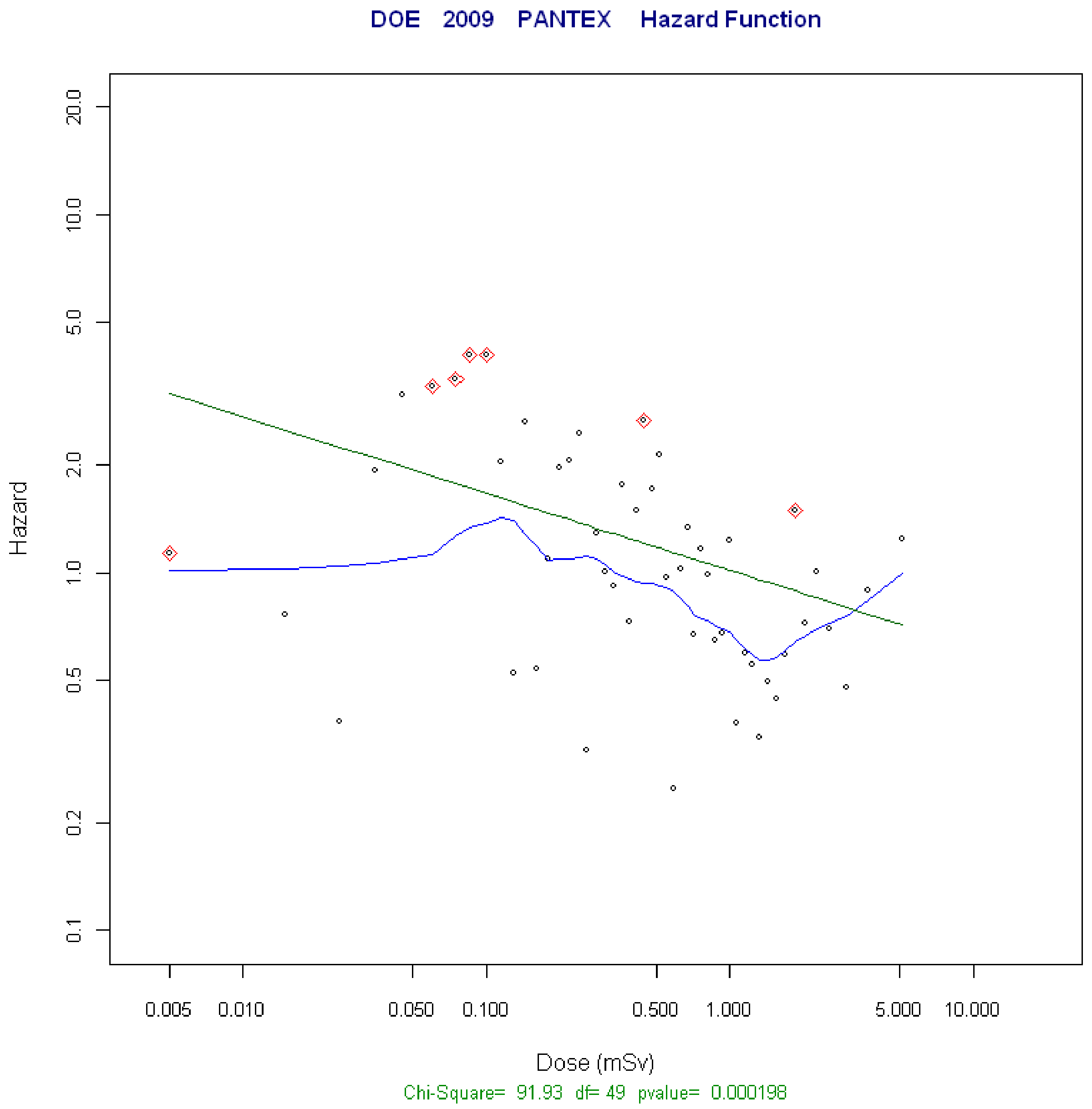

Figure B31: Weibull Goodness of Fit Plot for Pantex Plant.

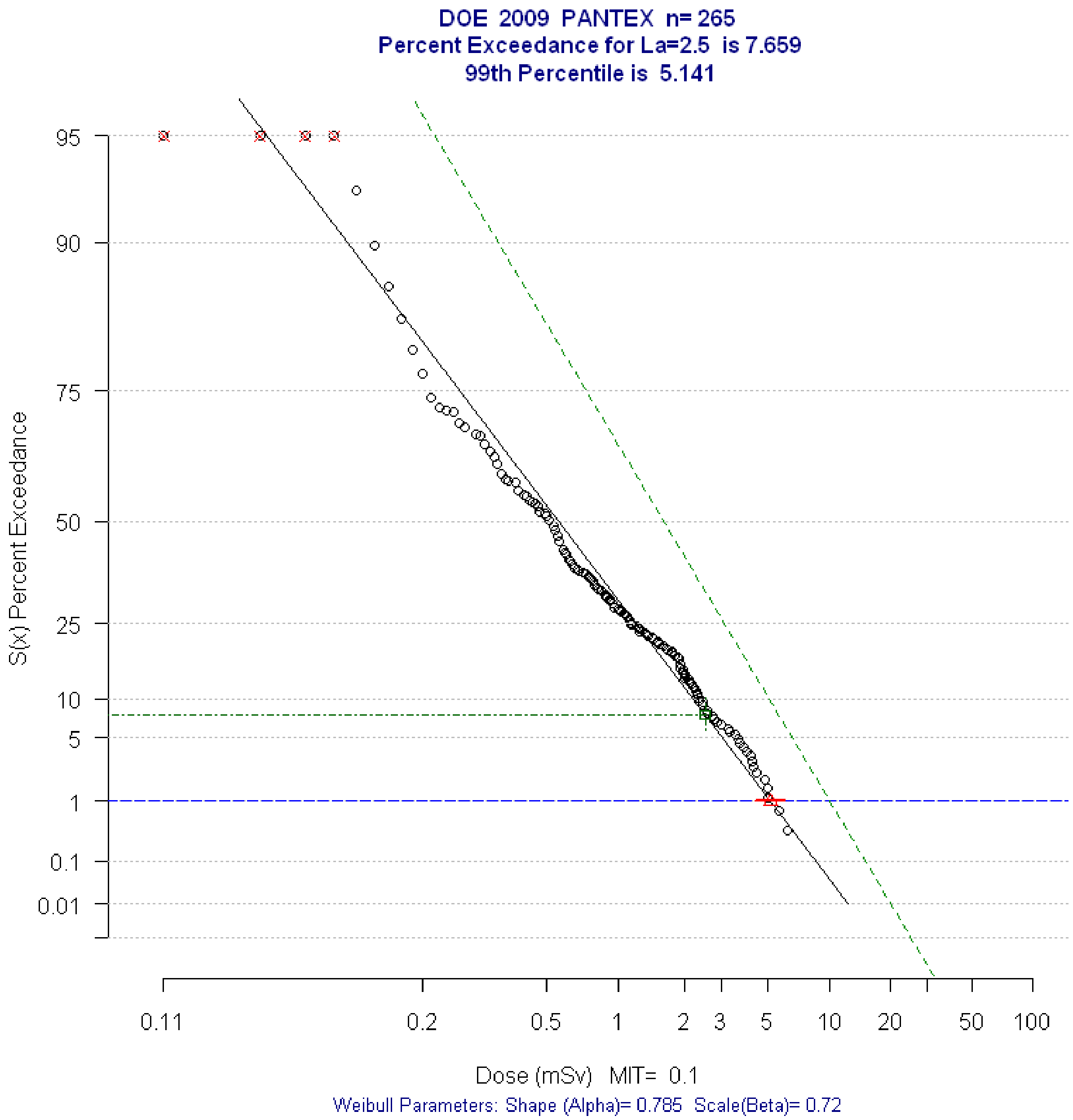

Figure B32: Weibull Probability Plot for Pantex Plant.

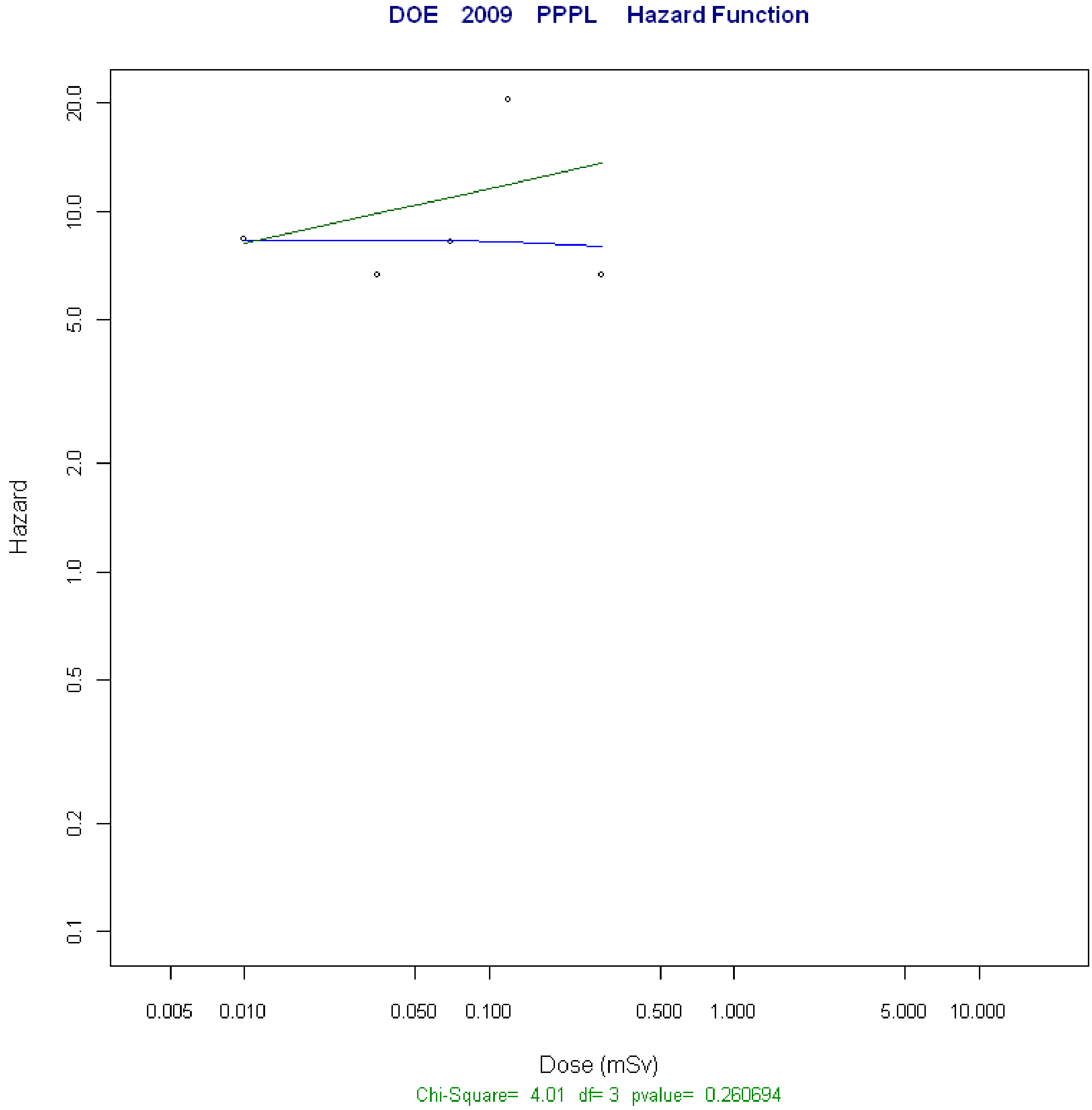

Figure B33: Weibull Goodness of Fit Plot for Princeton Plasma Physics Laboratory.

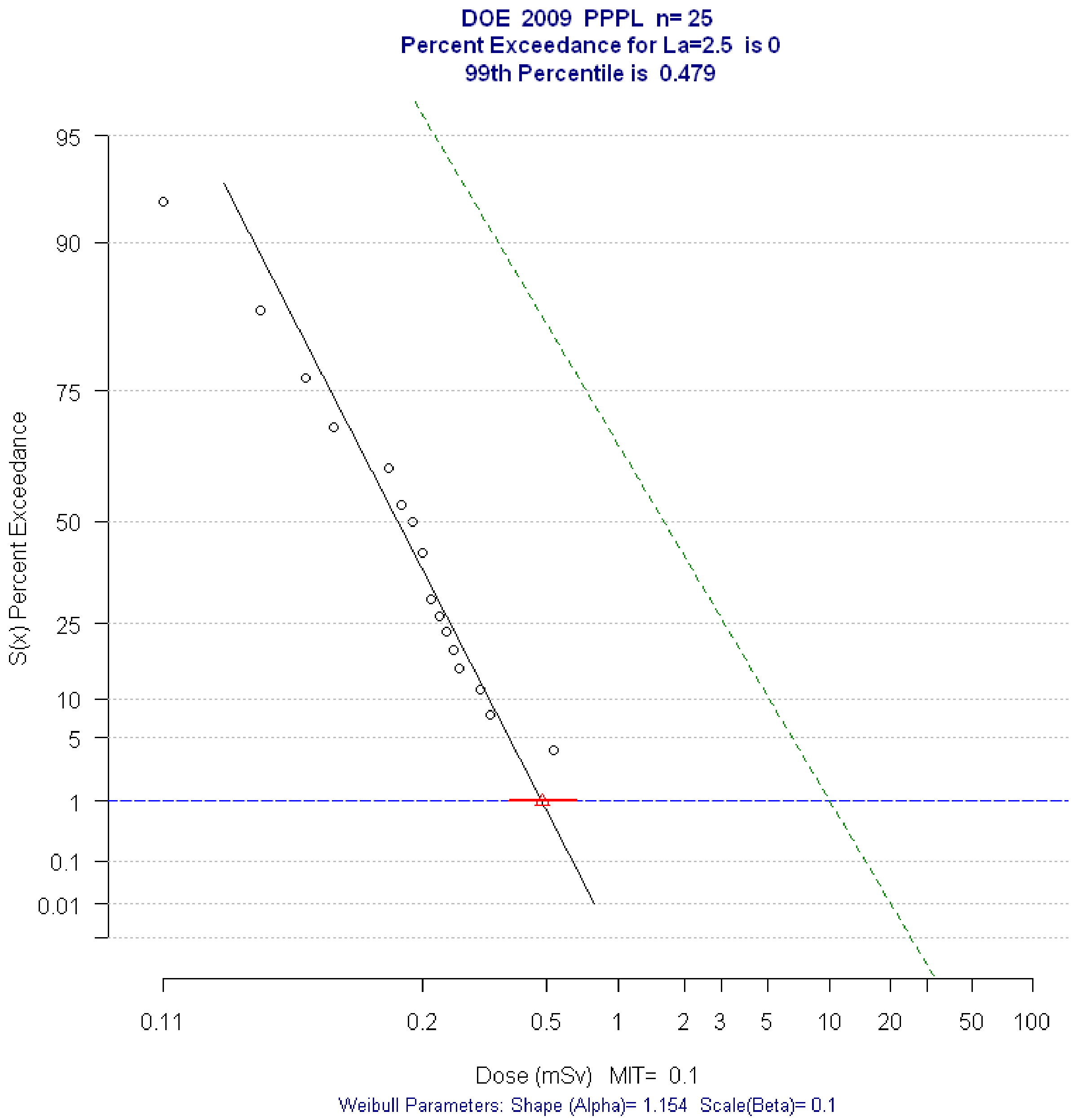

Figure B34: Weibull Probability Plot for Princeton Plasma Physics Laboratory.

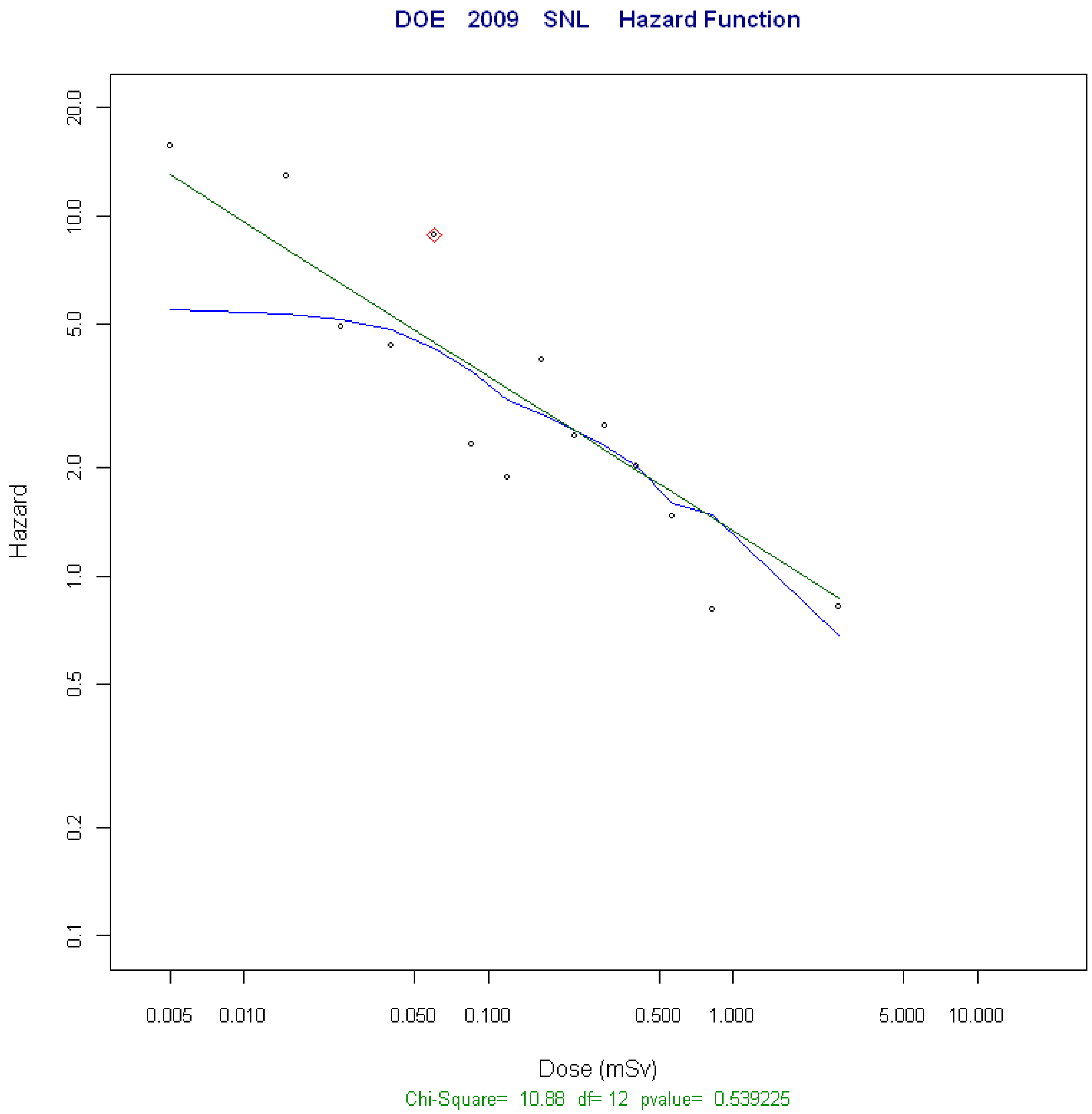

Figure B35: Weibull Goodness of Fit Plot for Sandia National Laboratory.

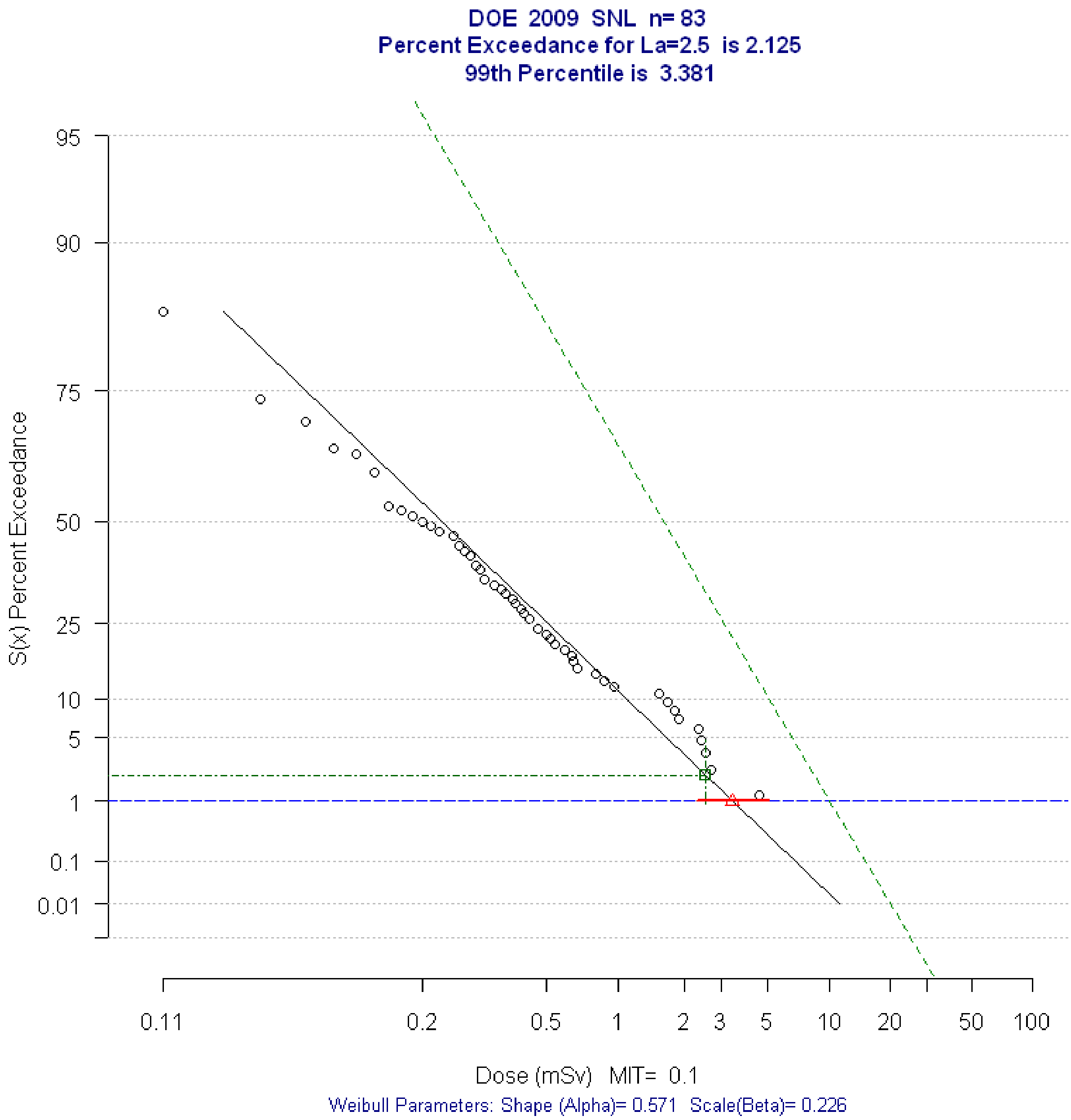

Figure B36: Weibull Probability Plot for Sandia National Laboratory.

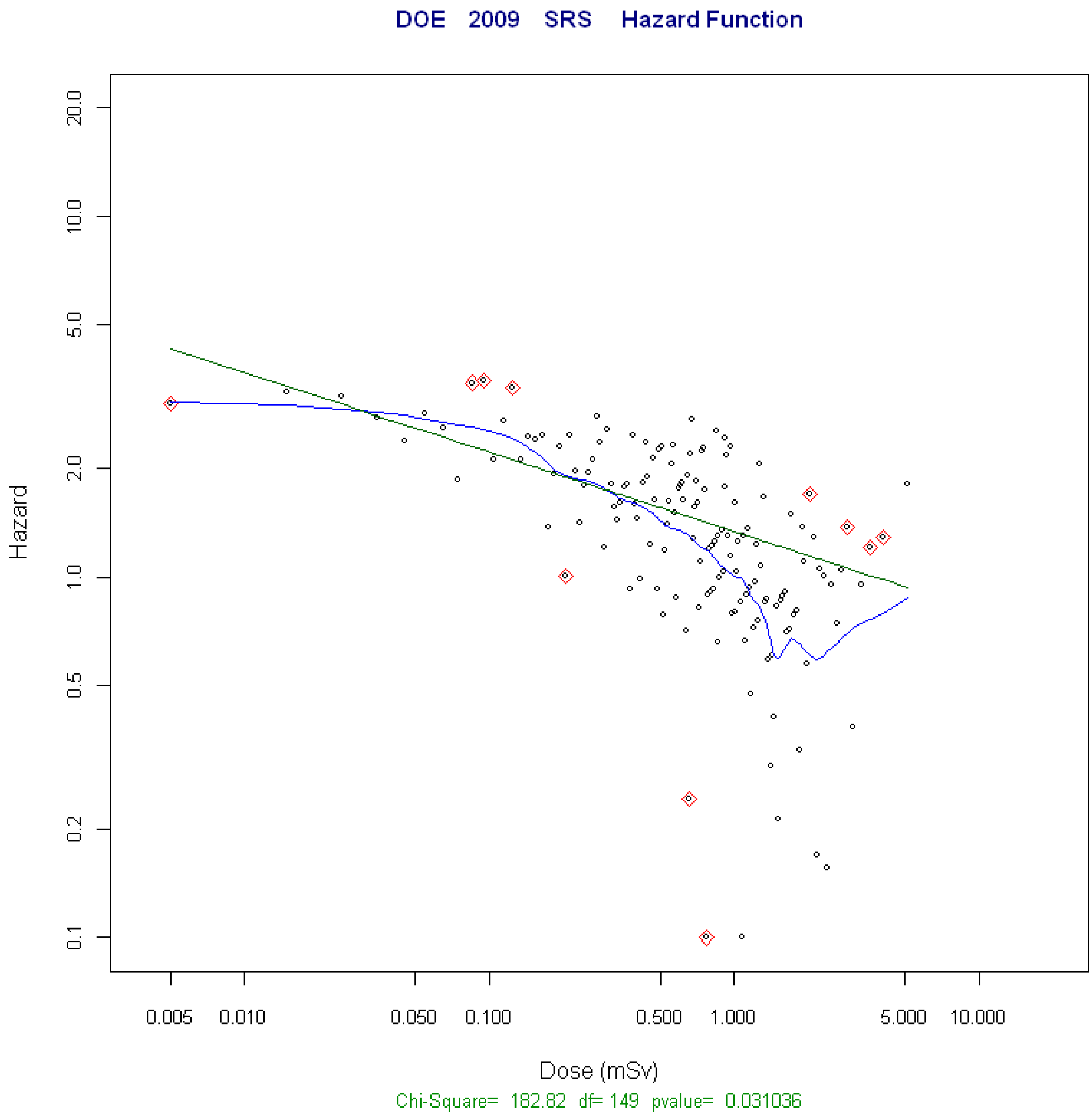

Figure B37: Weibull Goodness of Fit Plot for Savannah River Site.

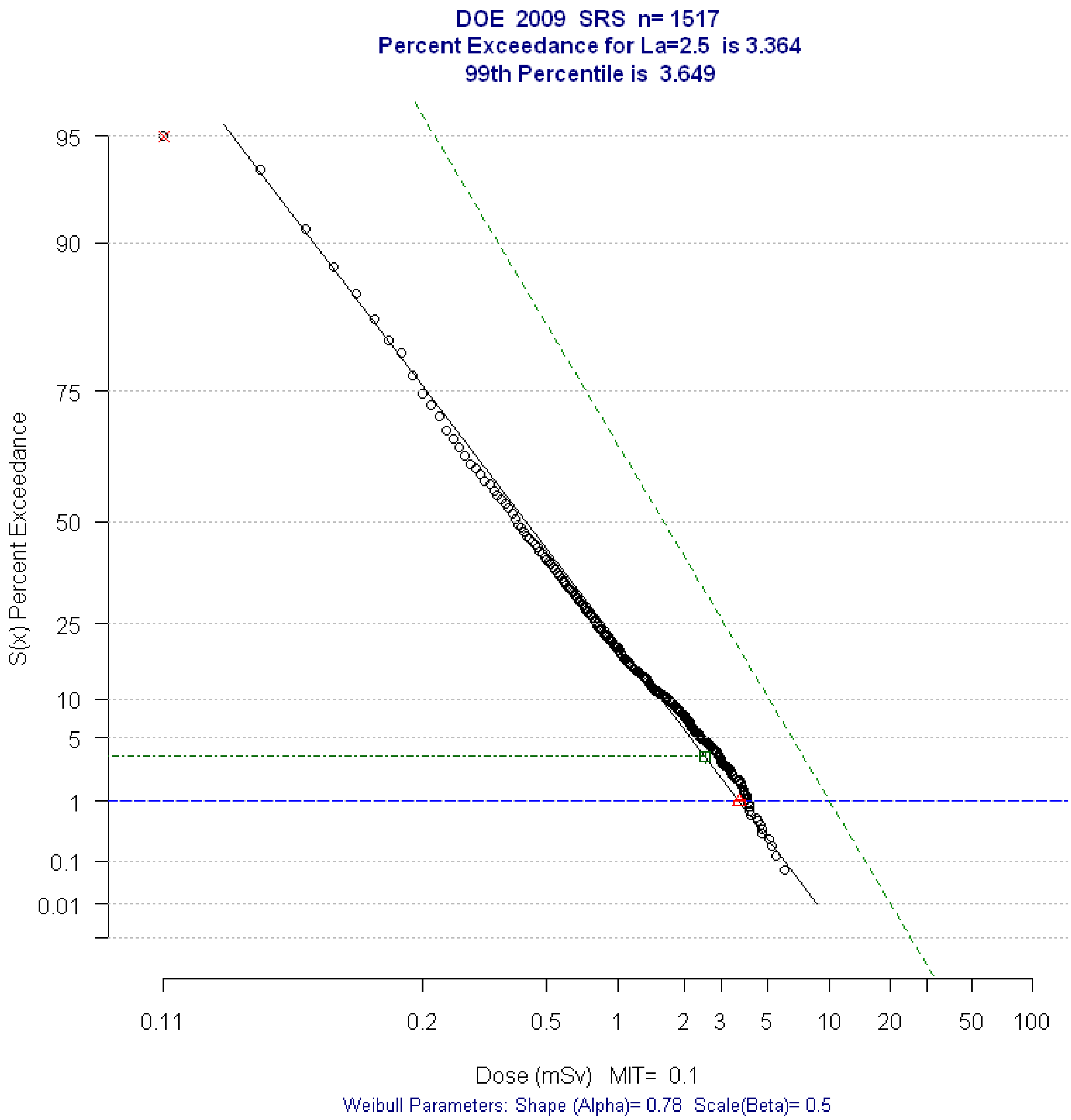

Figure B38: Weibull Probability Plot for Savannah River Site.

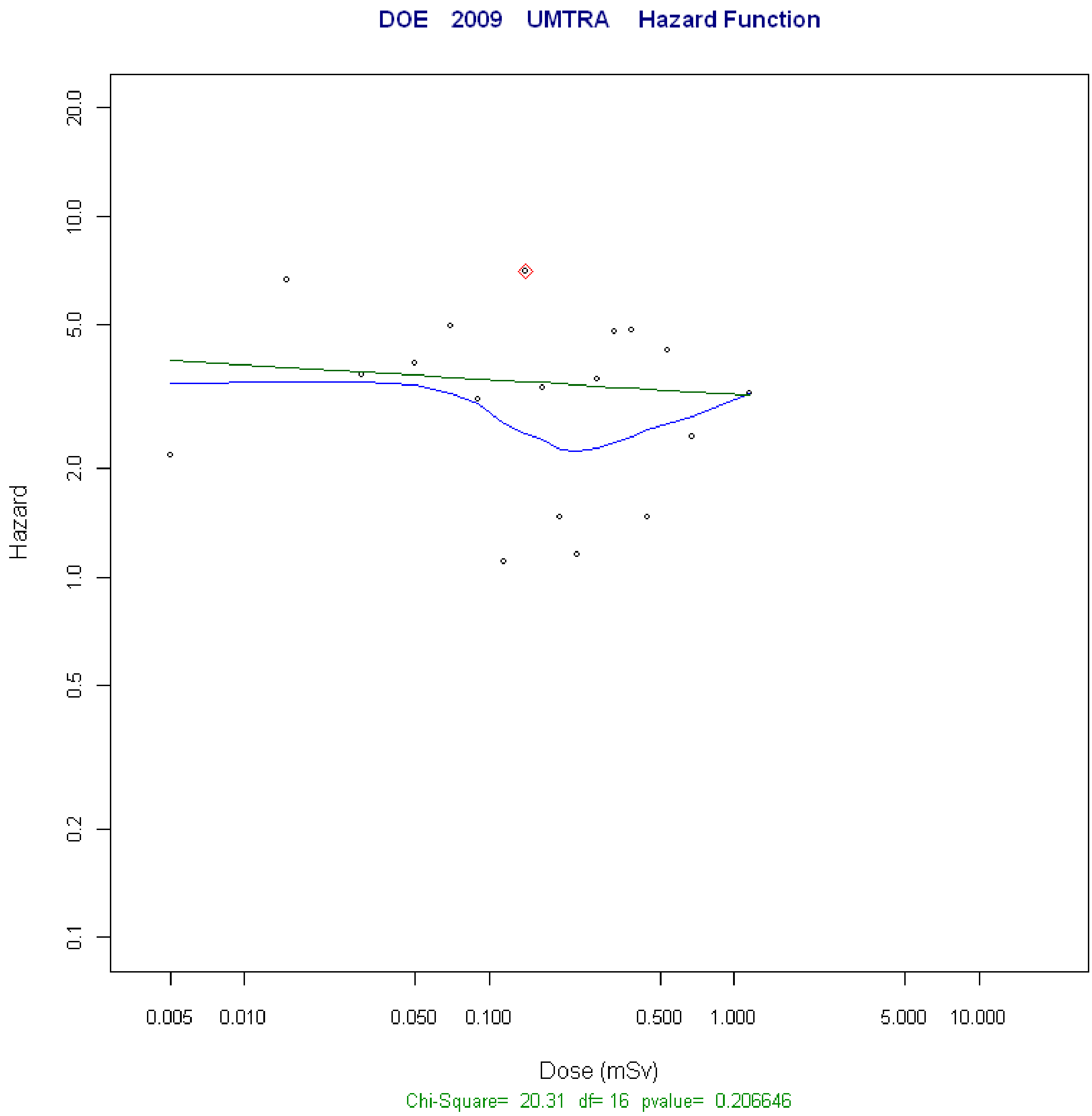

Figure B39: Weibull Goodness of Fit Plot for Uranium Mill Tailings Remedial Action Project.

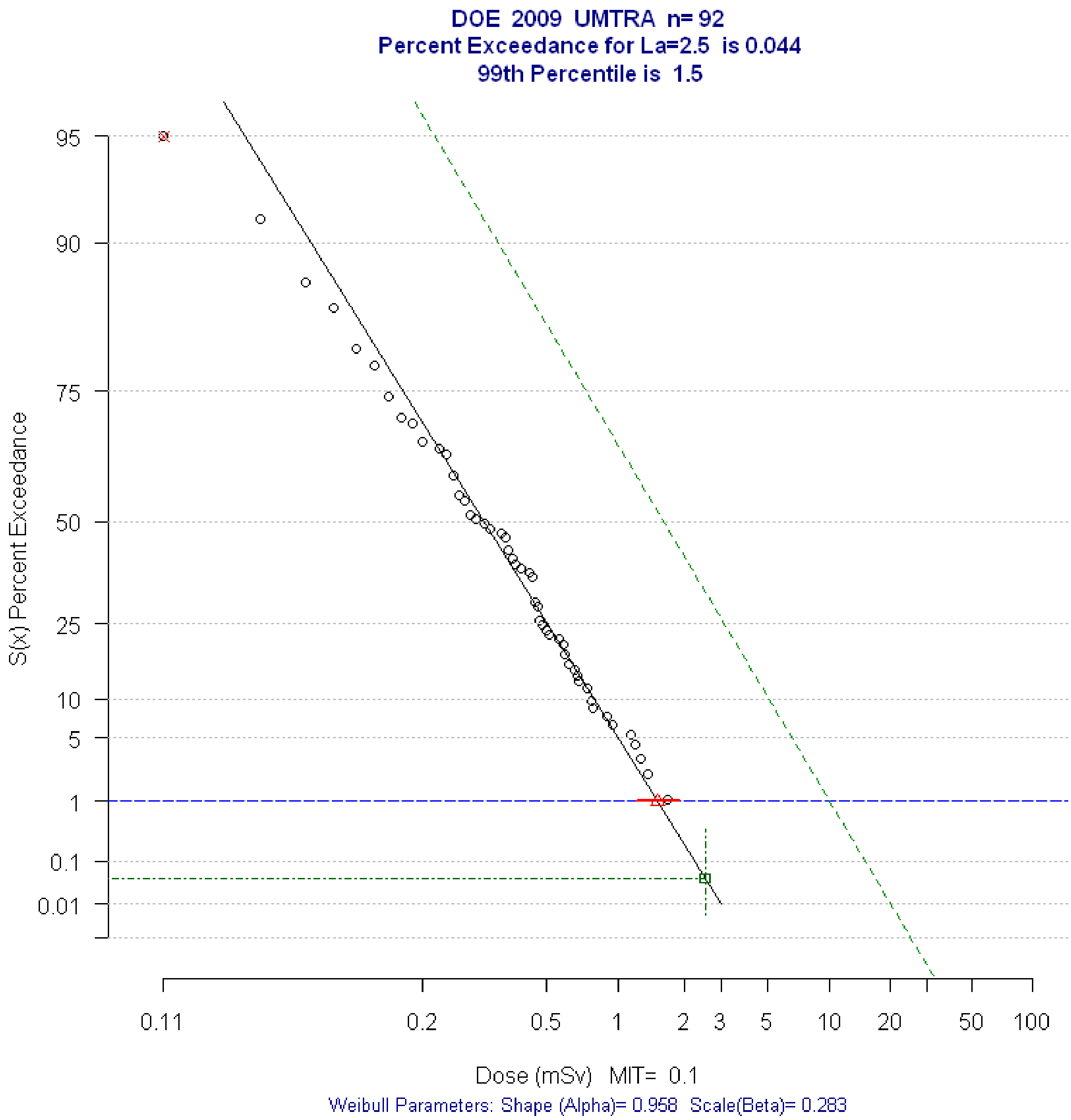

Figure B40: Weibull Probability Plot for Uranium Mill Tailings Remedial Action Project.

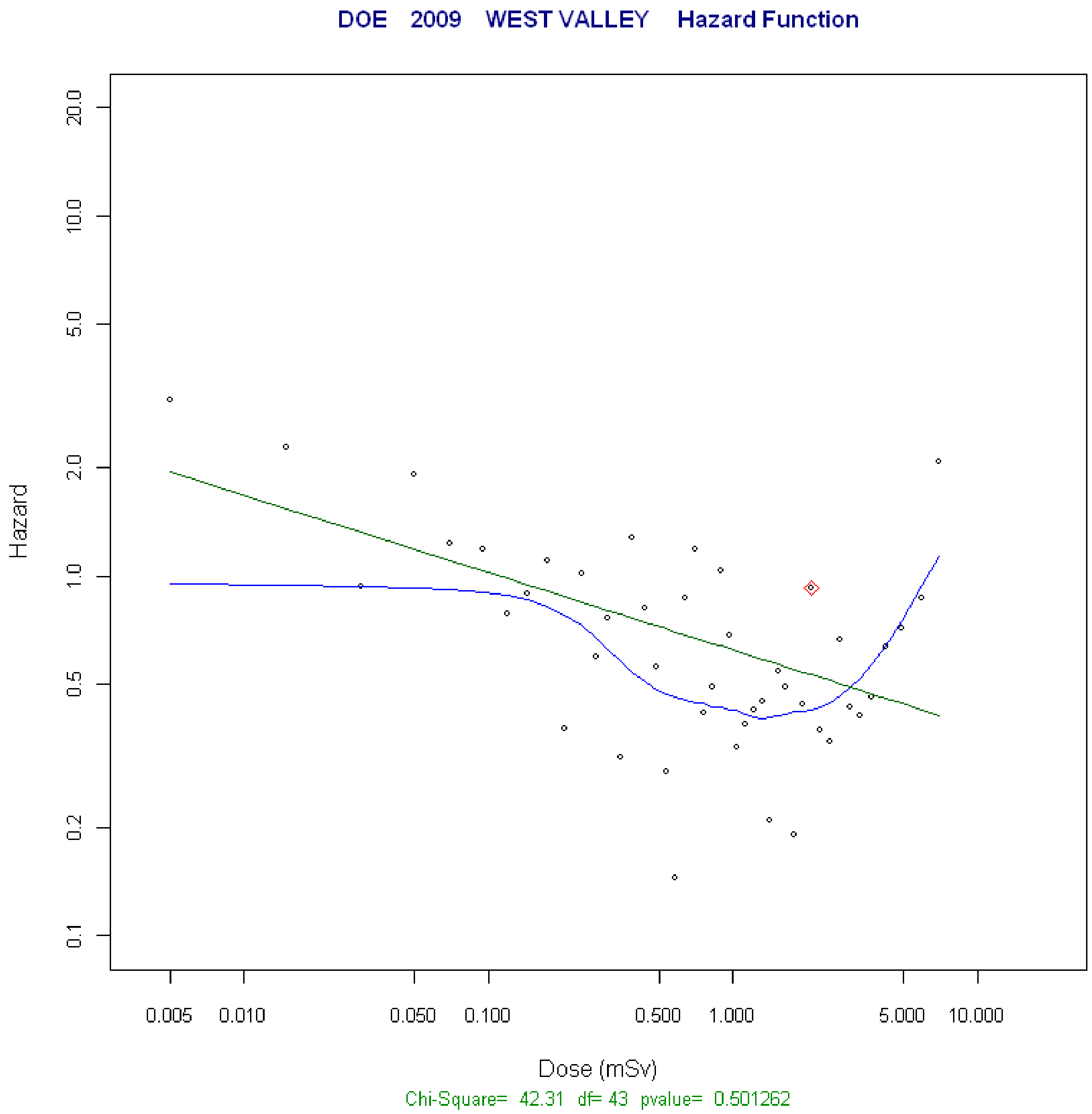

Figure B41: Weibull Goodness of Fit Plot for West Valley Environment Services, LLC.

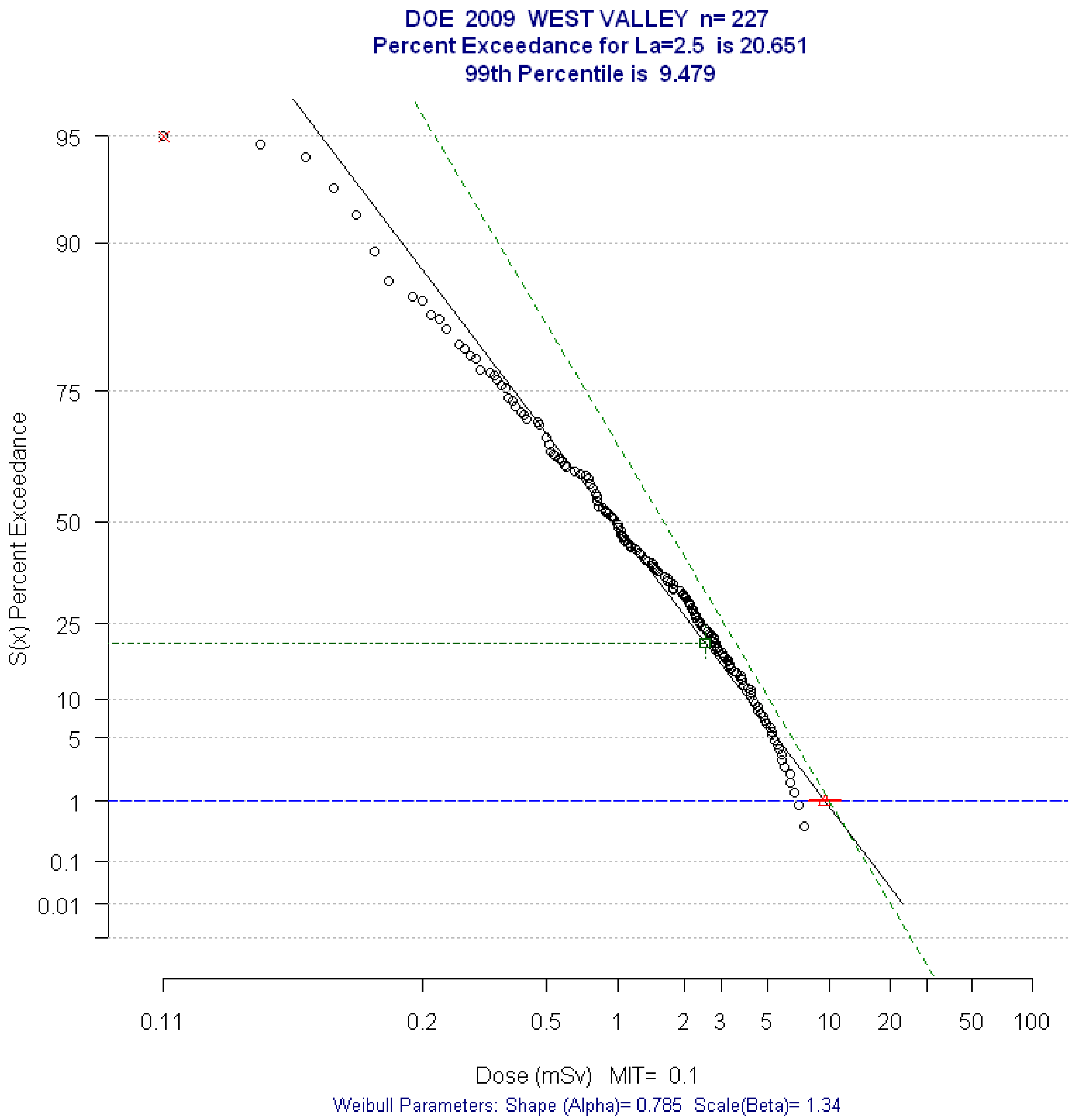

Figure B42: Weibull Probability Plot for West Valley Environment Services, LLC.

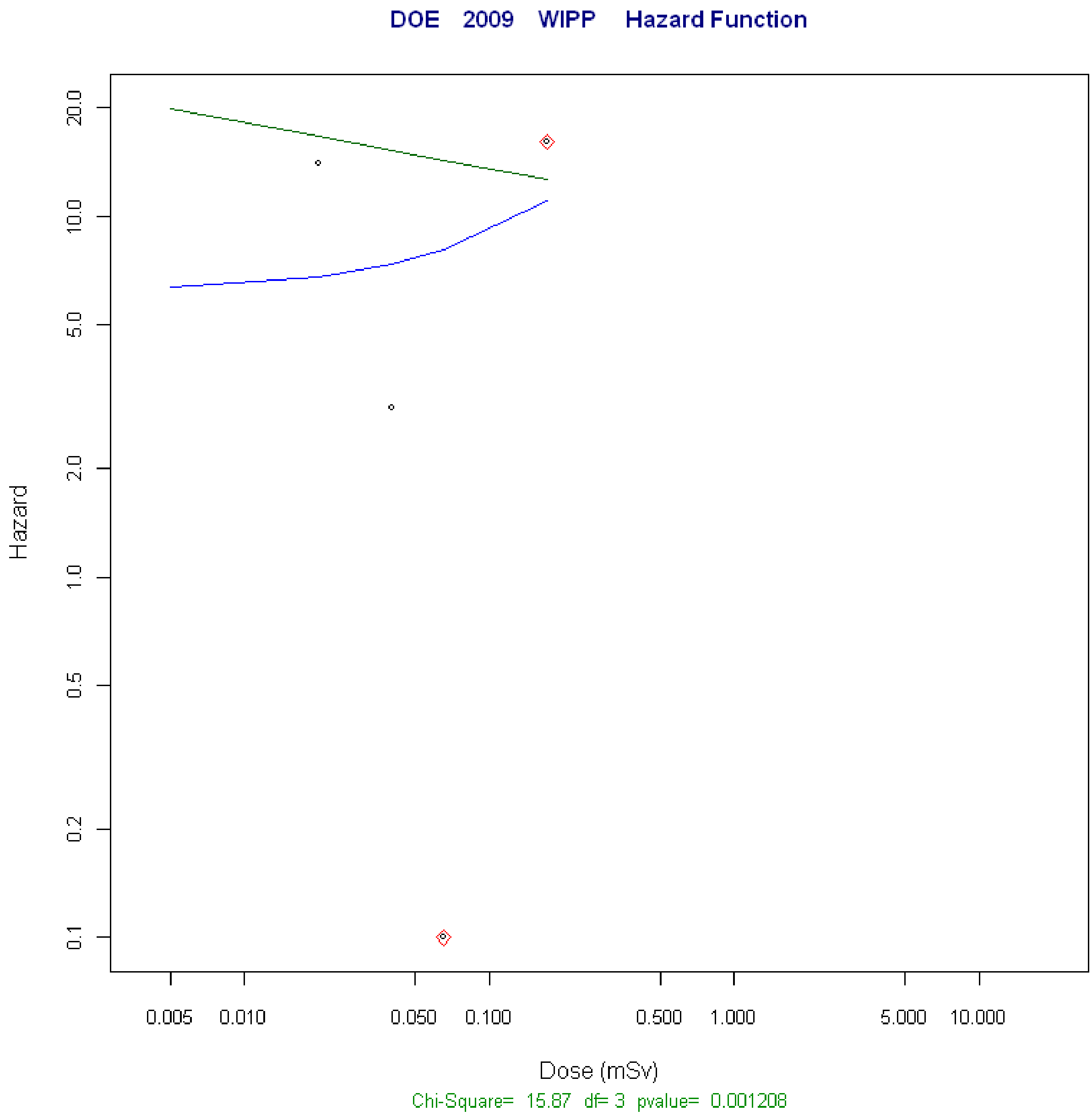

Figure B43: Weibull Goodness of Fit Plot for Waste Isolation Pilot Plant.

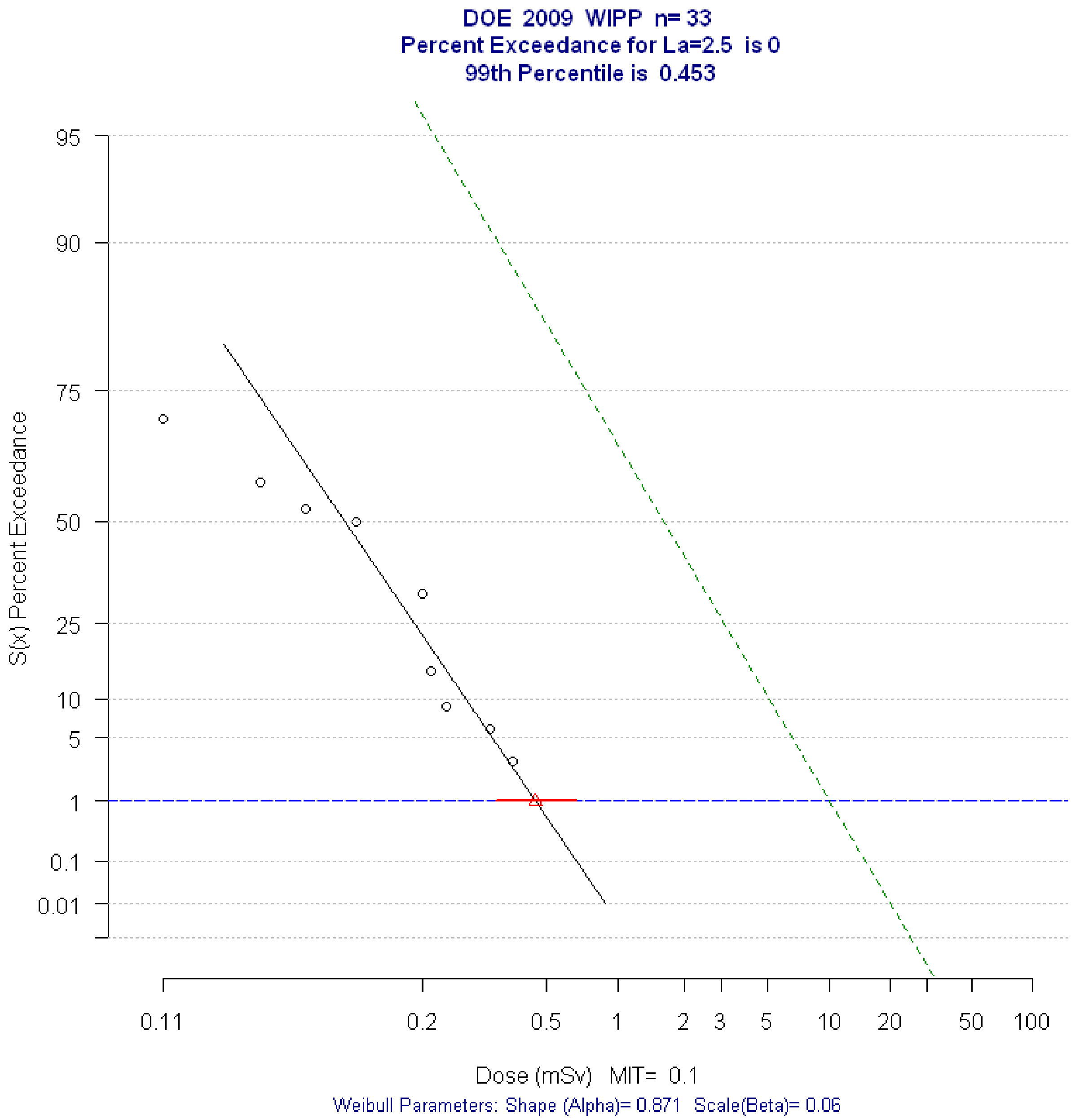

Figure B44: Weibull Probability Plot for Waste Isolation Pilot Plant.

APPENDIX C: Customized Weibull Probability Plots by Site for NRC 2009

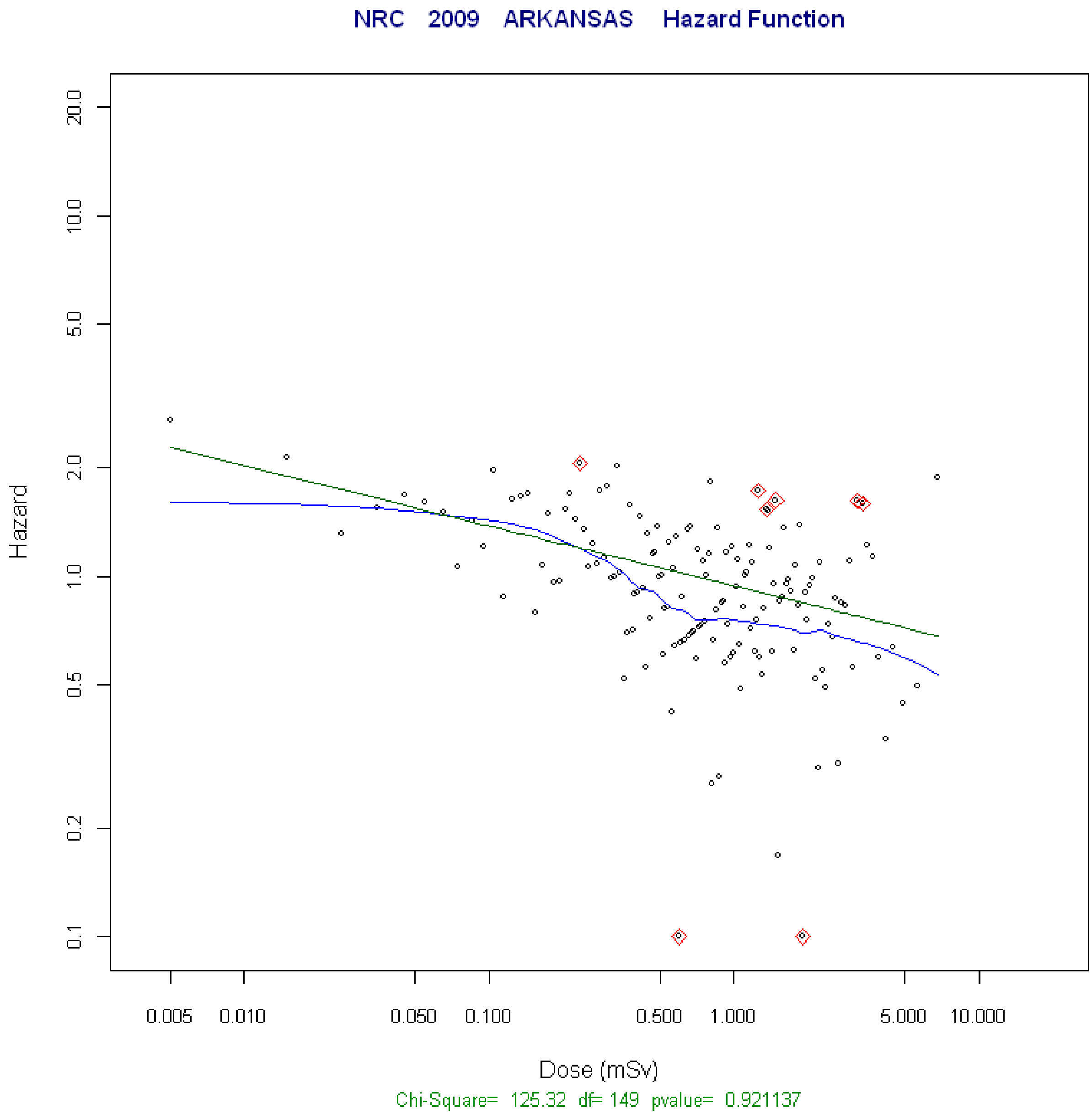

Figure C1: Weibull Goodness of Fit Plot for Arkansas.

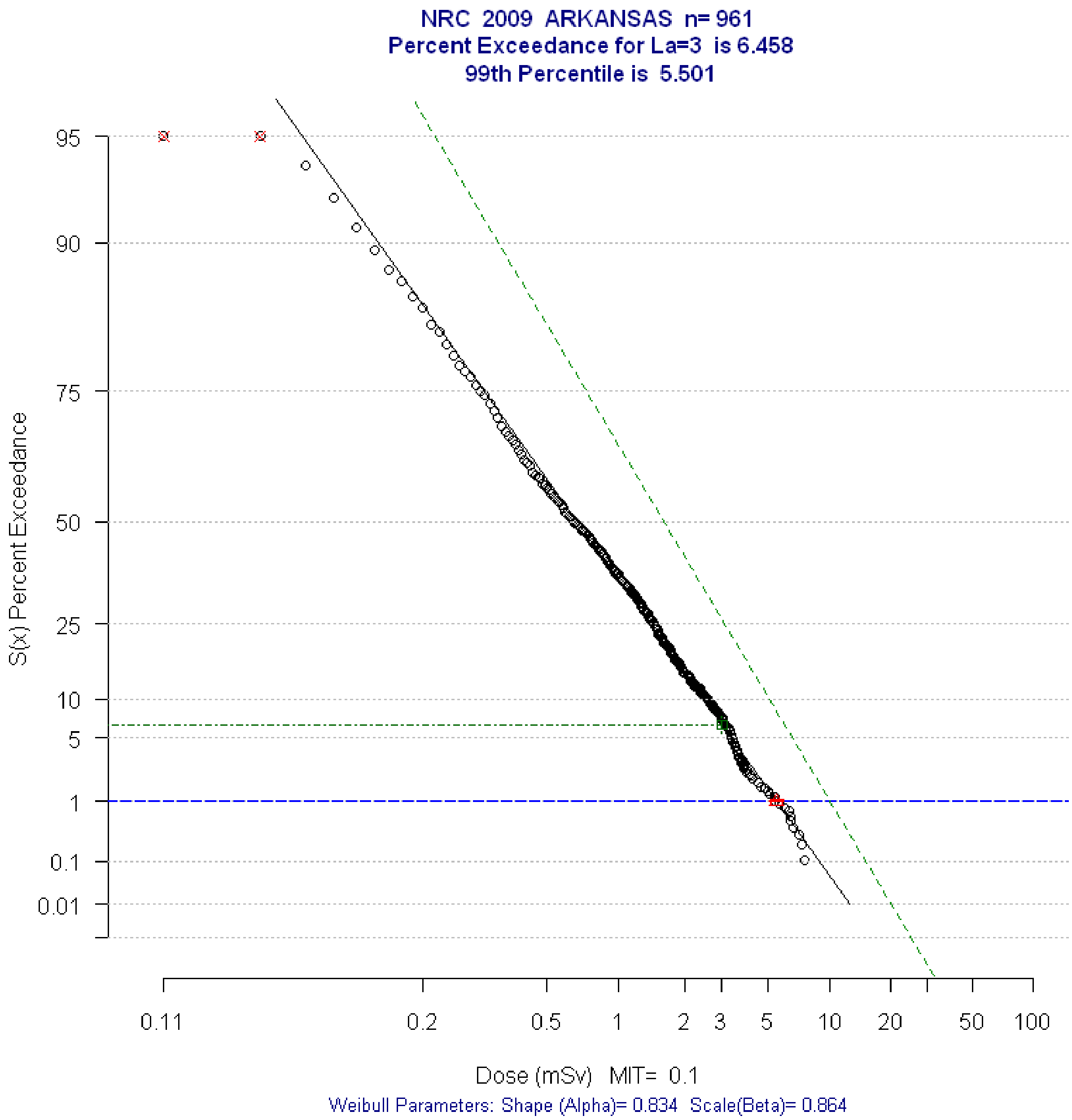

Figure C2: Weibull Probability Plot for Arkansas.

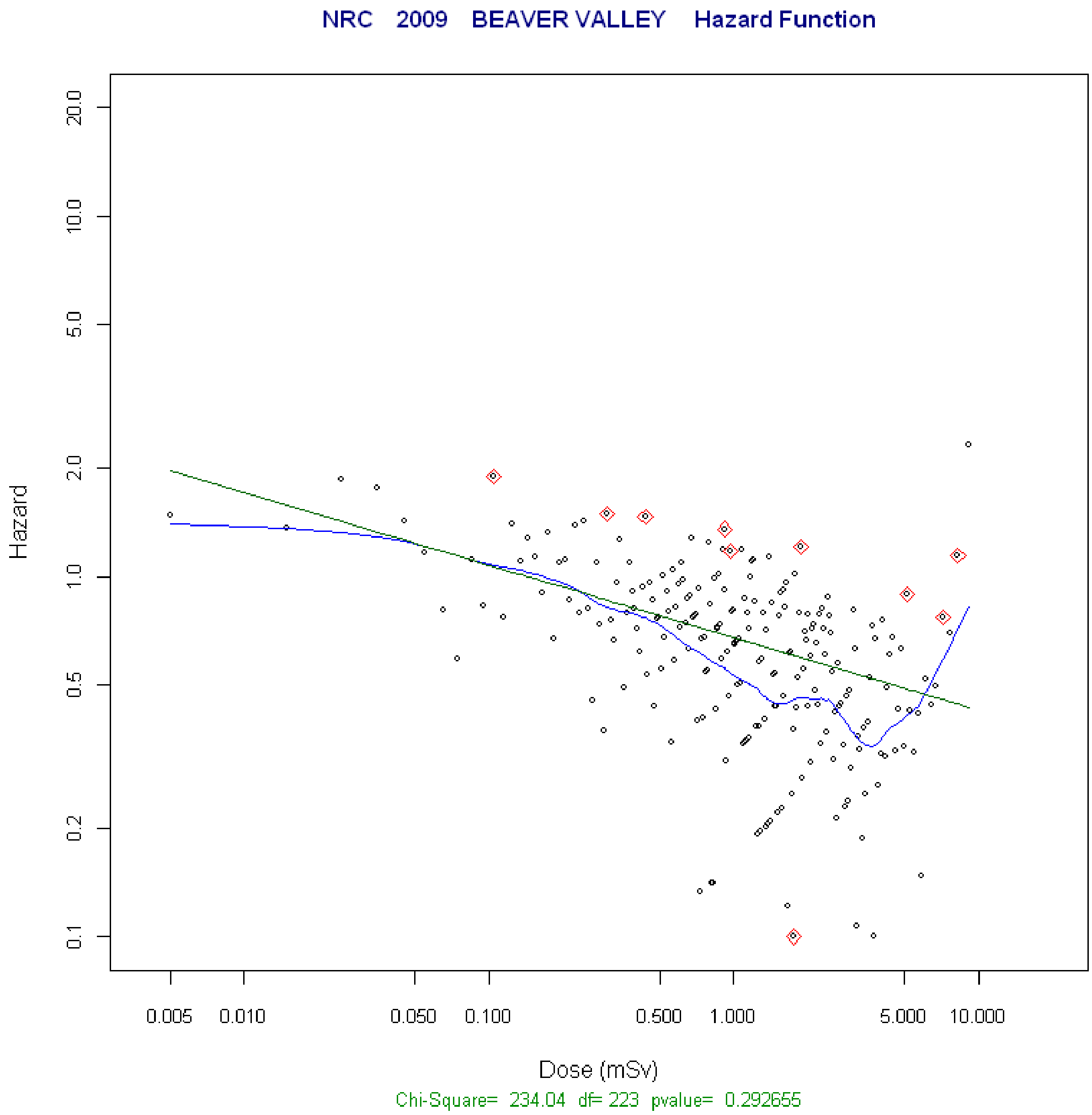

Figure C3: Weibull Goodness of Fit Plot for Beaver Valley.

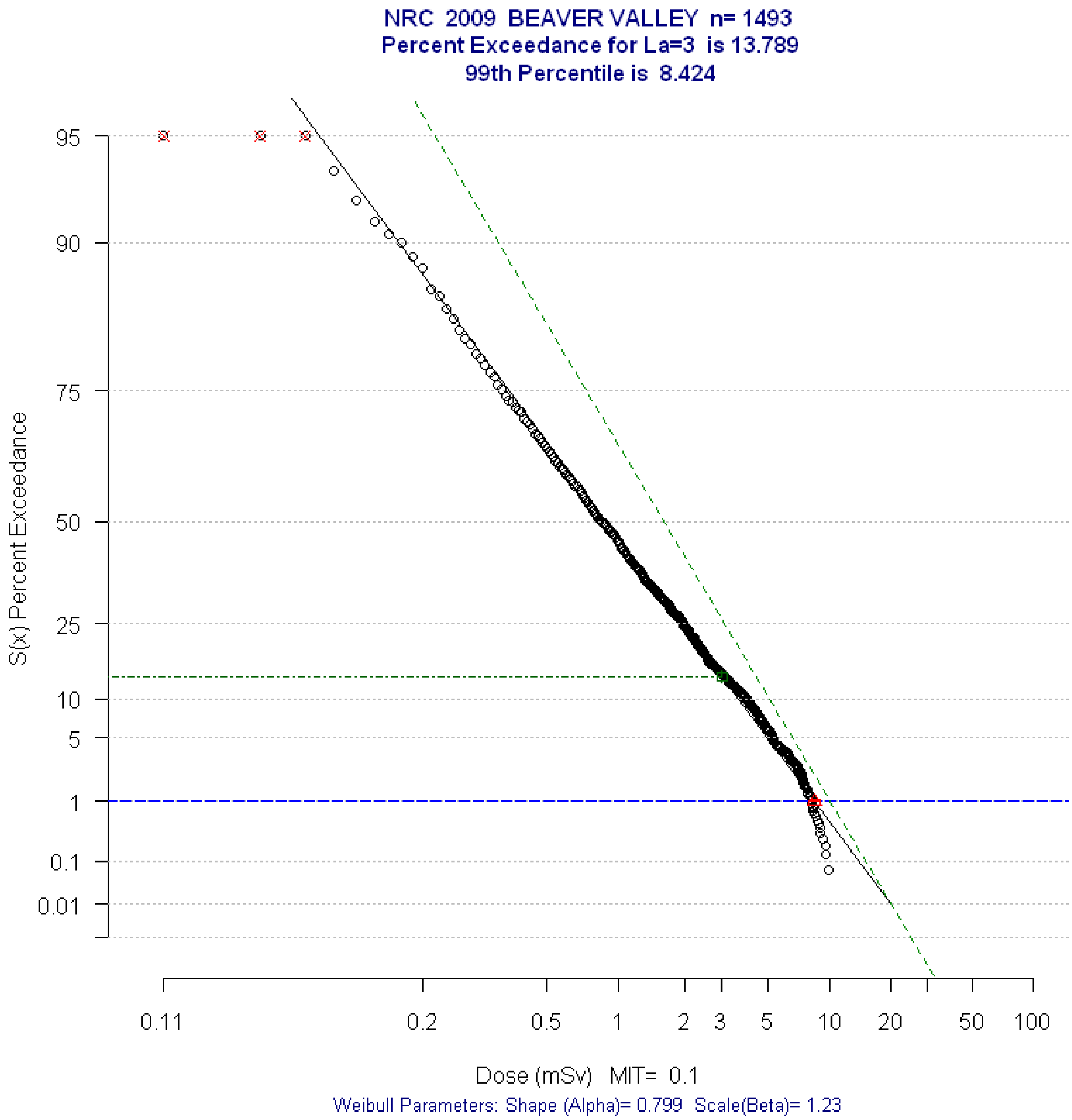

Figure C4: Weibull Probability Plot for Beaver Valley.

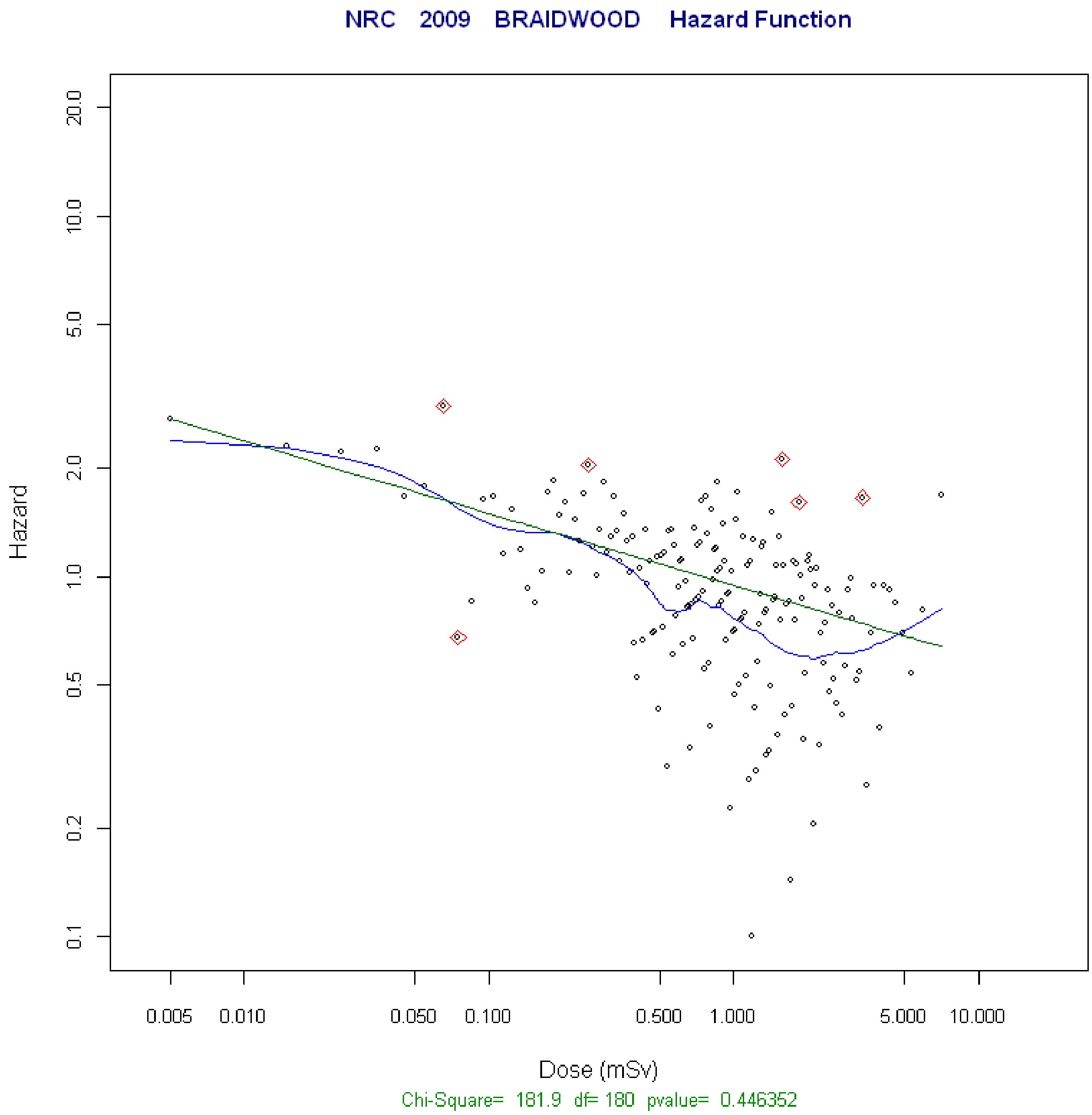

Figure C5: Weibull Goodness of Fit Plot for Braidwood.

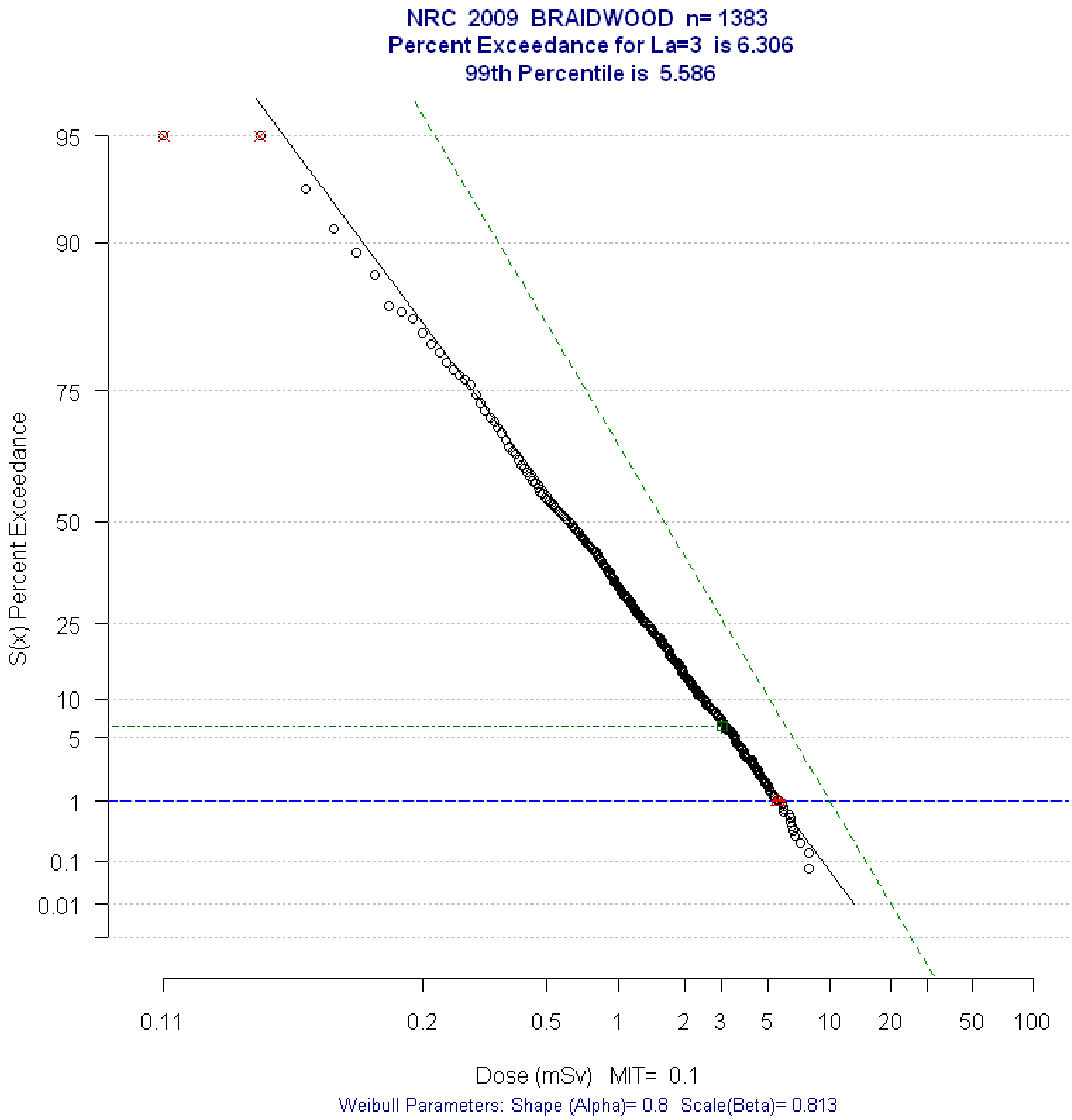

Figure C6: Weibull Probability Plot for Braidwood.

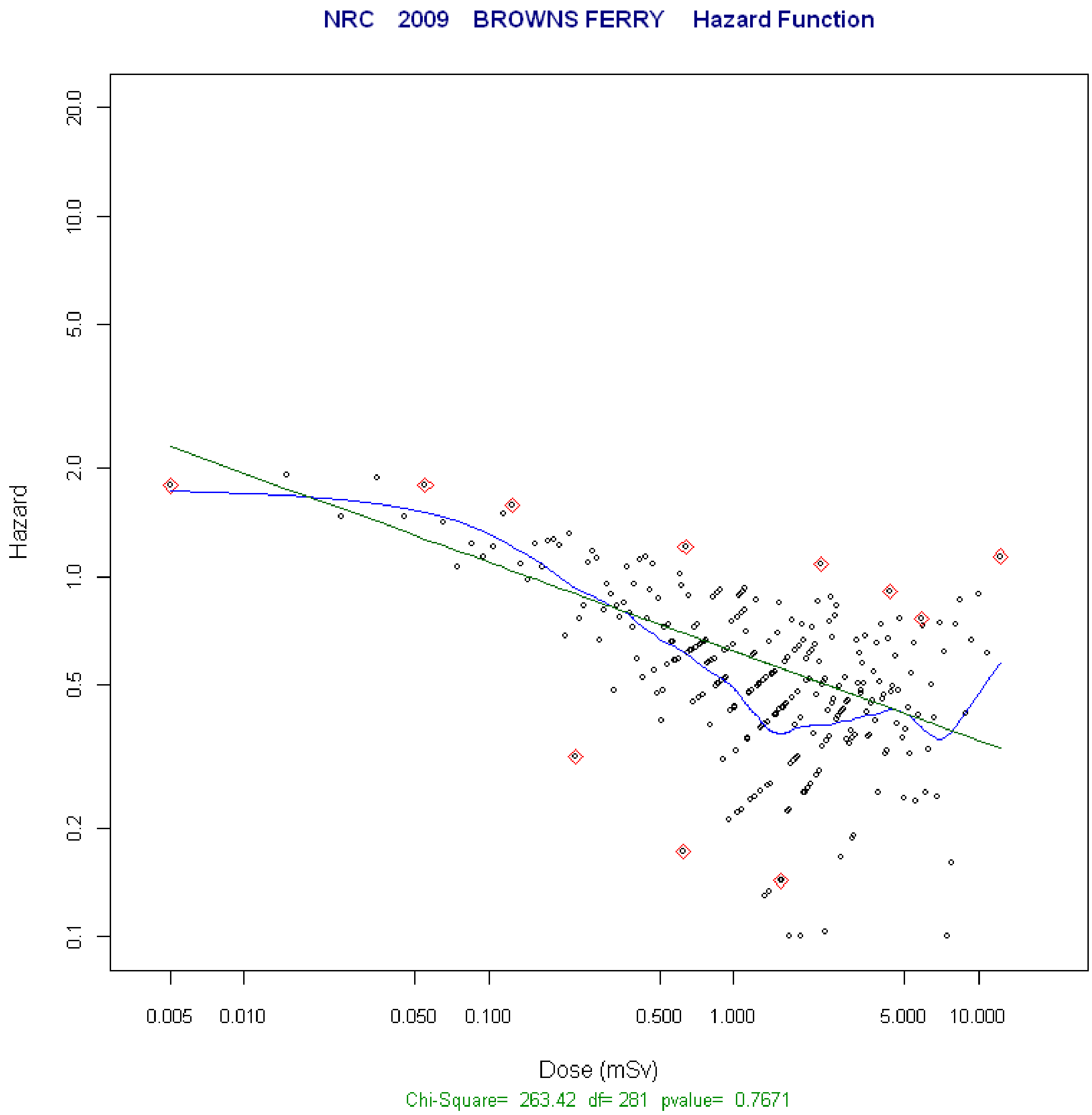

Figure C7: Weibull Goodness of Fit Plot for Browns Ferry.

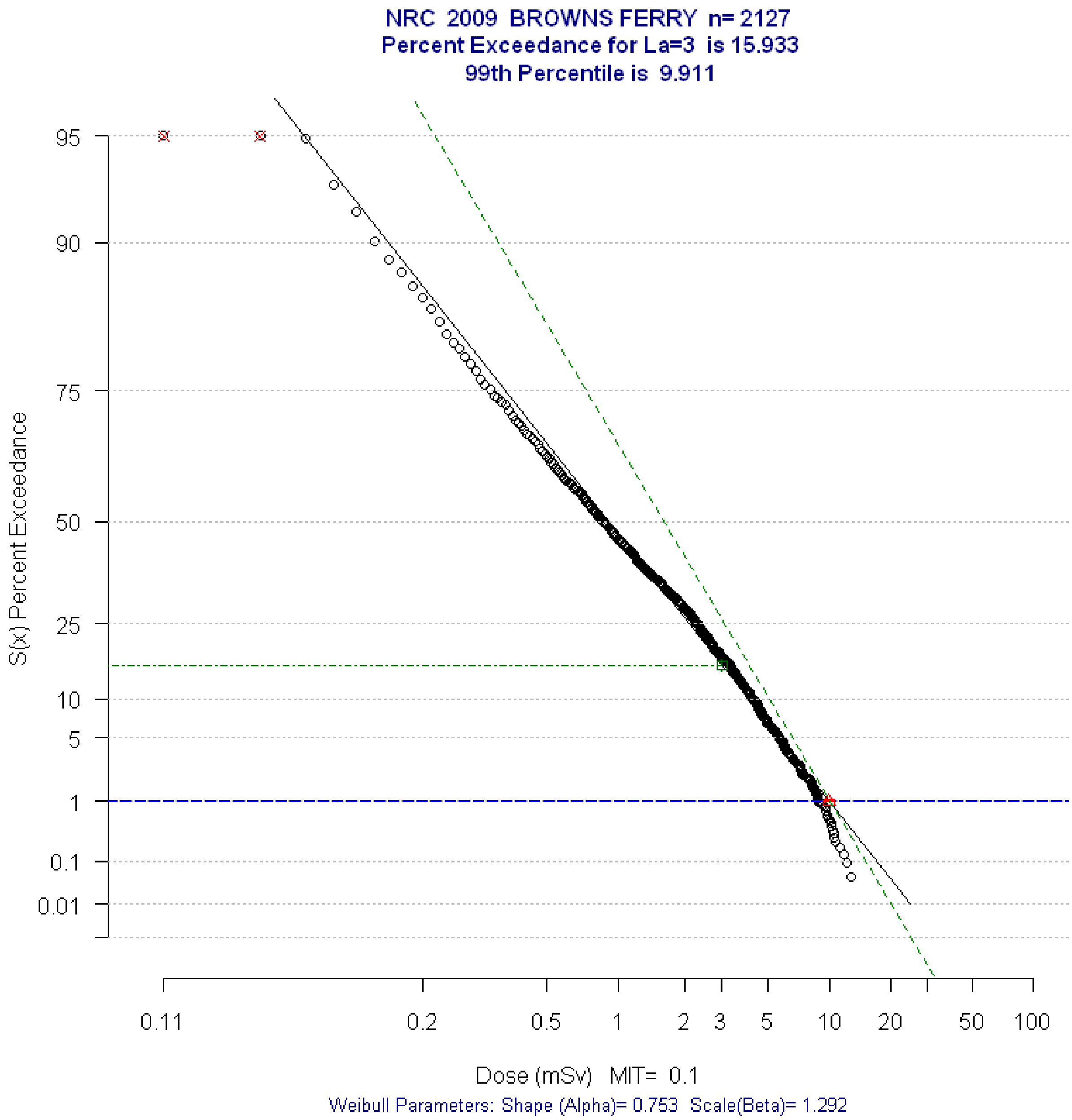

Figure C8: Weibull Probability Plot for Browns Ferry.

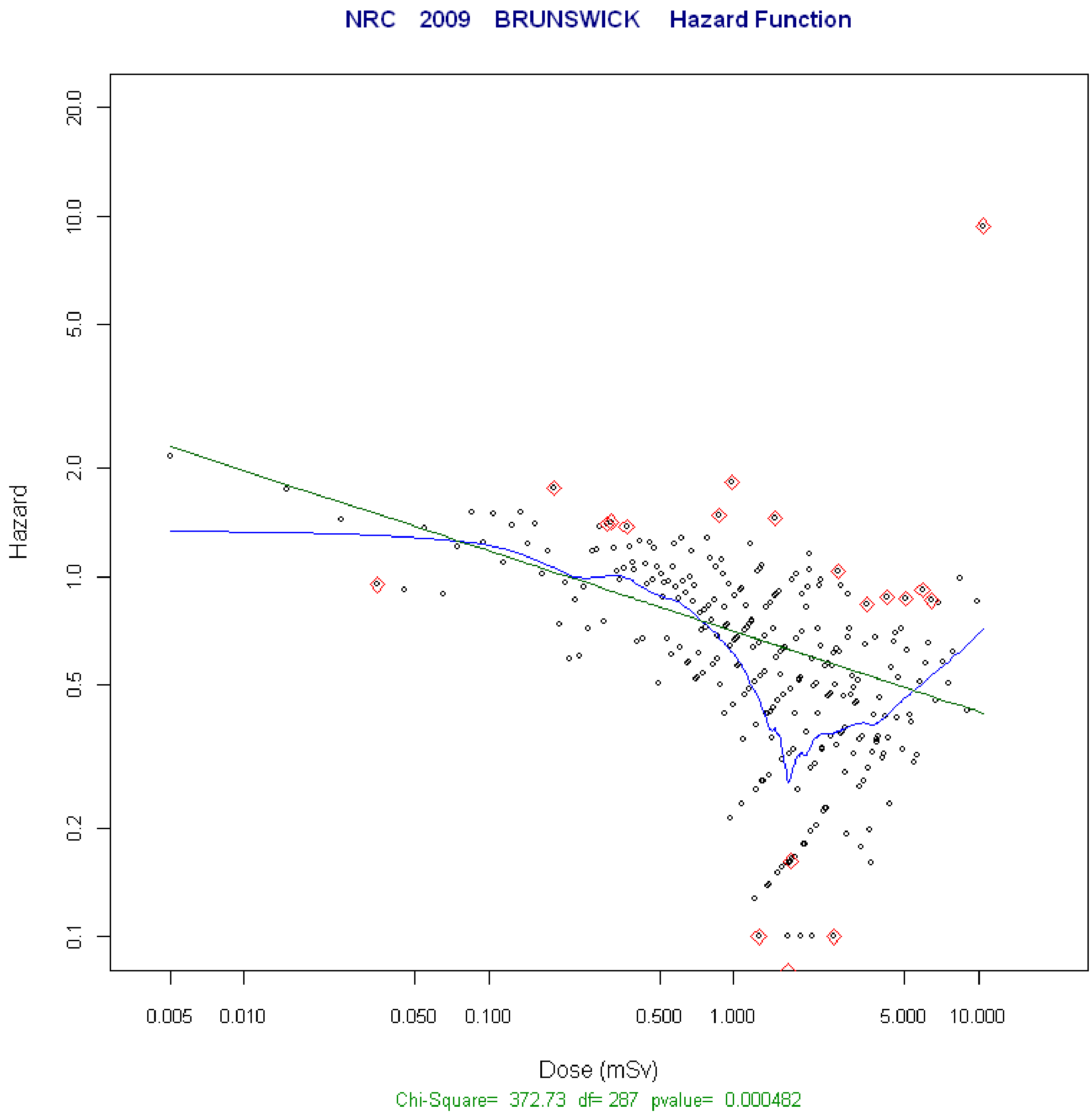

Figure C9: Weibull Goodness of Fit Plot for Brunswick.

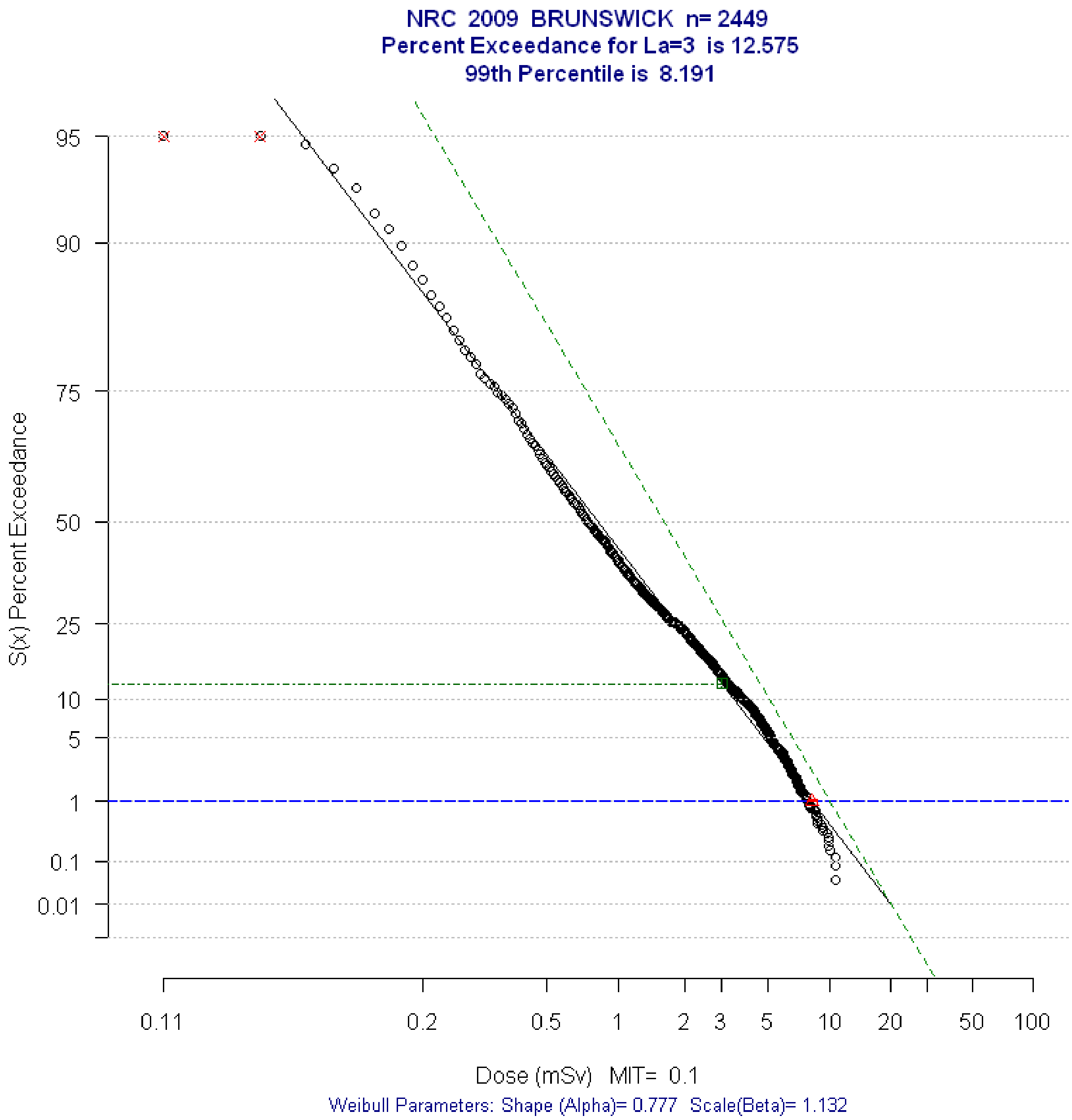

Figure C10: Weibull Probability Plot for Brunswick.

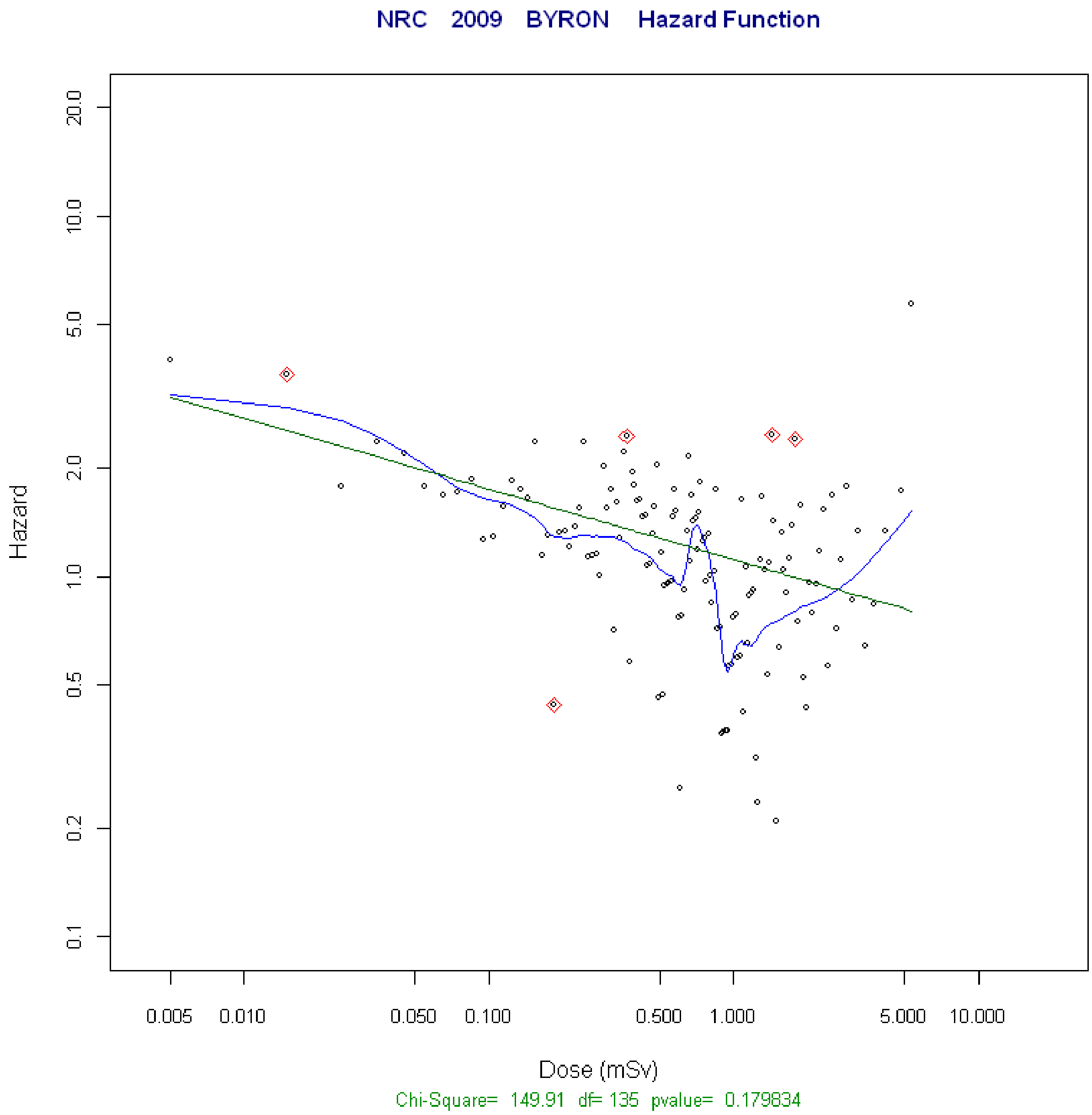

Figure C11: Weibull Goodness of Fit Plot for Byron.

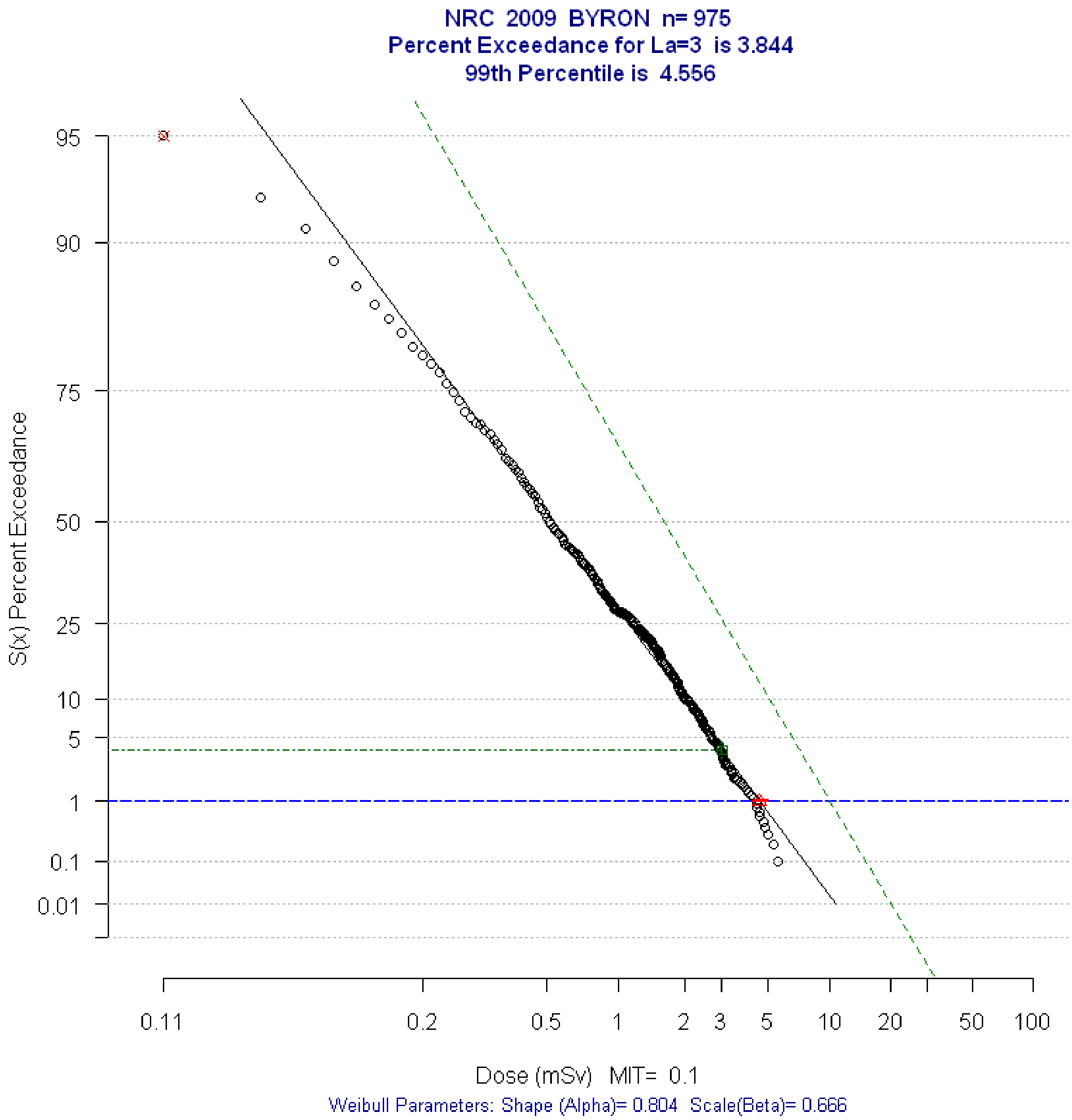

Figure C12: Weibull Probability Plot for Byron.

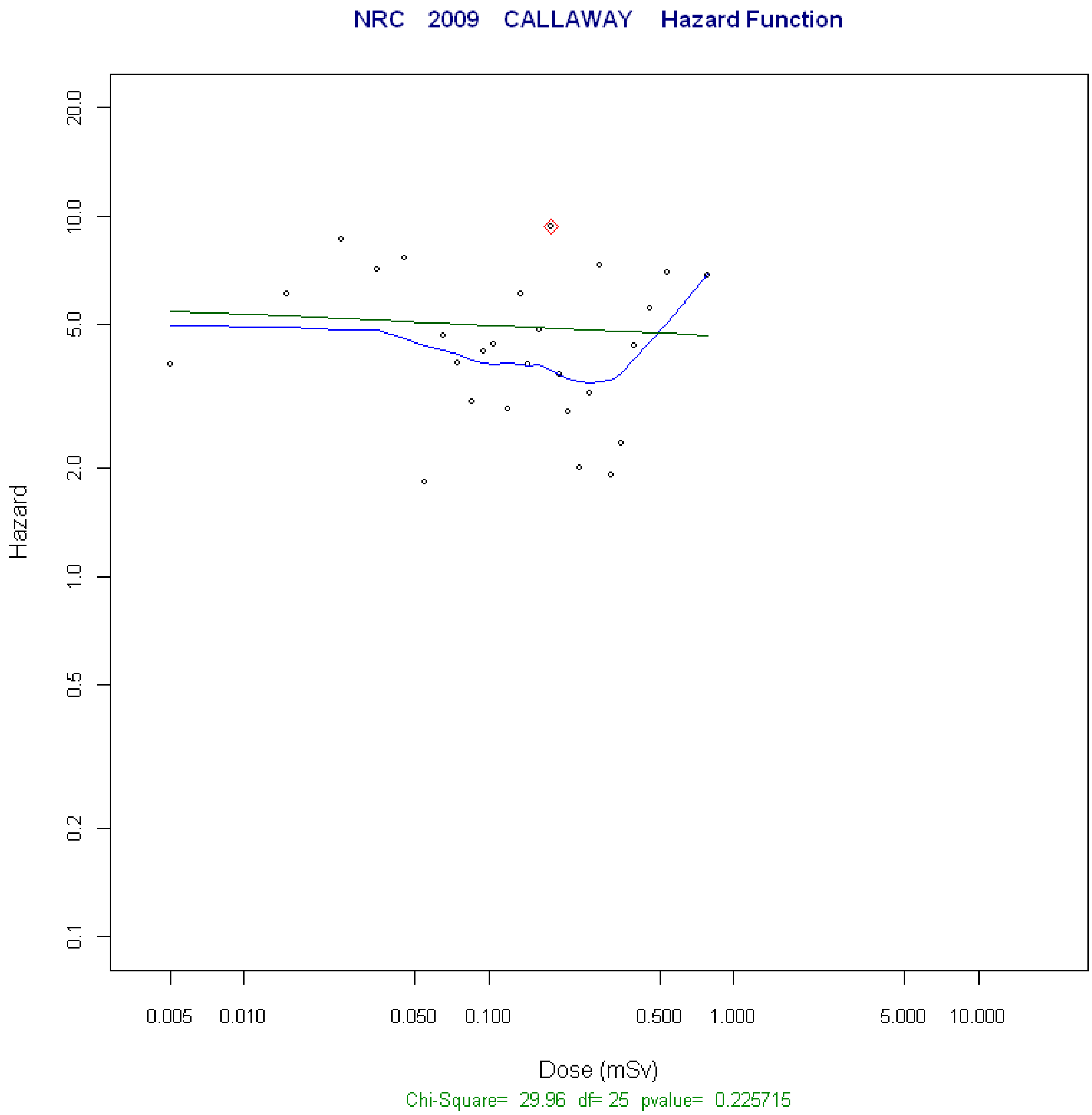

Figure C13: Weibull Goodness of Fit Plot for Callaway.

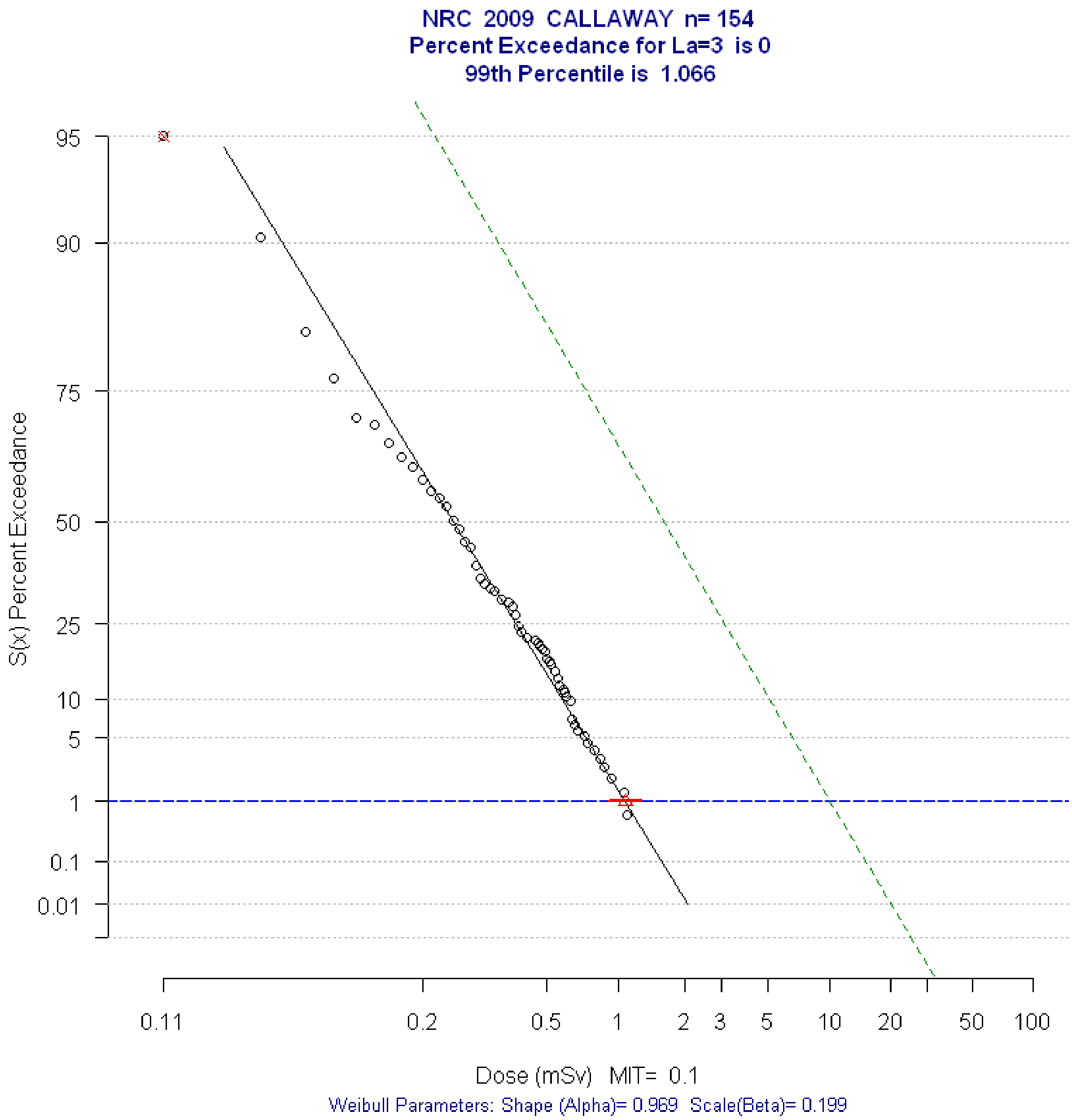

Figure C14: Weibull Probability Plot for Callaway.

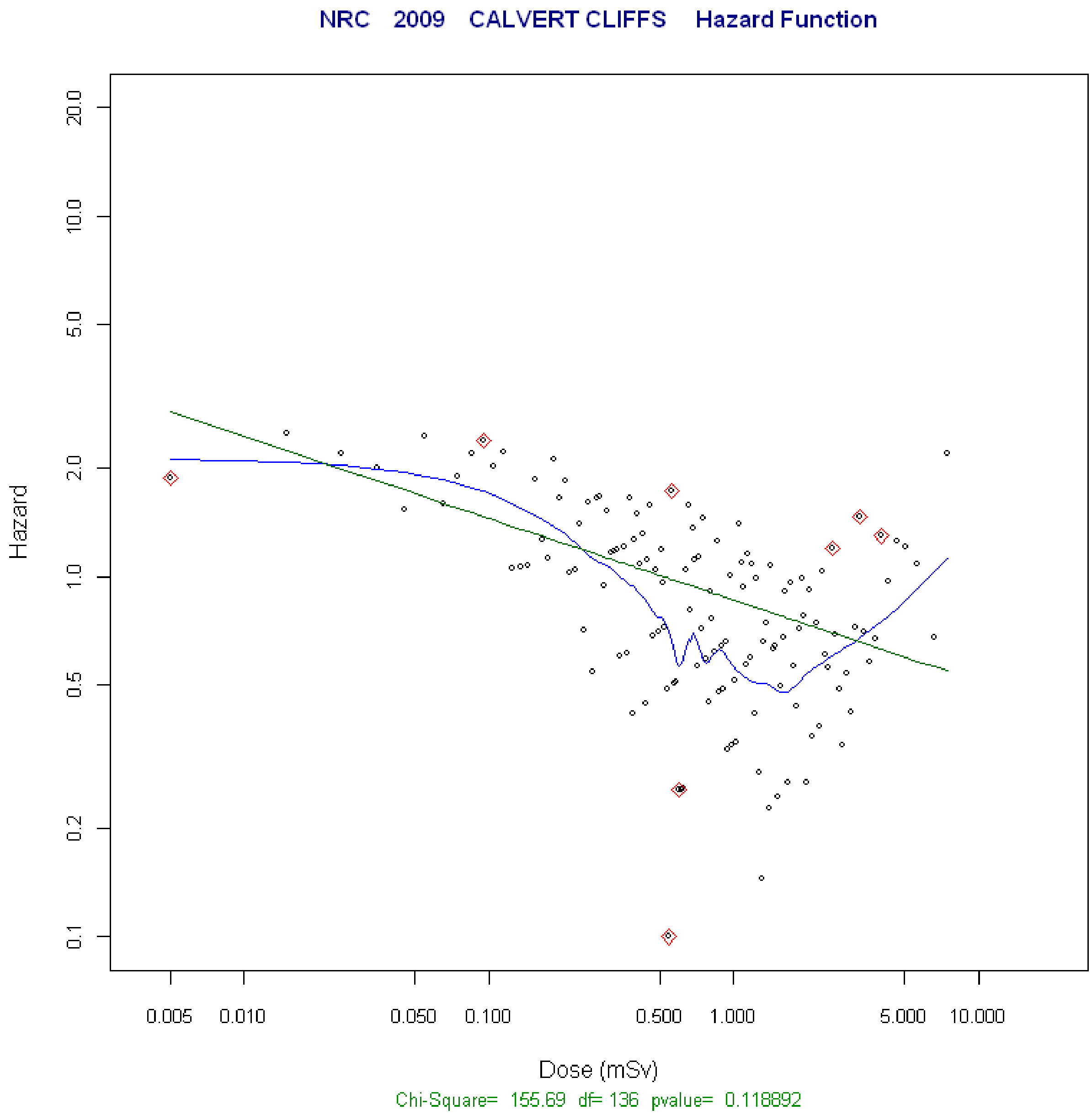

Figure C15: Weibull Goodness of Fit Plot for Calvert Cliffs.

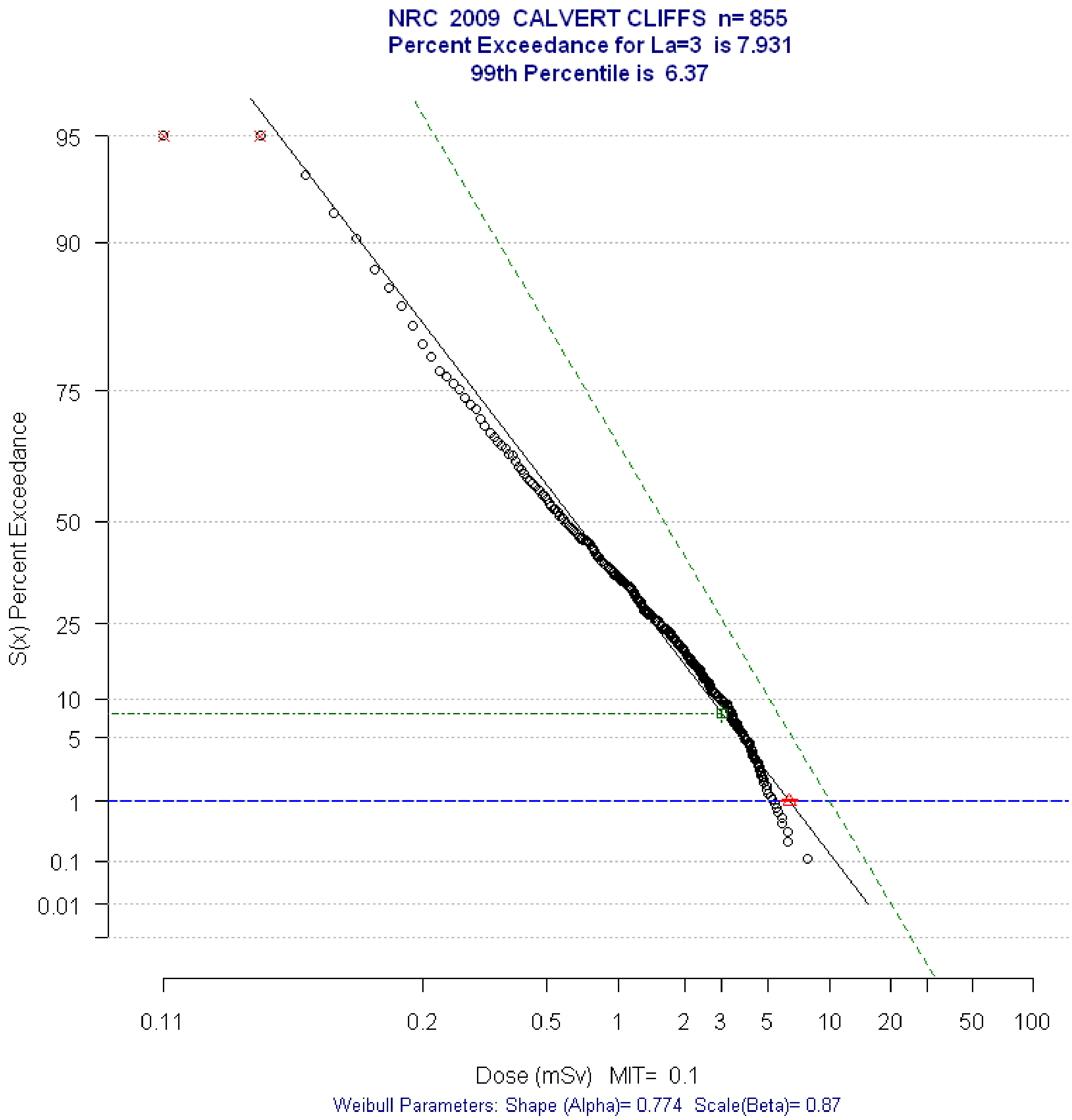

Figure C16: Weibull Probability Plot for Calvert Cliffs.

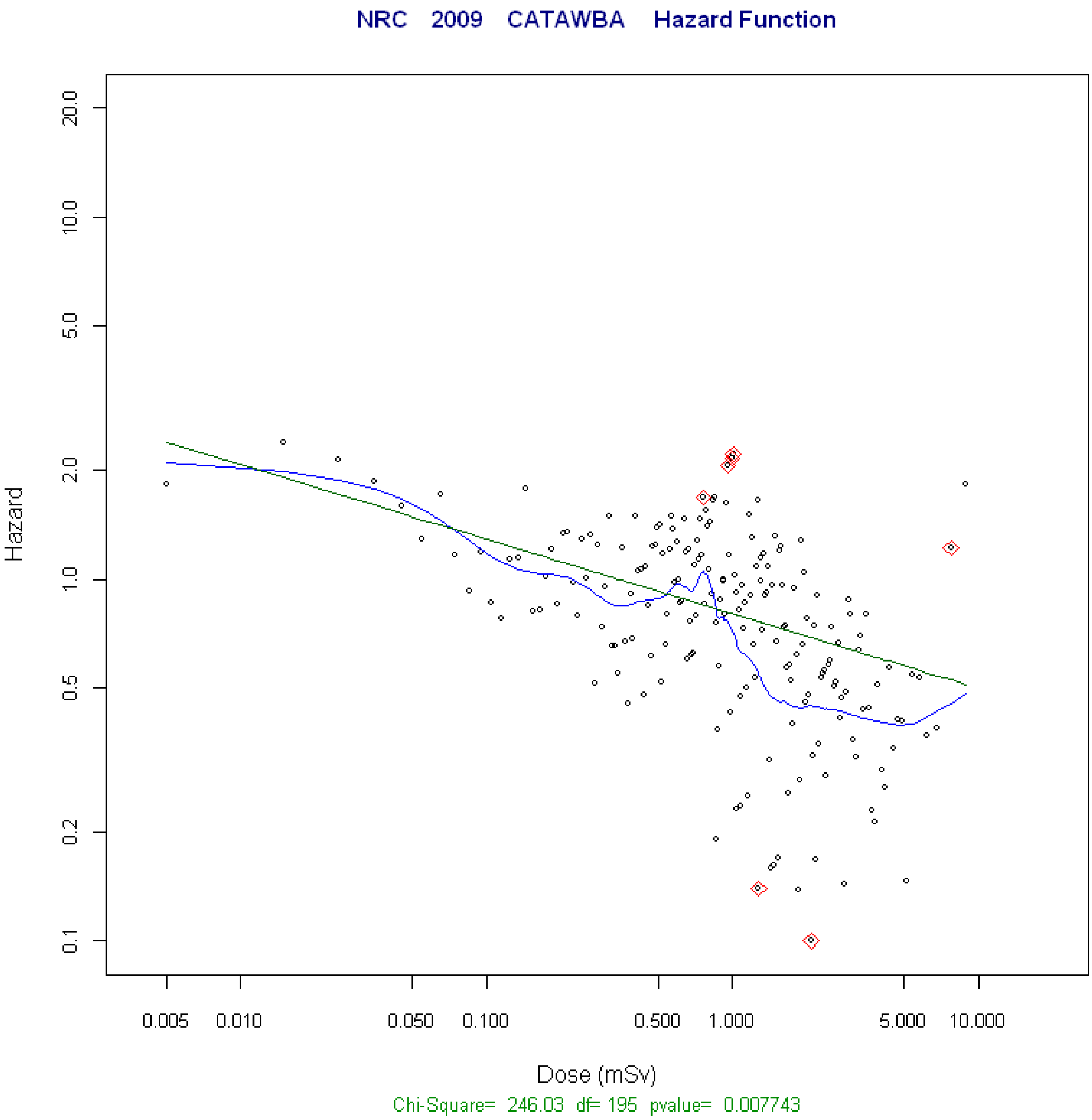

Figure C17: Weibull Goodness of Fit Plot for Catawba.

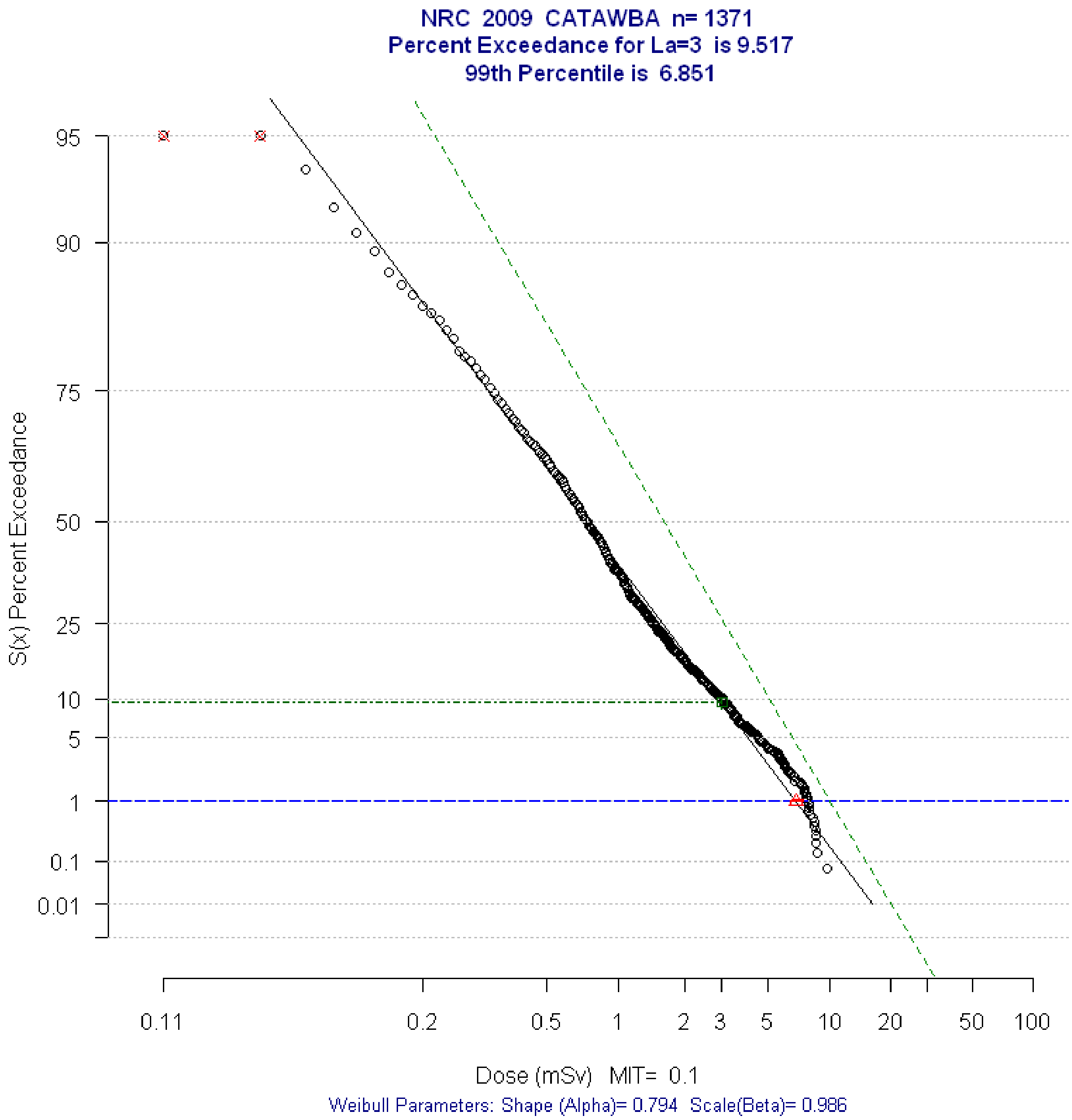

Figure C18: Weibull Probability Plot for Catawba.

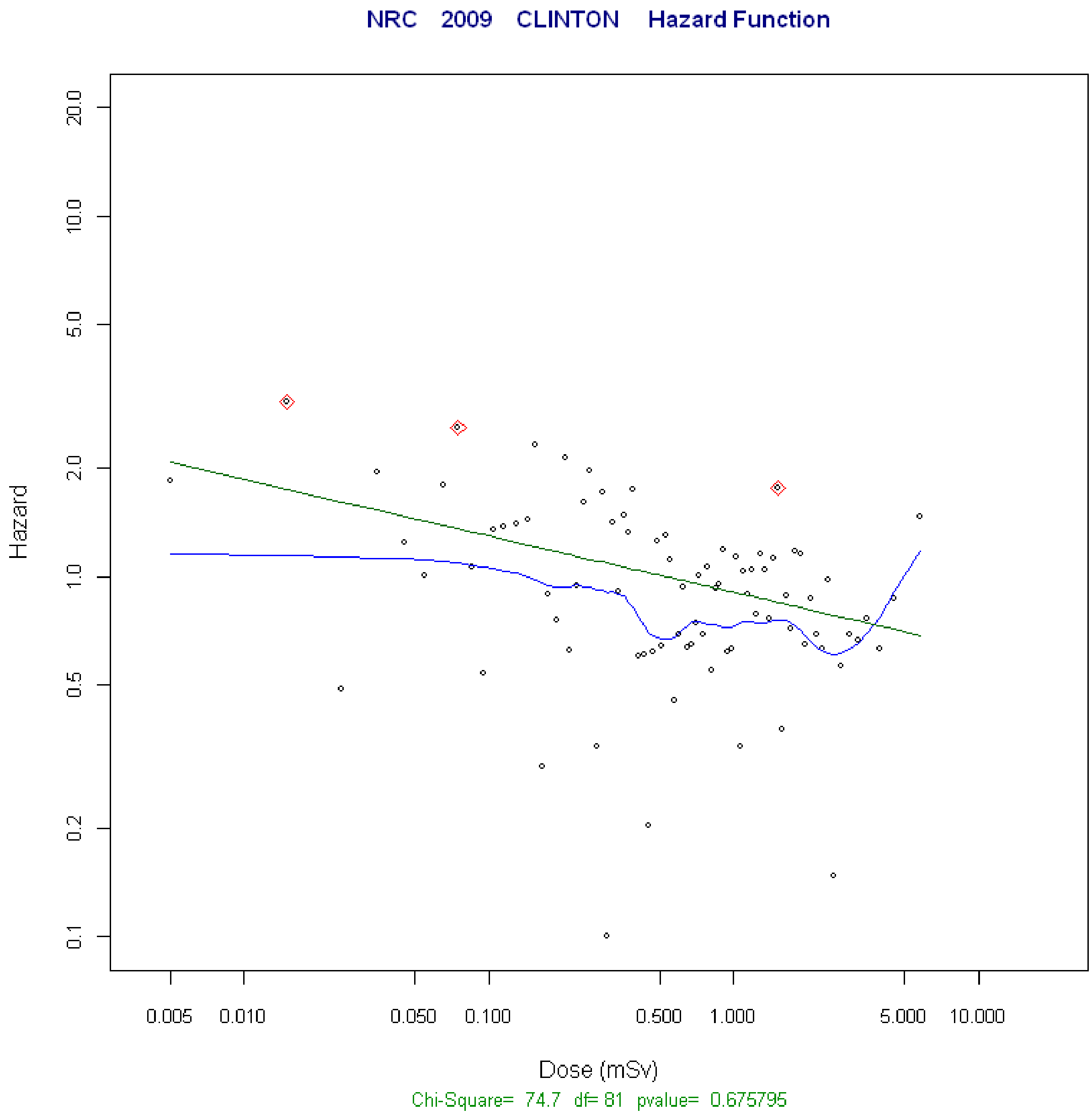

Figure C19: Weibull Goodness of Fit Plot for Clinton

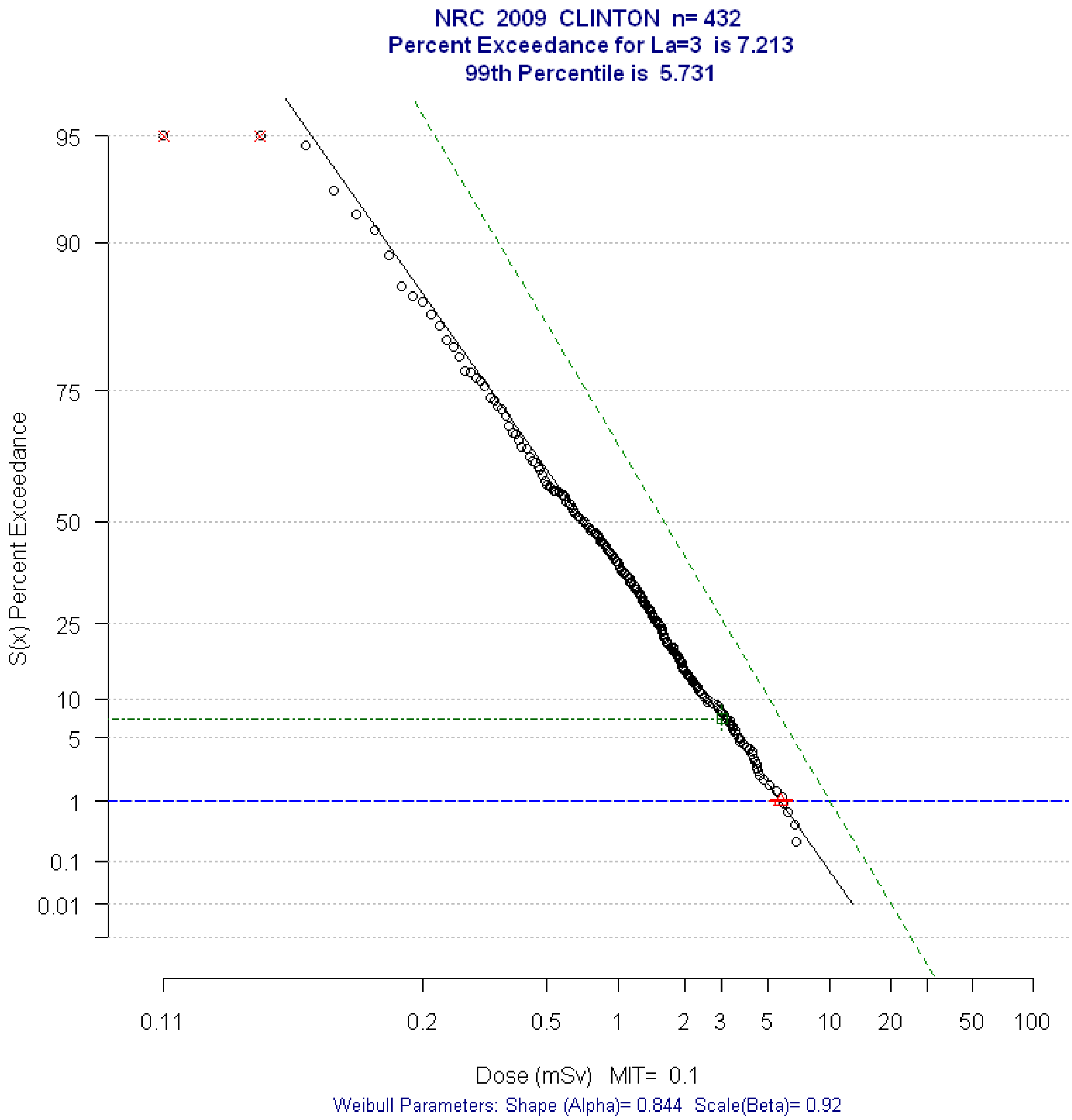

Figure C20: Weibull Probability Plot for Clinton.

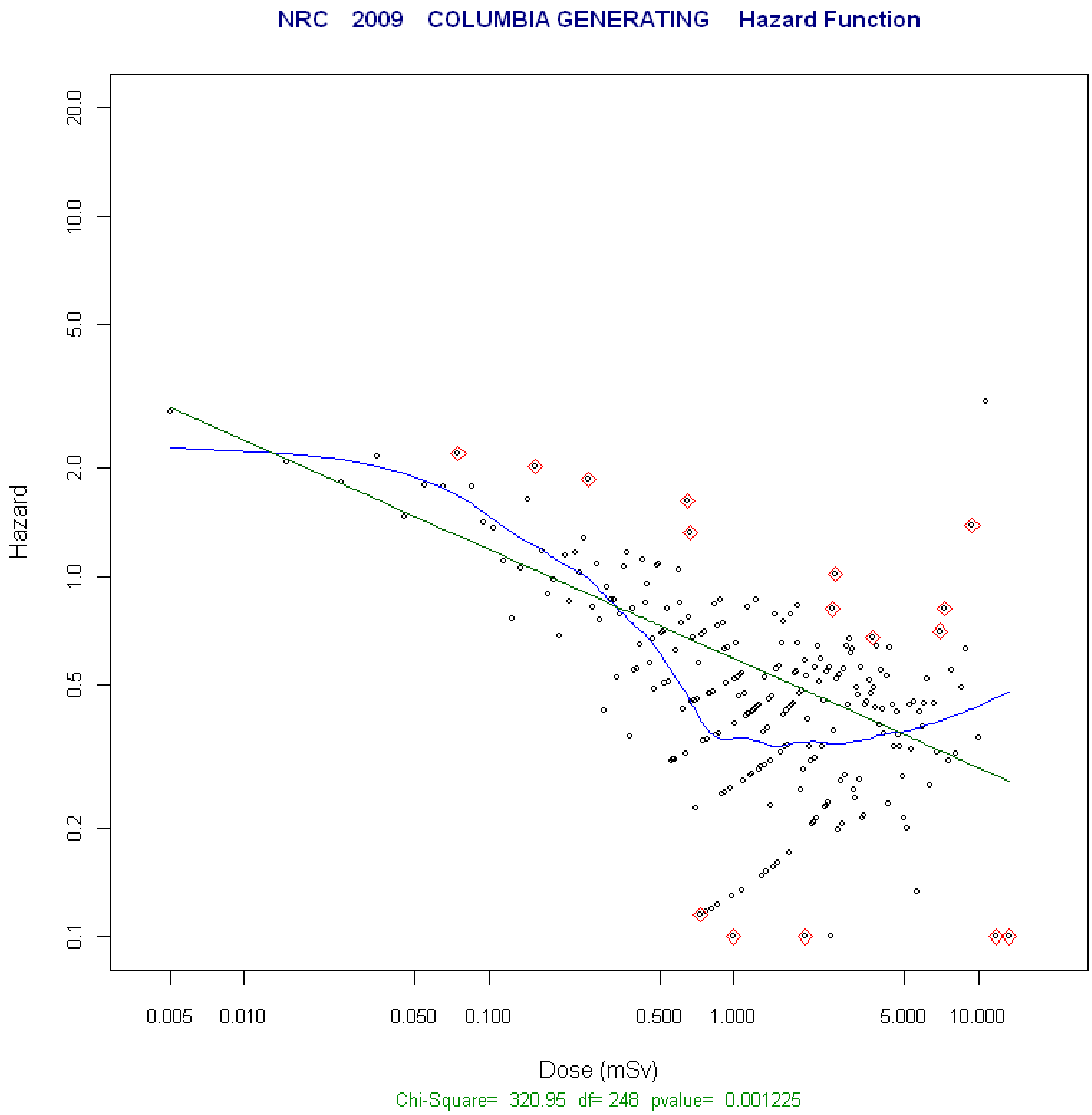

Figure C21: Weibull Goodness of Fit Plot for Columbia Generating.

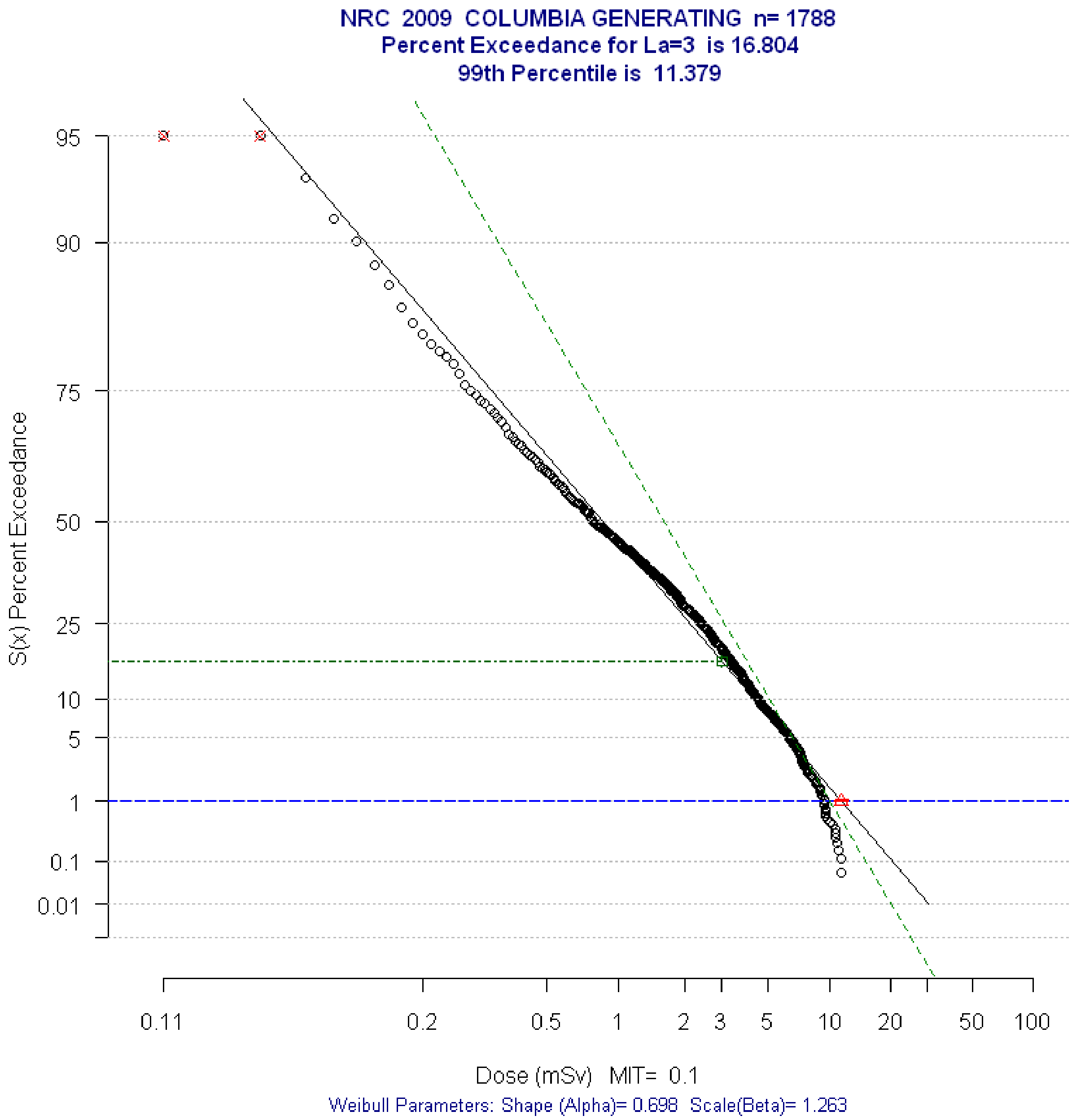

Figure C22: Weibull Probability Plot for Columbia Generating.

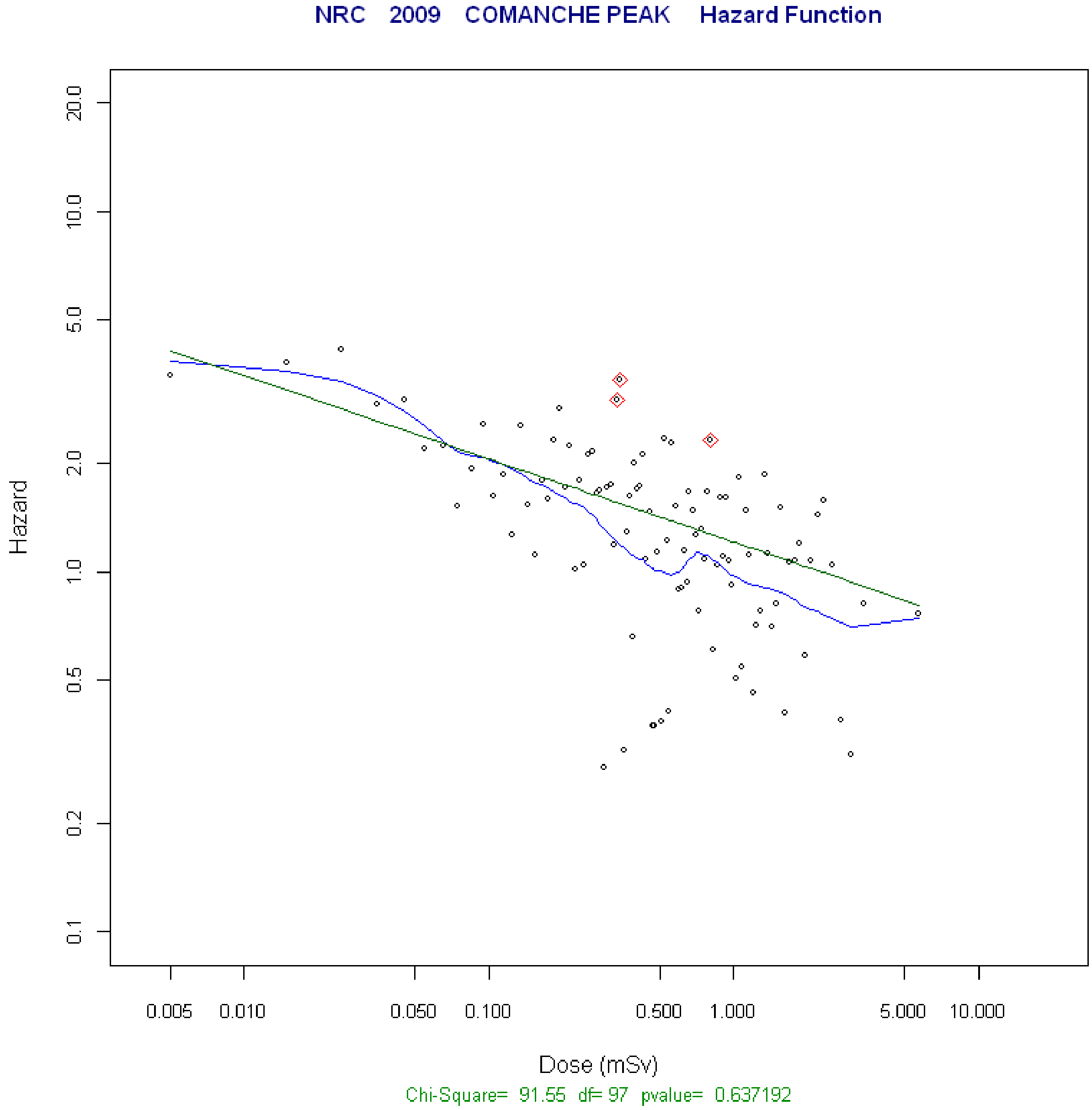

Figure C23: Weibull Goodness of Fit Plot for Comanche Peak.

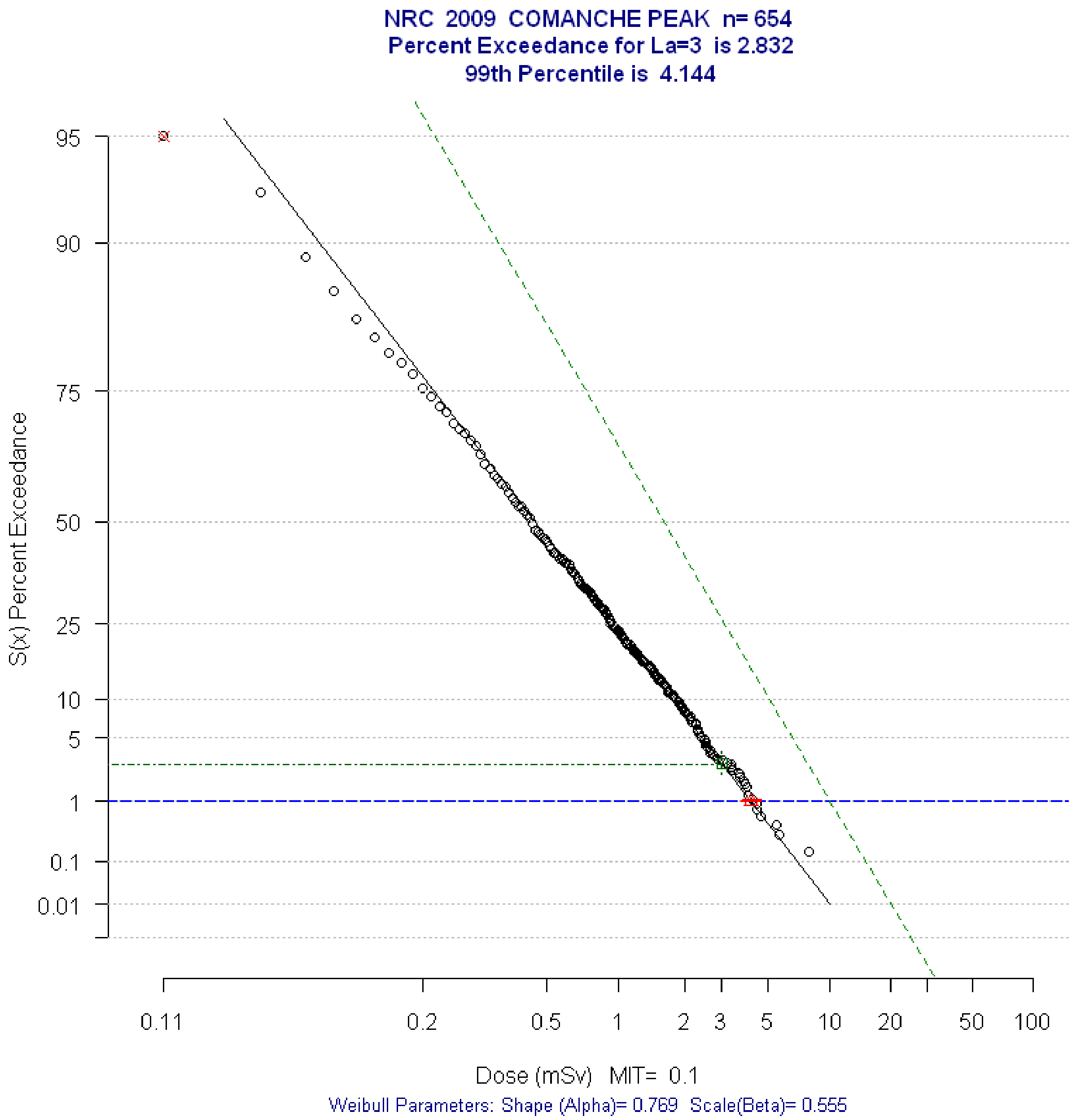

Figure C24: Weibull Probability Plot for Comanche Peak.

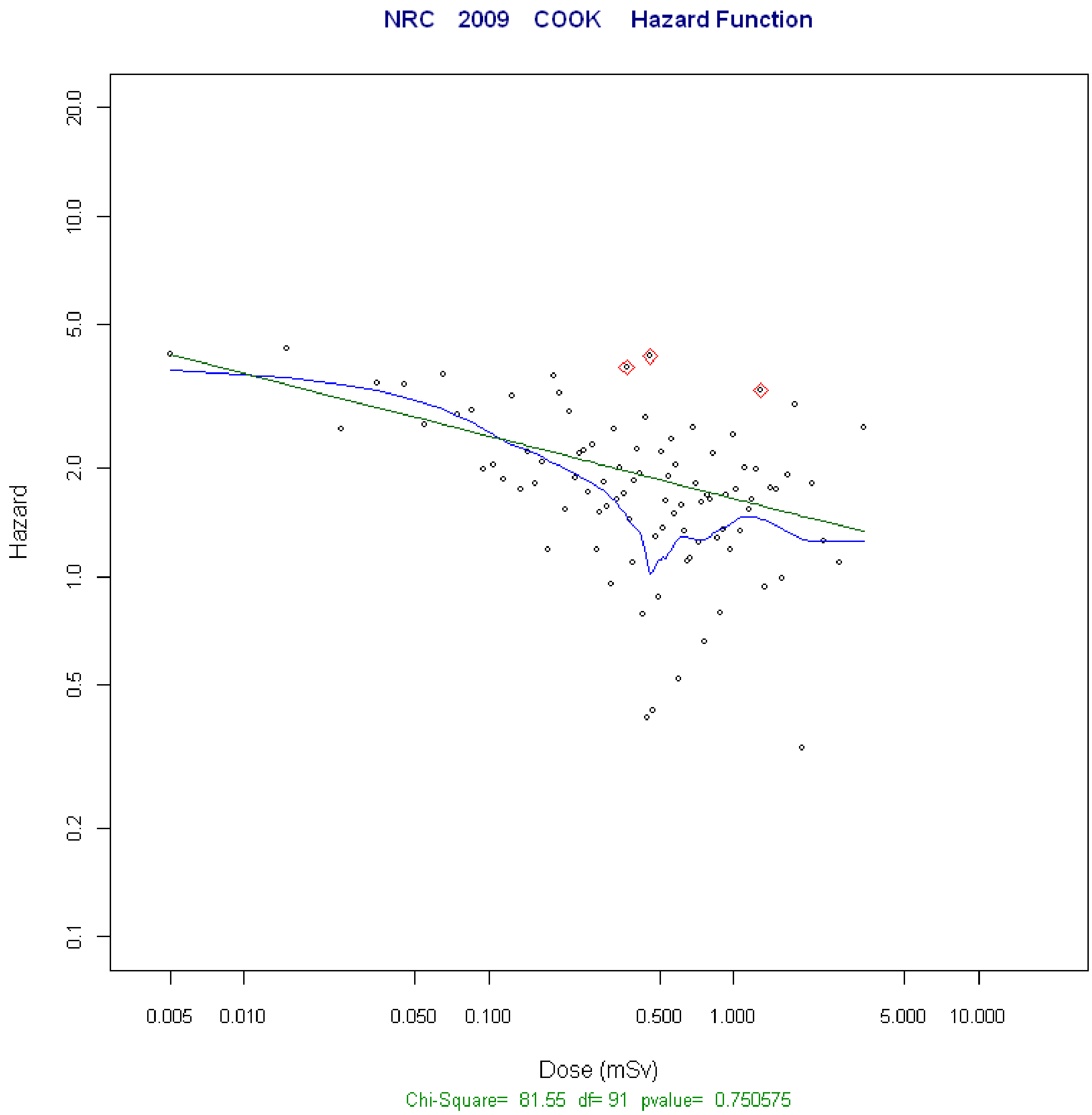

Figure C25: Weibull Goodness of Fit Plot for Cook.

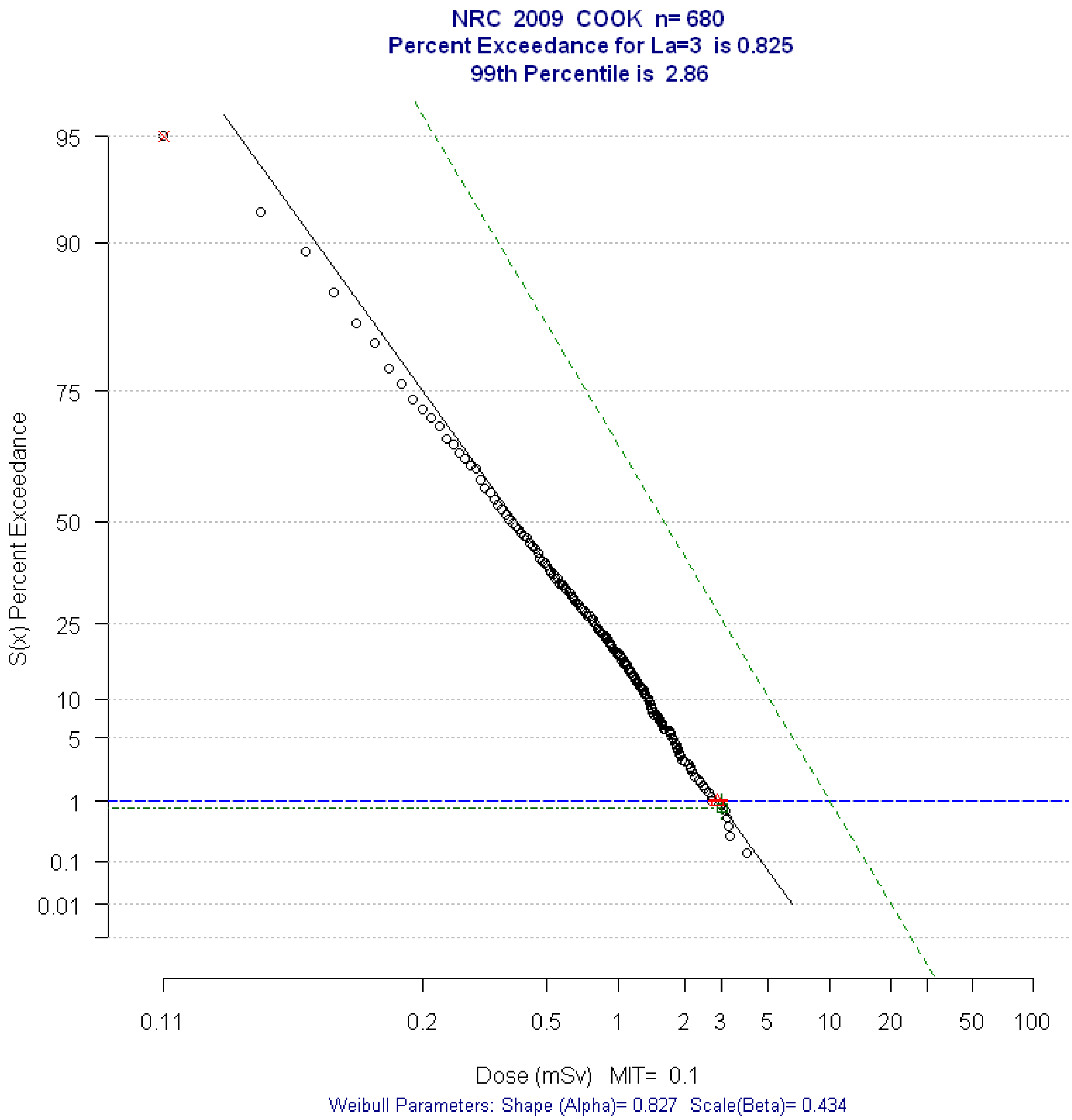

Figure C26: Weibull Probability Plot for Cook.

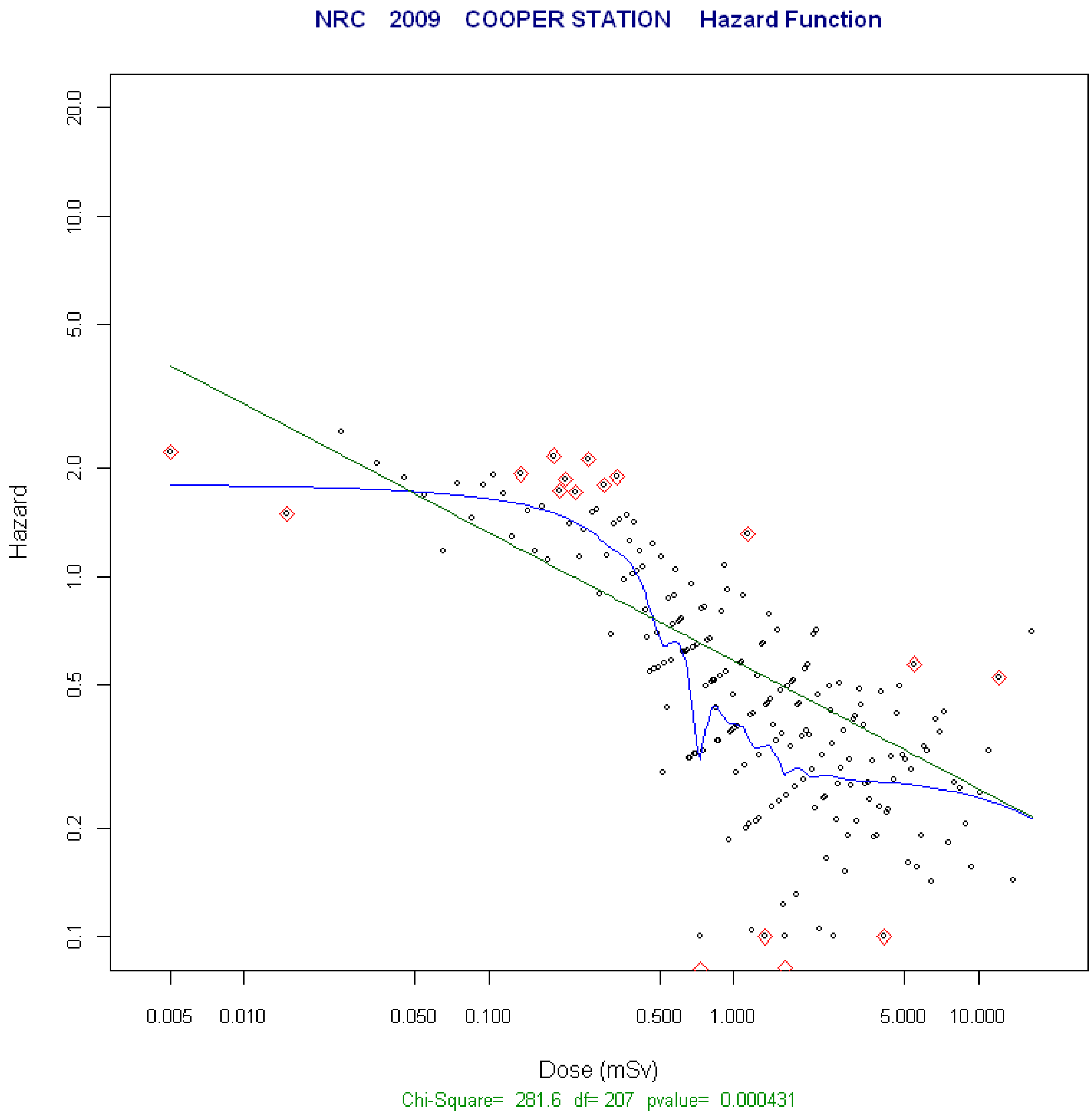

Figure C27: Weibull Goodness of Fit Plot for Cooper Station.

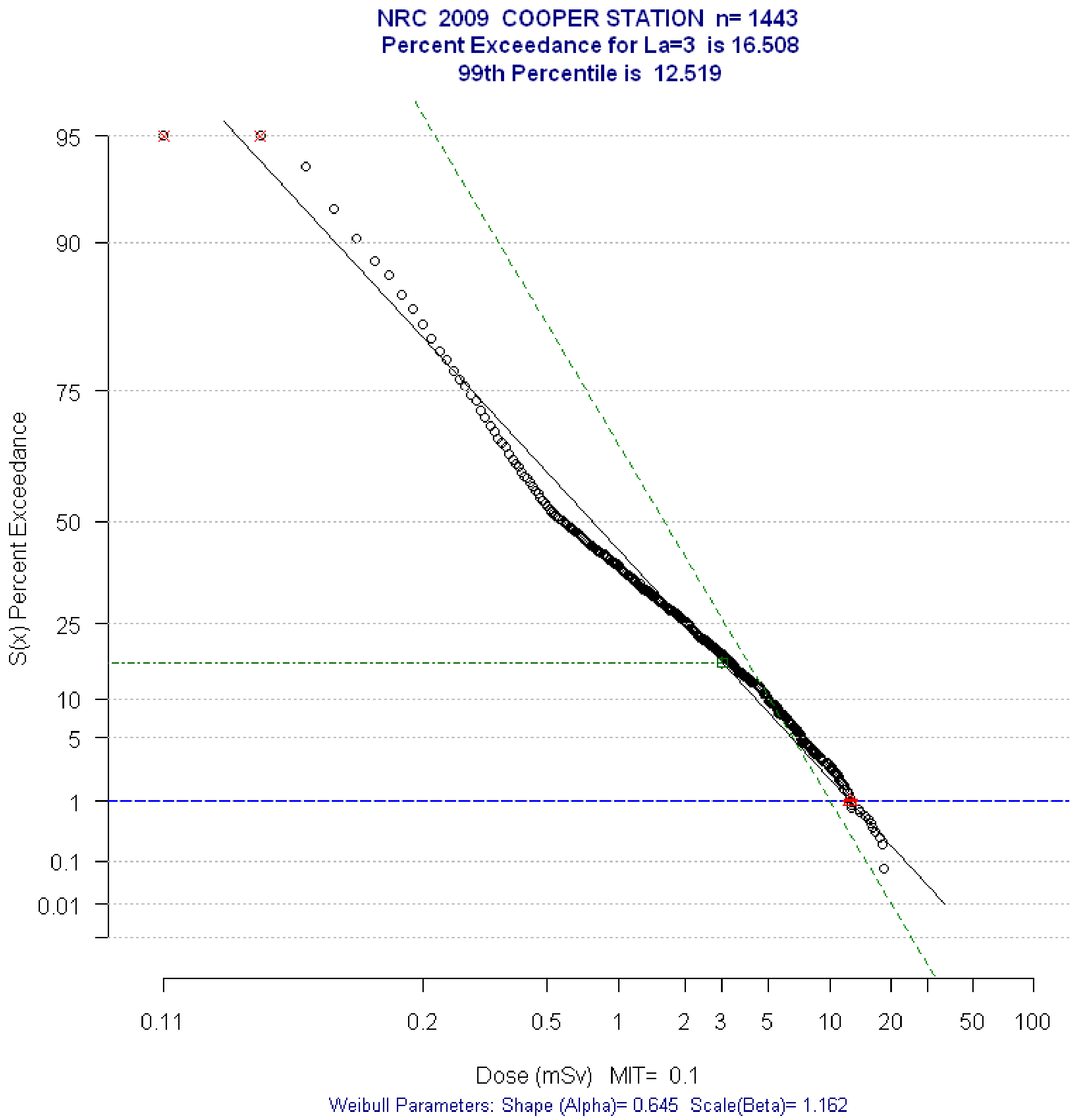

Figure C28: Weibull Probability Plot for Cooper Station.

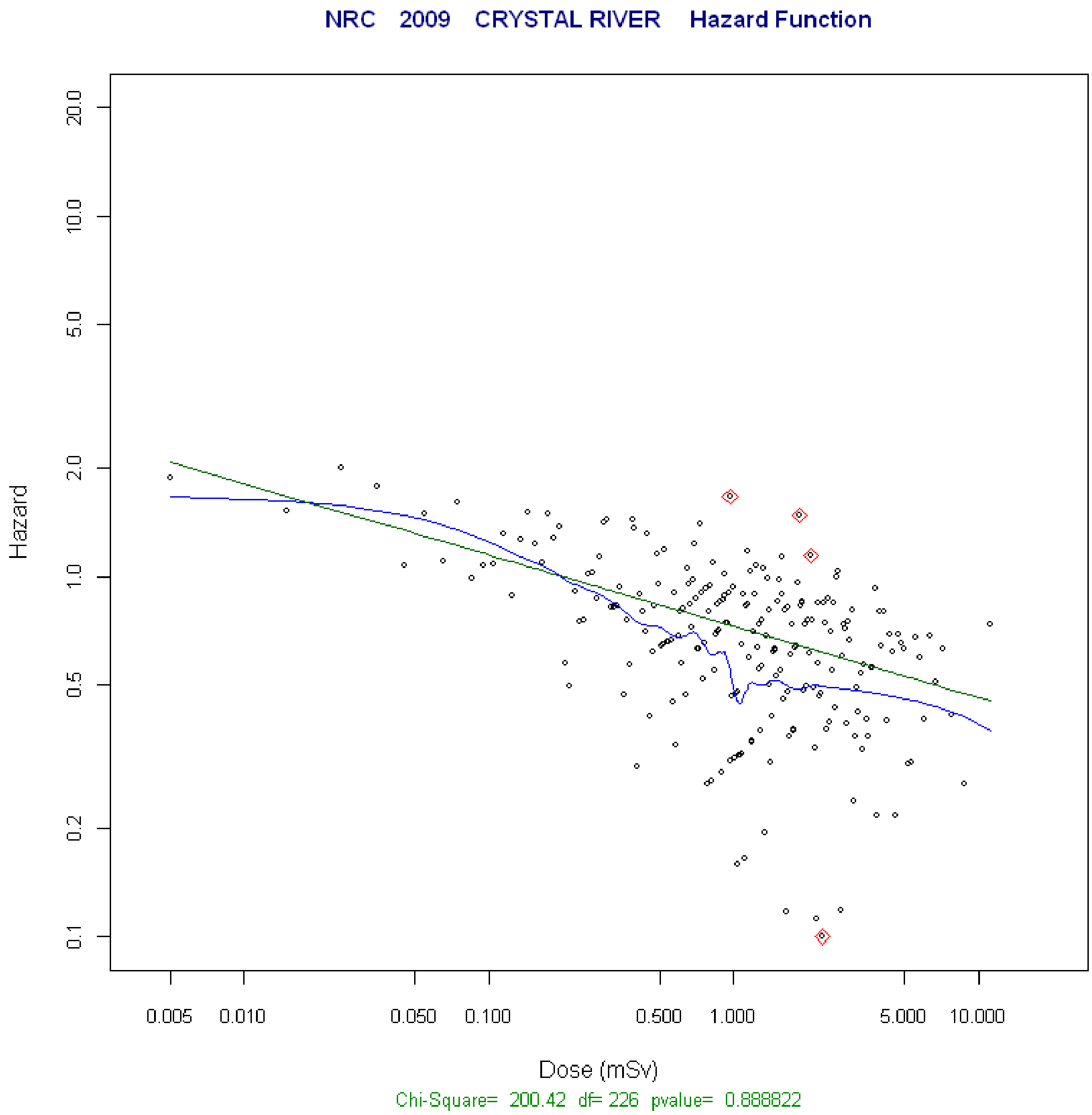

Figure C29: Weibull Goodness of Fit Plot for Crystal River.

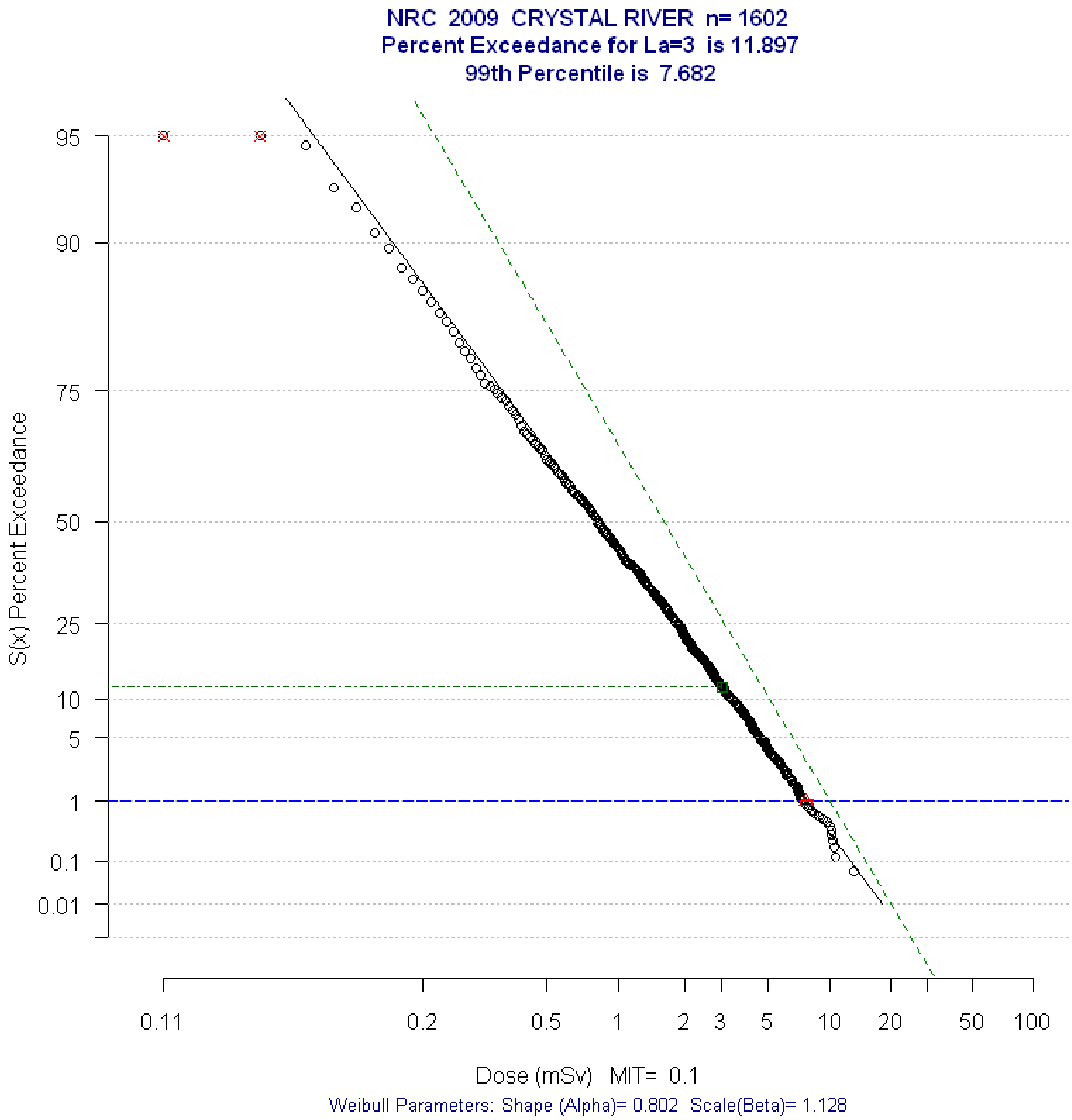

Figure C30: Weibull Probability Plot for Crystal River.

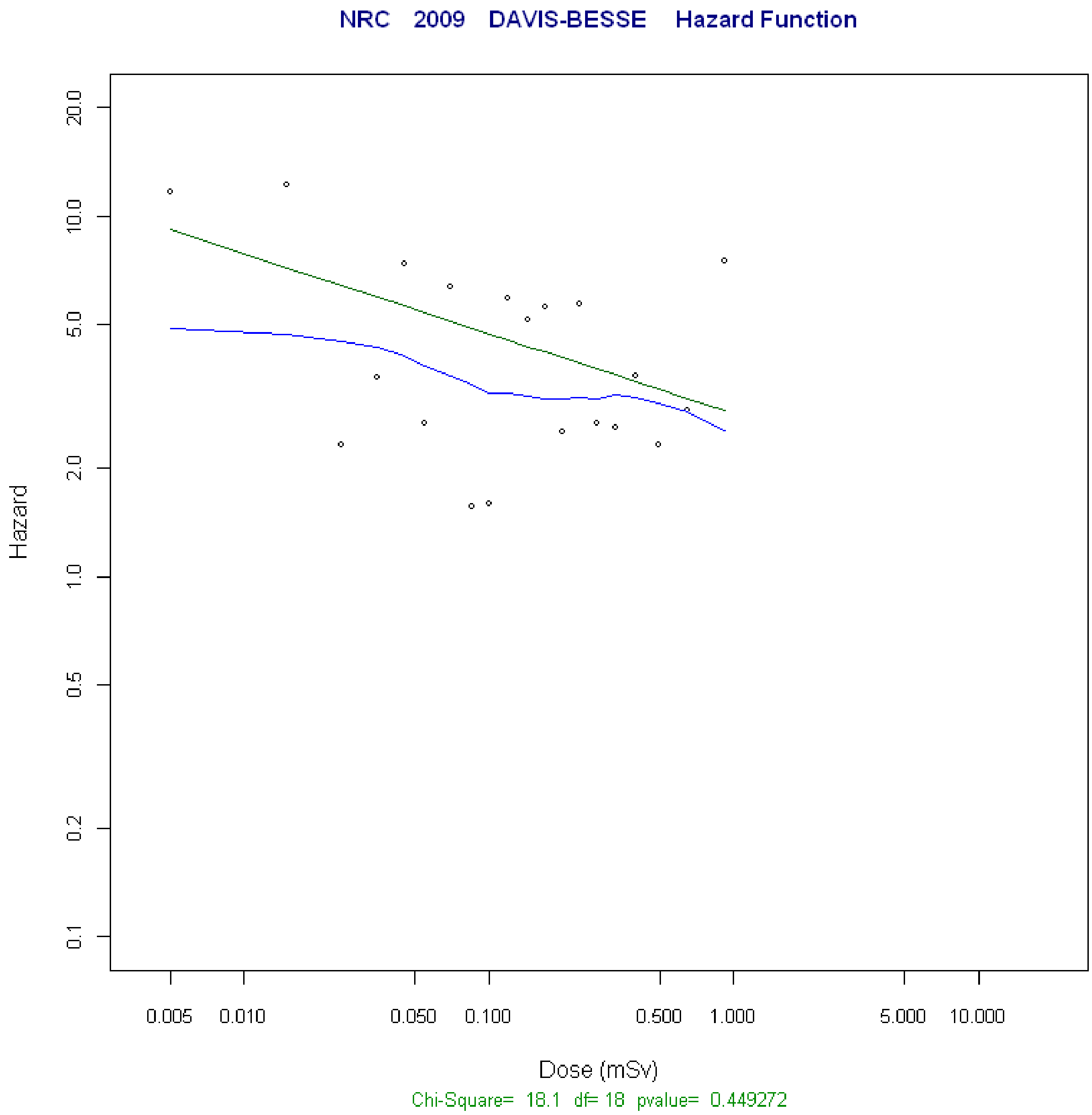

Figure C31: Weibull Goodness of Fit Plot for Davis-Besse.

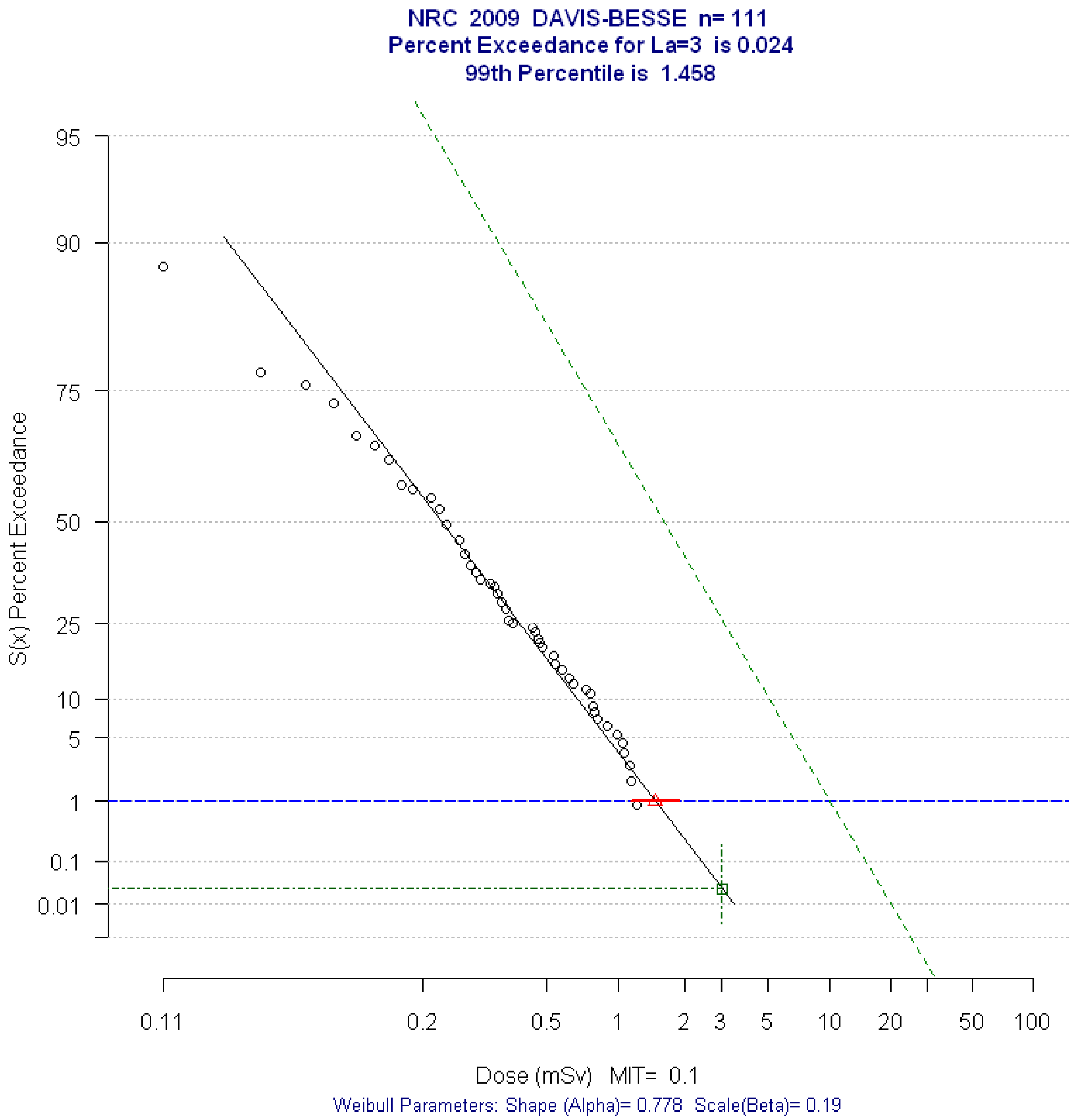

Figure C32: Weibull Probability Plot for Davis-Besse.

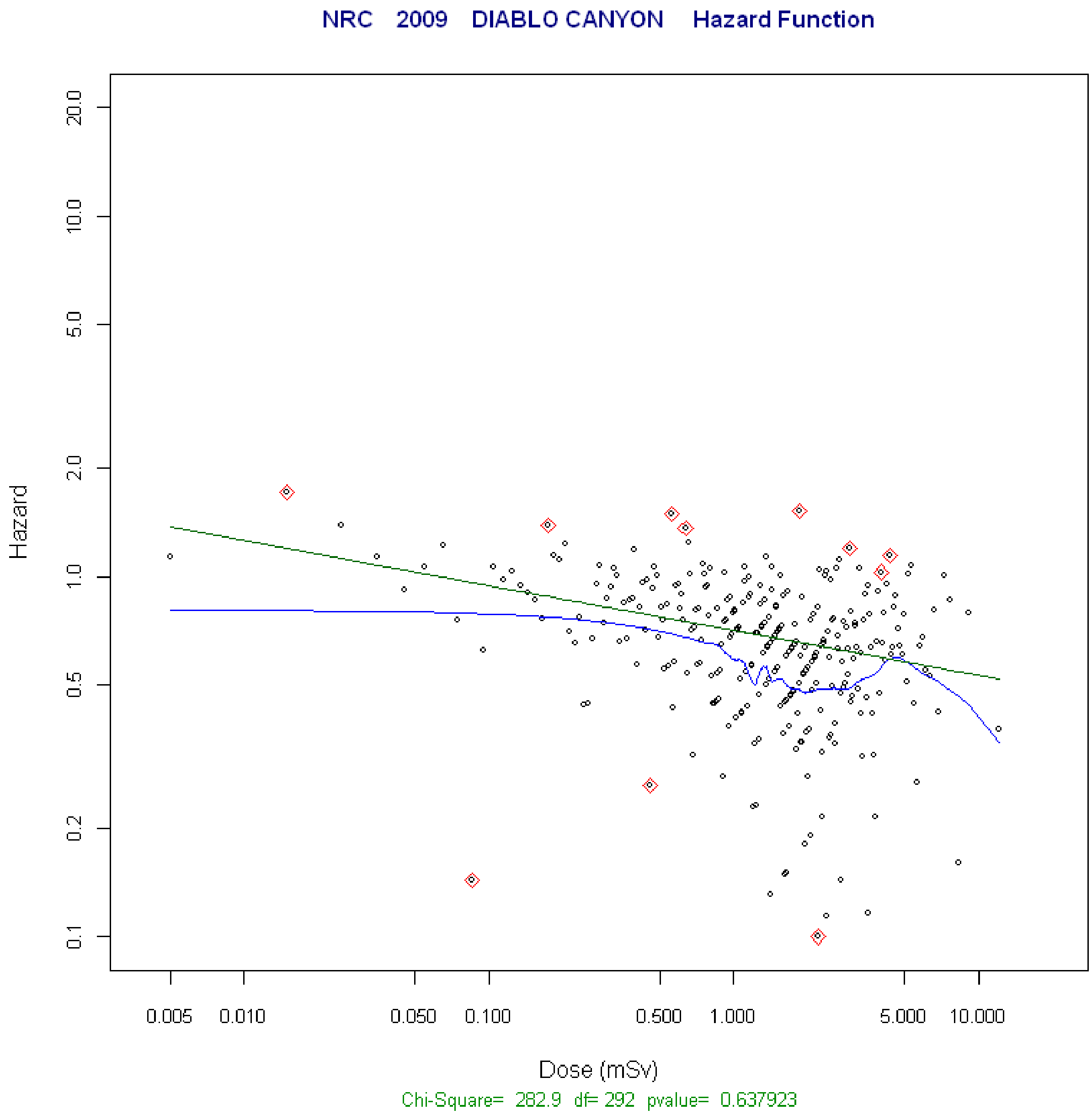

Figure C33: Weibull Goodness of Fit Plot for Diablo Canyon.

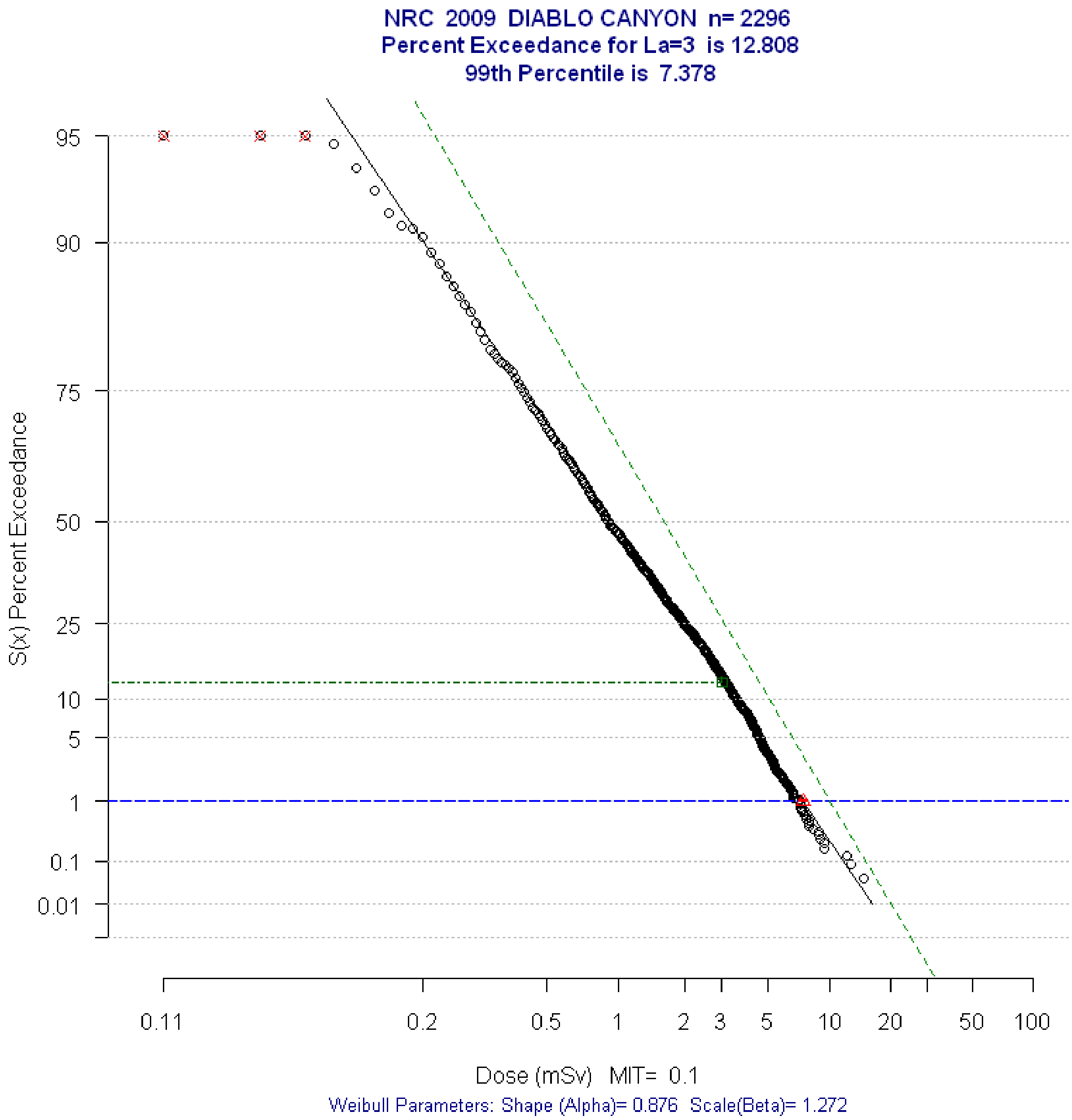

Figure C34: Weibull Probability Plot for Diablo Canyon.

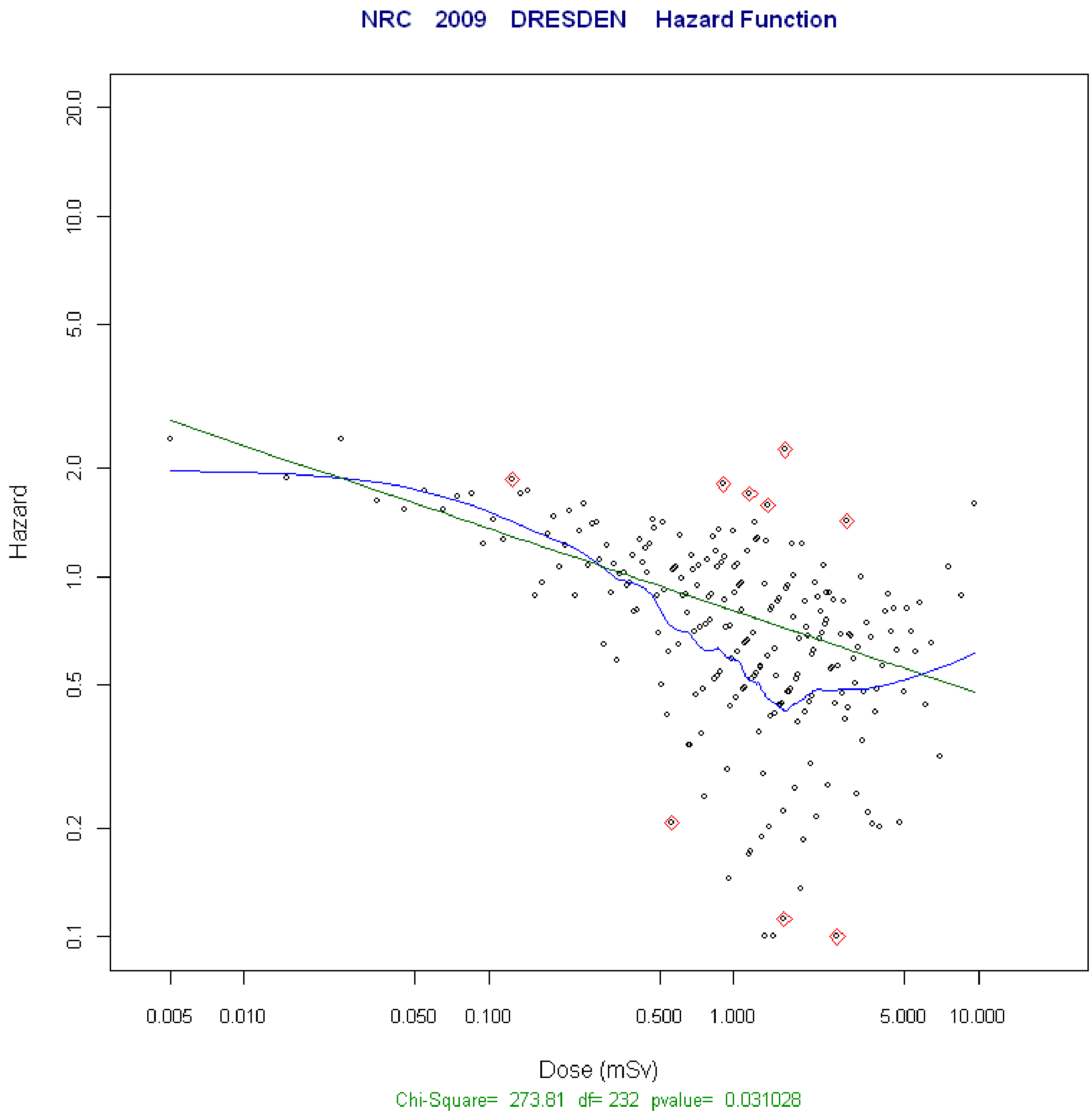

Figure C35: Weibull Goodness of Fit Plot for Dresden.

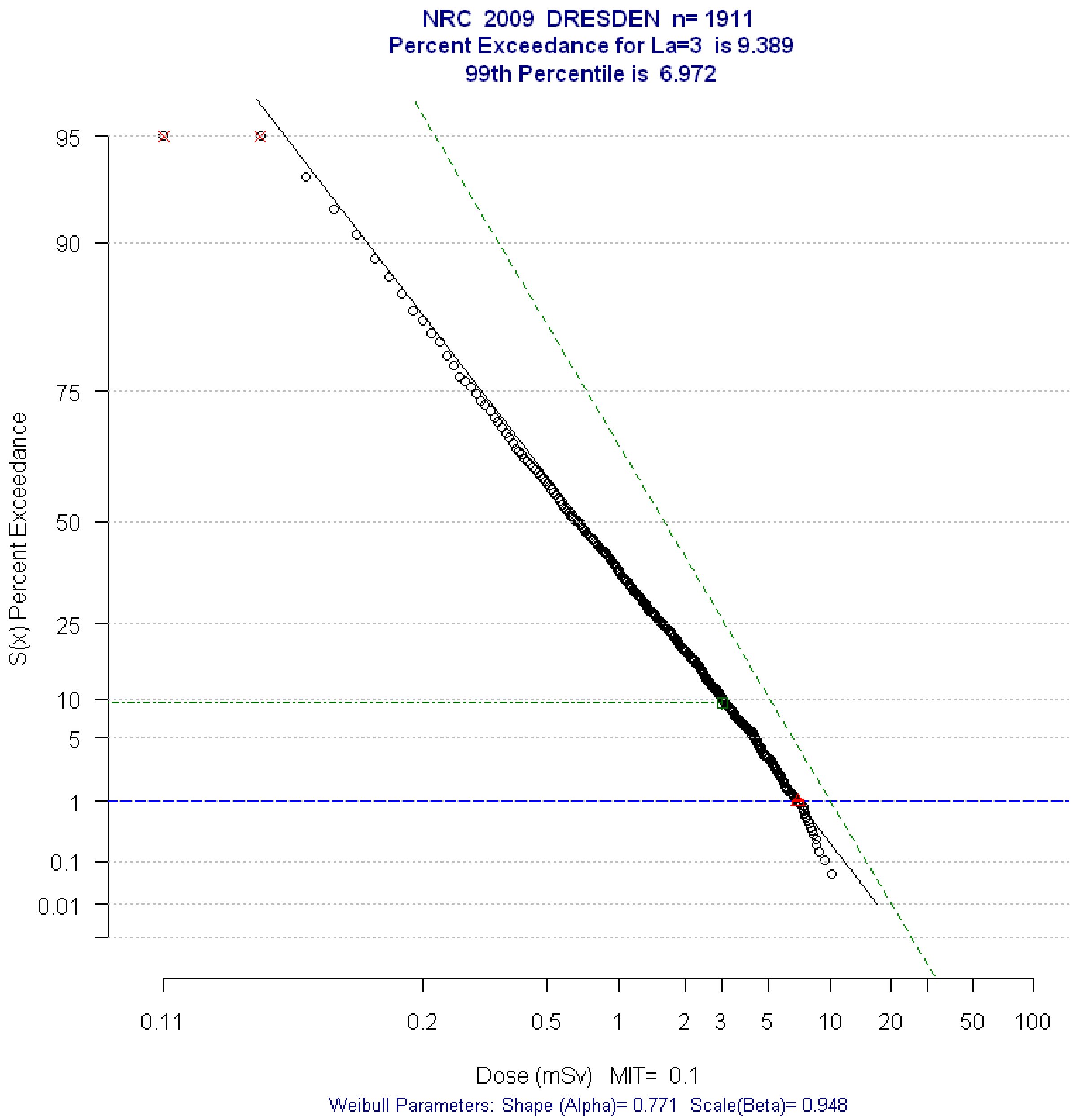

Figure C36: Weibull Probability Plot for Dresden.

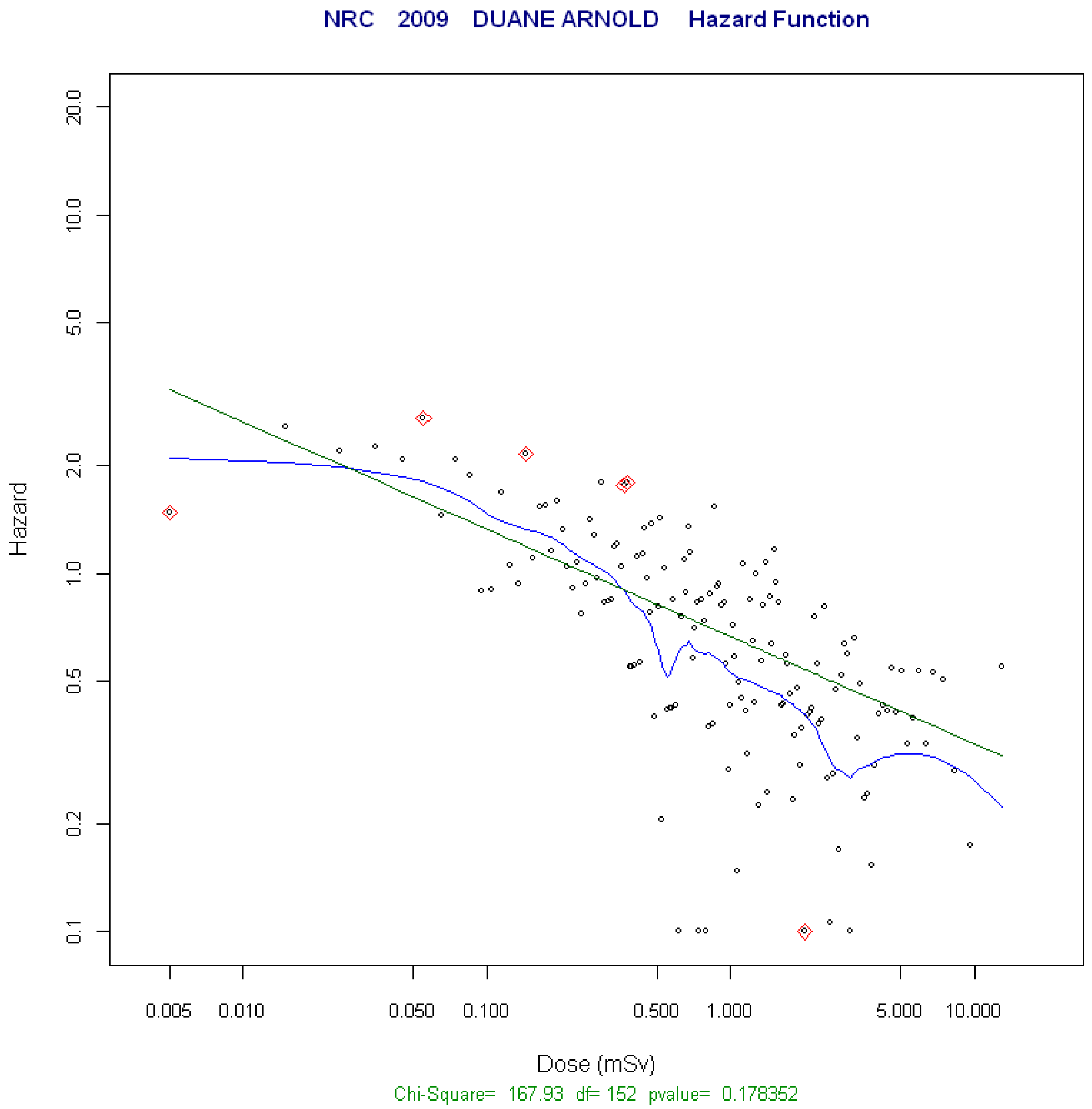

Figure C37: Weibull Goodness of Fit Plot for Duane Arnold.

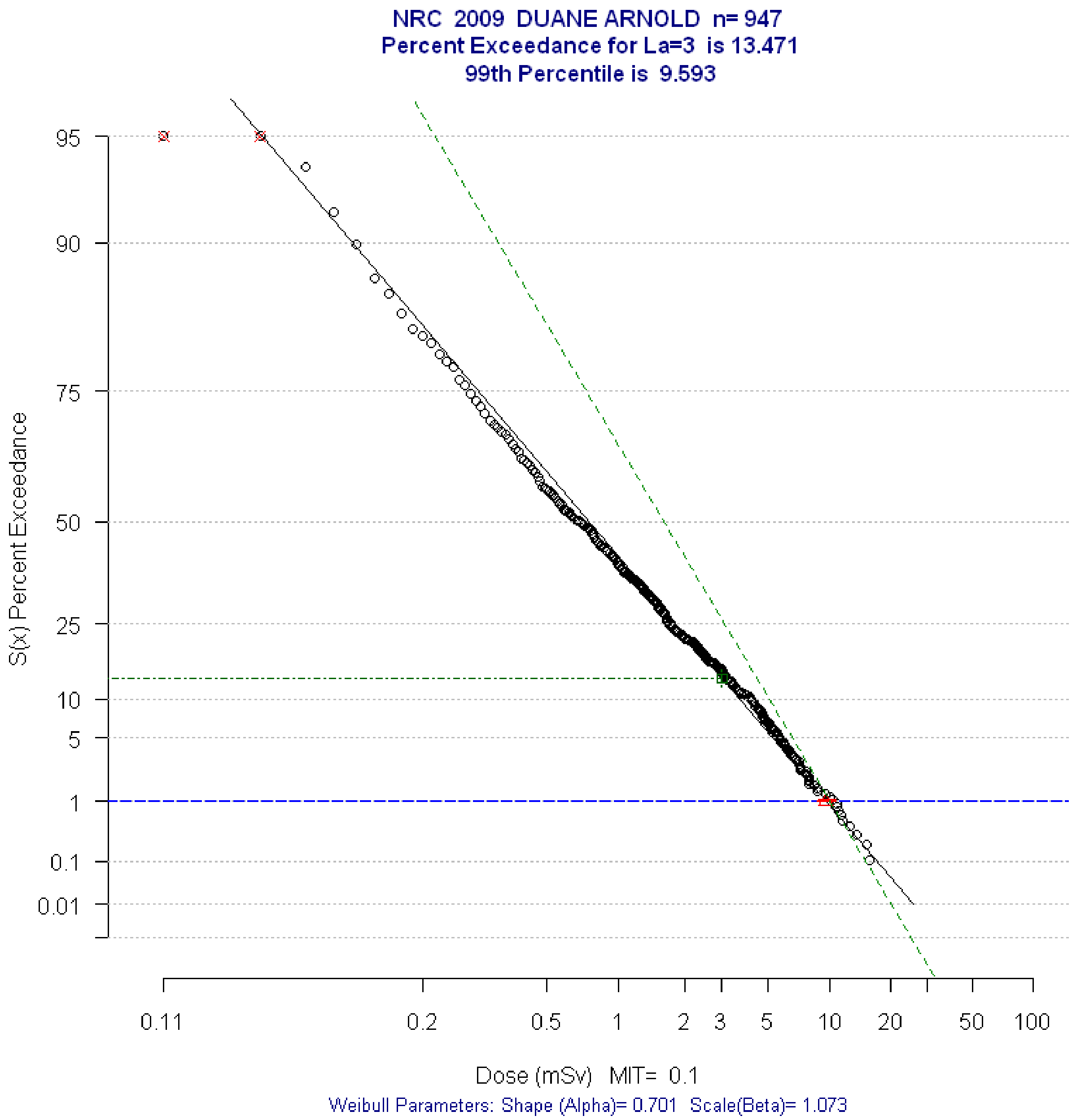

Figure C38: Weibull Probability Plot for Duane Arnold.

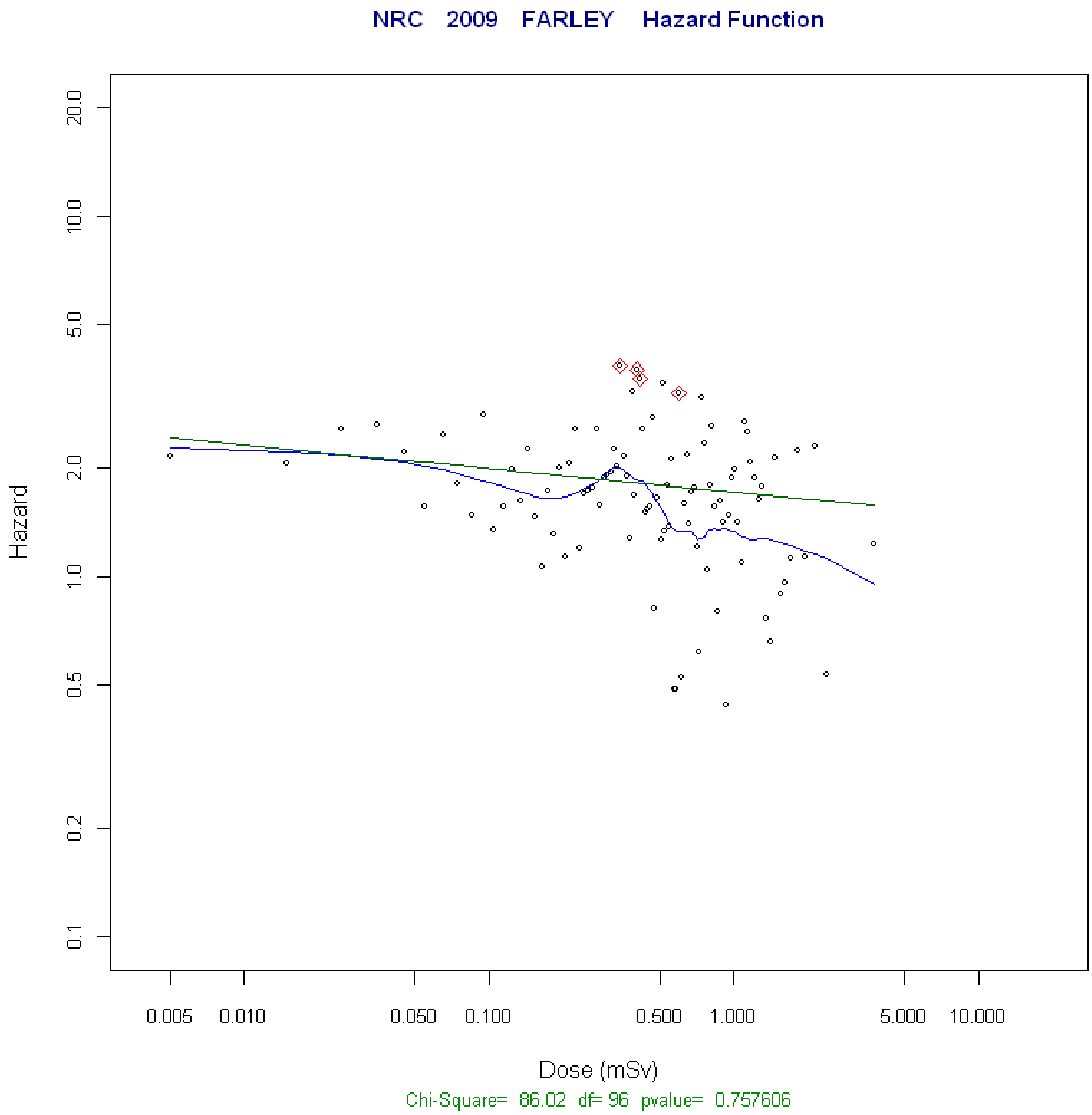

Figure C39: Weibull Goodness of Fit Plot for Farley.

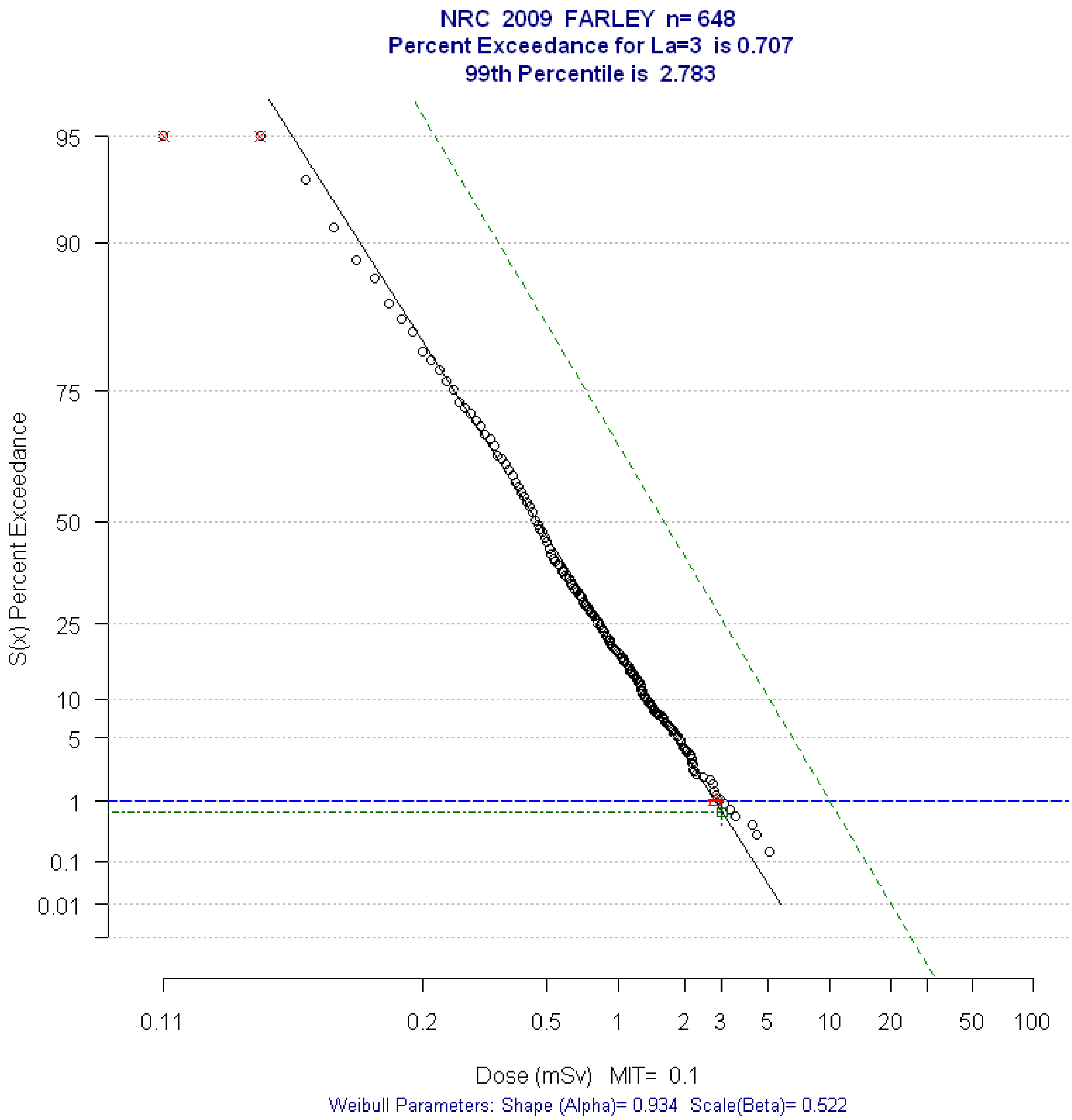

Figure C40: Weibull Probability Plot for Farley.

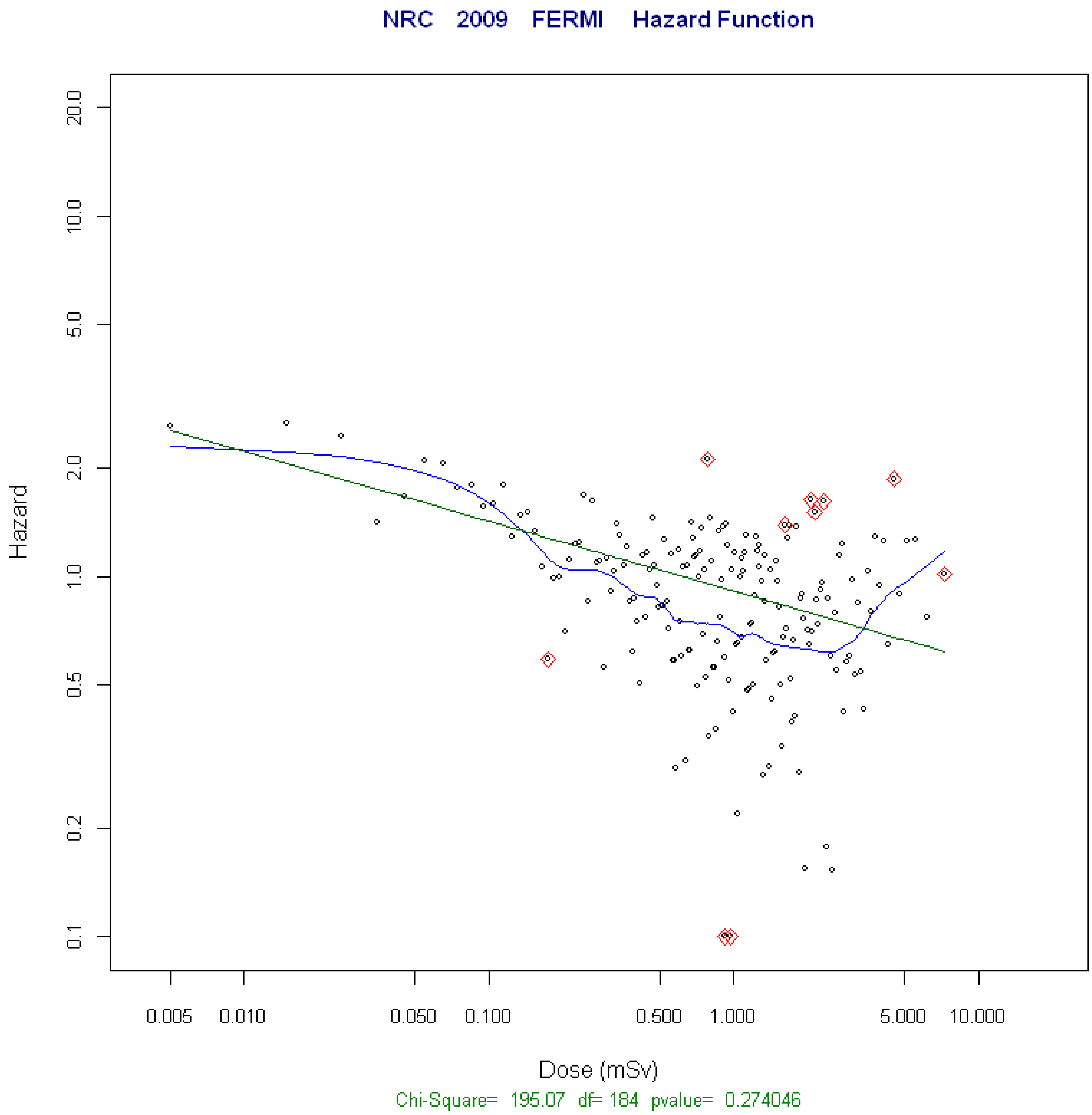

Figure C41: Weibull Goodness of Fit Plot for Fermi.

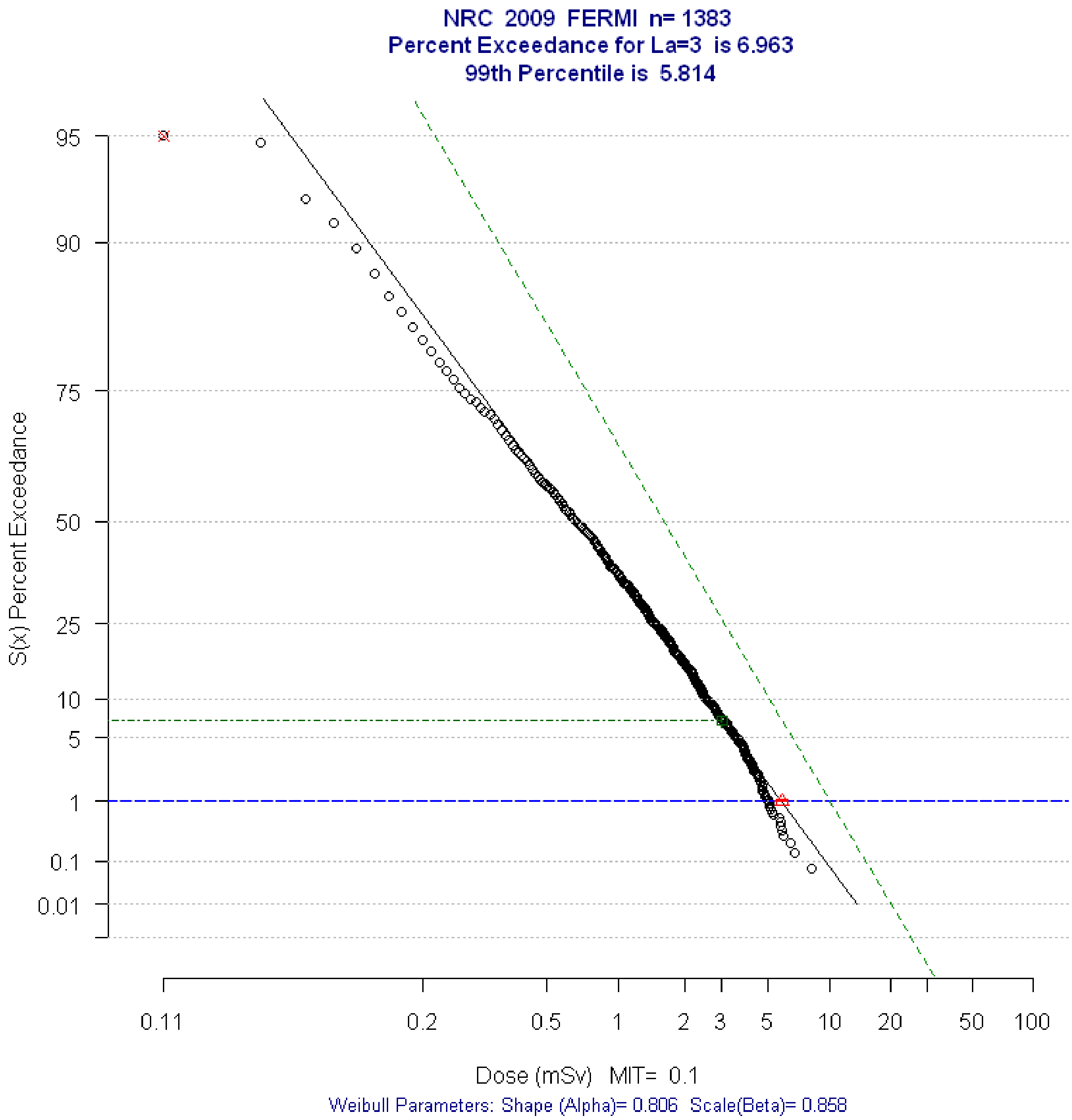

Figure C42: Weibull Probability Plot for Fermi.

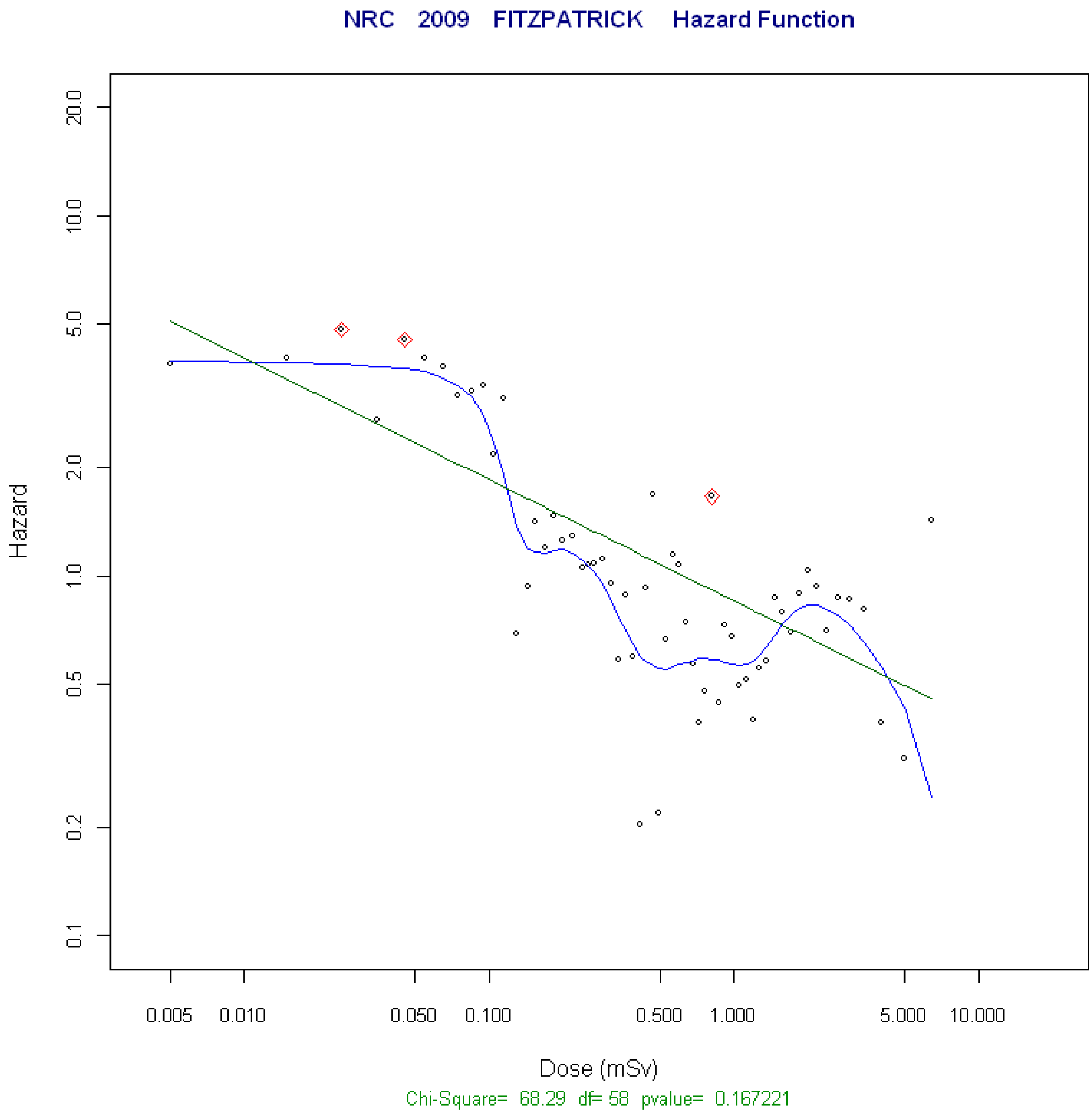

Figure C43: Weibull Goodness of Fit Plot for Fitzpatrick.

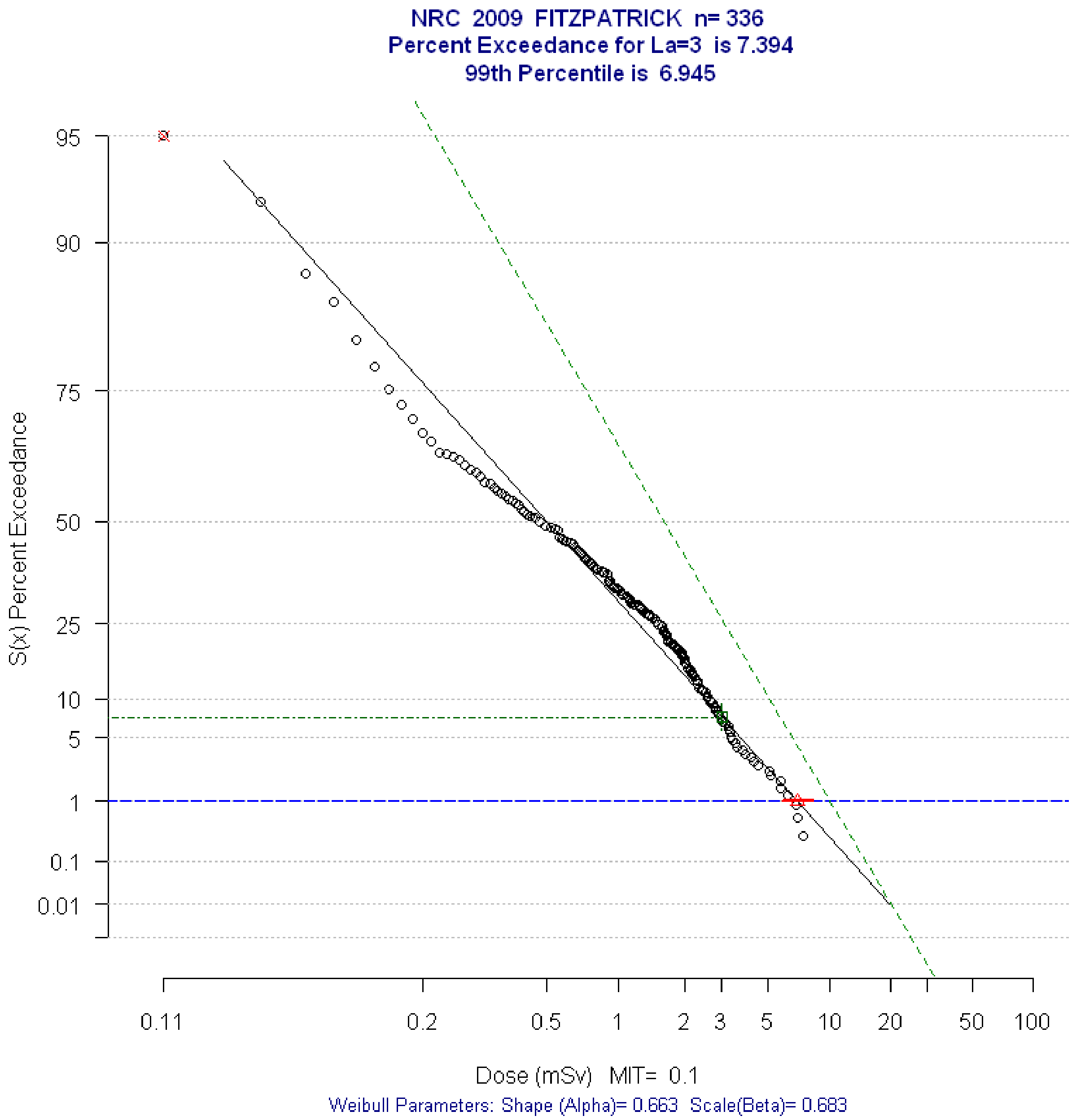

Figure C44: Weibull Probability Plot for Fitzpatrick.

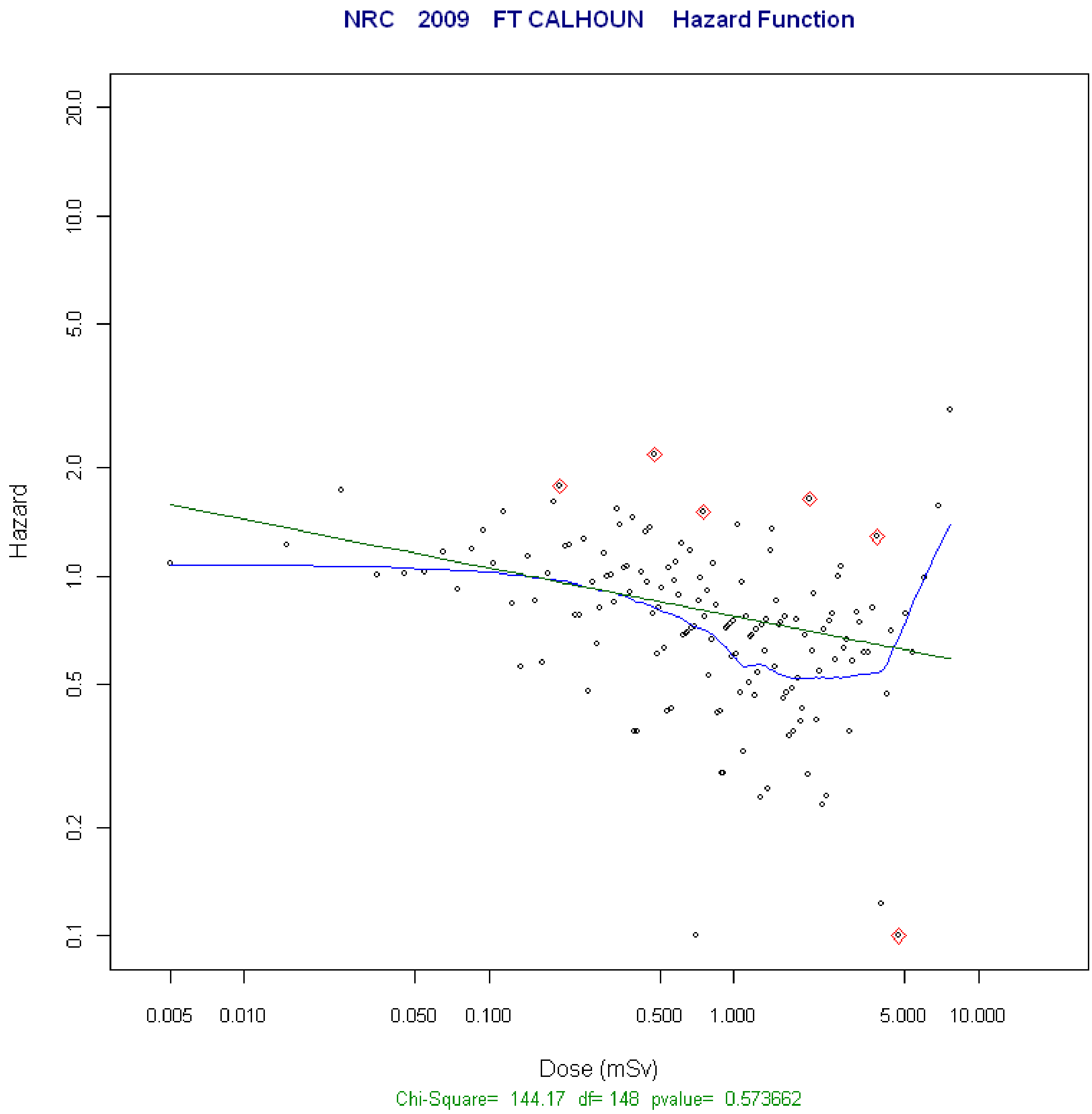

Figure C45: Weibull Goodness of Fit Plot for Fort Calhoun.

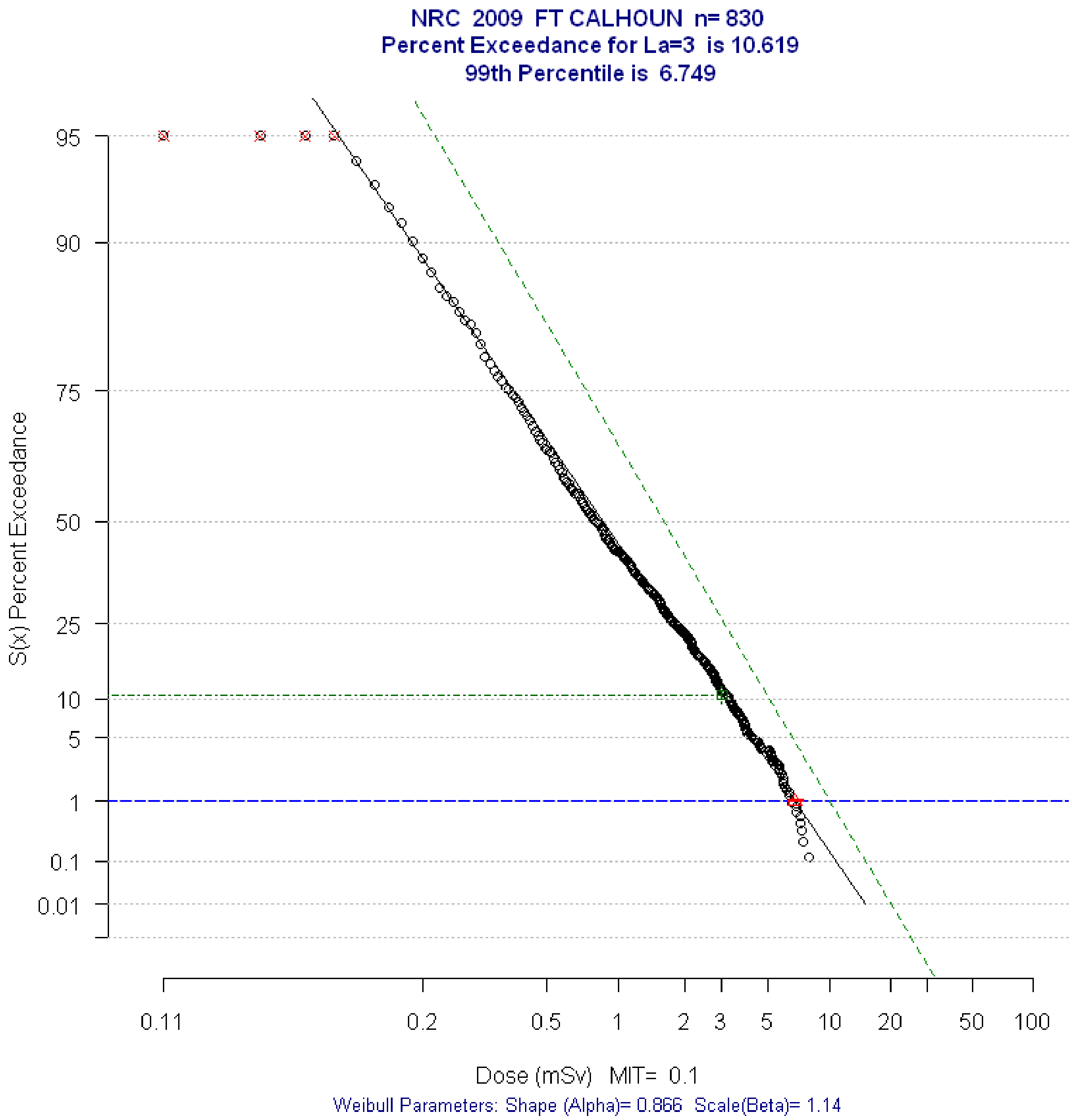

Figure C46: Weibull Probability Plot for Fort Calhoun.

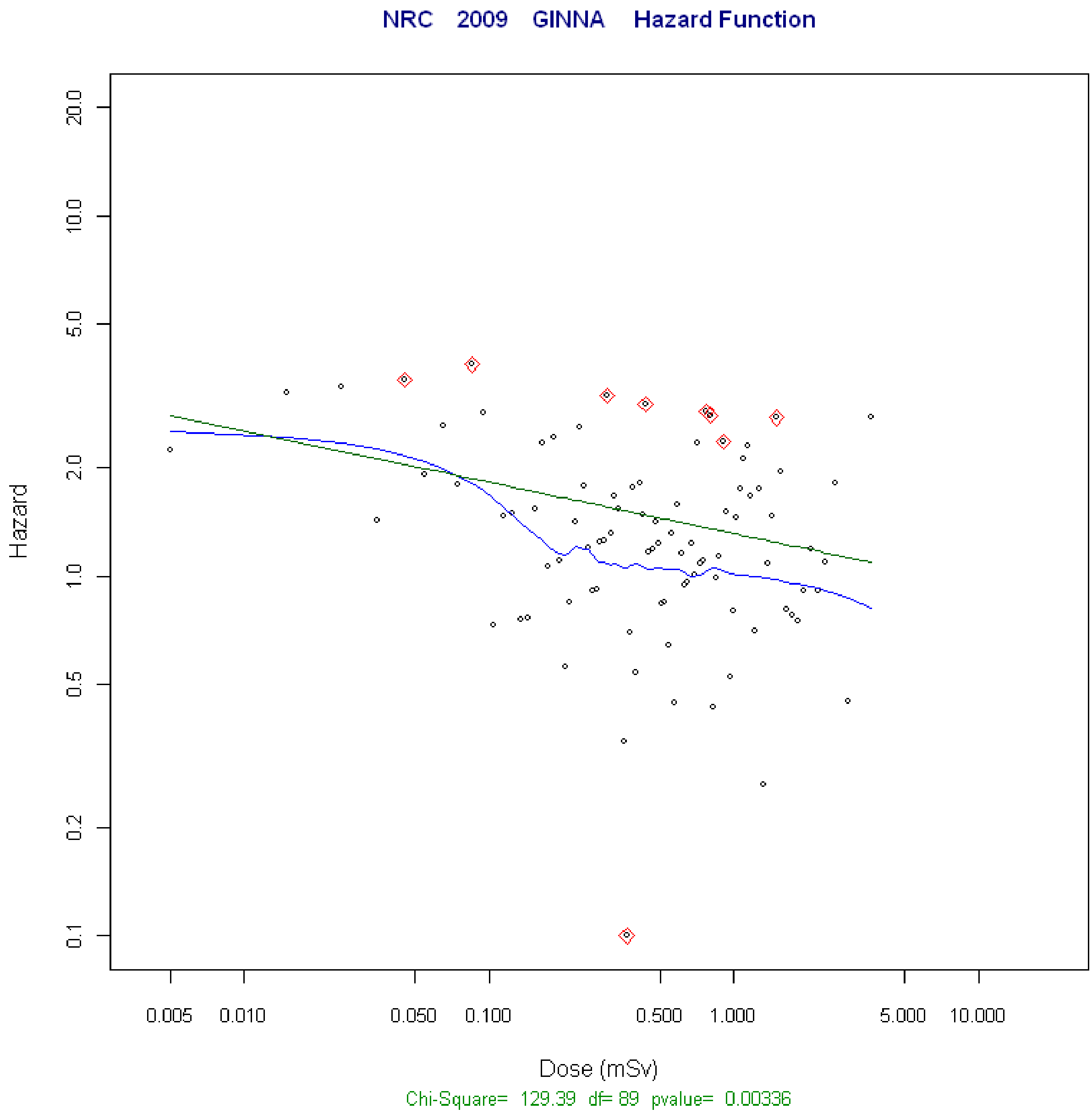

Figure C47: Weibull Goodness of Fit Plot for Ginna.

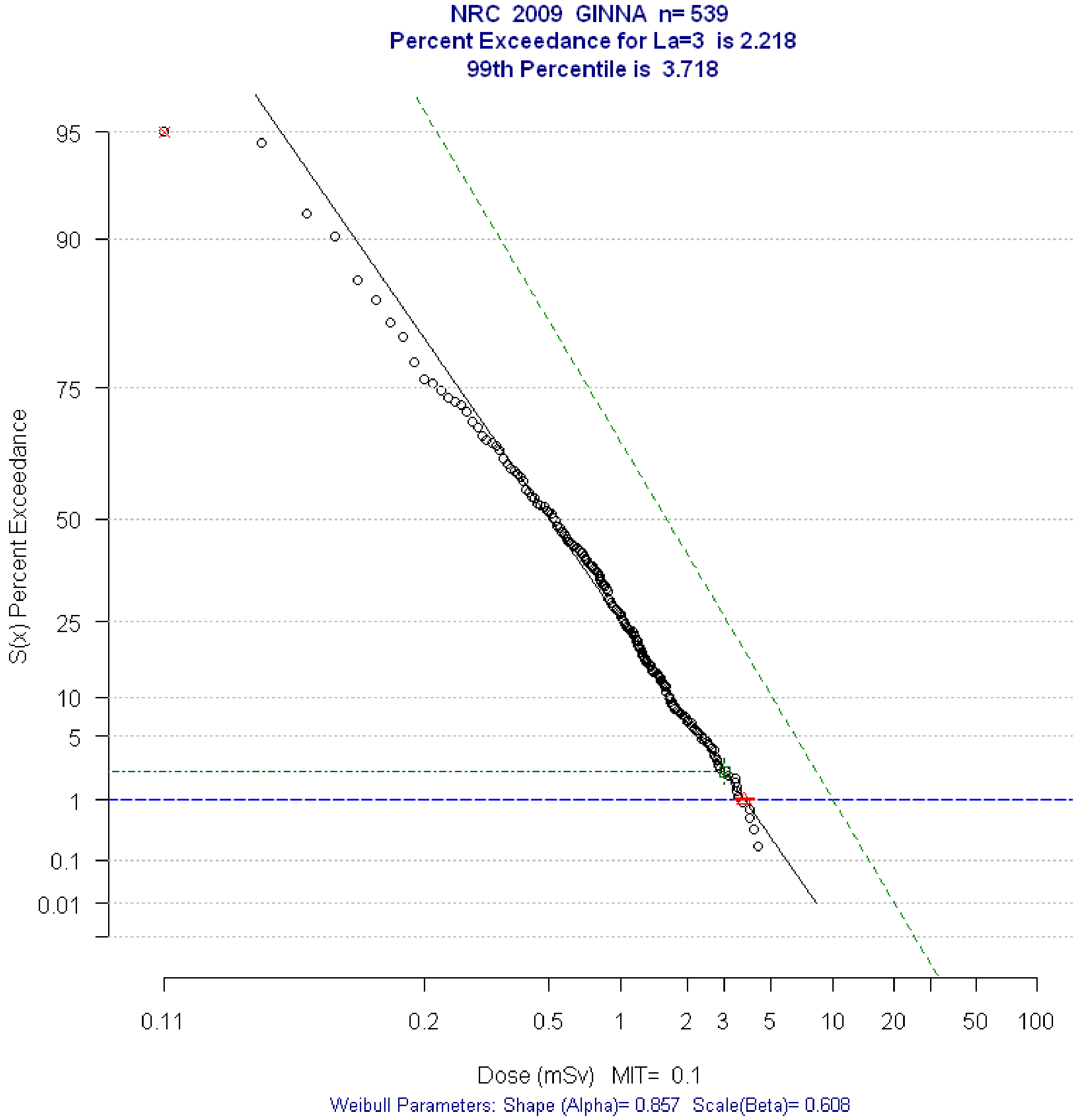

Figure C48: Weibull Probability Plot for Ginna.

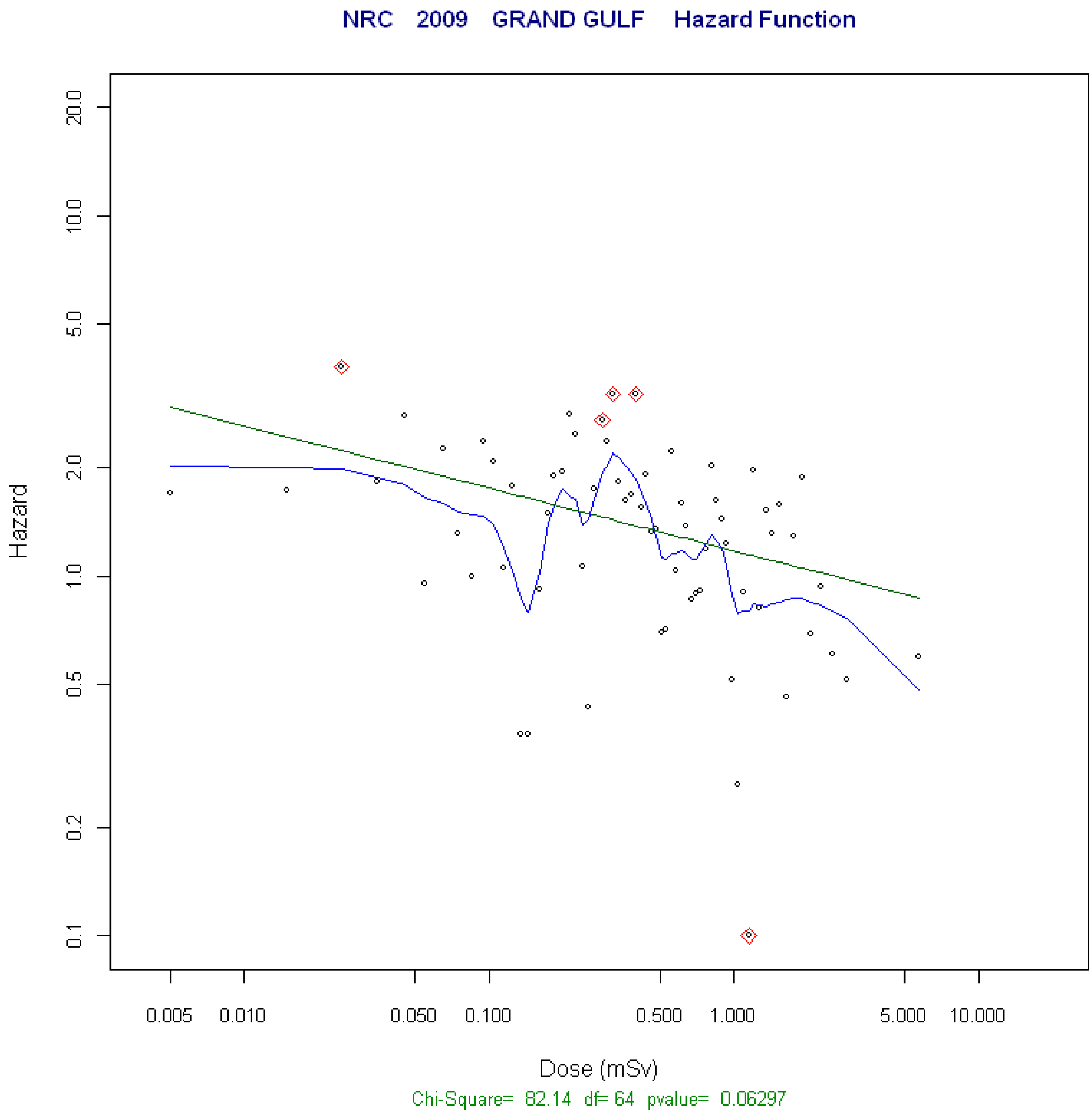

Figure C49: Weibull Goodness of Fit Plot for Grand Gulf.

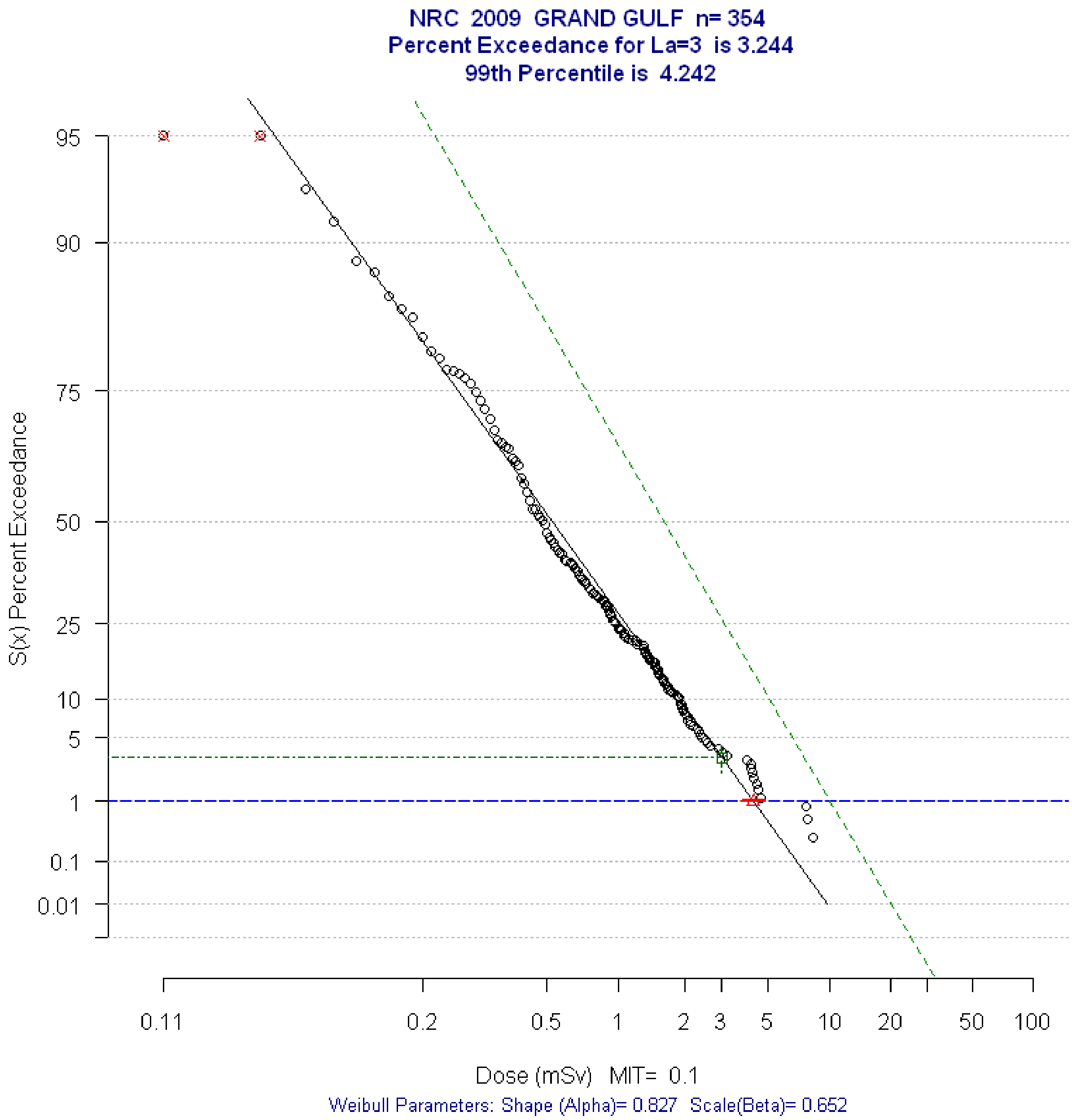

Figure C50: Weibull Probability Plot for Grand Gulf.

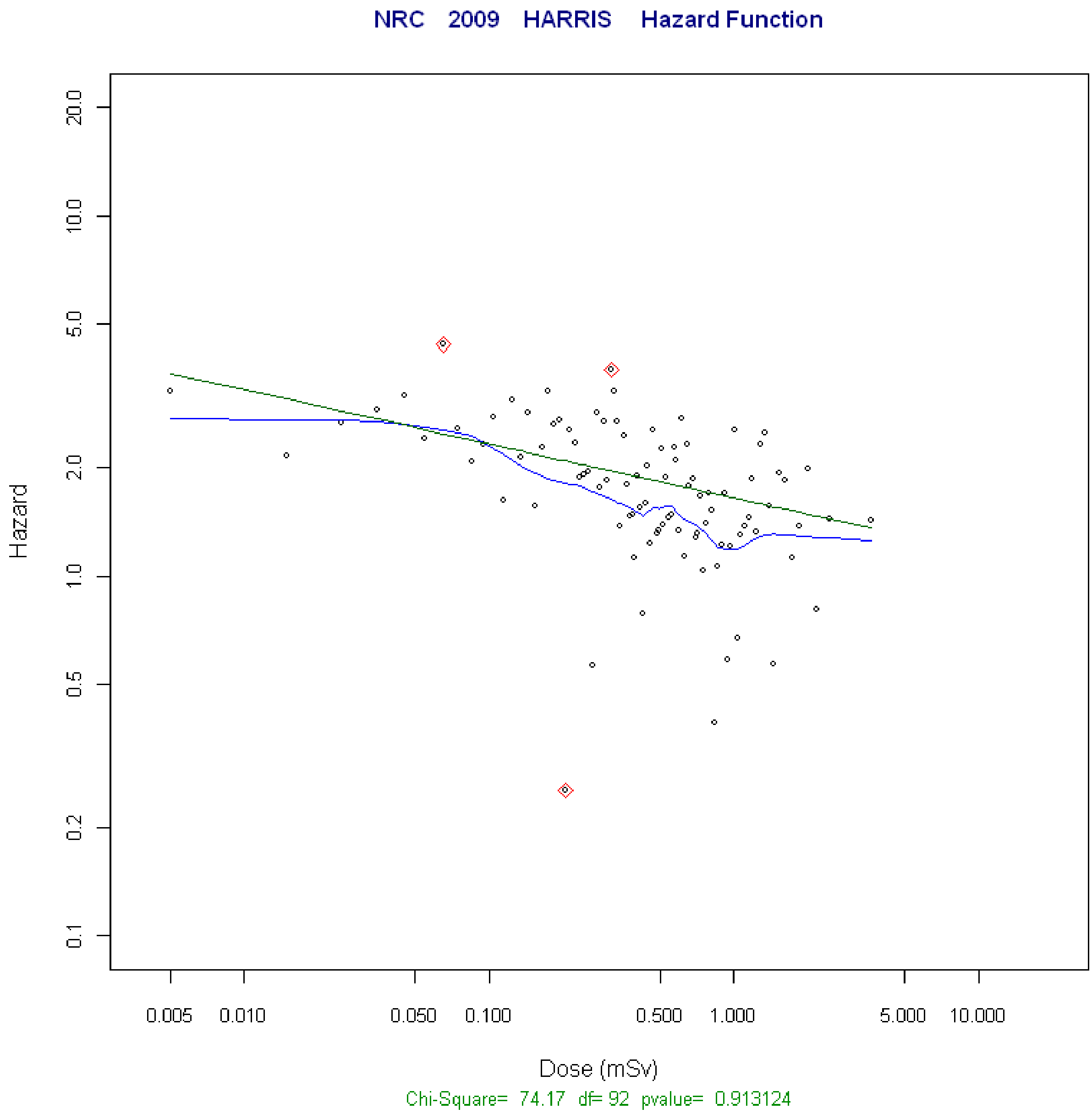

Figure C51: Weibull Goodness of Fit Plot for Harris.

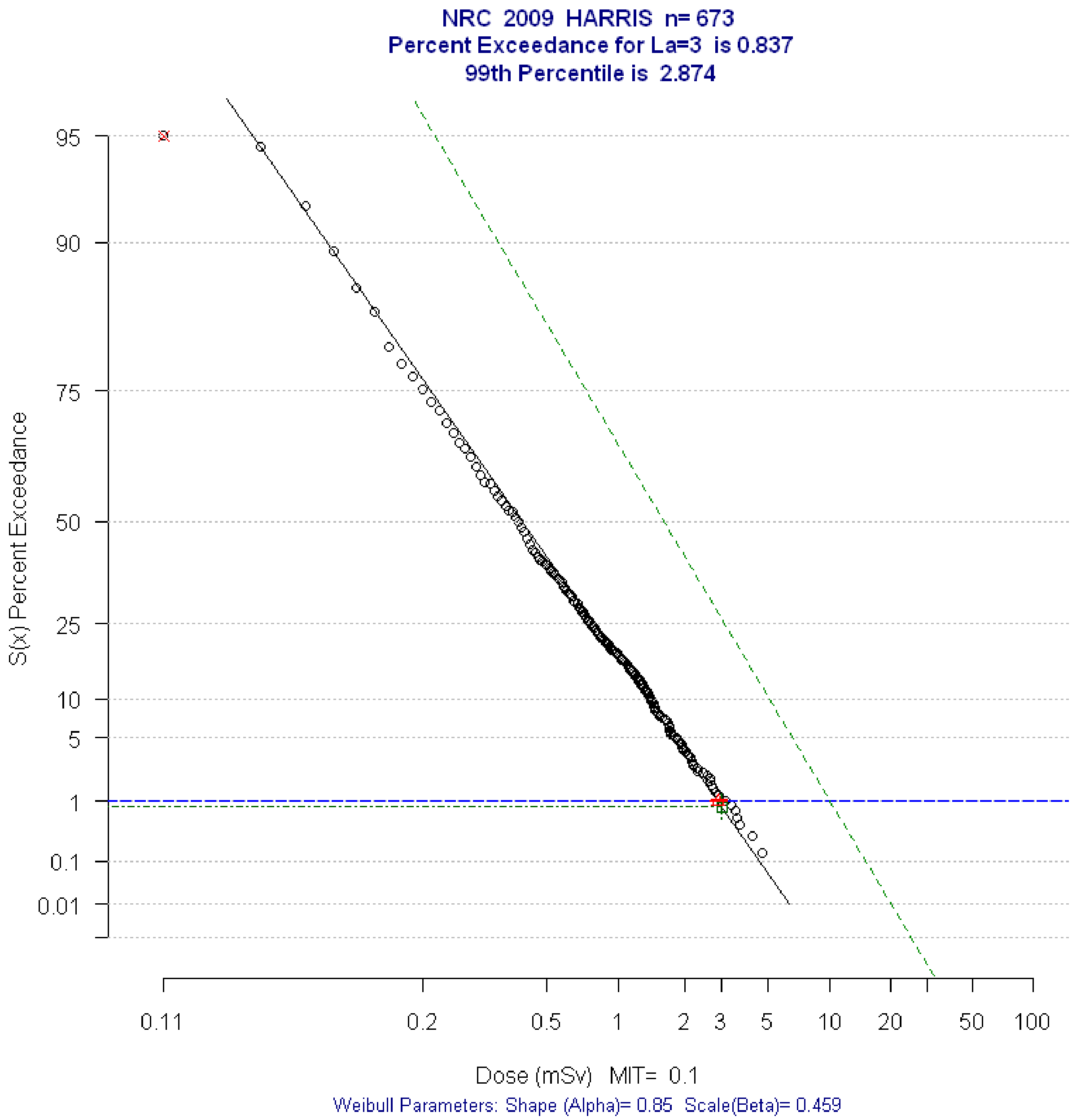

Figure C52: Weibull Probability Plot for Harris.

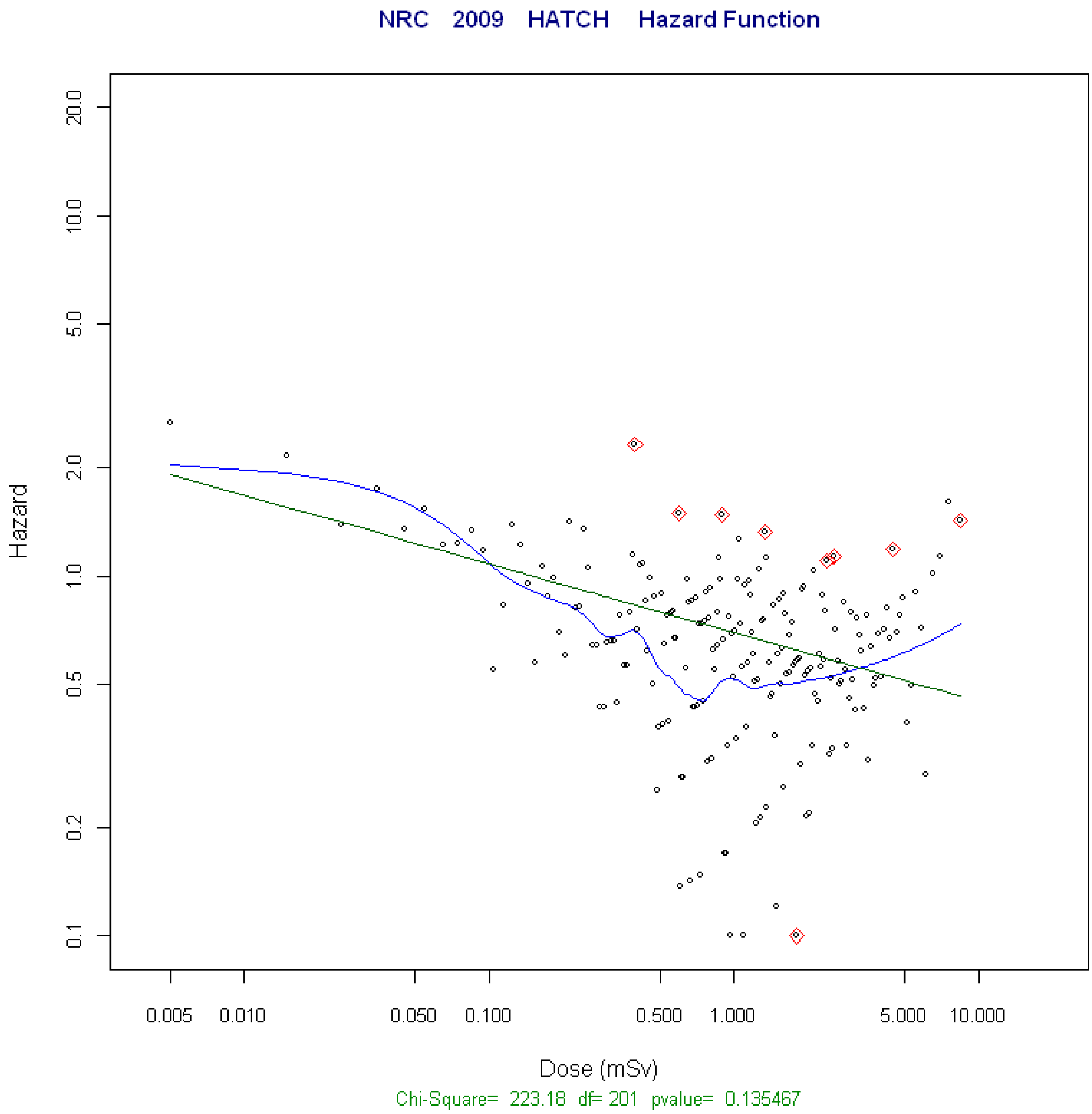

Figure C53: Weibull Goodness of Fit Plot for Hatch.

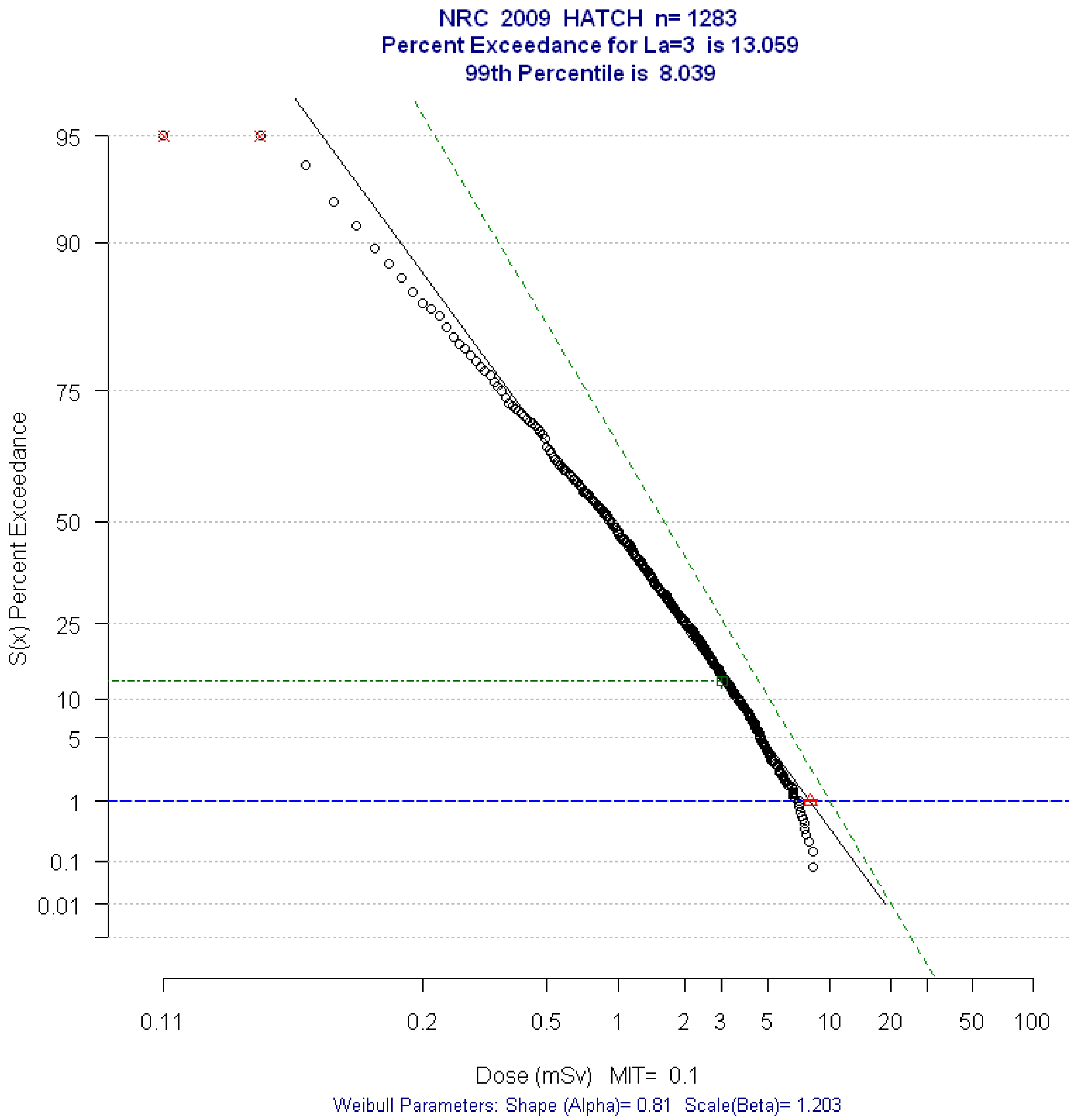

Figure C54: Weibull Probability Plot for Hatch.

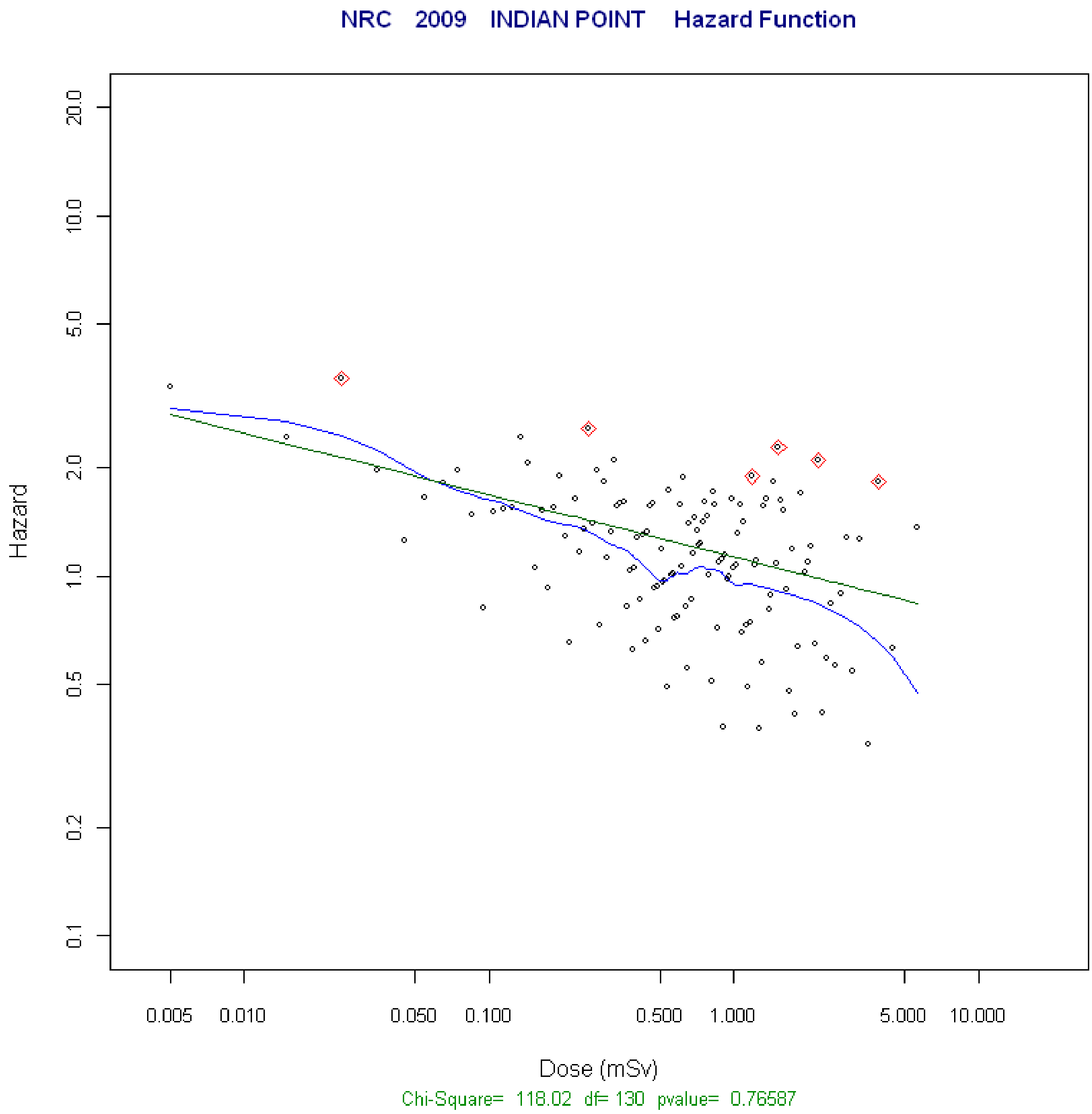

Figure C55: Weibull Goodness of Fit Plot for Indian Point.

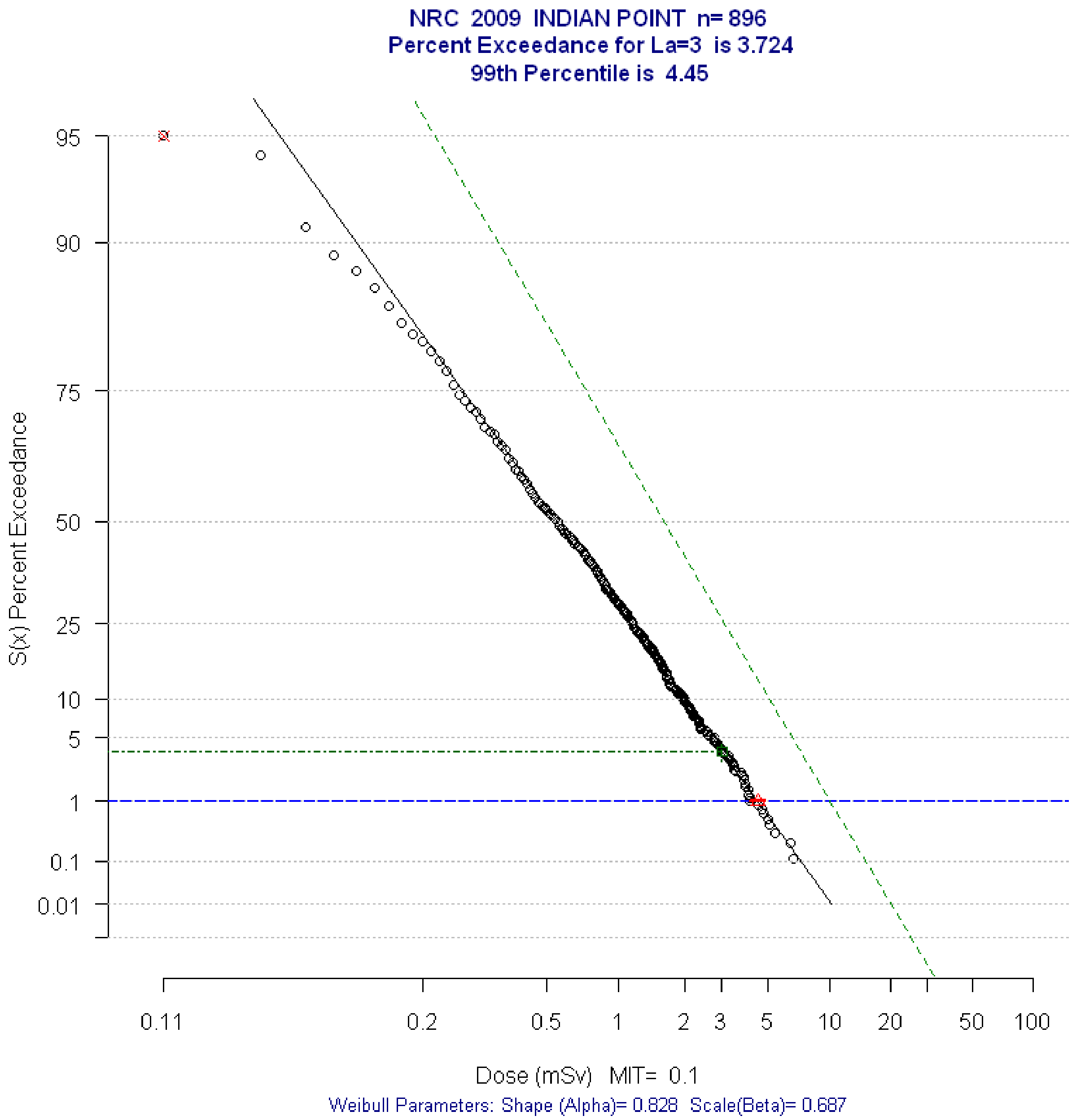

Figure C56: Weibull Probability Plot for Indian Point.

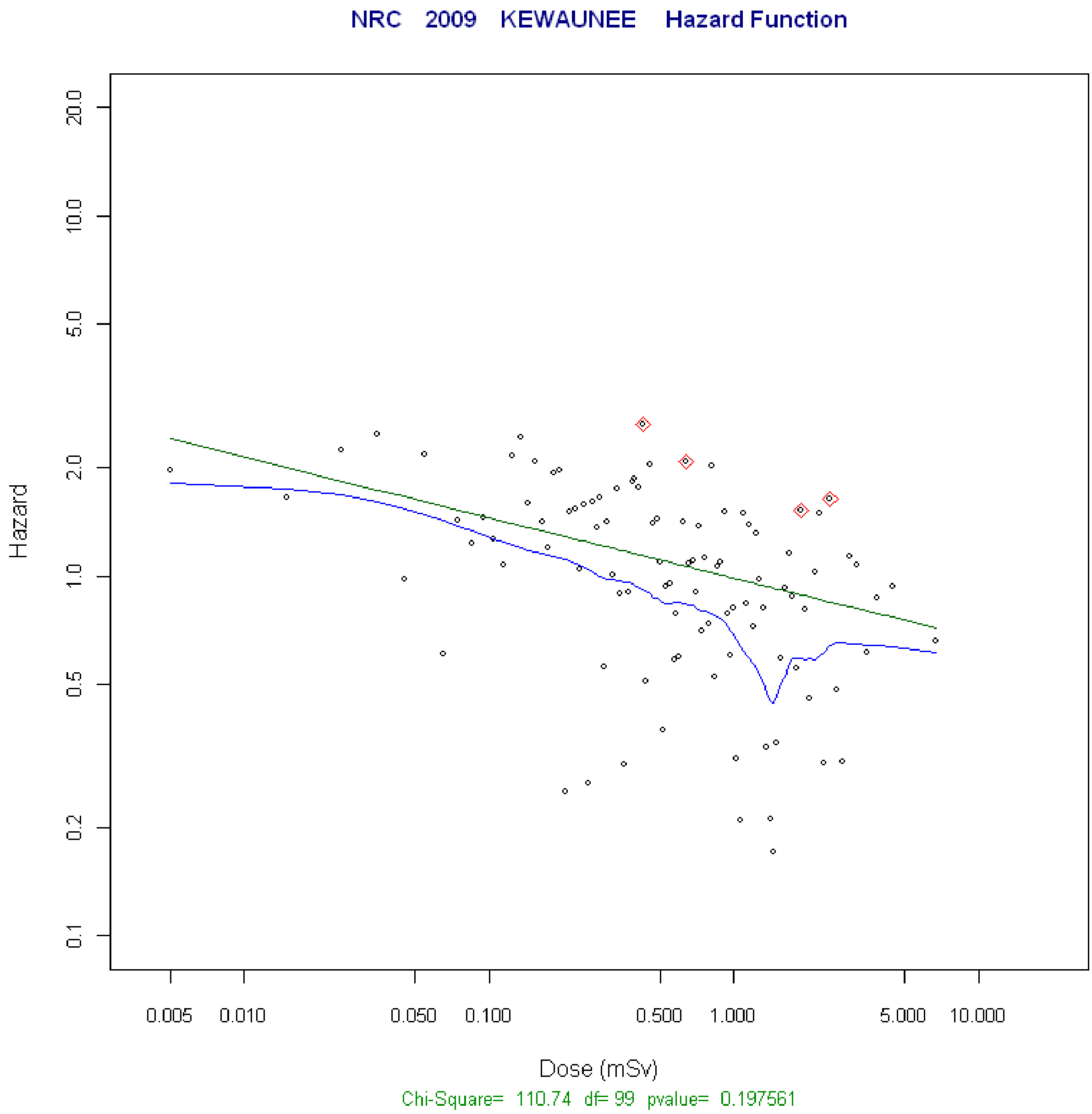

Figure C57: Weibull Goodness of Fit Plot for Kewaunee.

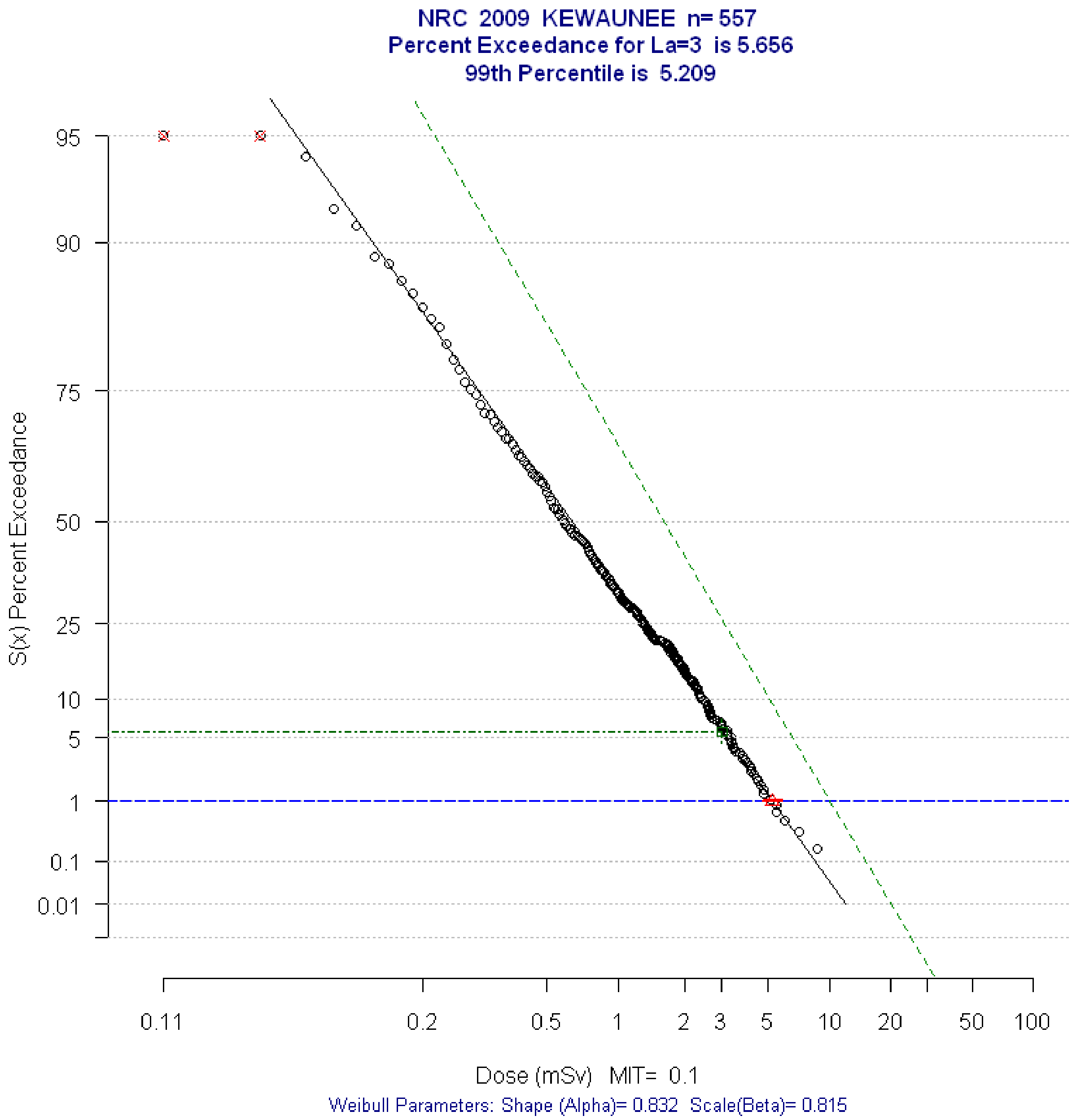

Figure C58: Weibull Probability Plot for Kewaunee.

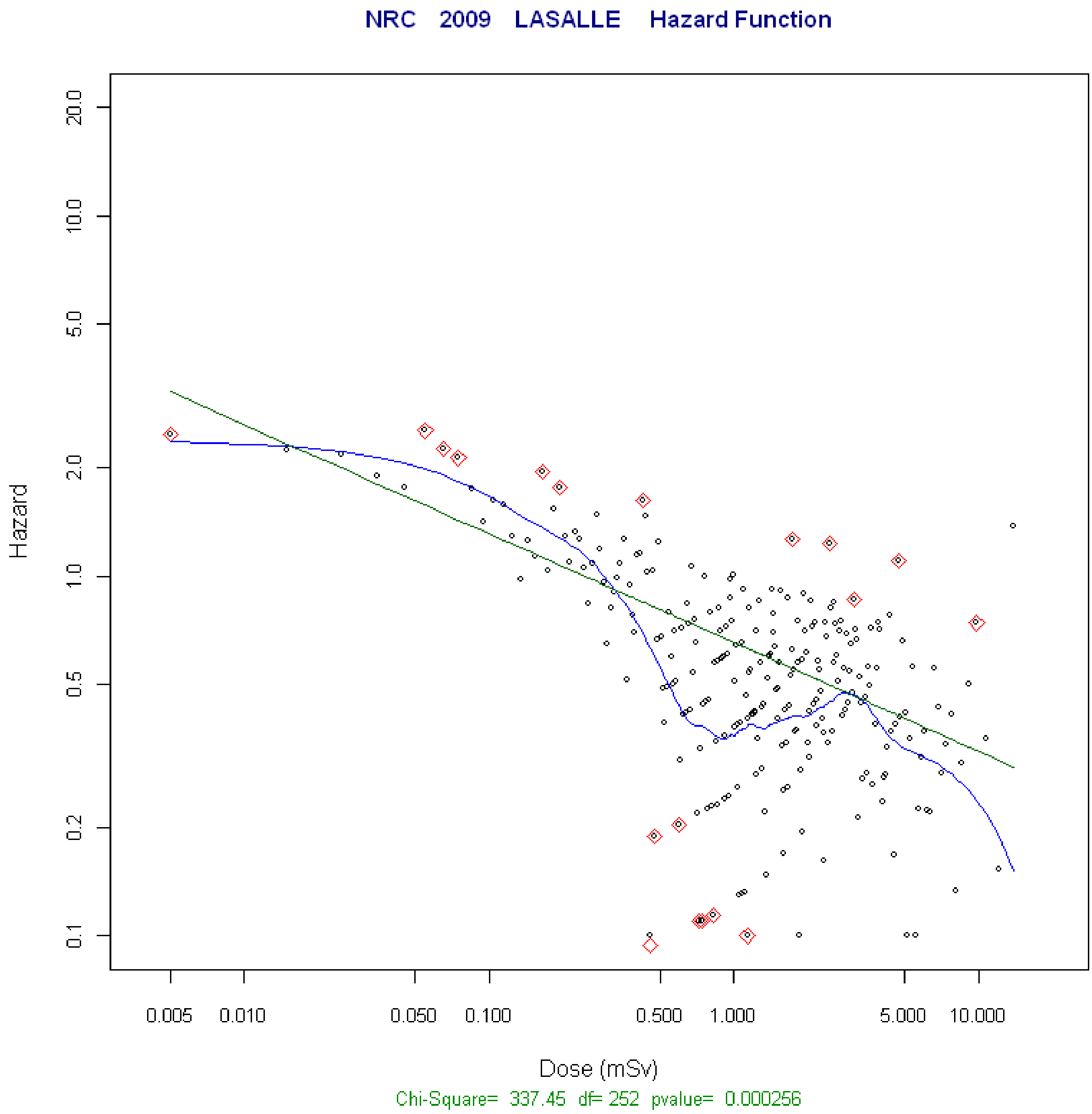

Figure C59: Weibull Goodness of Fit Plot for LaSalle.

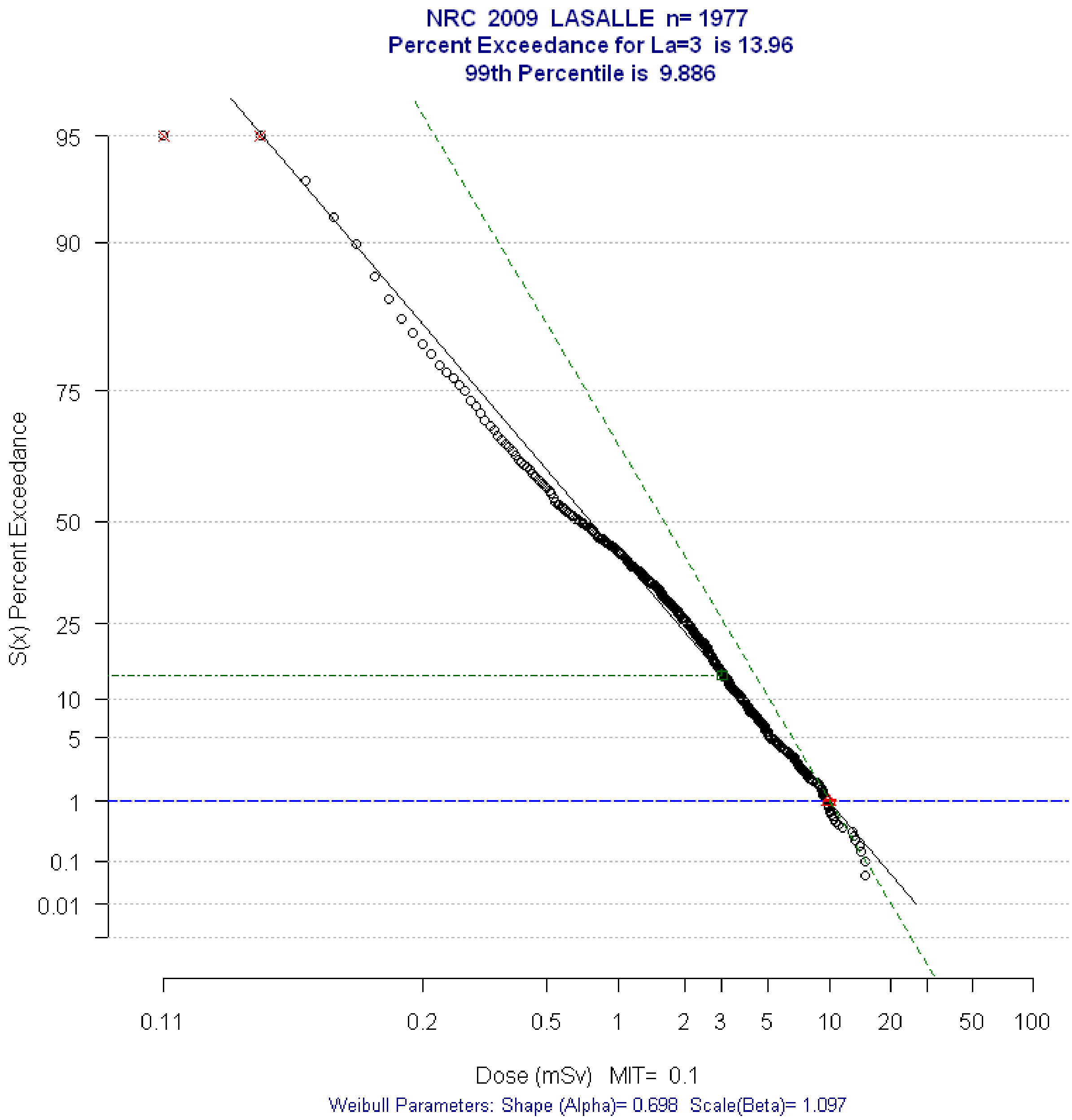

Figure C60: Weibull Probability Plot for LaSalle.

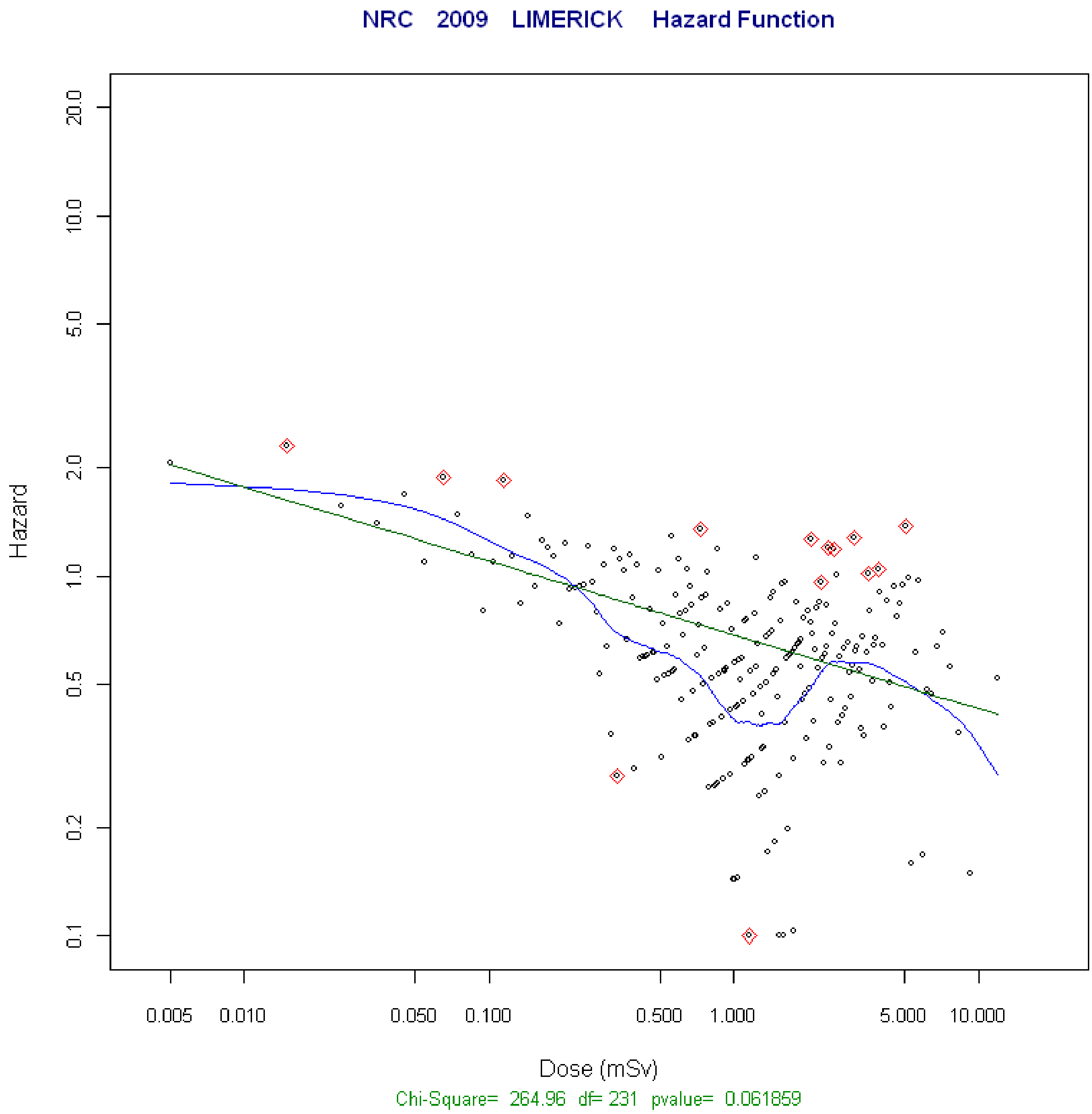

Figure C61: Weibull Goodness of Fit Plot for Limerick.

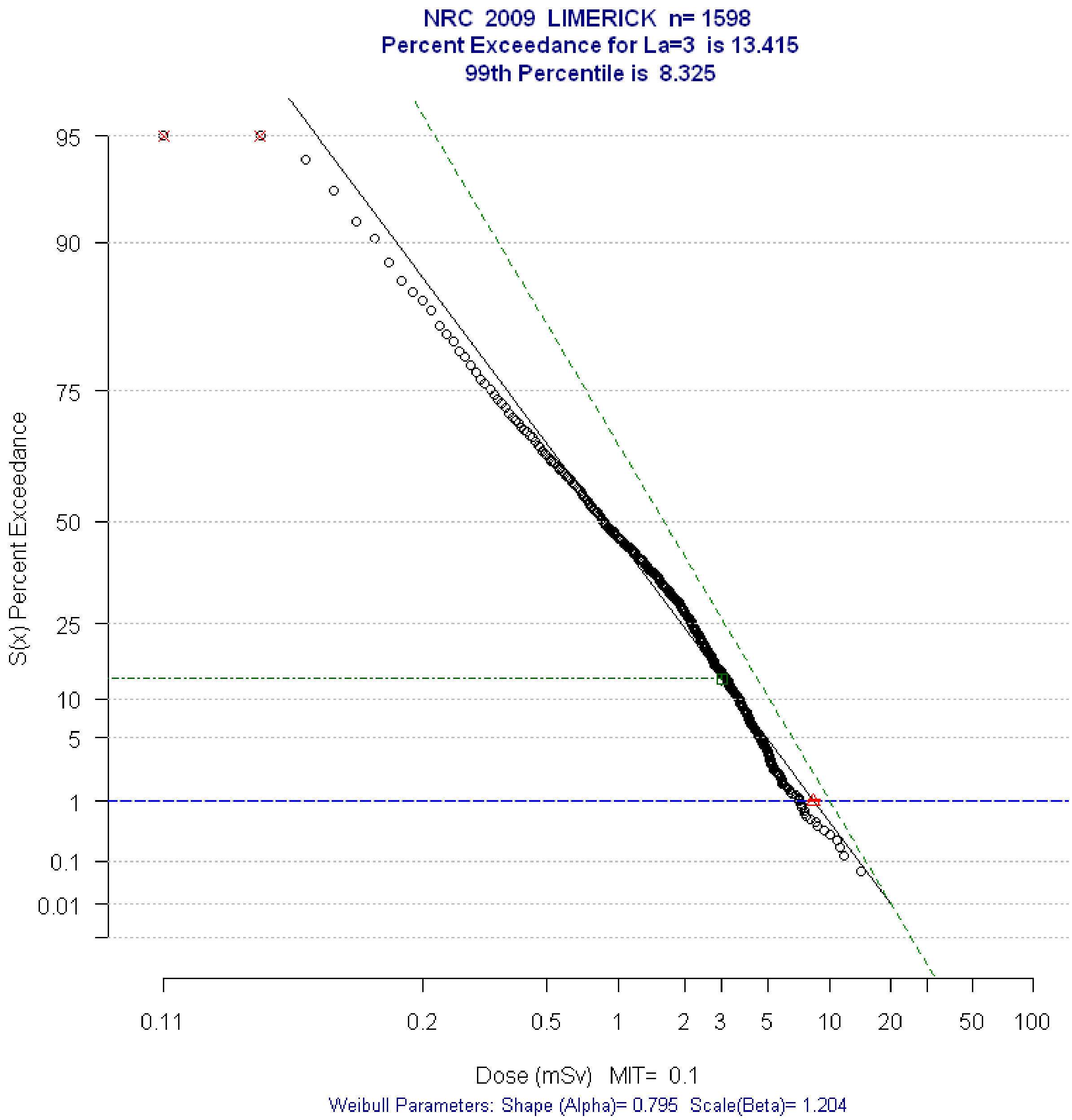

Figure C62: Weibull Probability Plot for Limerick.

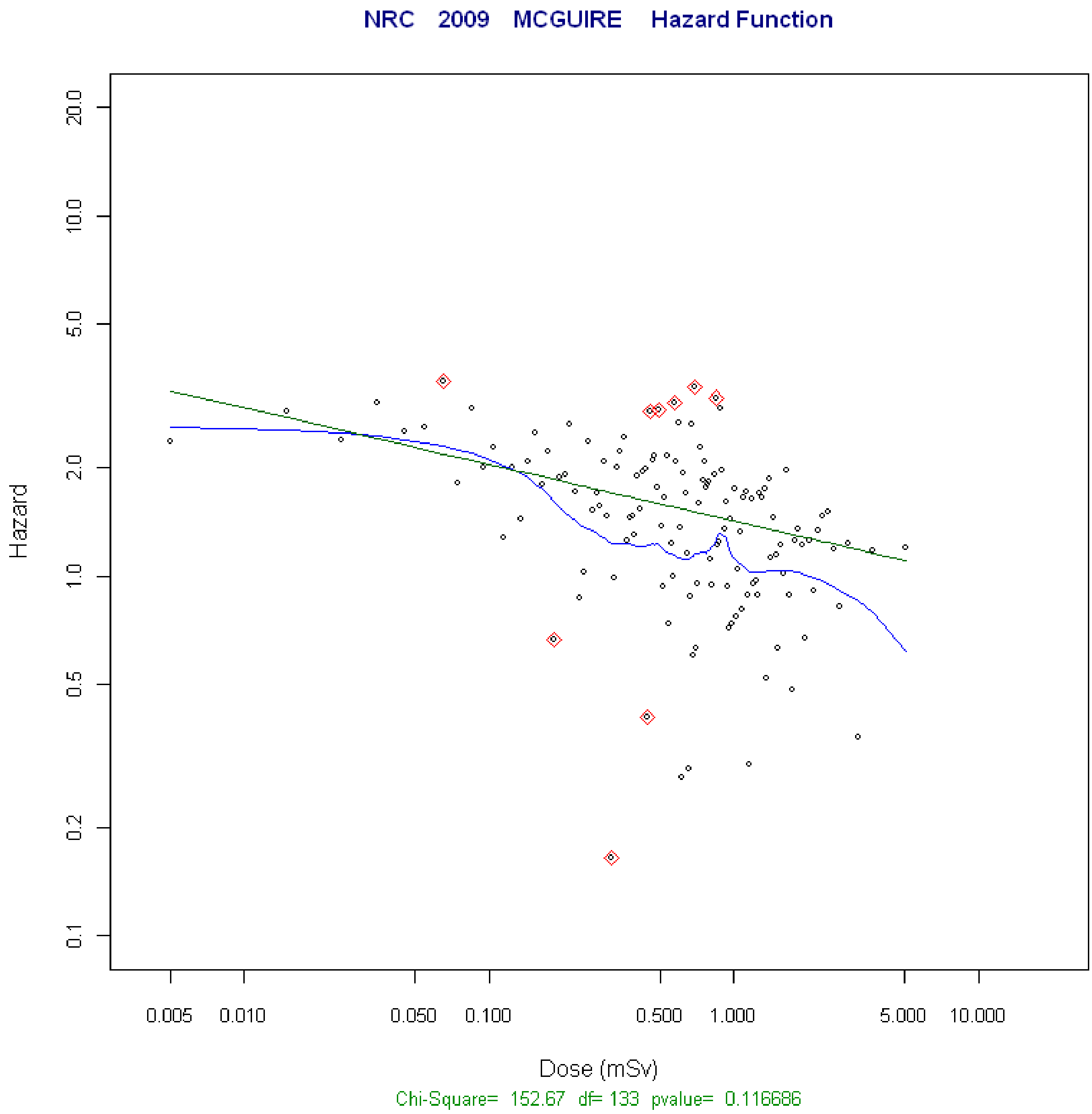

Figure C63: Weibull Goodness of Fit Plot for McGuire.

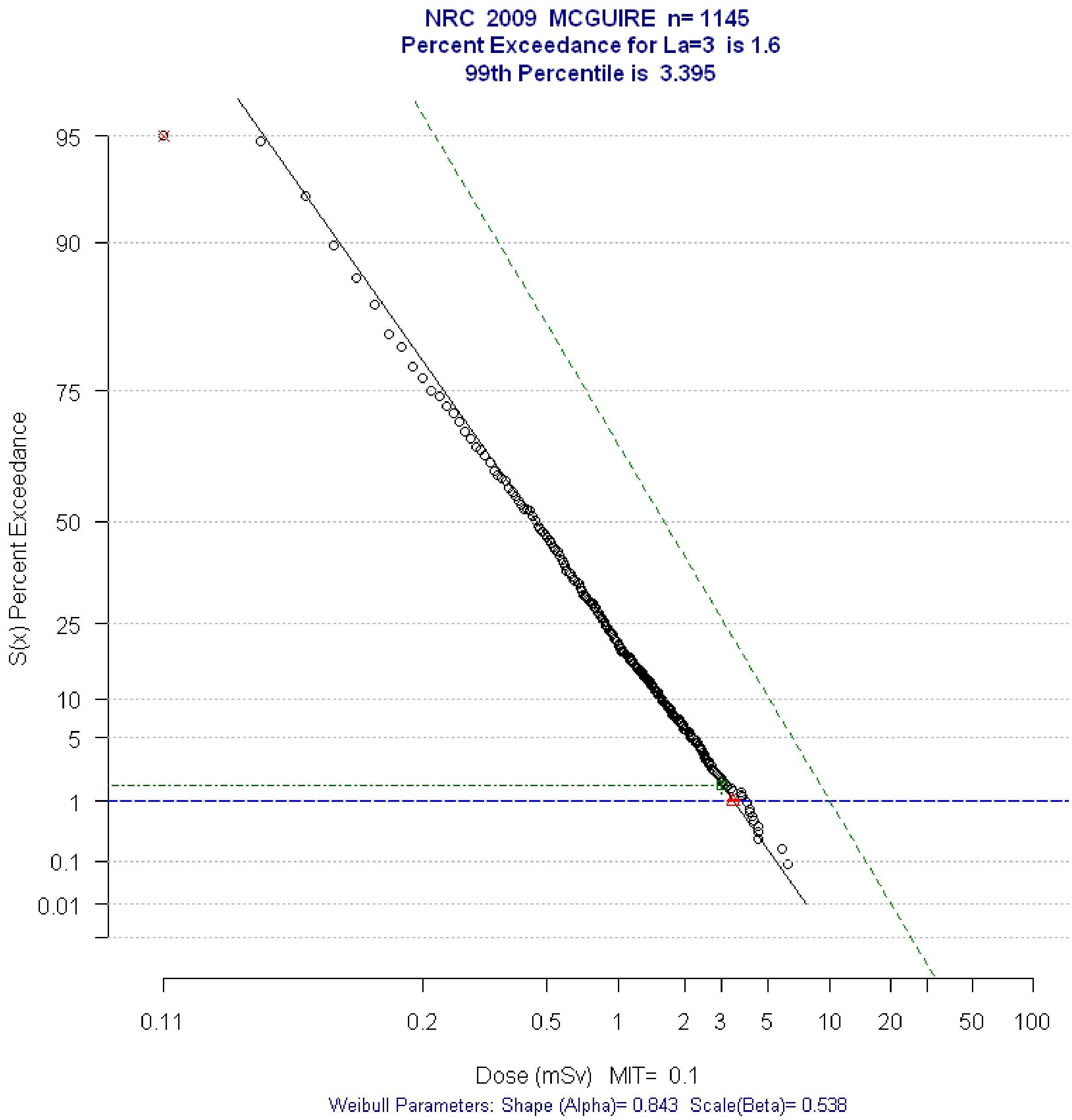

Figure C64: Weibull Probability Plot for McGuire.

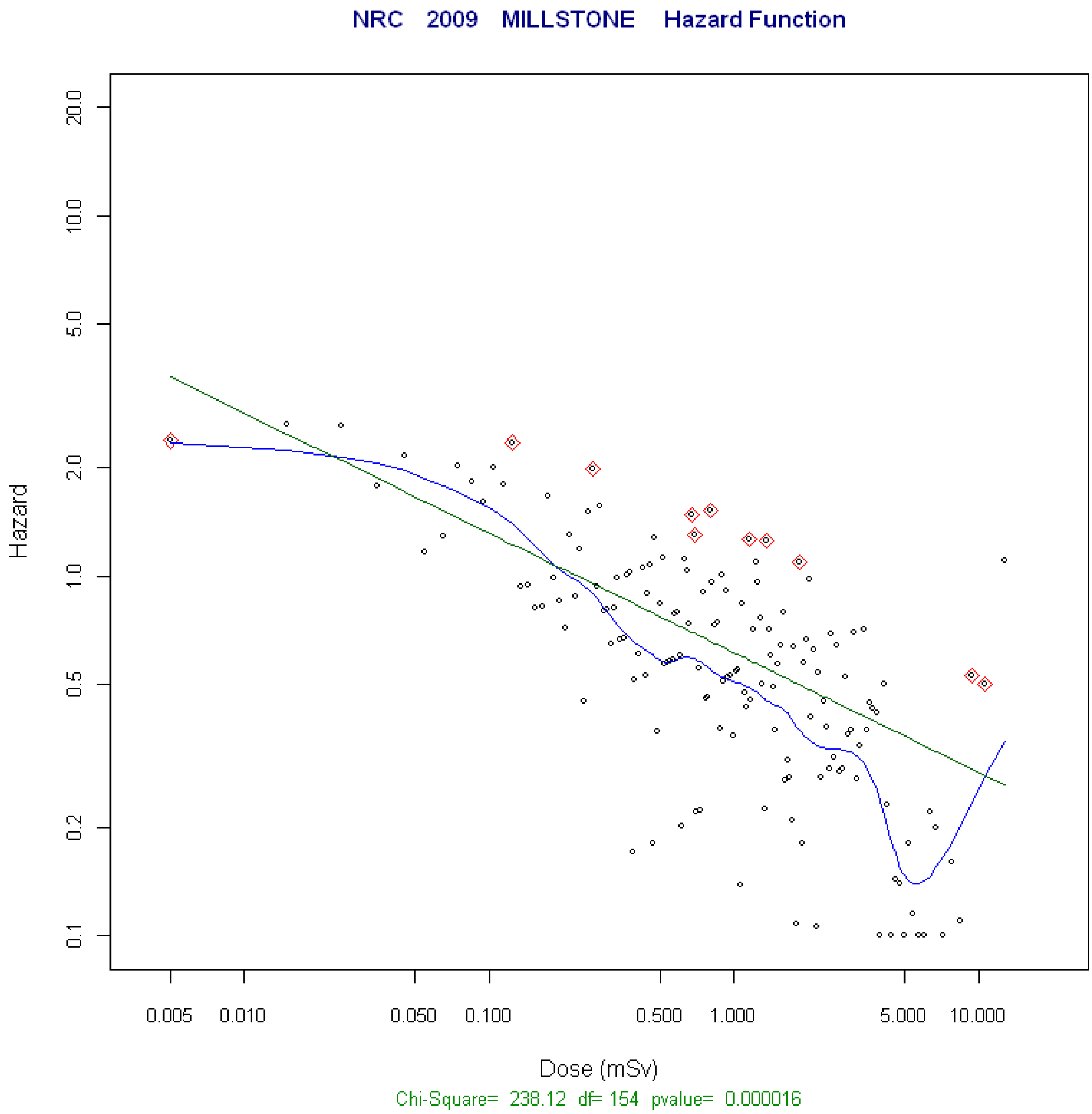

Figure C65: Weibull Goodness of Fit Plot for Millstone.

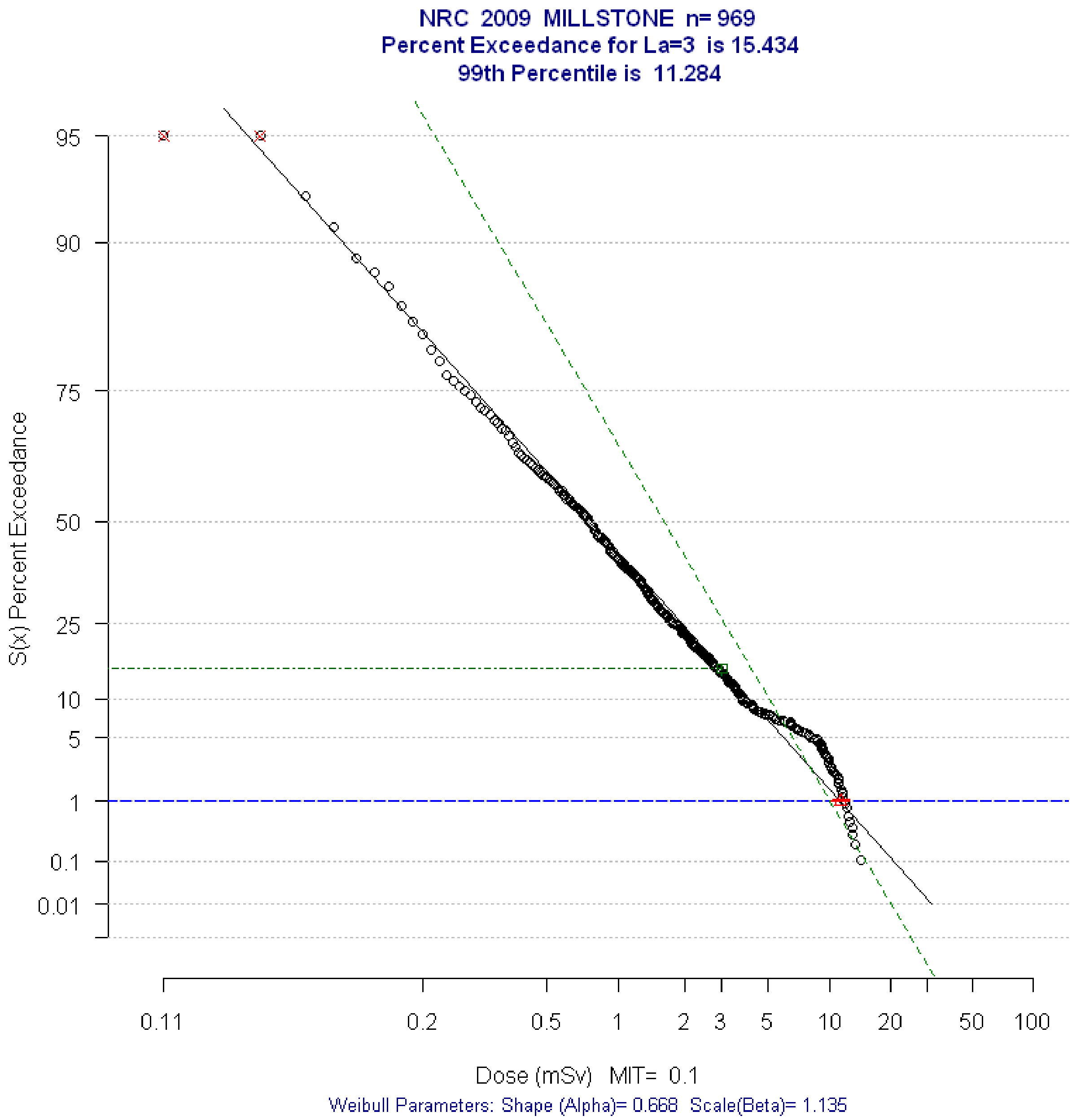

Figure C66: Weibull Probability Plot for Millstone.

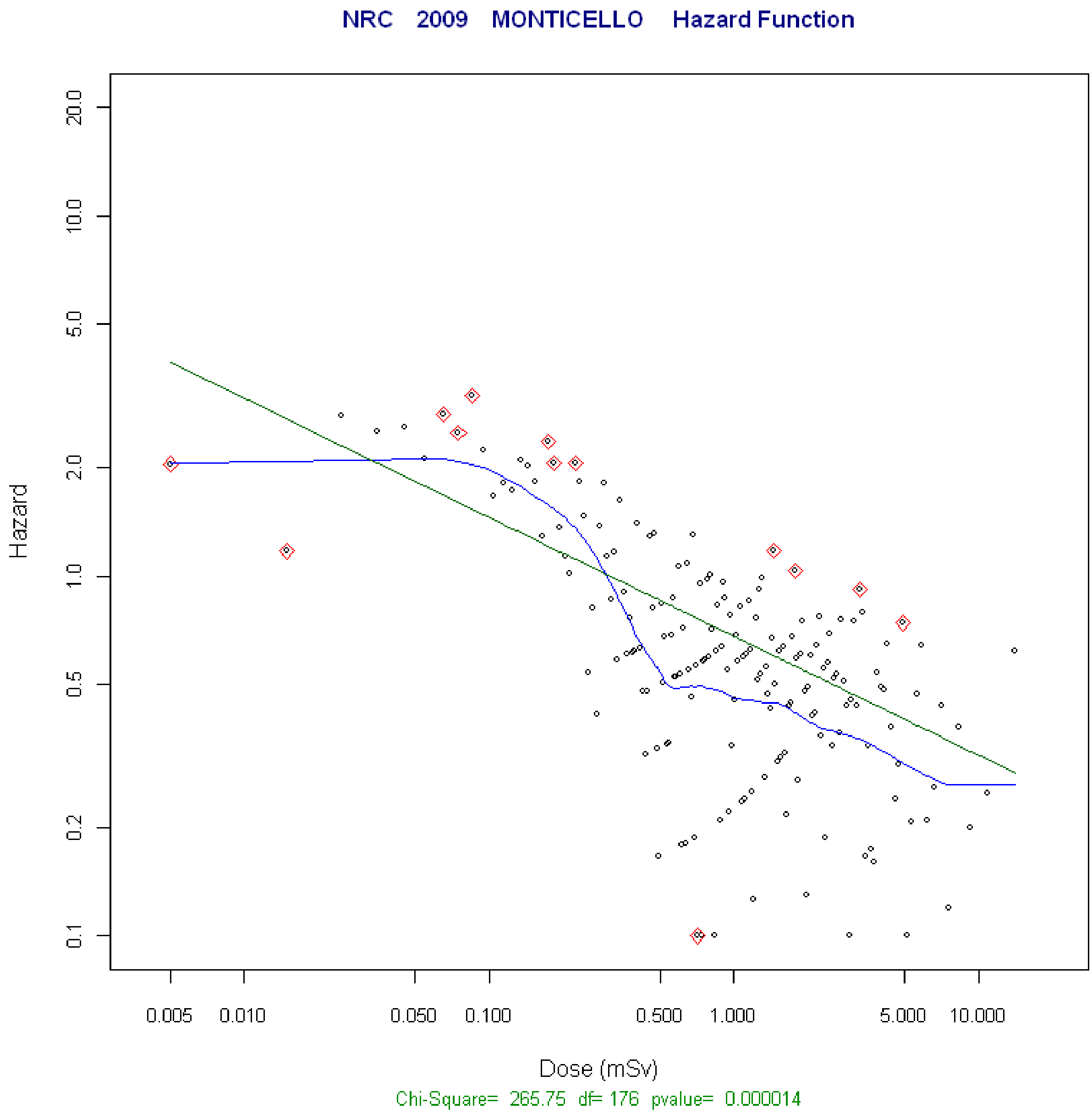

Figure C67: Weibull Goodness of Fit Plot for Monticello.

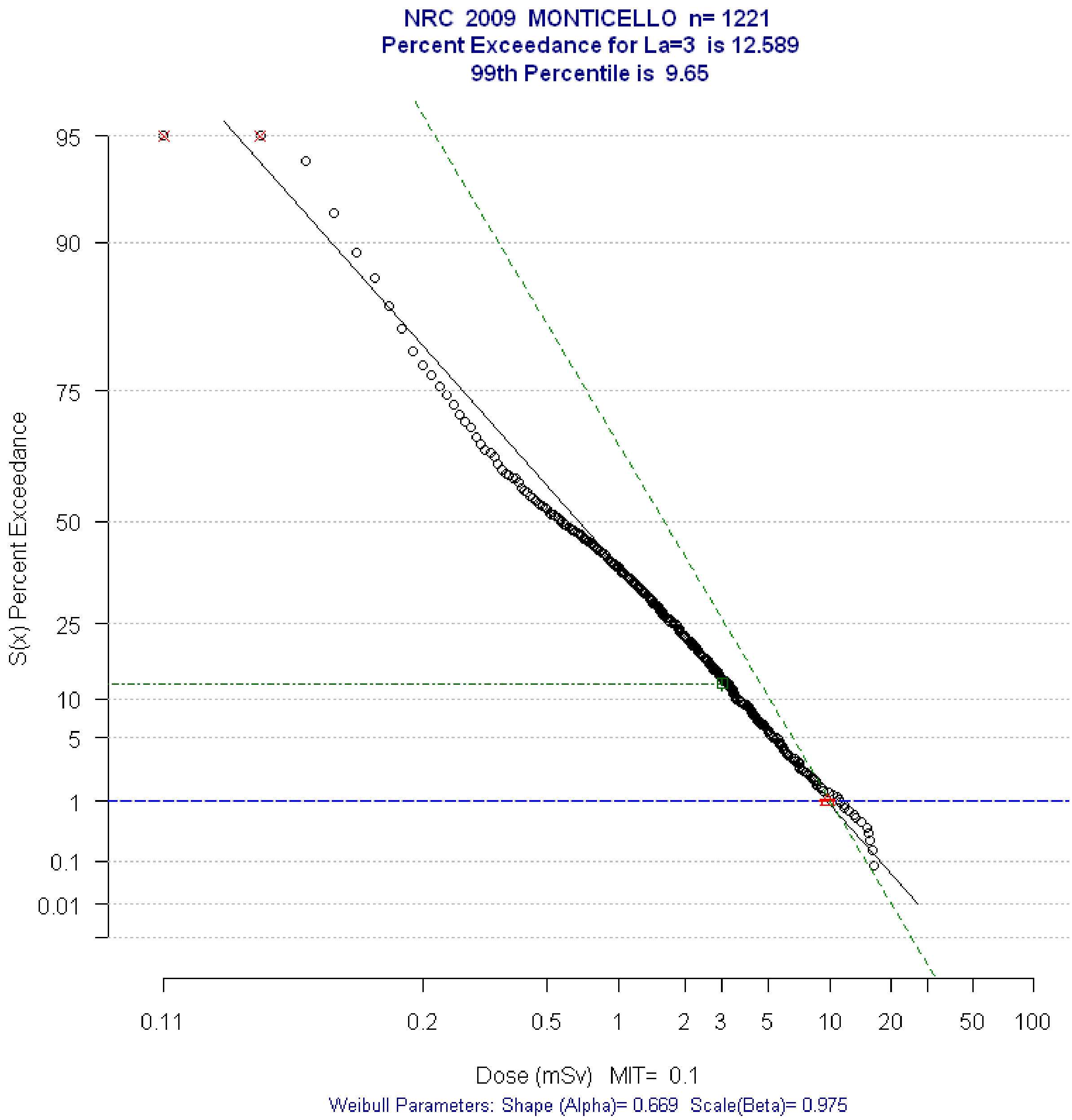

Figure C68: Weibull Probability Plot for Monticello.

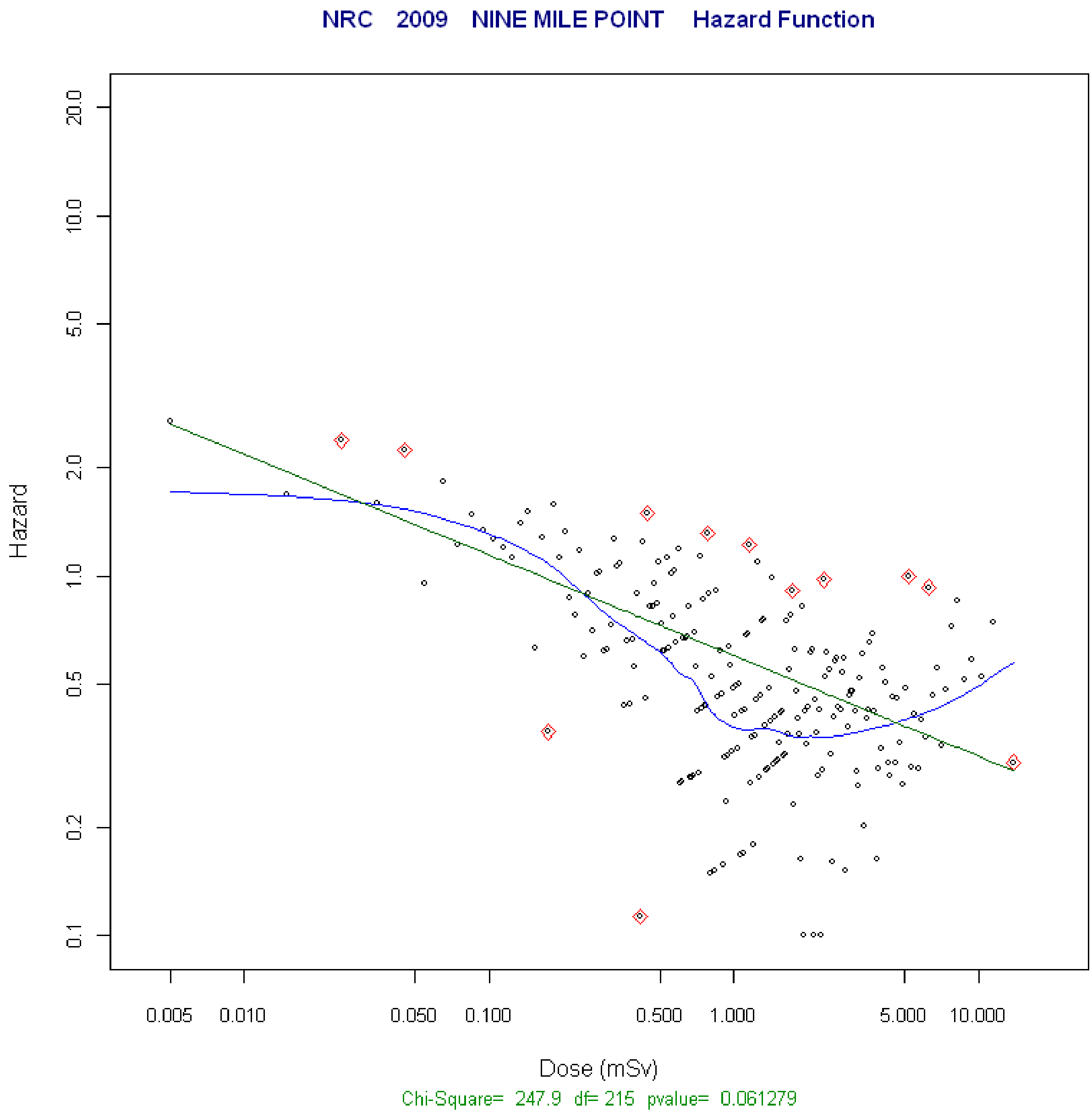

Figure C69: Weibull Goodness of Fit Plot for Nine Mile Point.

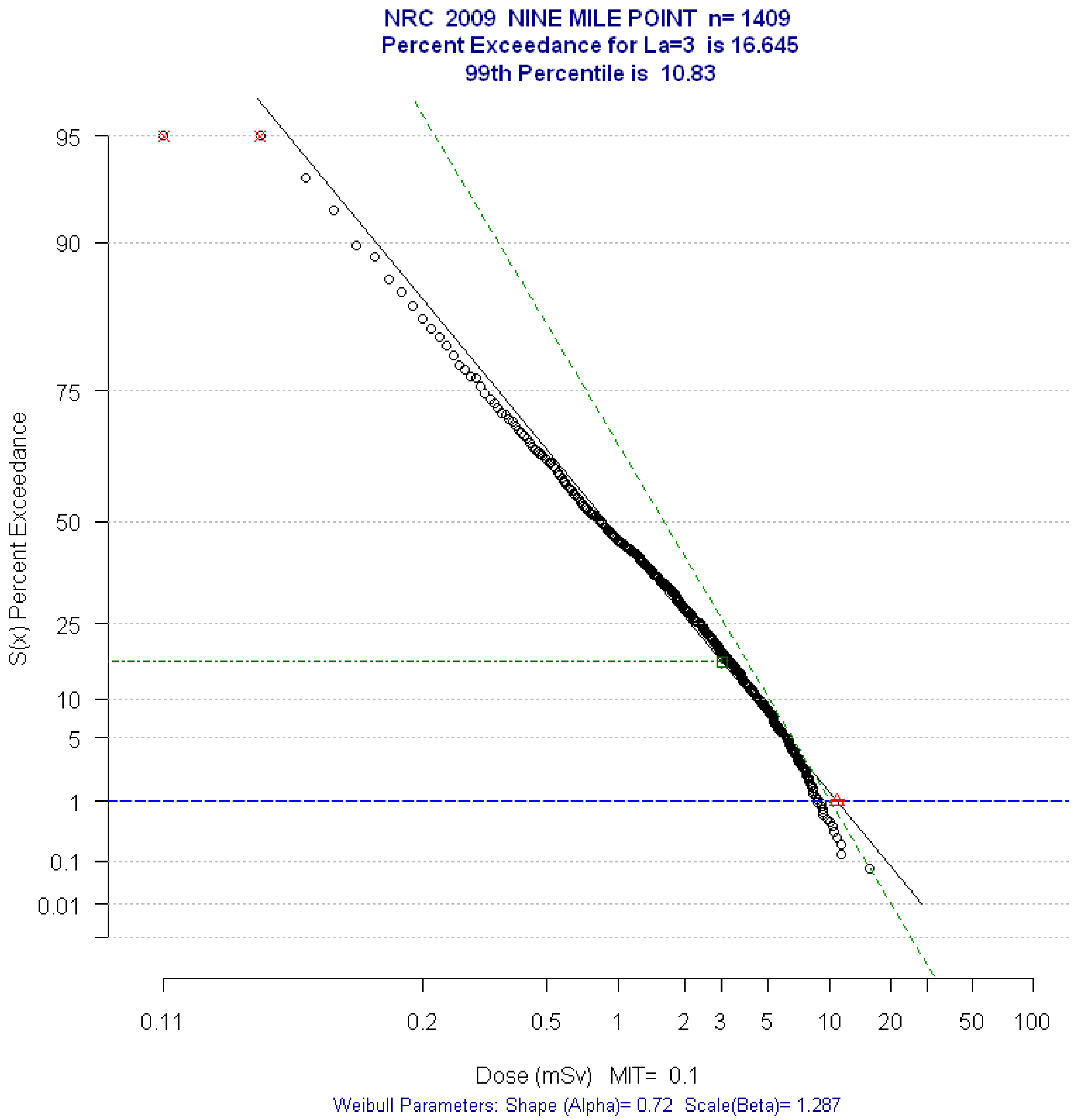

Figure C70: Weibull Probability Plot for Nine Mile Point.

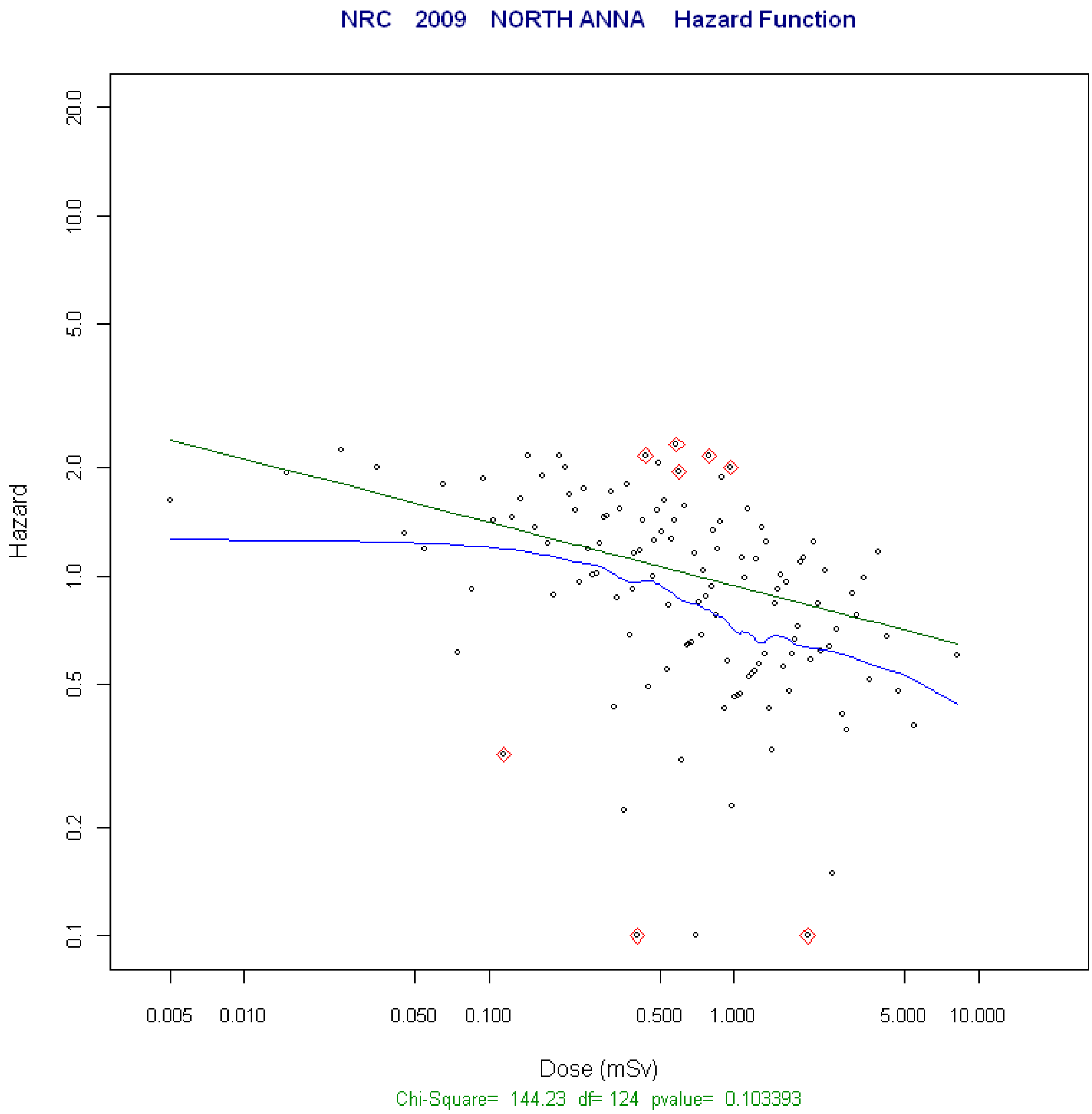

Figure C71: Weibull Goodness of Fit Plot for North Anna.

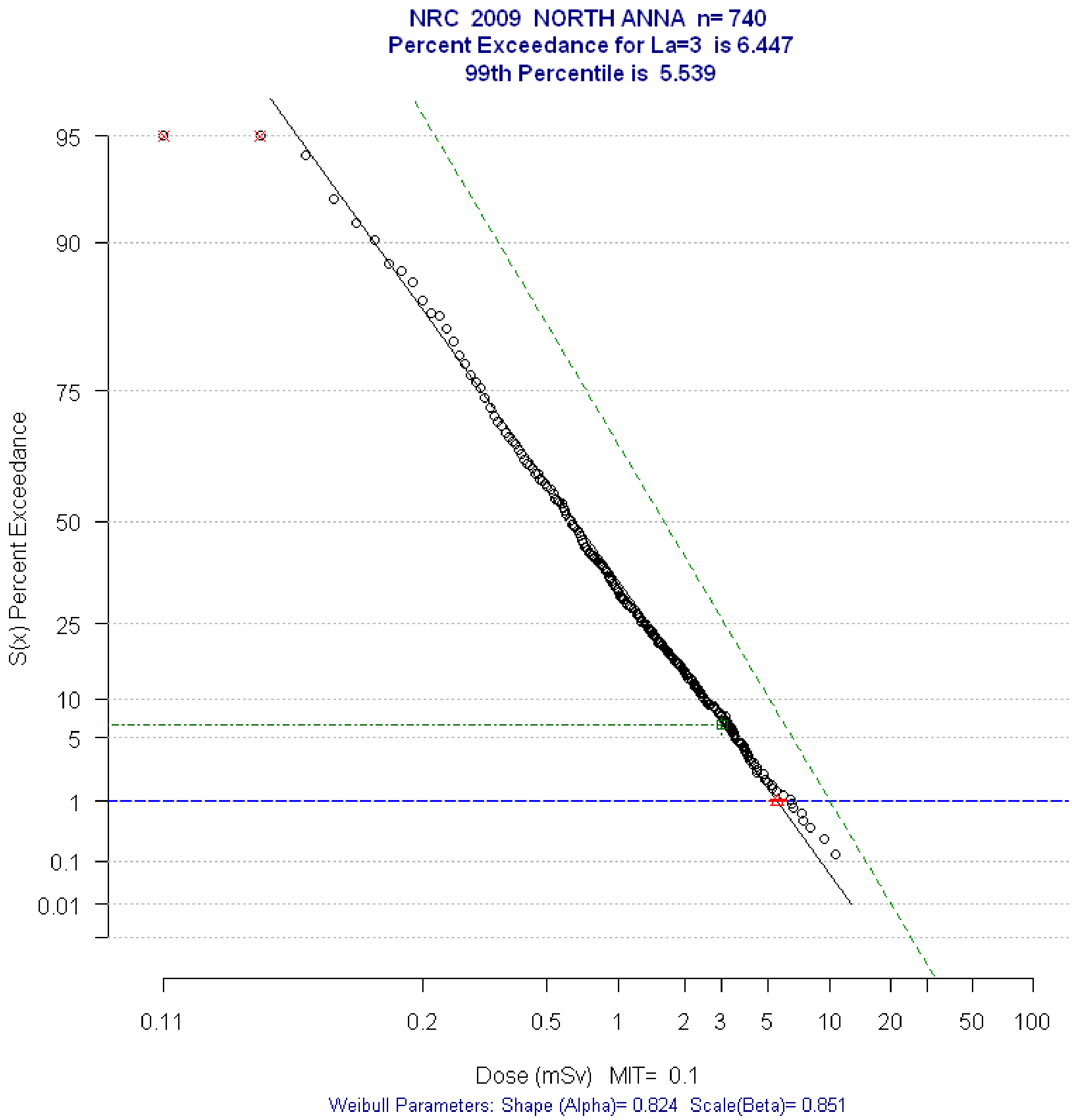

Figure C72: Weibull Probability Plot for North Anna.

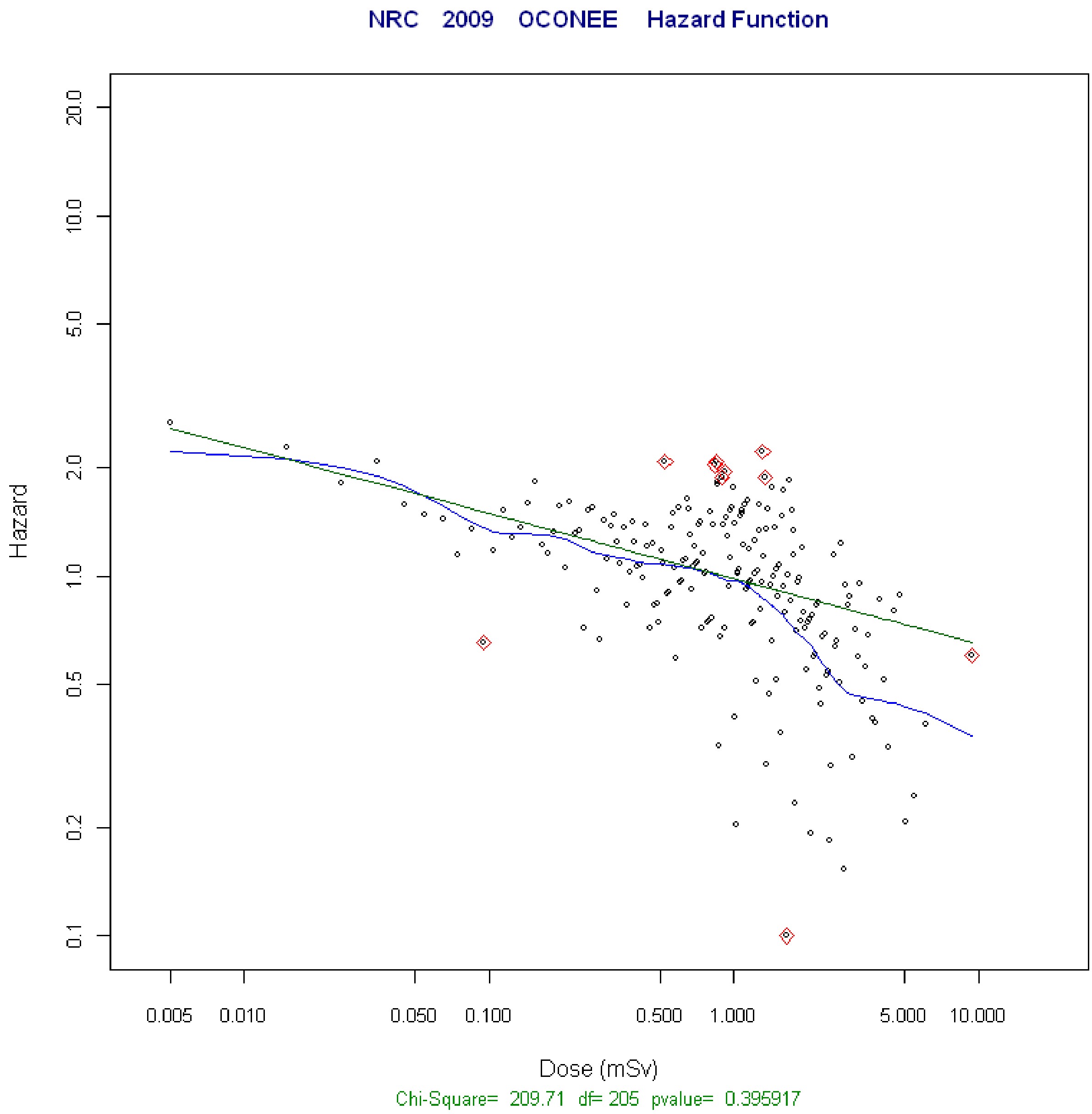

Figure C73: Weibull Goodness of Fit Plot for Oconee.

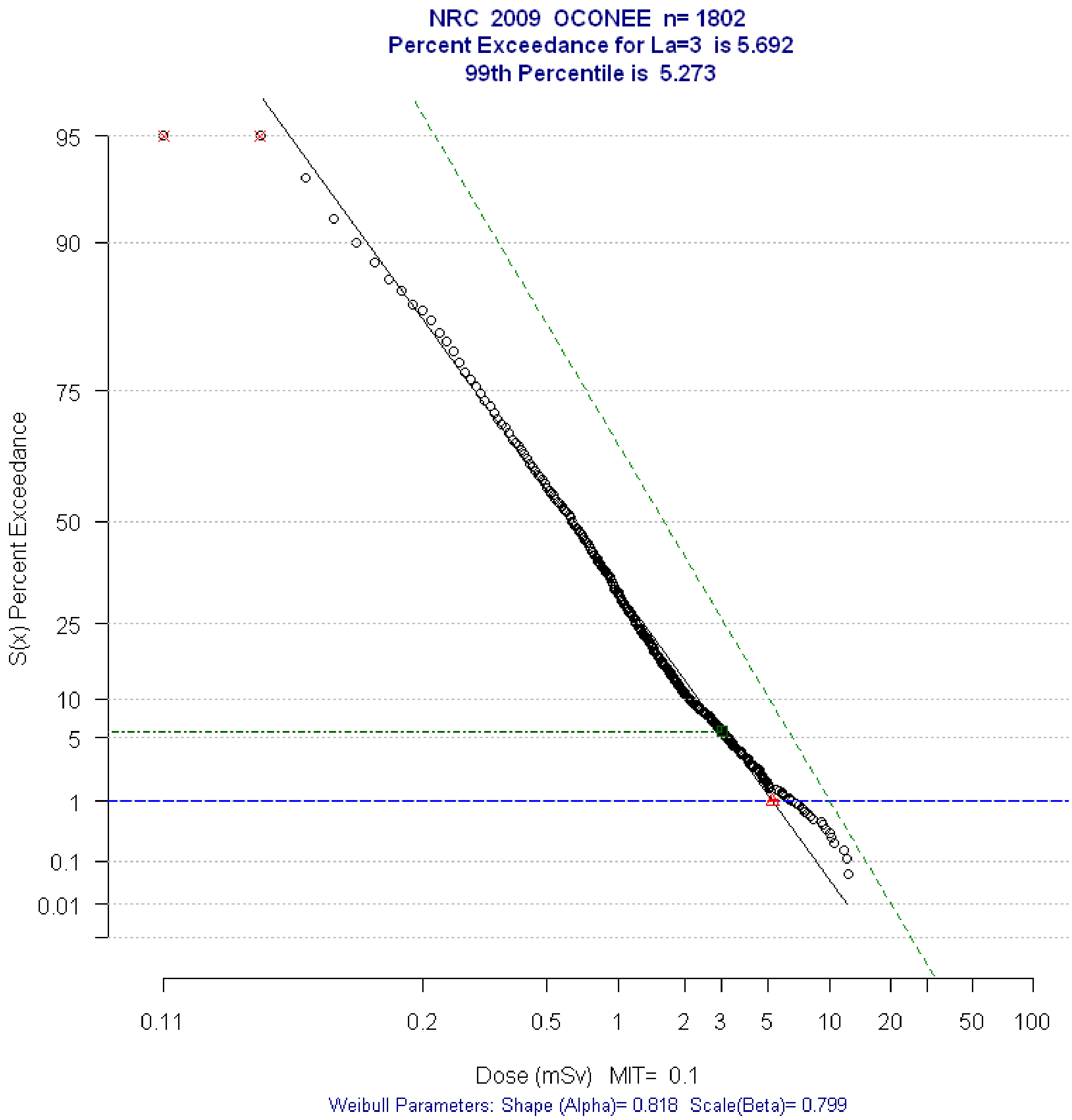

Figure C74: Weibull Probability Plot for Oconee.

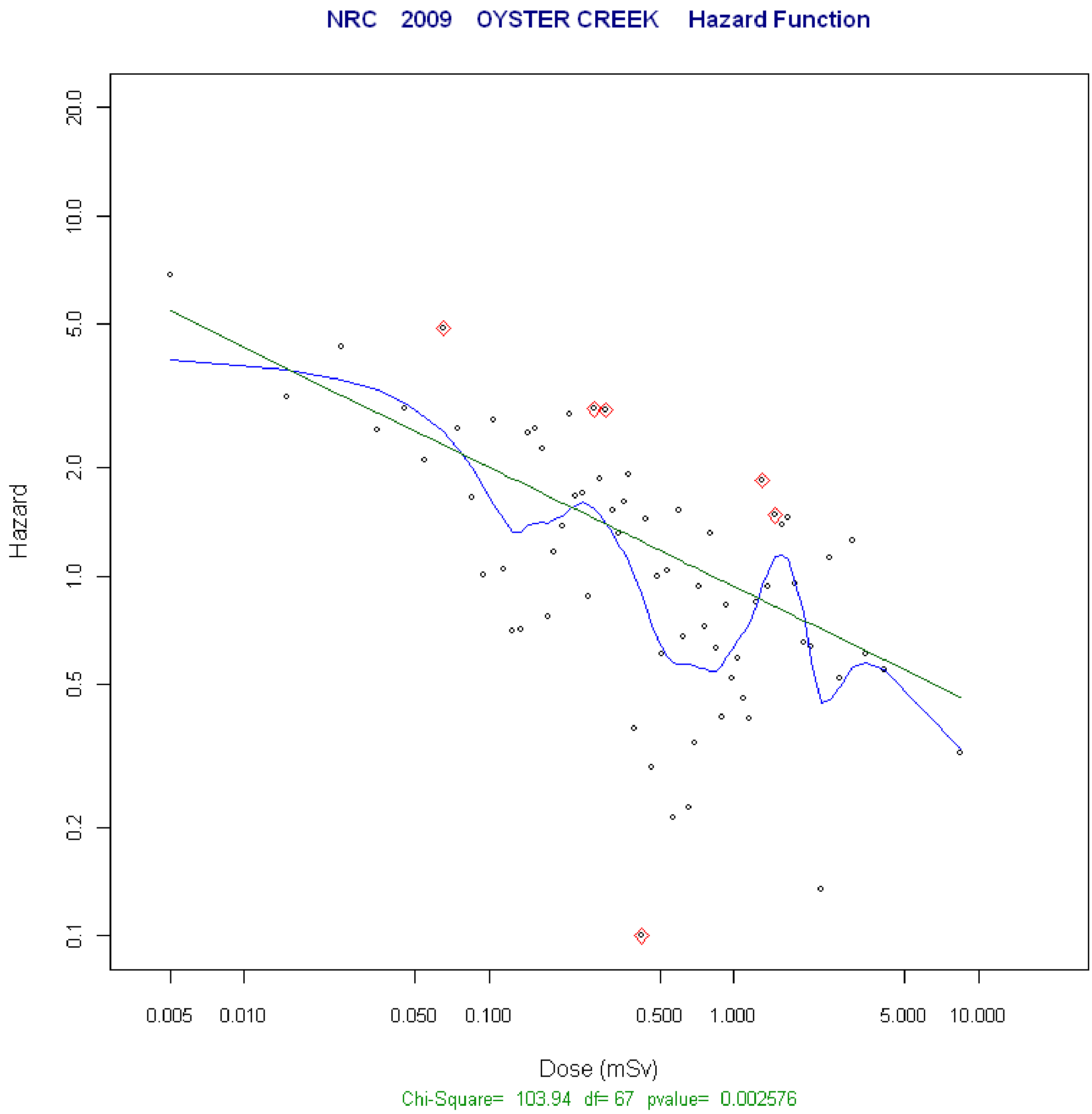

Figure C75: Weibull Goodness of Fit Plot for Oyster Creek.

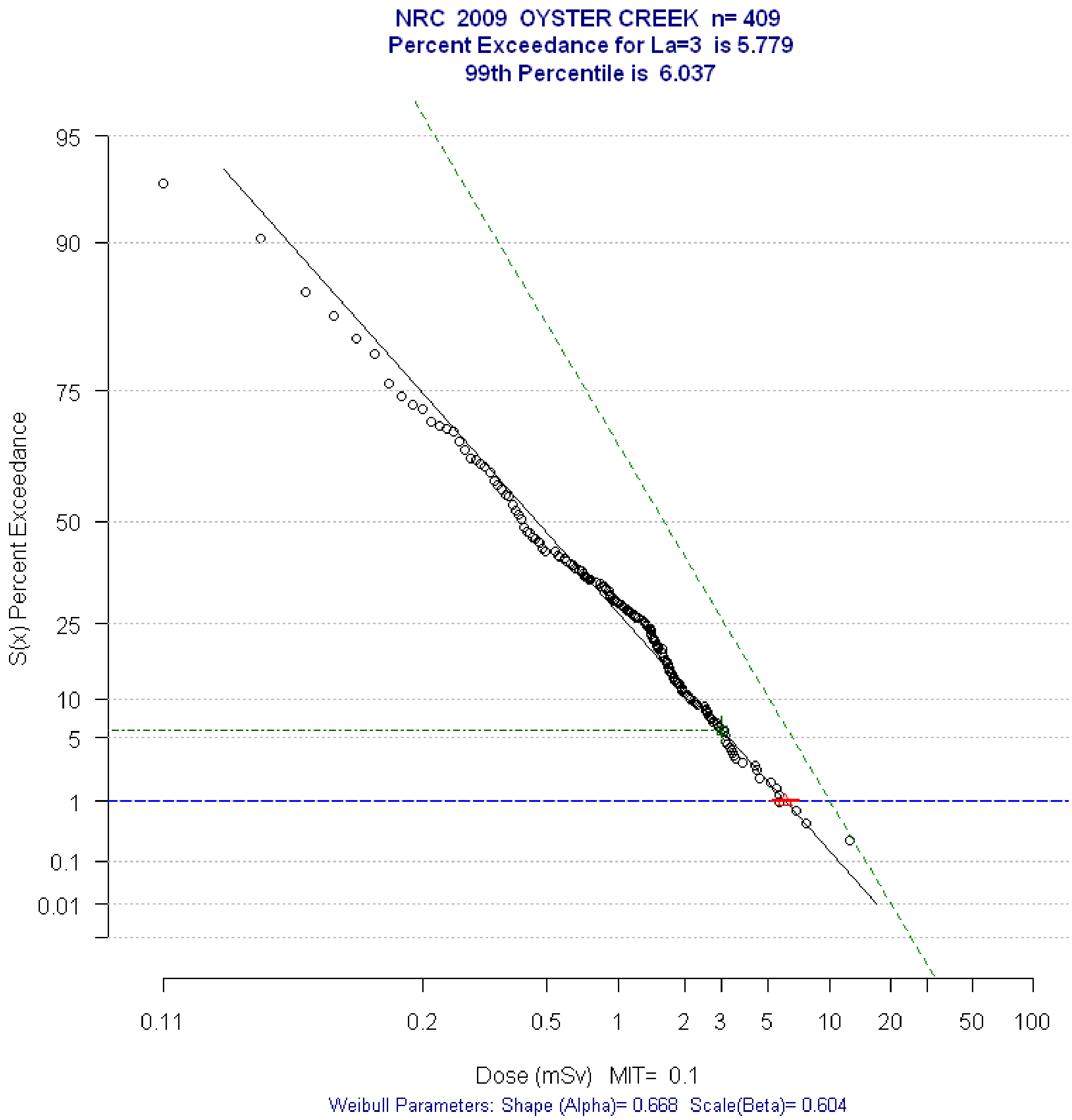

Figure C76: Weibull Probability Plot for Oyster Creek.

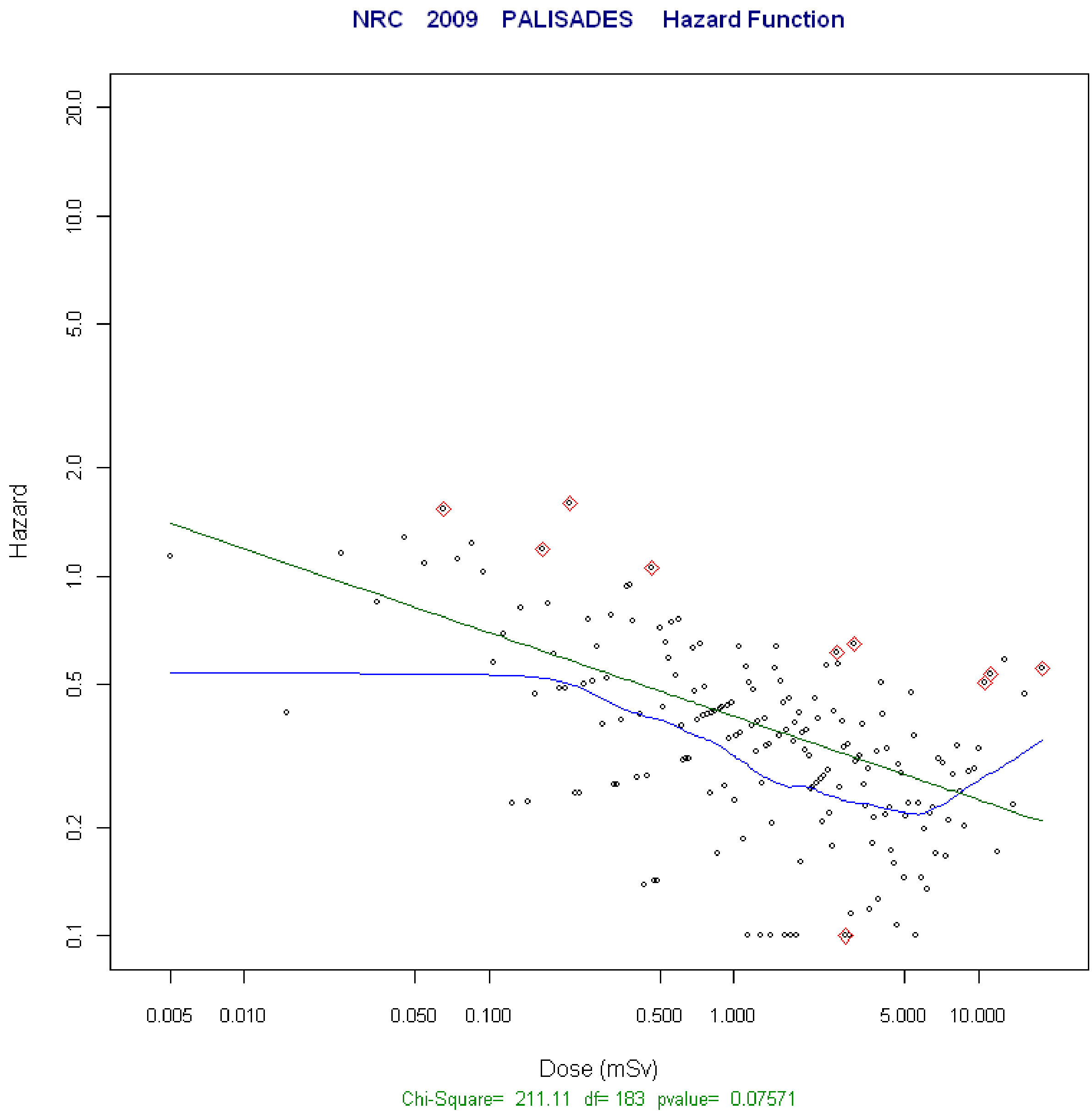

Figure C77: Weibull Goodness of Fit Plot for Palisades.

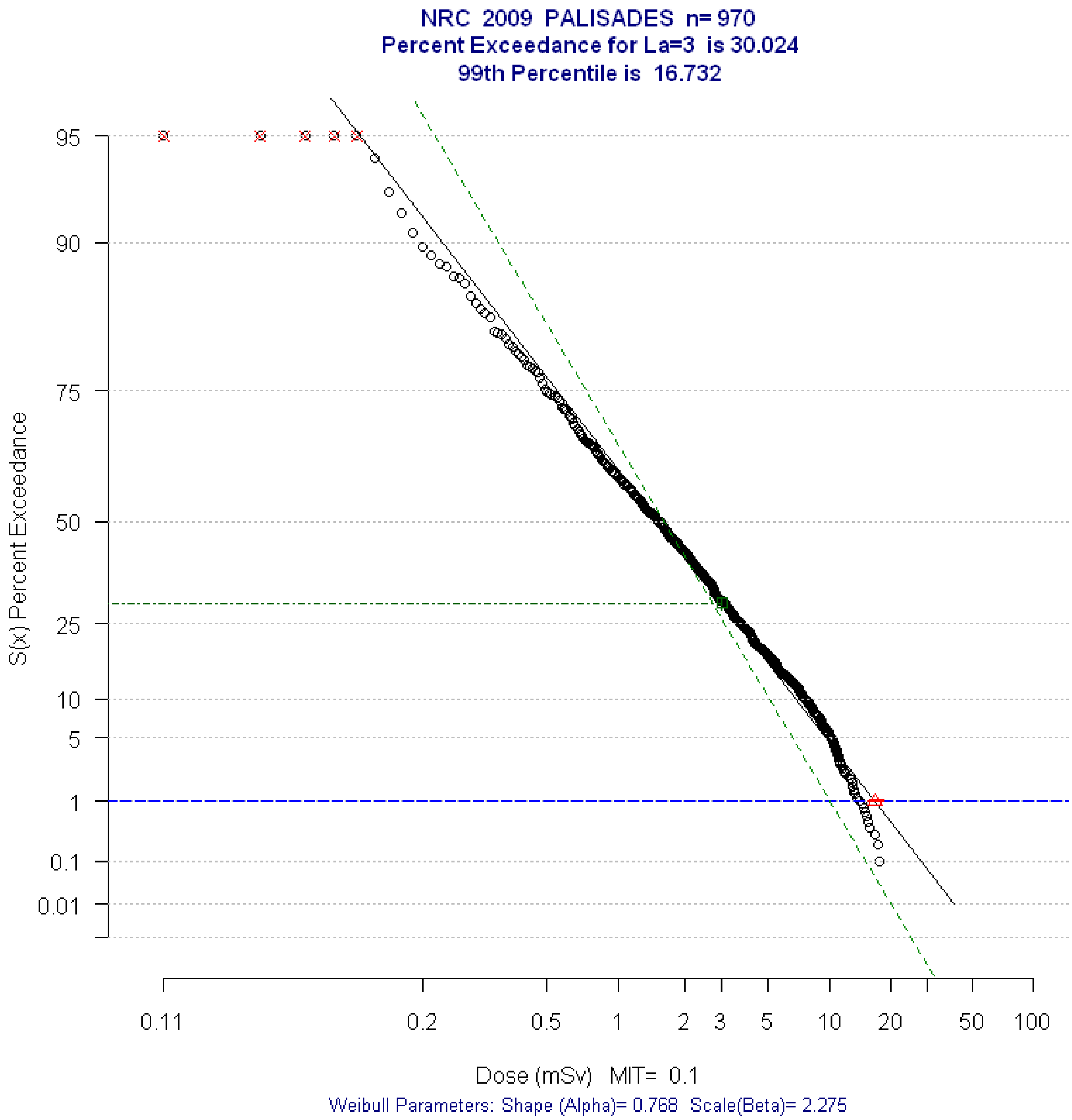

Figure C78: Weibull Probability Plot for Palisades.

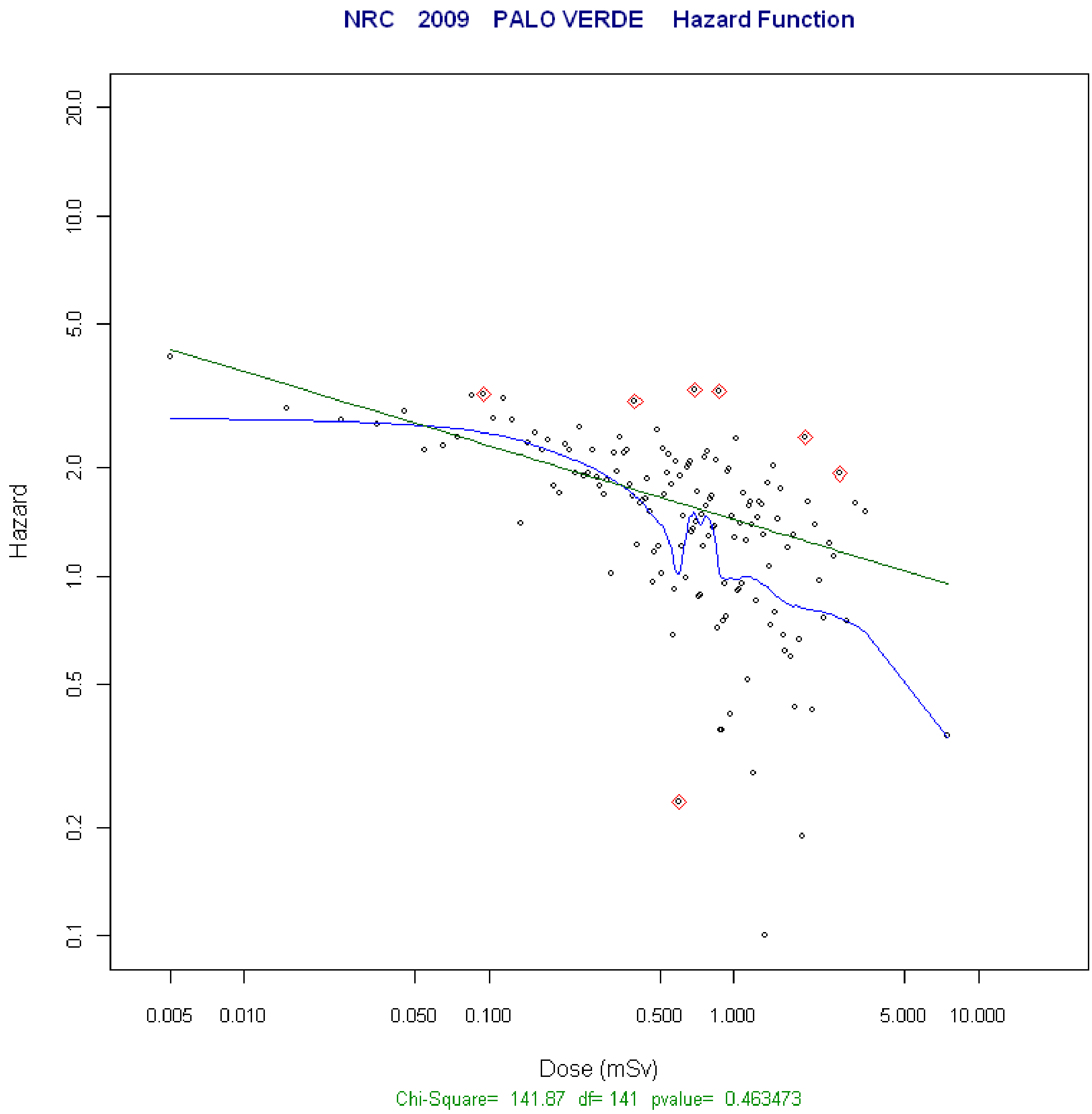

Figure C79: Weibull Goodness of Fit Plot for Palo Verde.

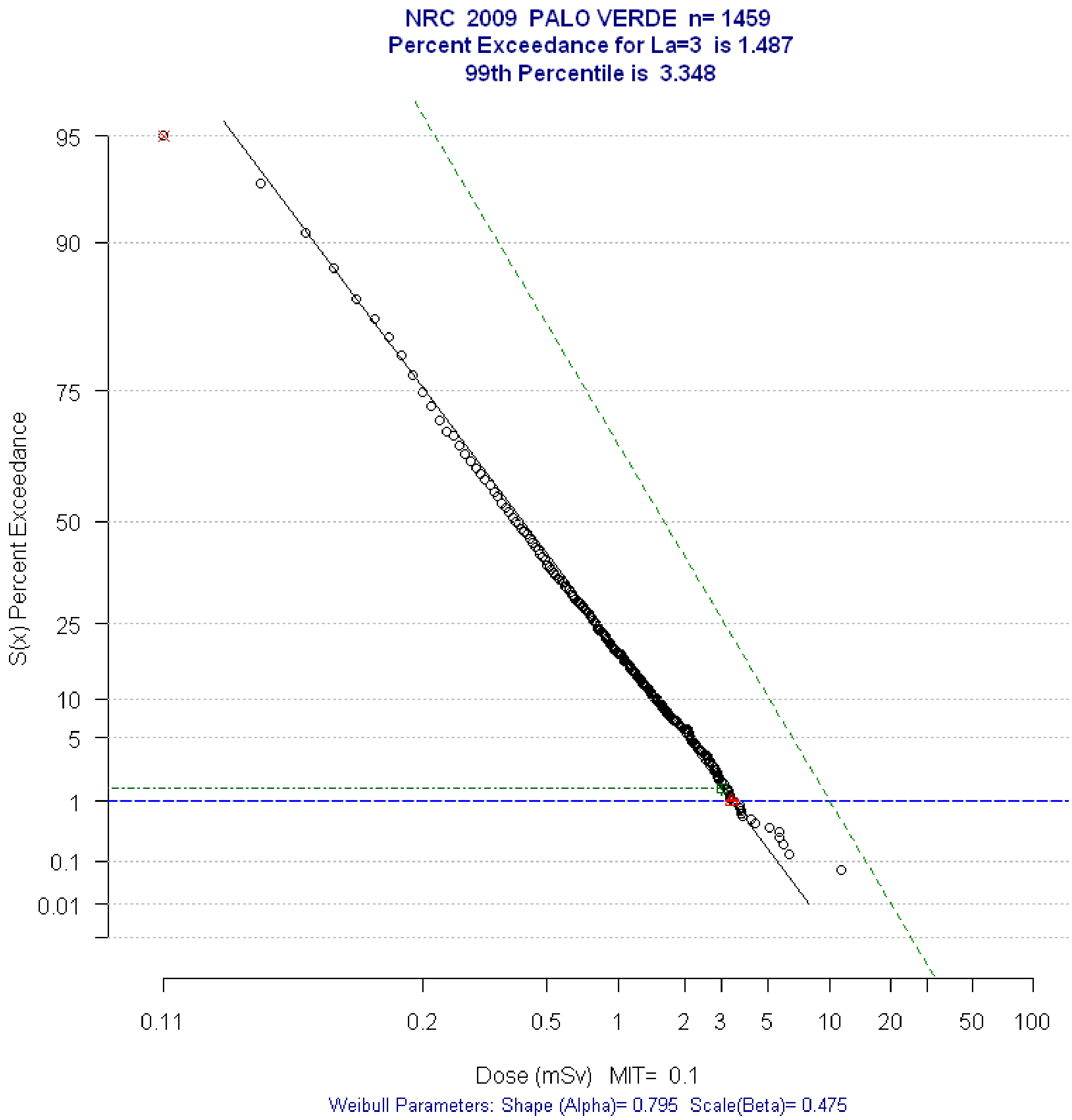

Figure C80: Weibull Probability Plot for Palo Verde.

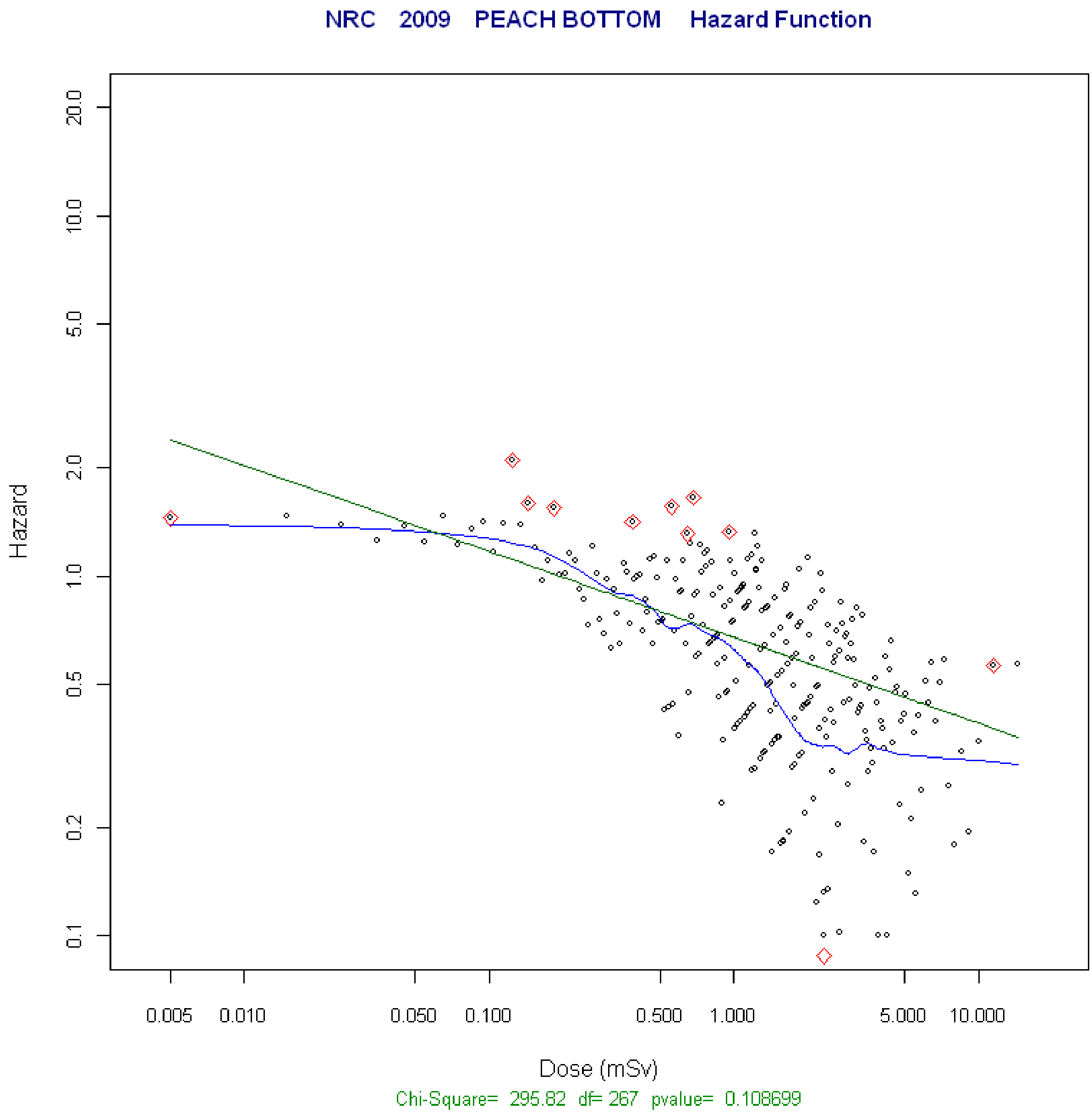

Figure C81: Weibull Goodness of Fit Plot for Peach Bottom.

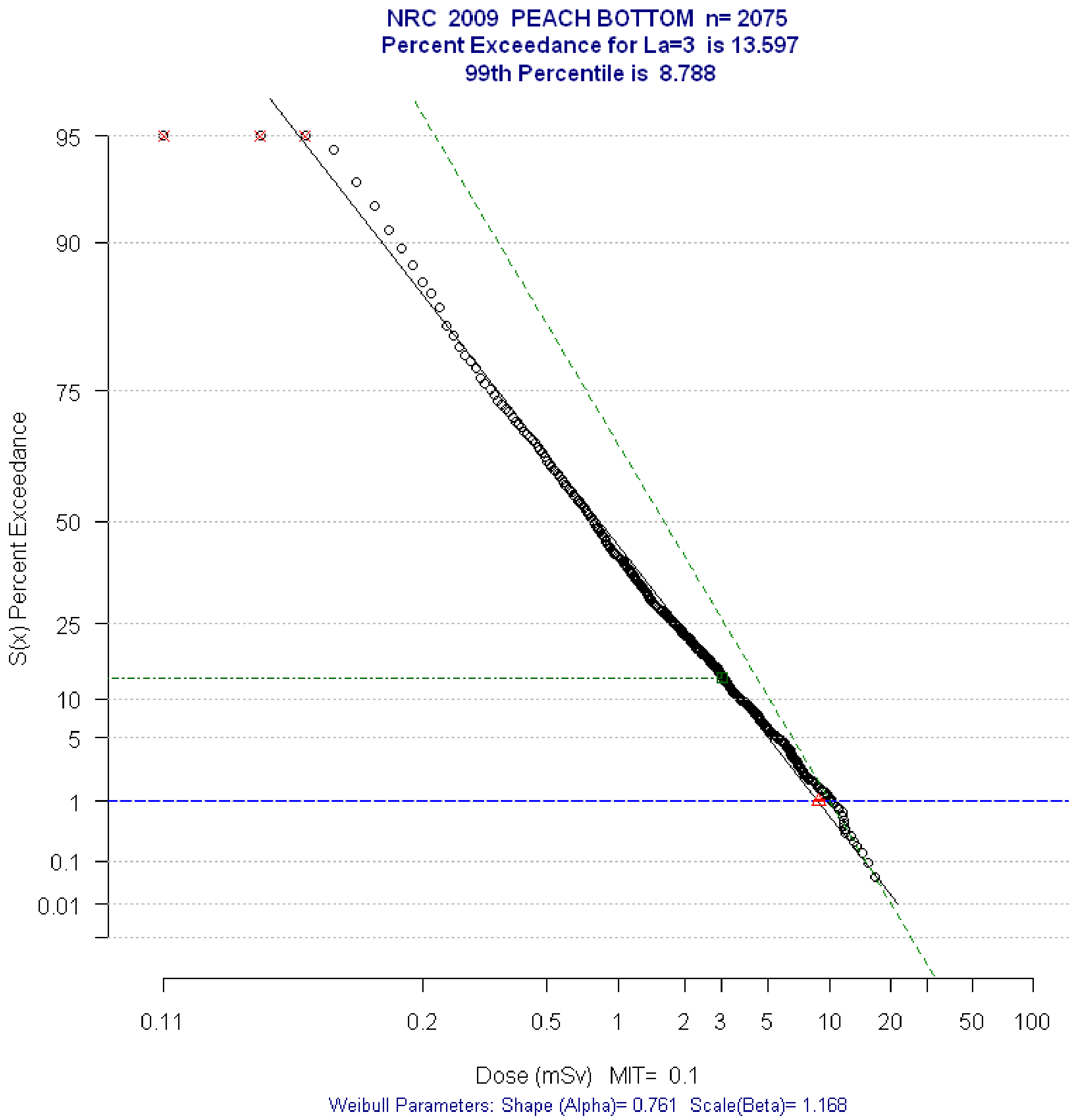

Figure C82: Weibull Probability Plot for Peach Bottom.

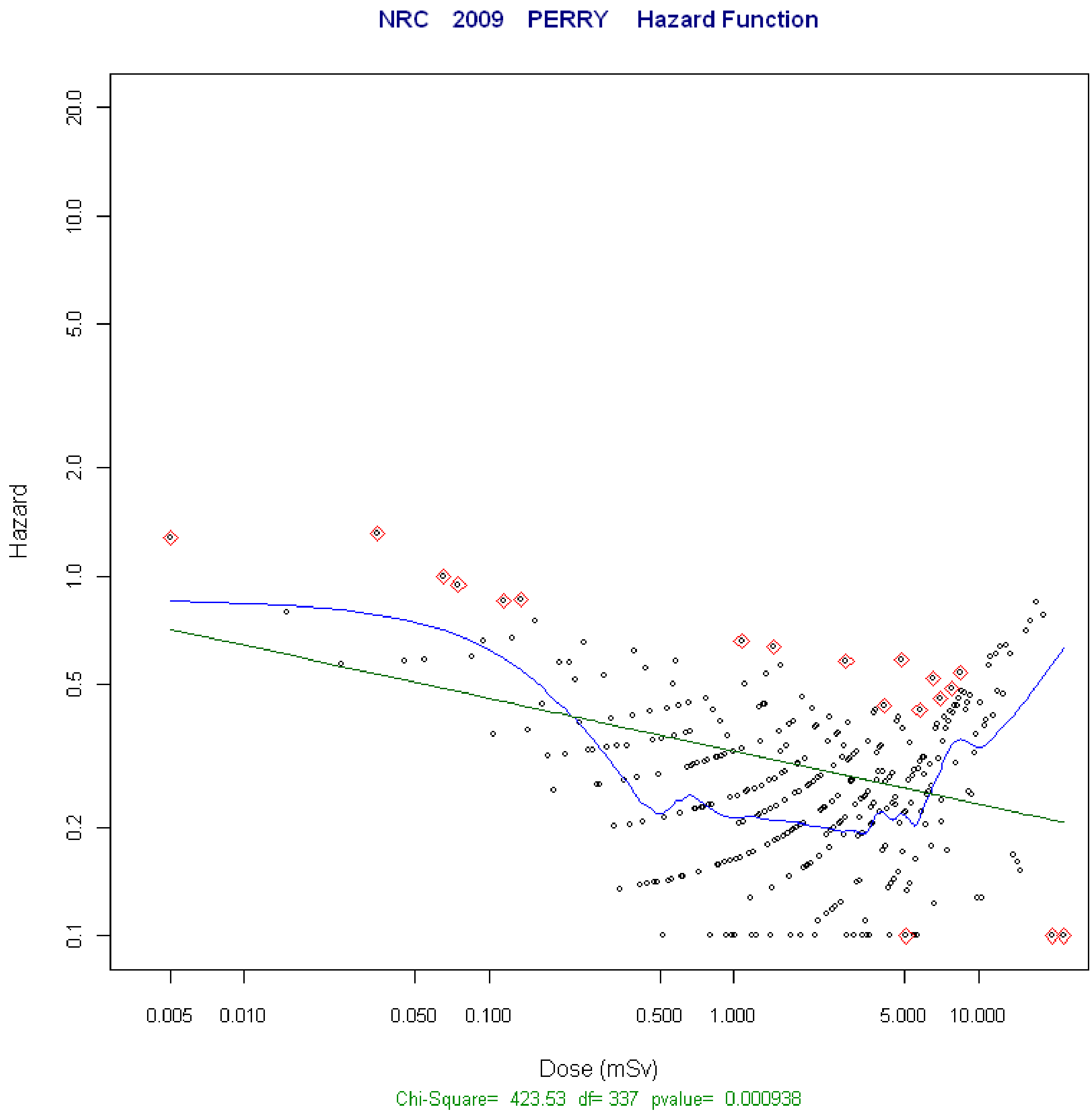

Figure C83: Weibull Goodness of Fit Plot for Perry.

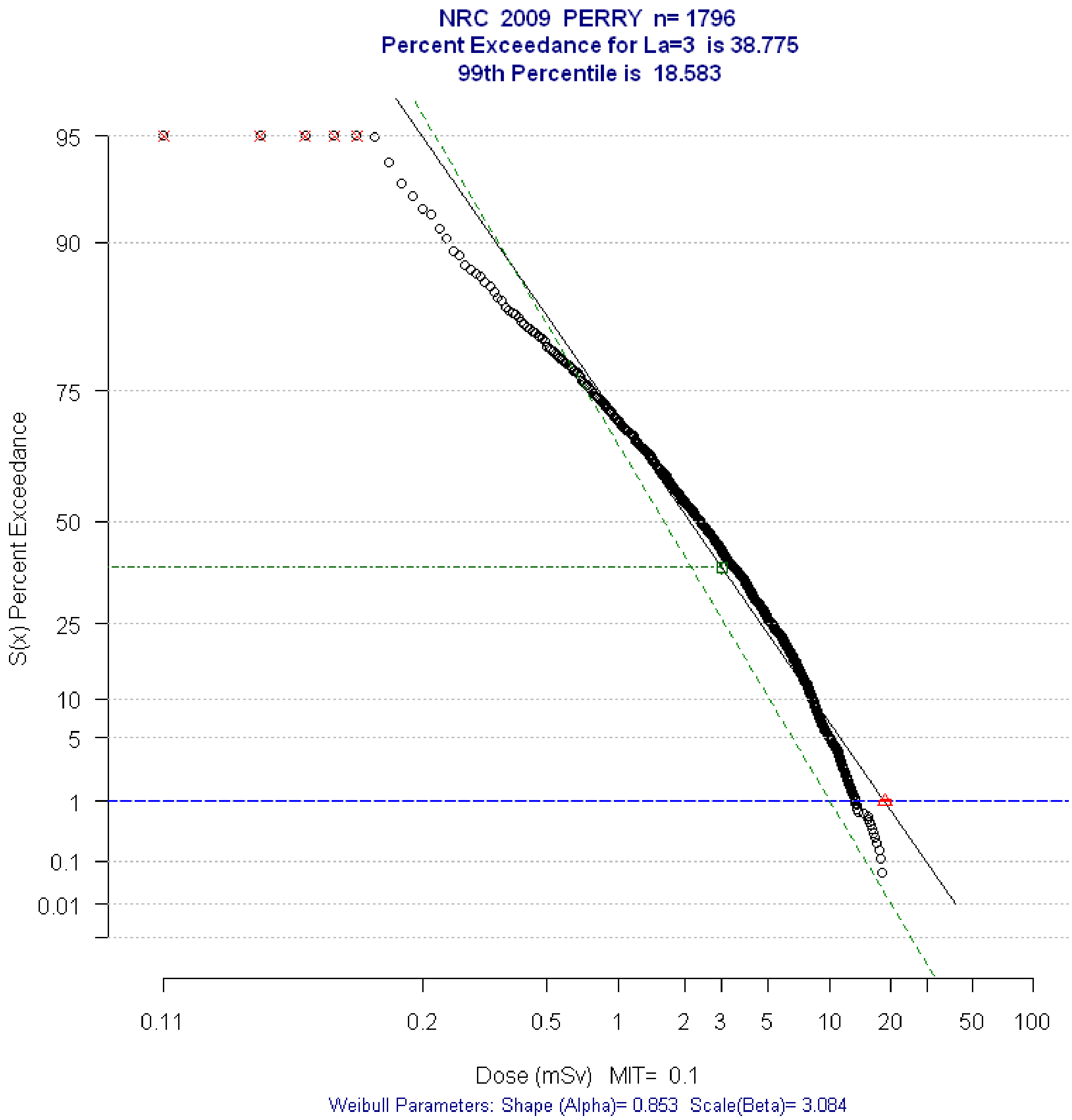

Figure C84: Weibull Probability Plot for Perry.

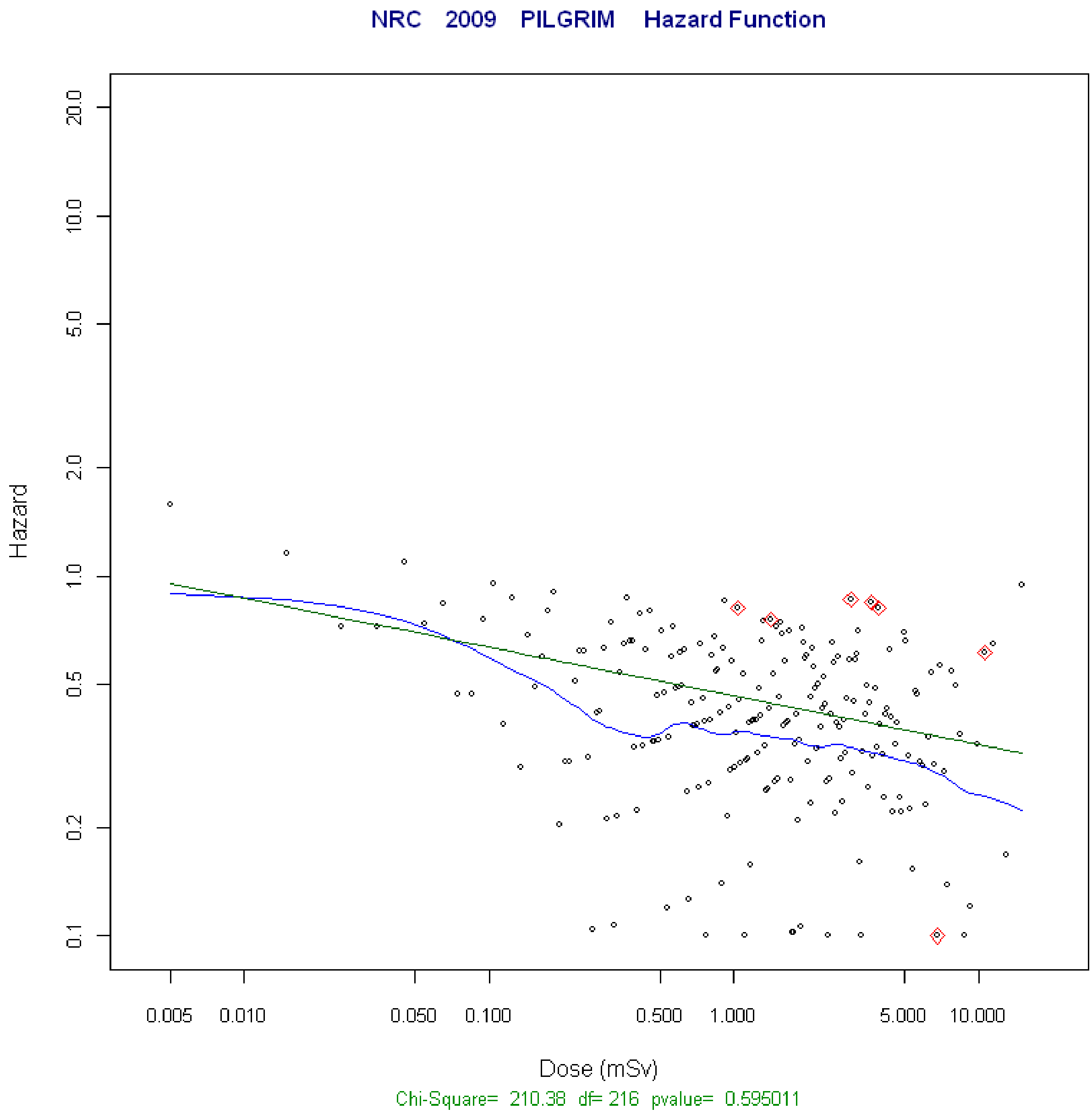

Figure C85: Weibull Goodness of Fit Plot for Pilgrim.

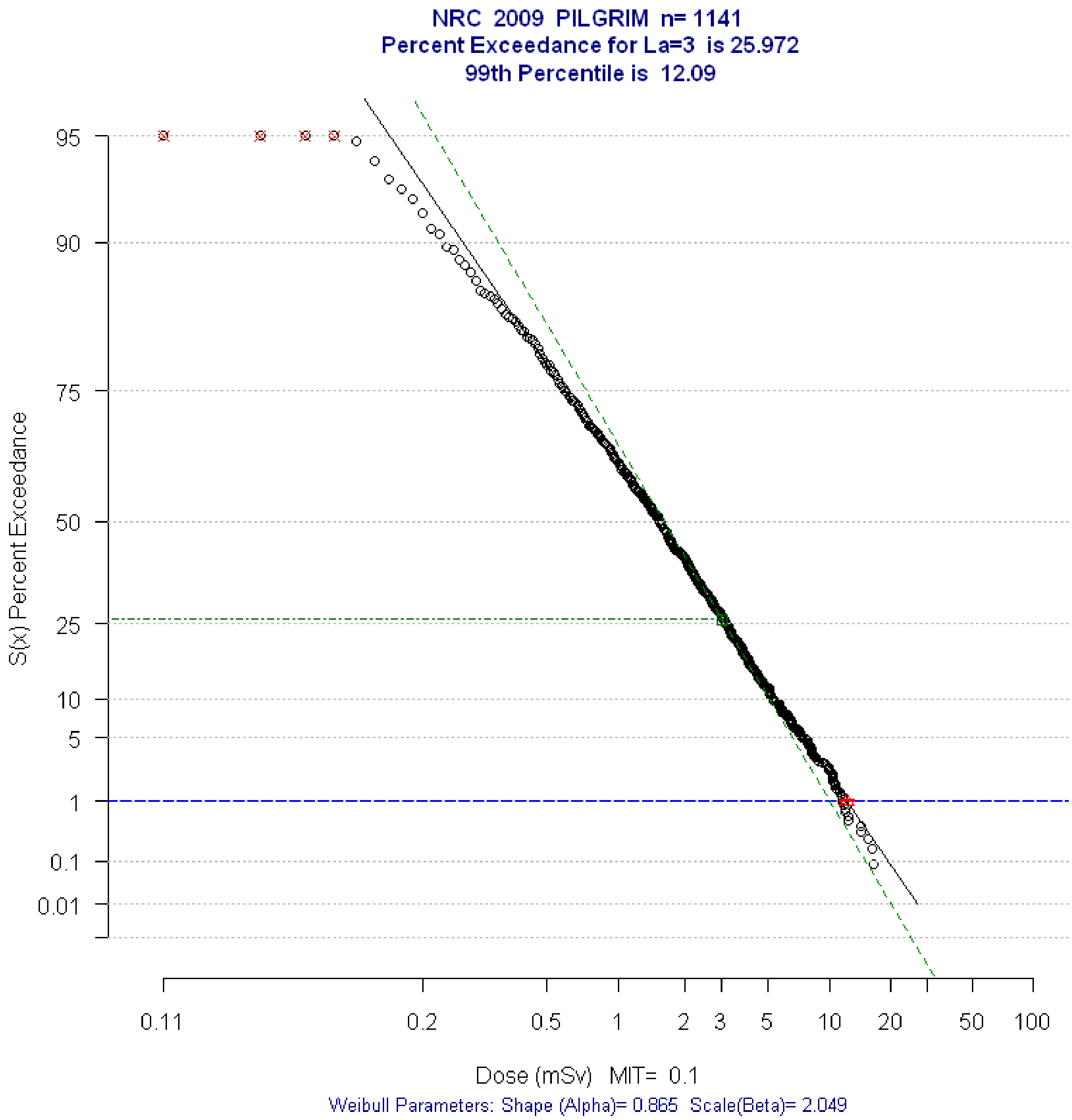

Figure C86: Weibull Probability Plot for Pilgrim.

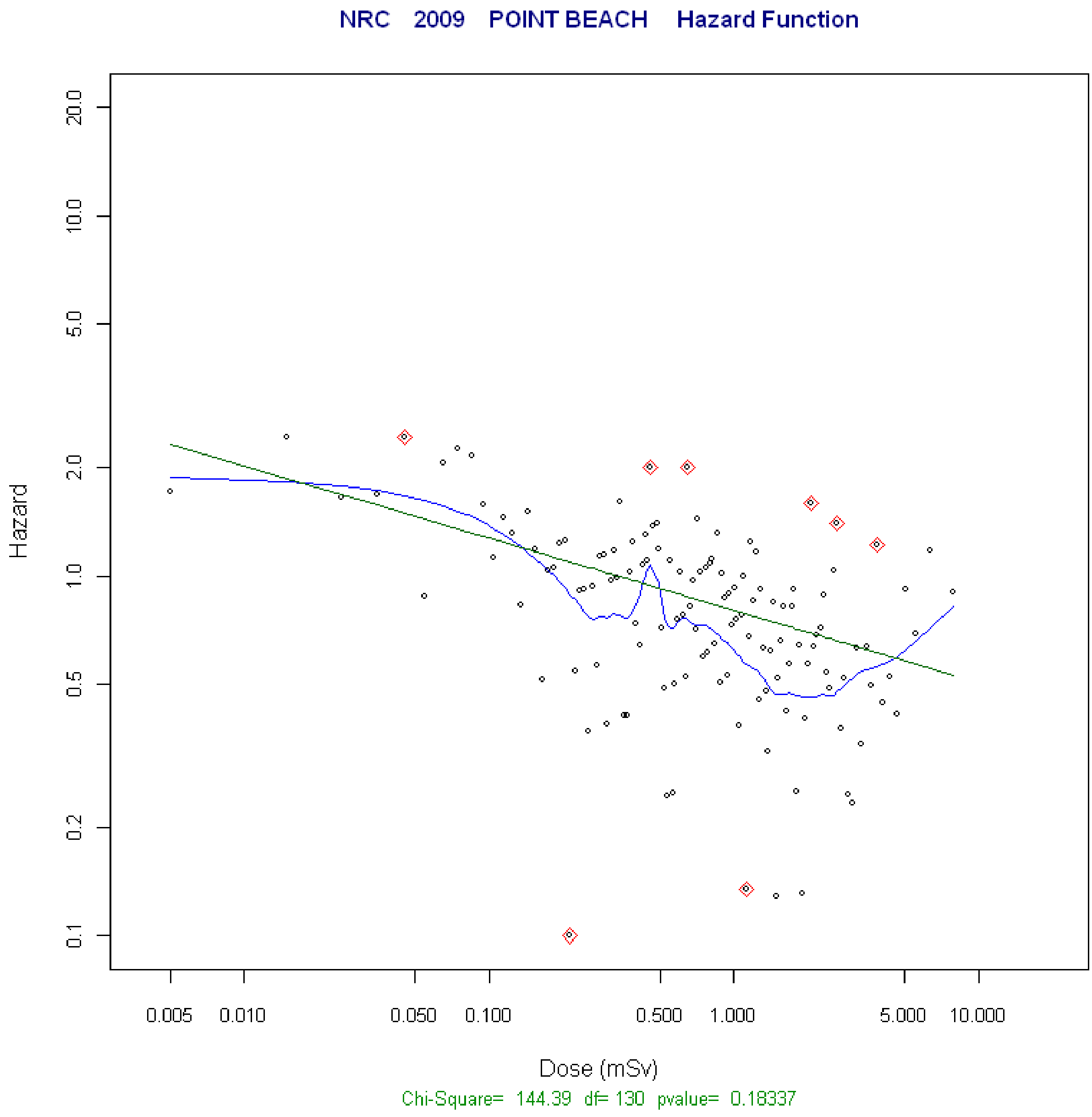

Figure C87: Weibull Goodness of Fit Plot for Point Beach.

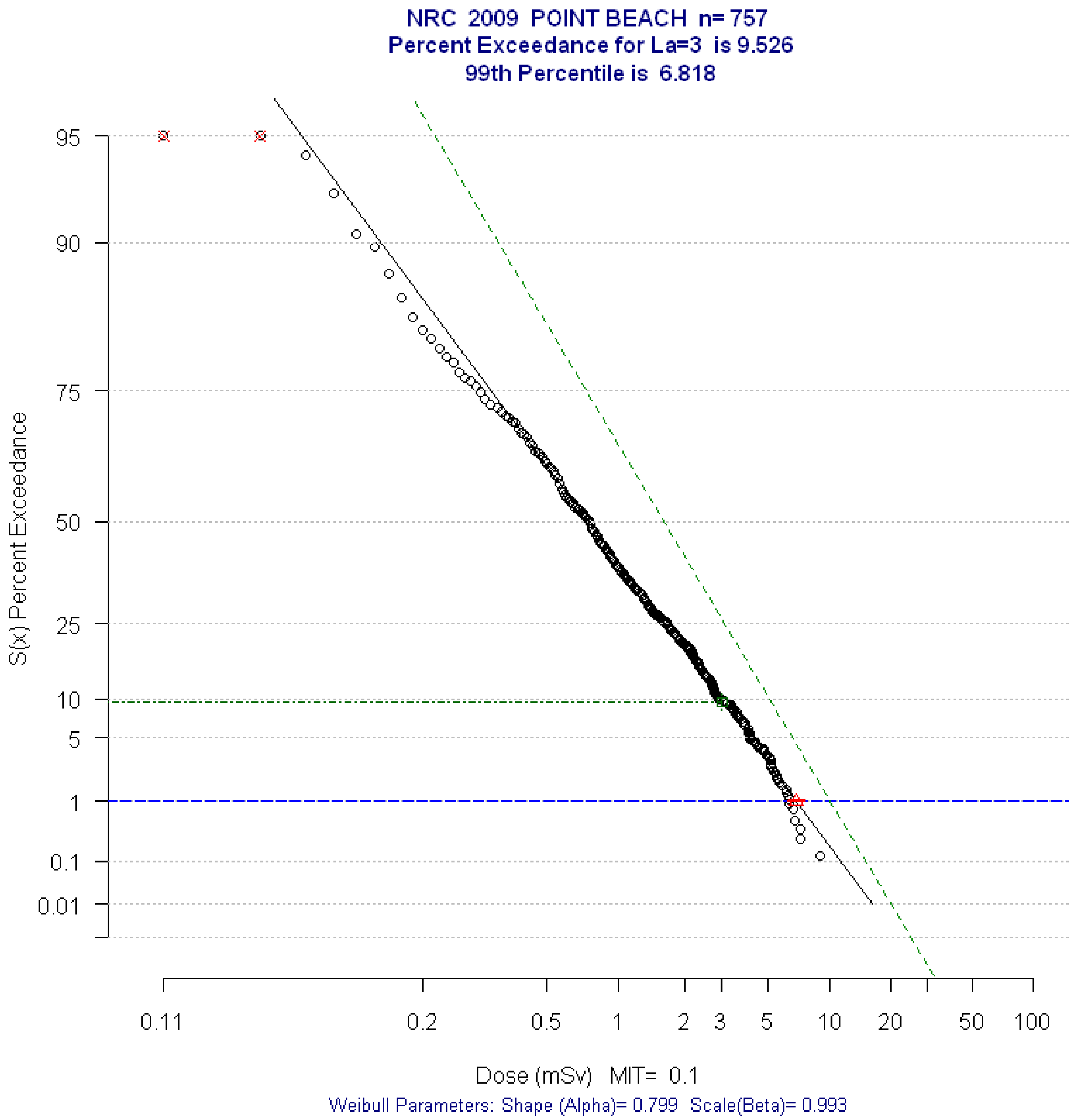

Figure C88: Weibull Probability Plot for Point Beach.

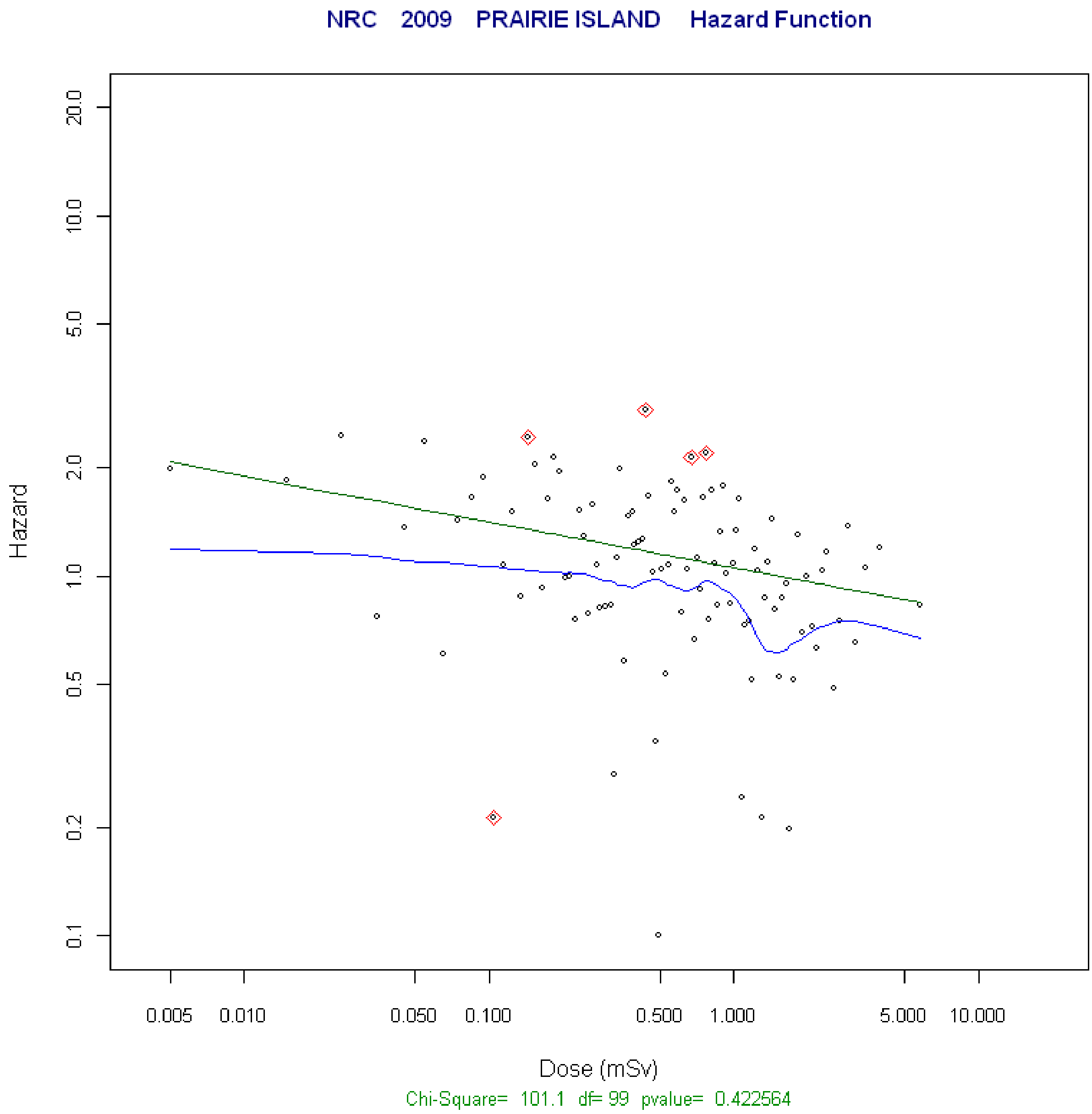

Figure C89: Weibull Goodness of Fit Plot for Prairie Island.

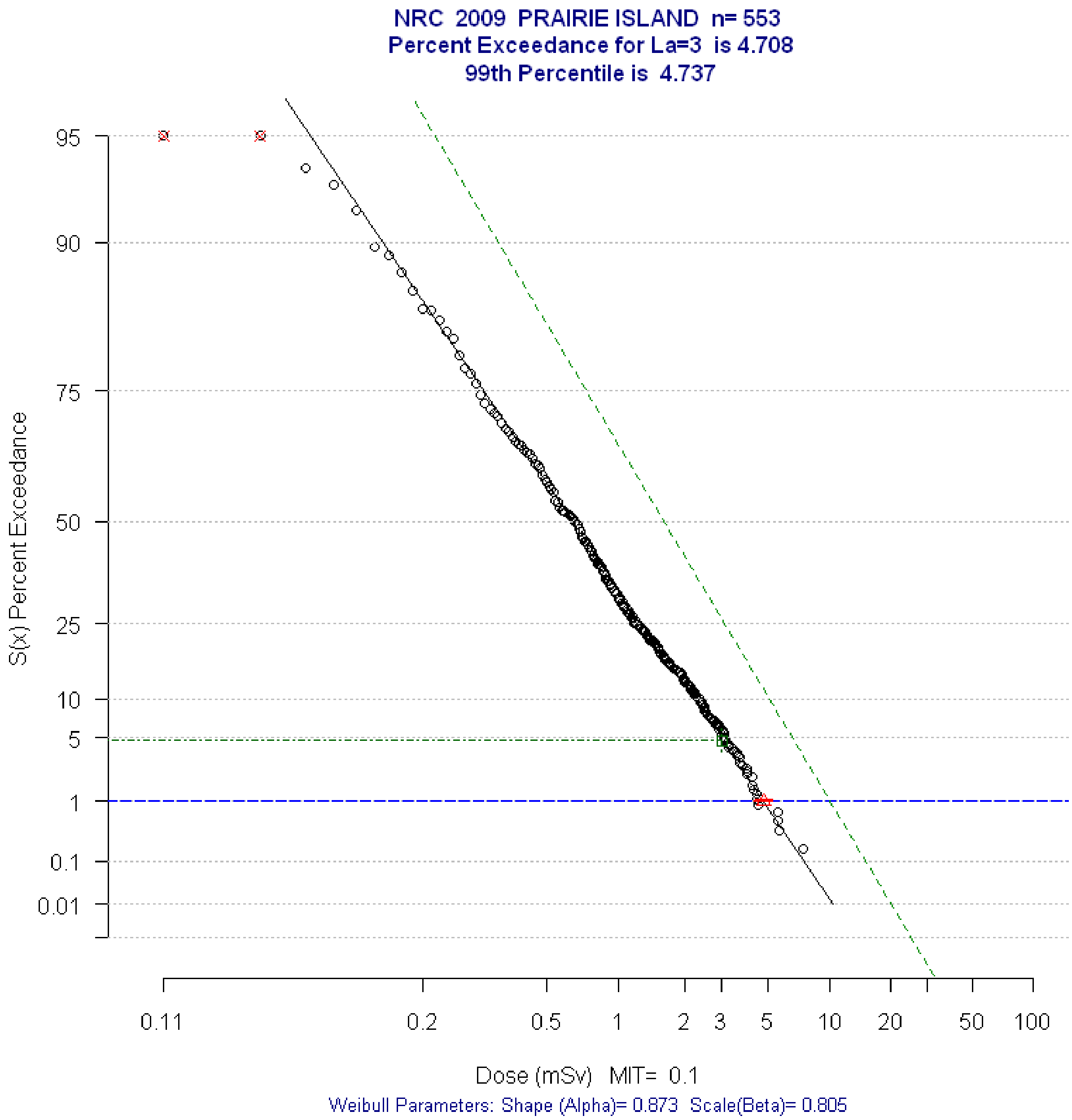

Figure C90: Weibull Probability Plot for Prairie Island.

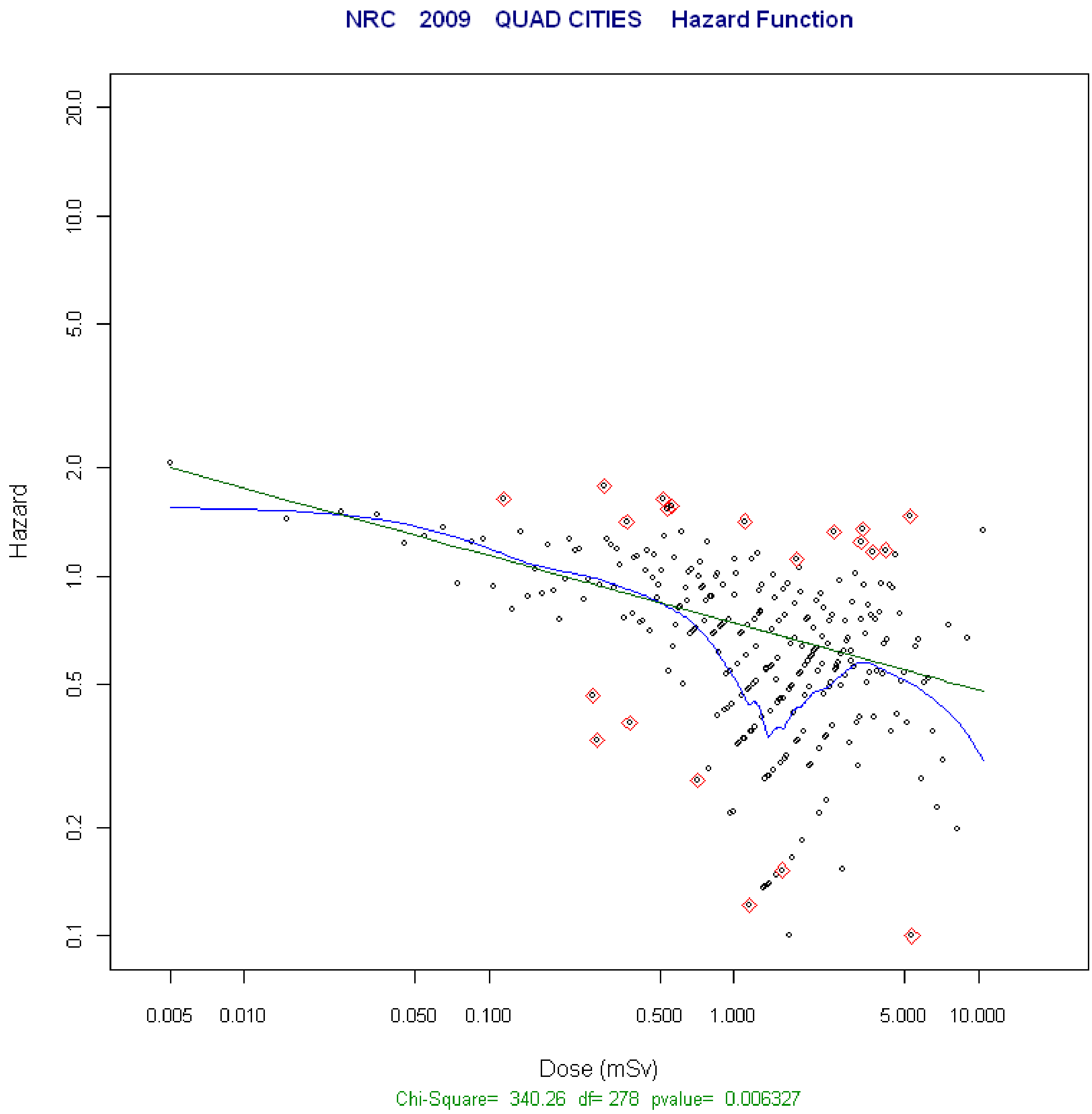

Figure C91: Weibull Goodness of Fit Plot for Quad Cities.

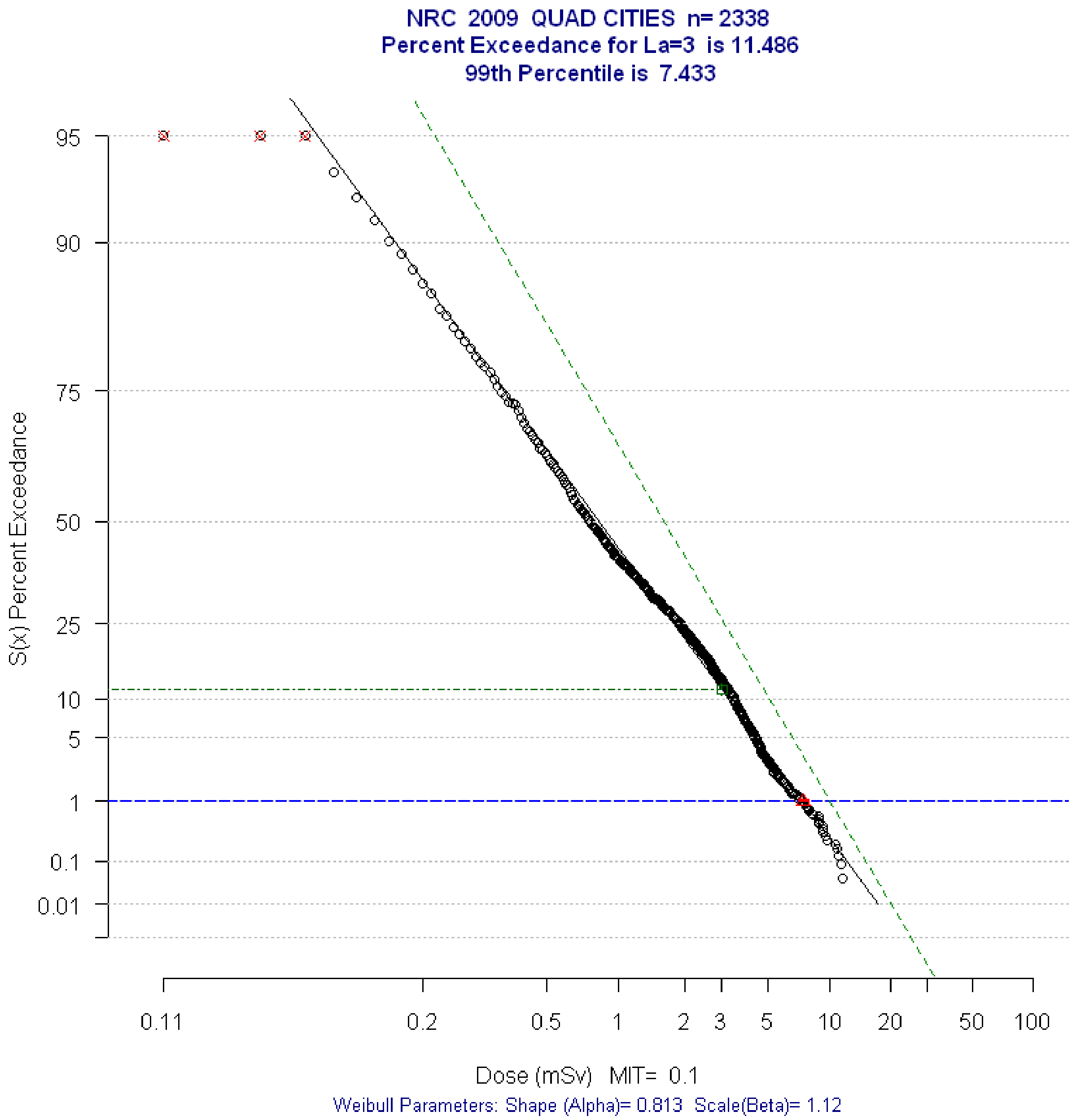

Figure C92: Weibull Probability Plot for Quad Cities.

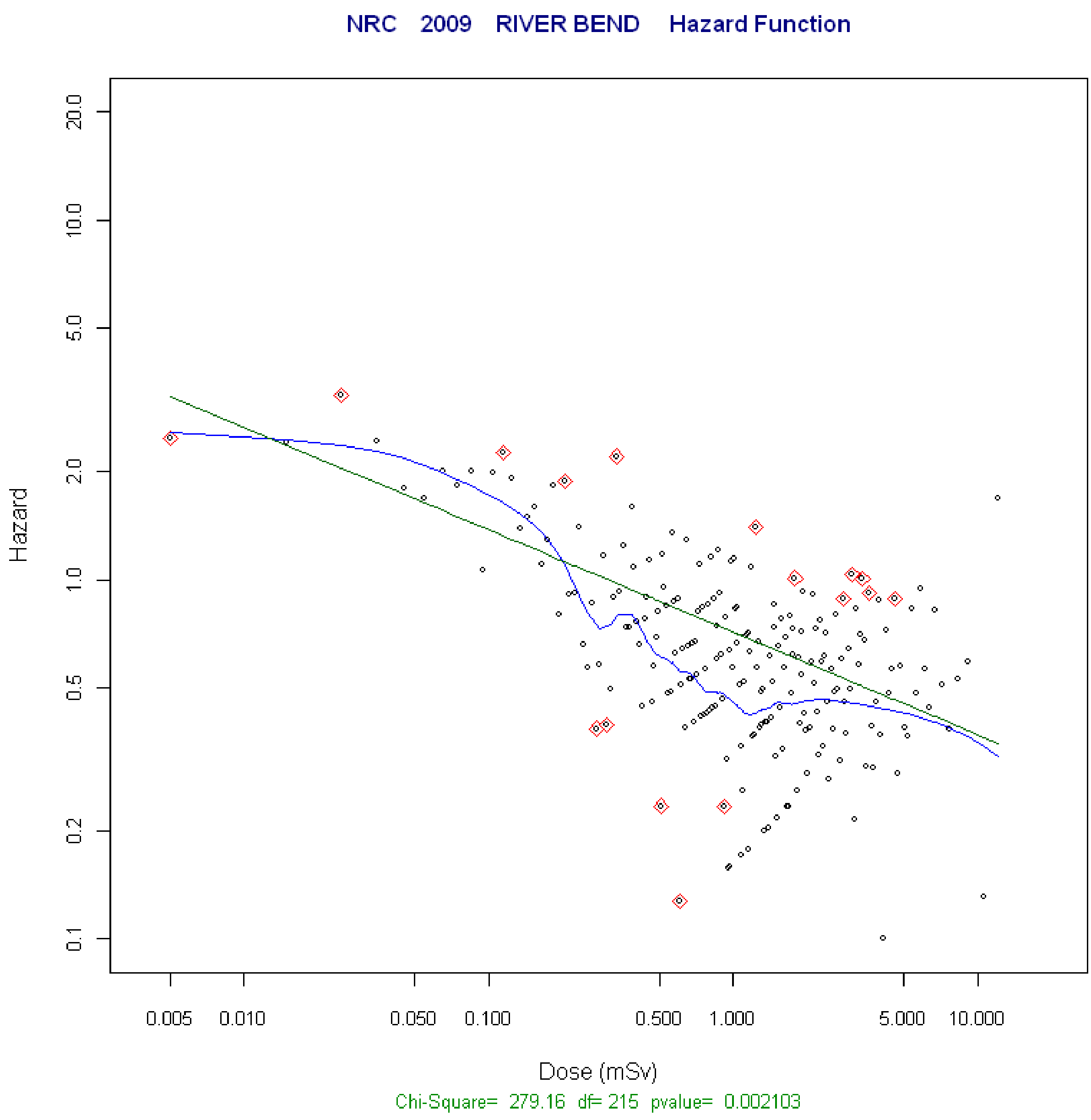

Figure C93: Weibull Goodness of Fit Plot for River Bend.

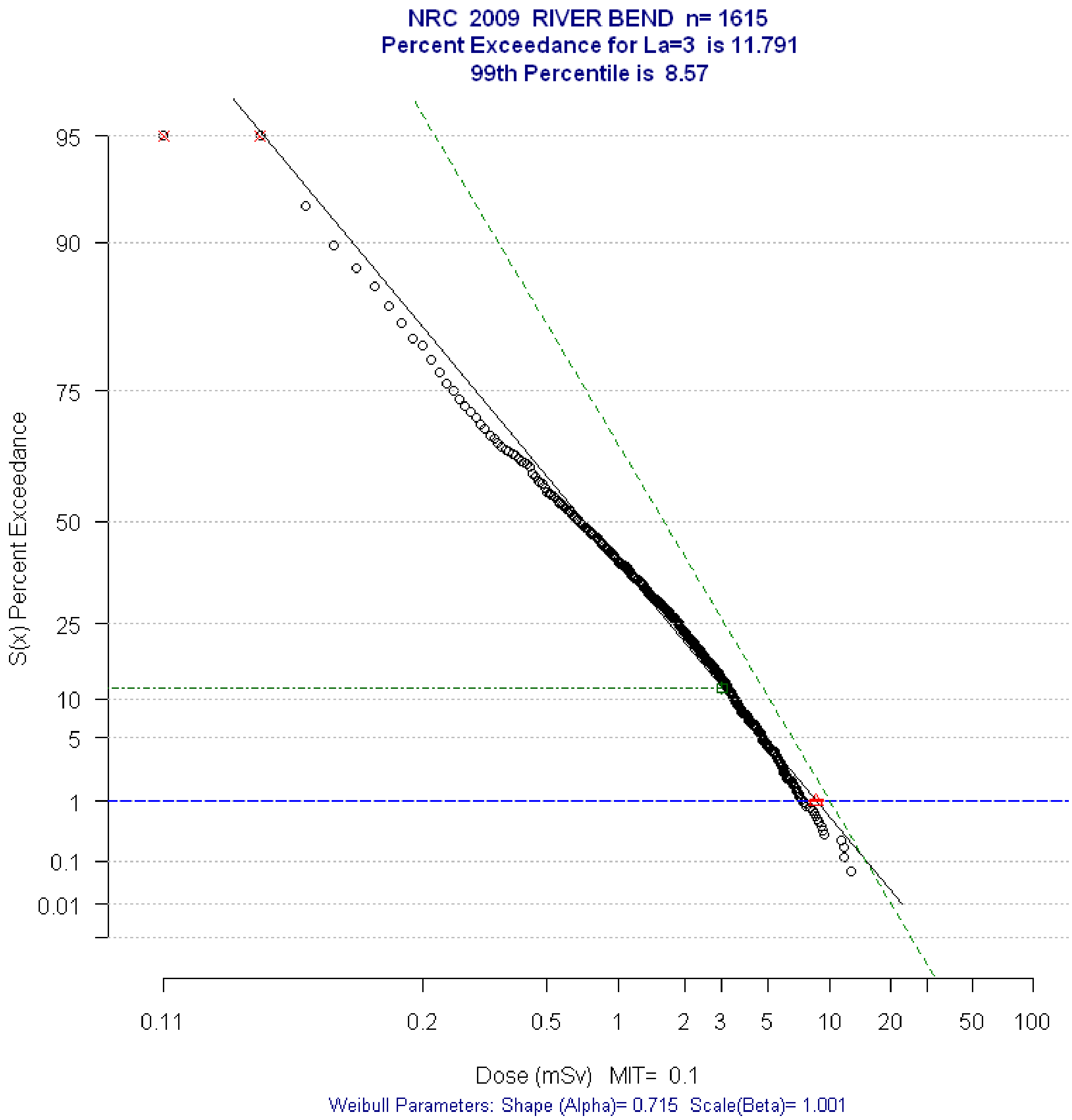

Figure C94: Weibull Probability Plot for River Bend.

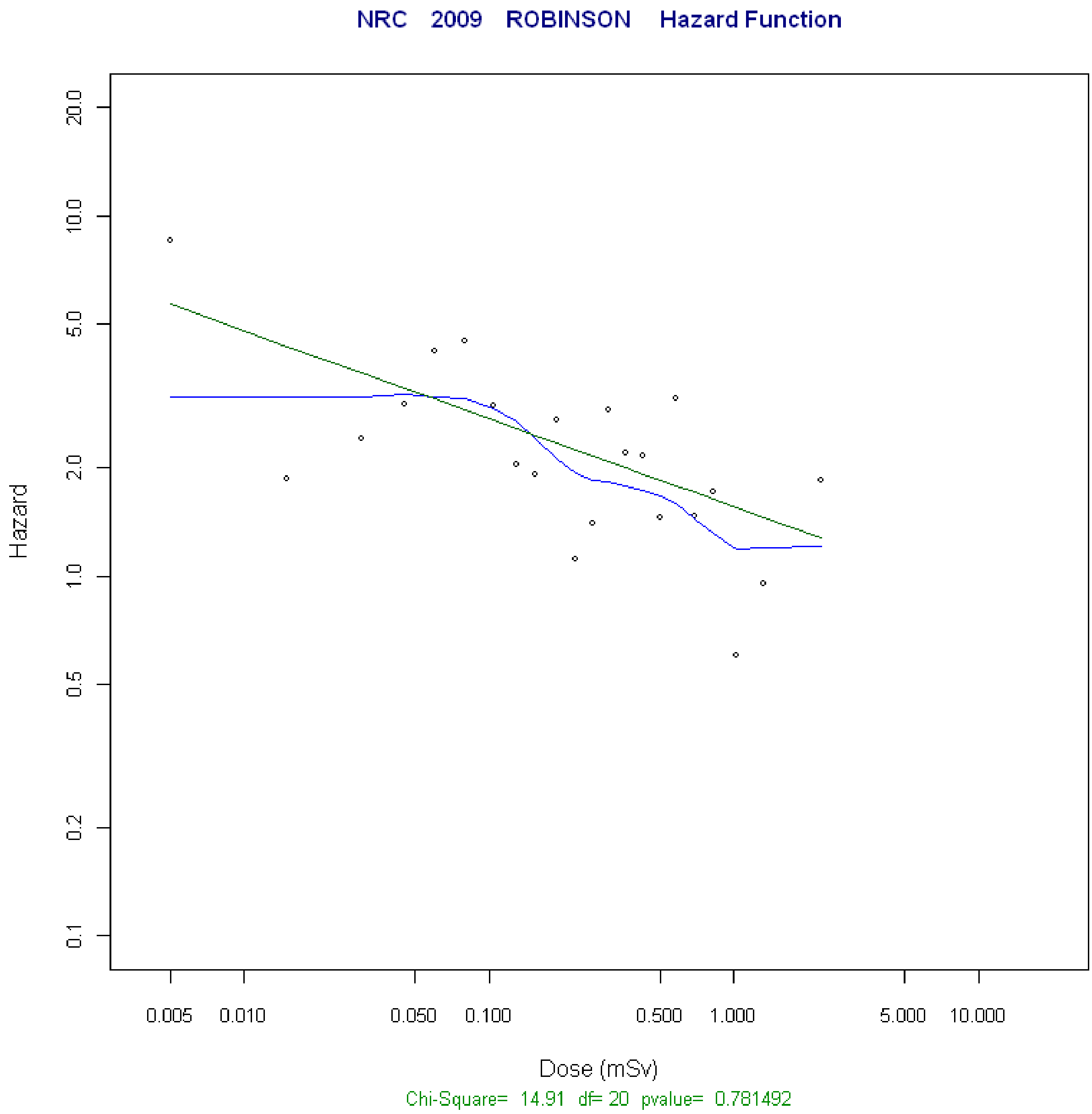

Figure C95: Weibull Goodness of Fit Plot for Robinson.

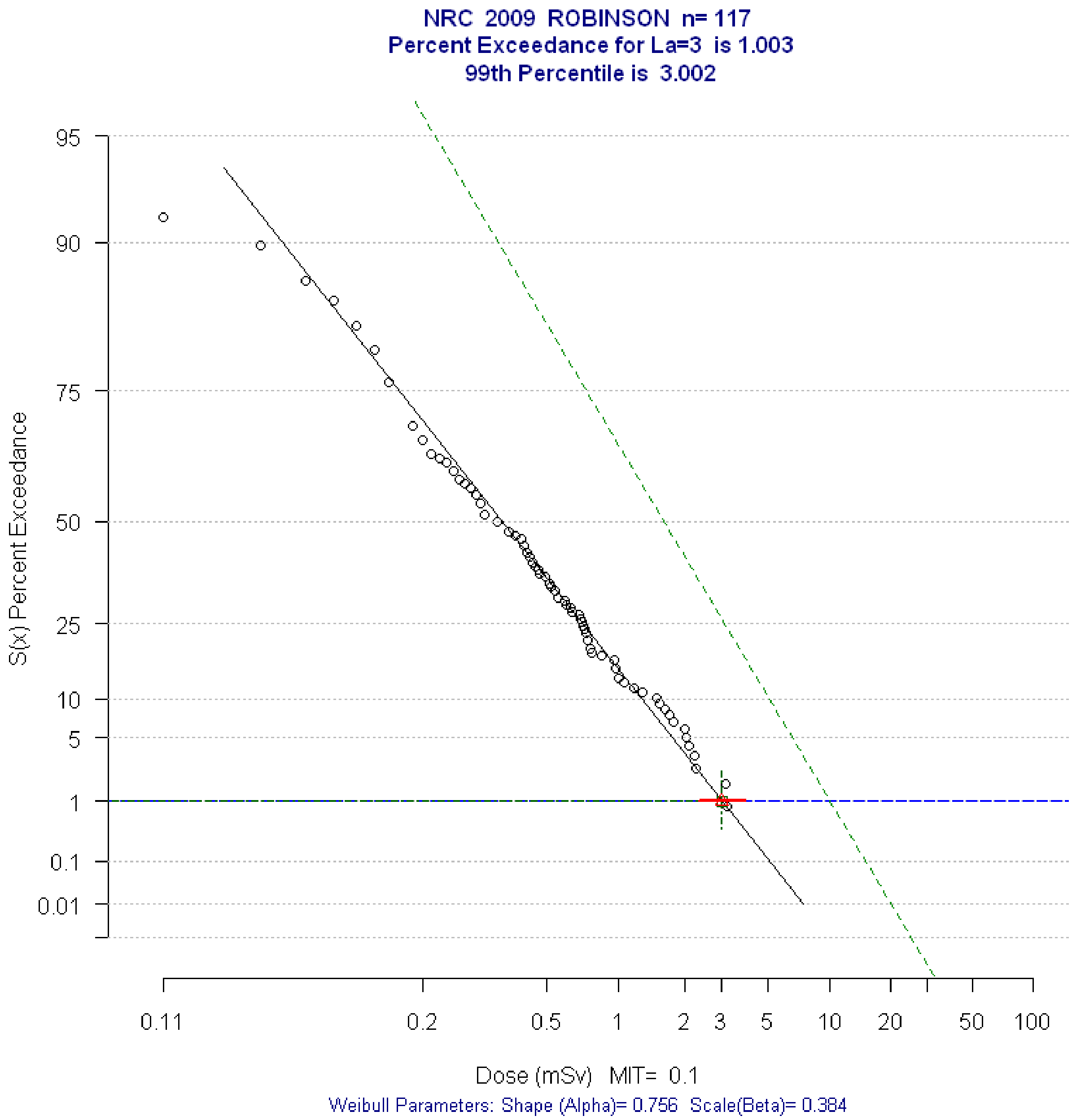

Figure C96: Weibull Probability Plot for Robinson.

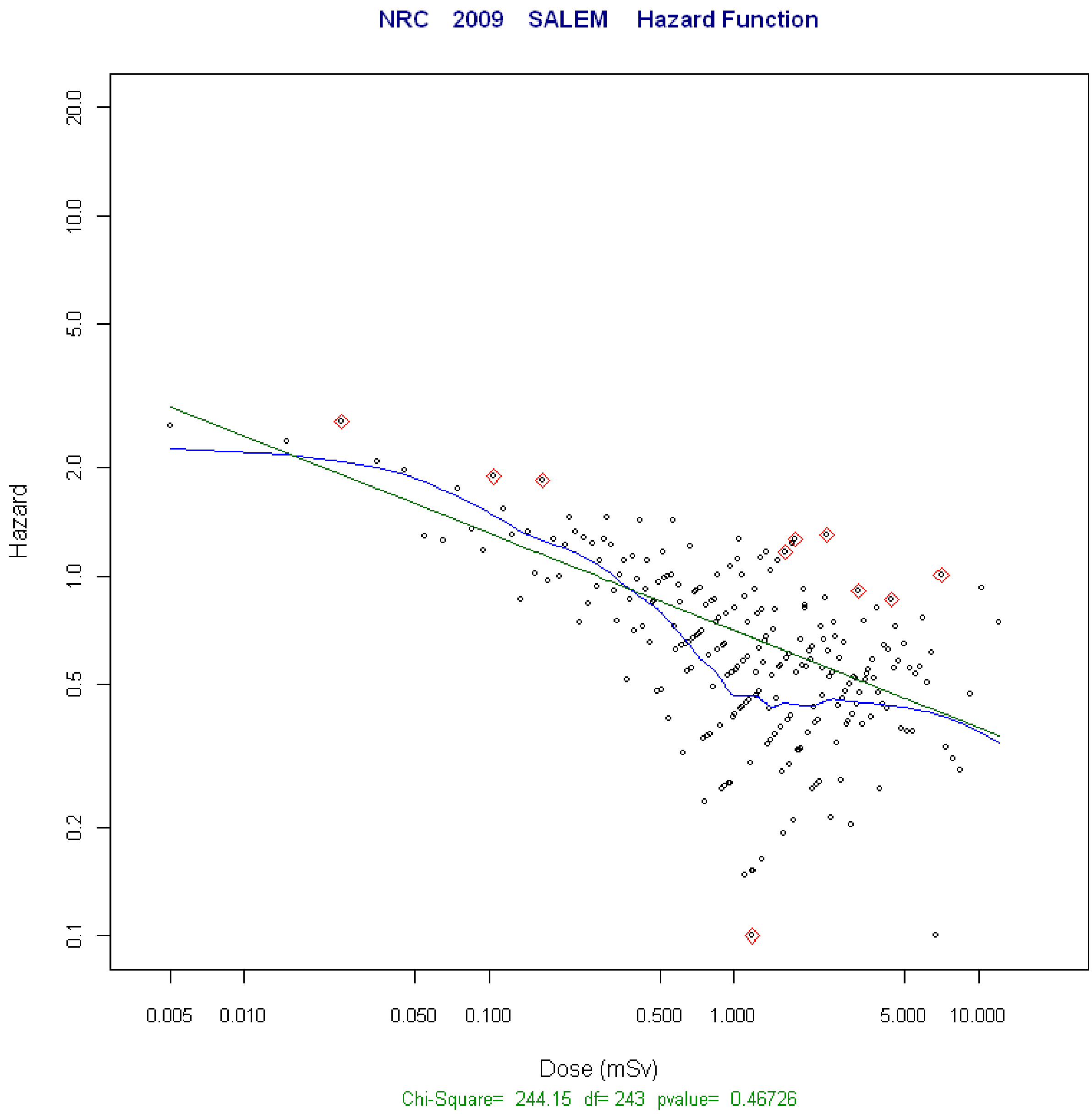

Figure C97: Weibull Goodness of Fit Plot for Salem.

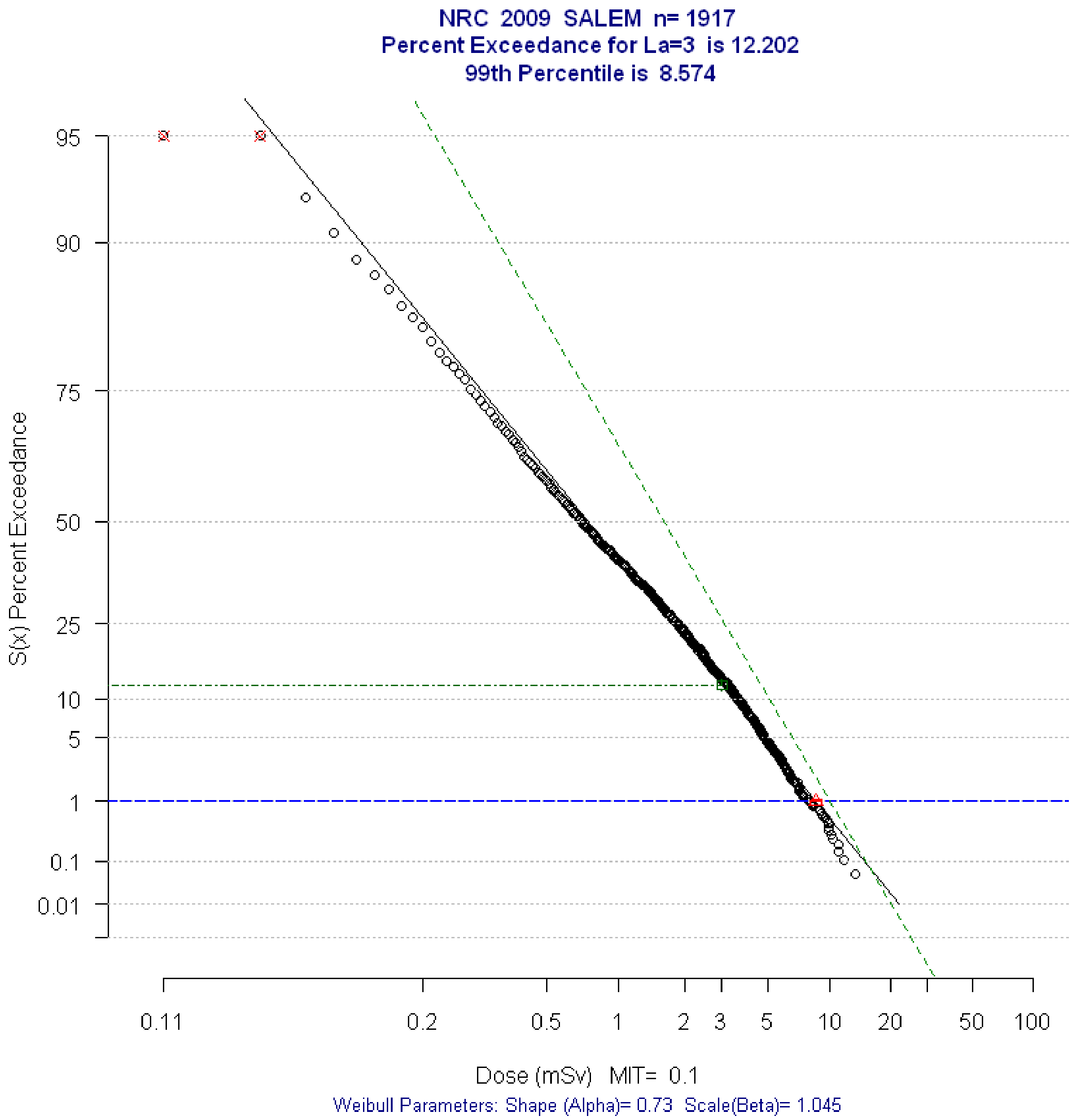

Figure C98: Weibull Probability Plot for Salem.

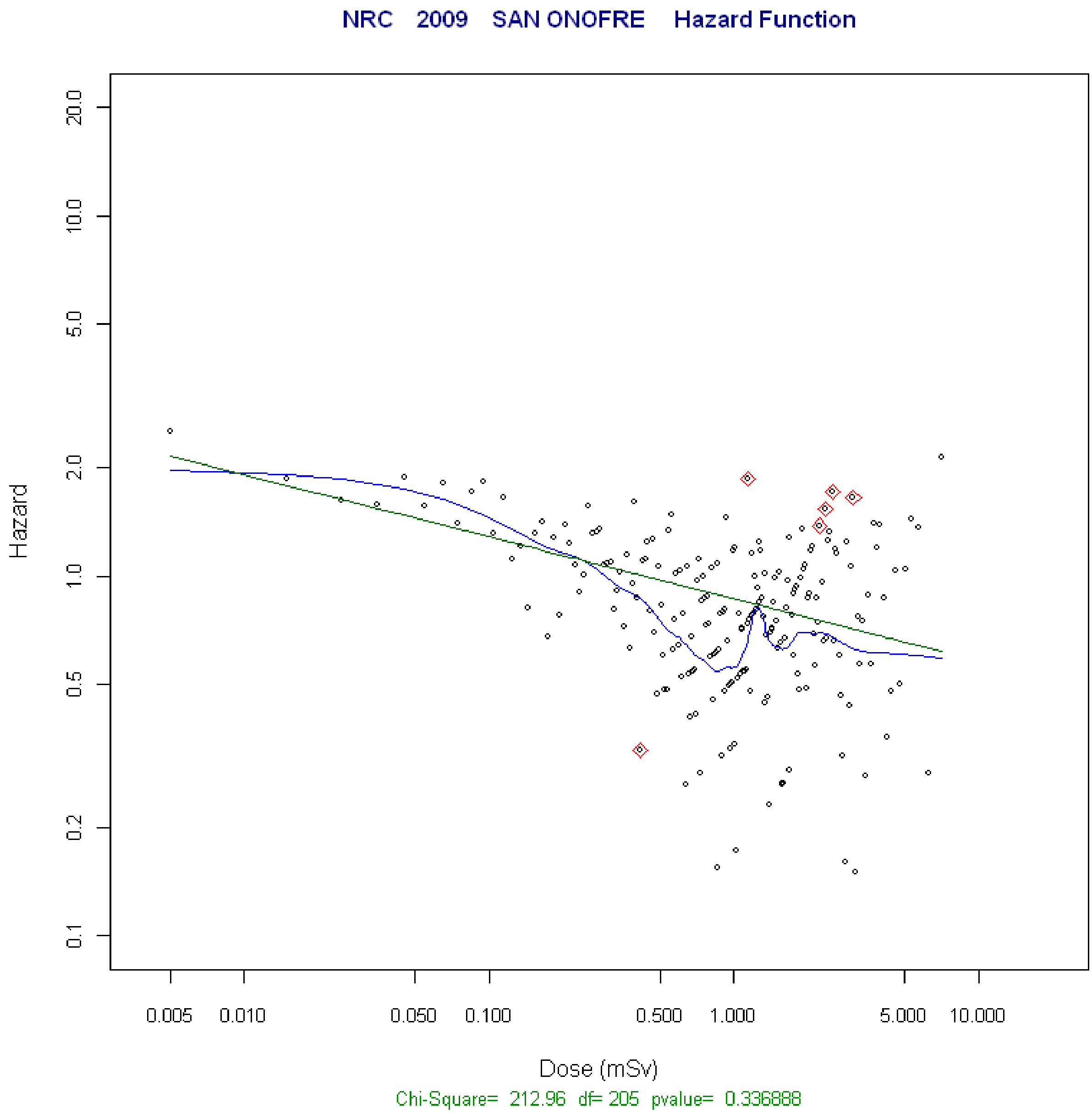

Figure C99: Weibull Goodness of Fit Plot for San Onofre.

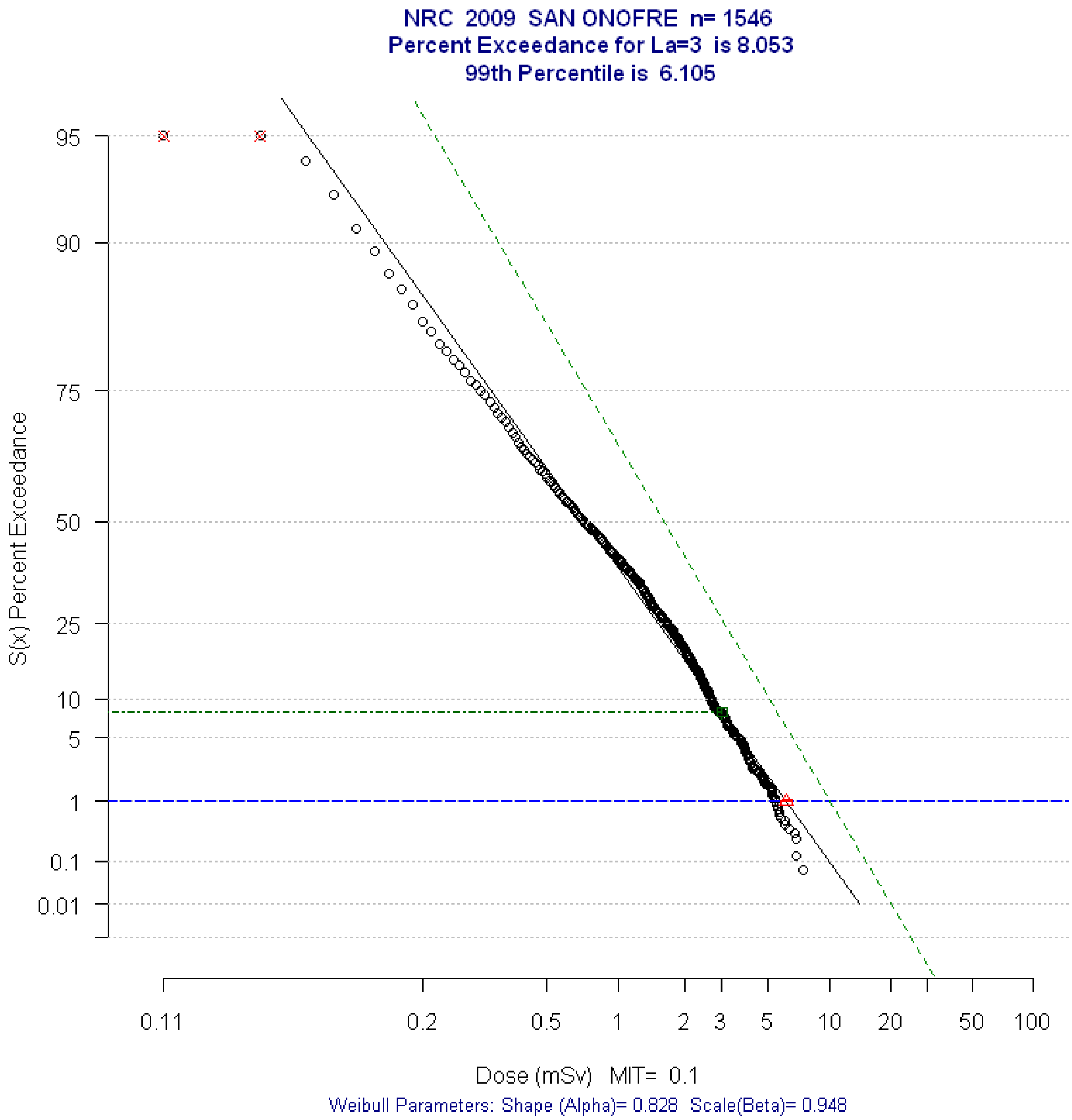

Figure C100: Weibull Probability Plot for San Onofre.

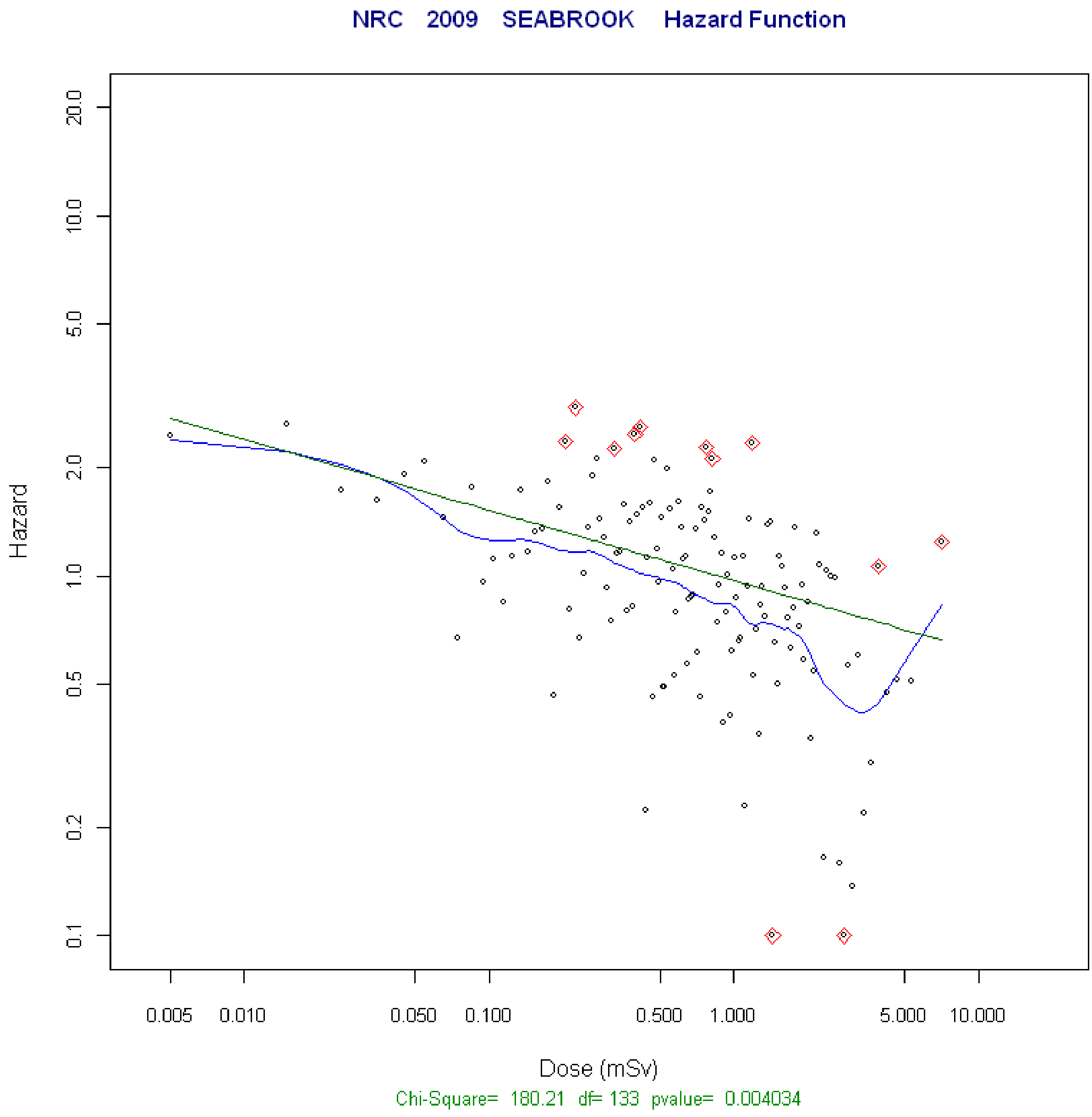

Figure C101: Weibull Goodness of Fit Plot for Seabrook.

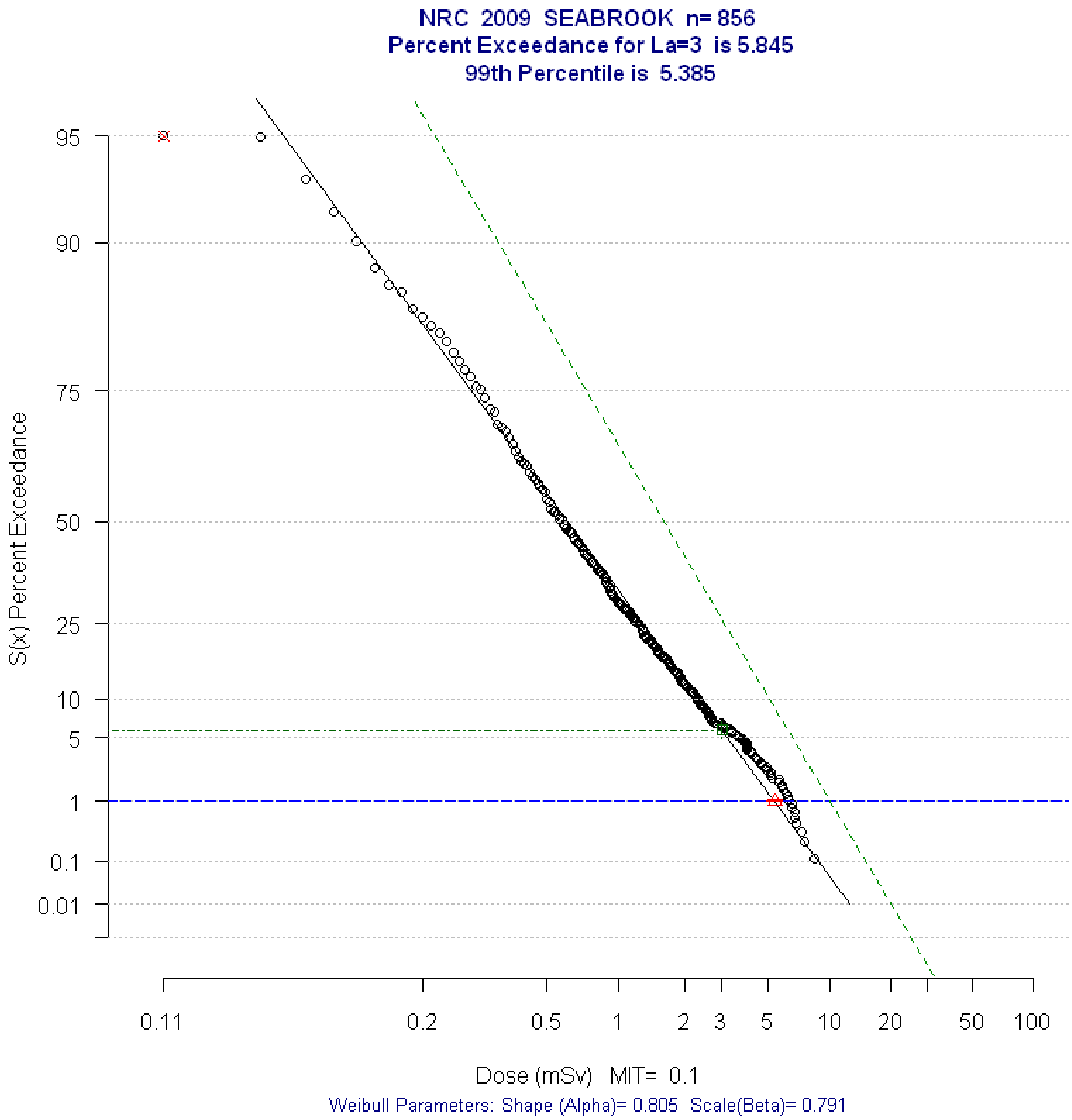

Figure C102: Weibull Probability Plot for Seabrook.

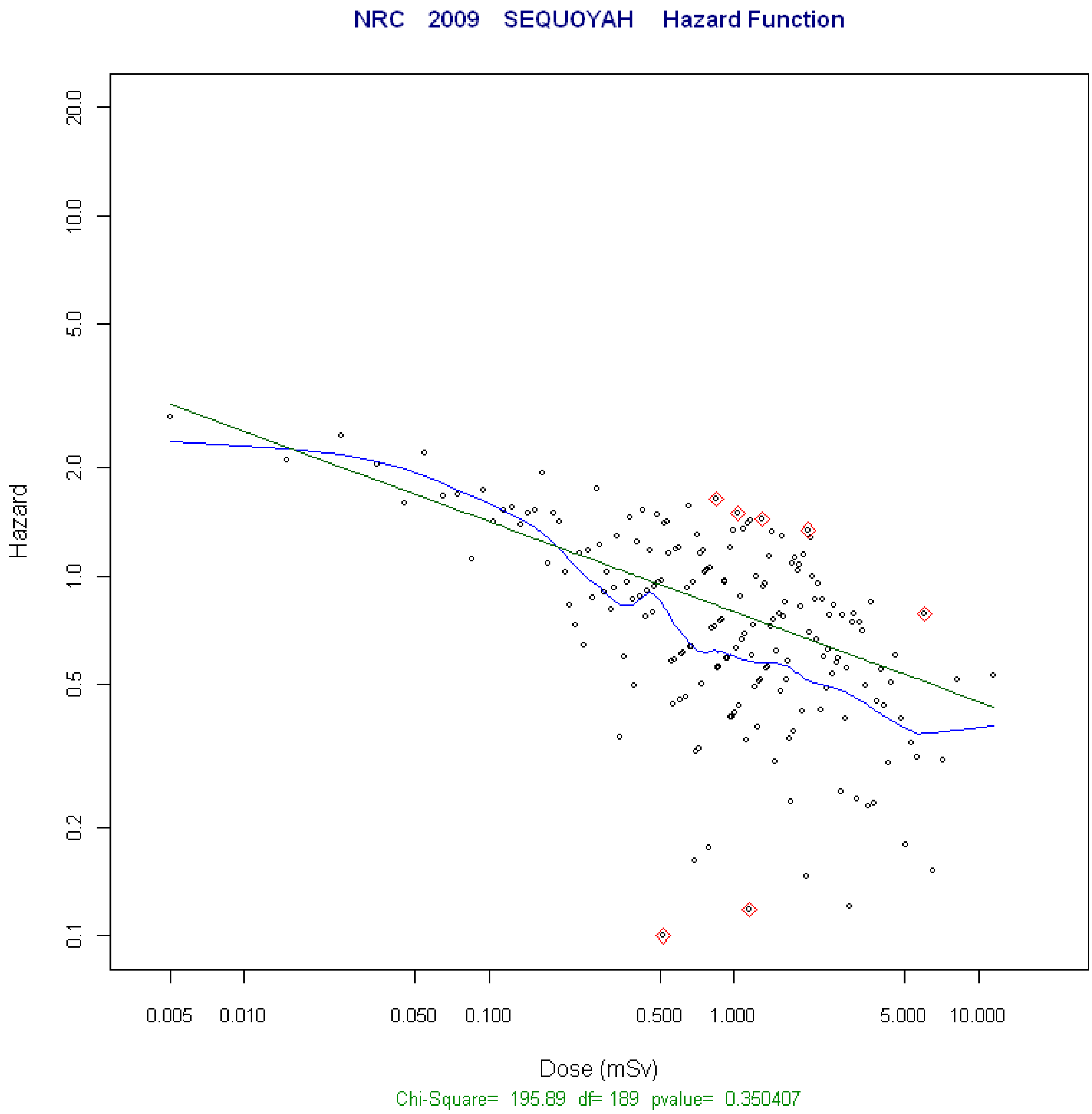

Figure C103: Weibull Goodness of Fit Plot for Sequoyah.

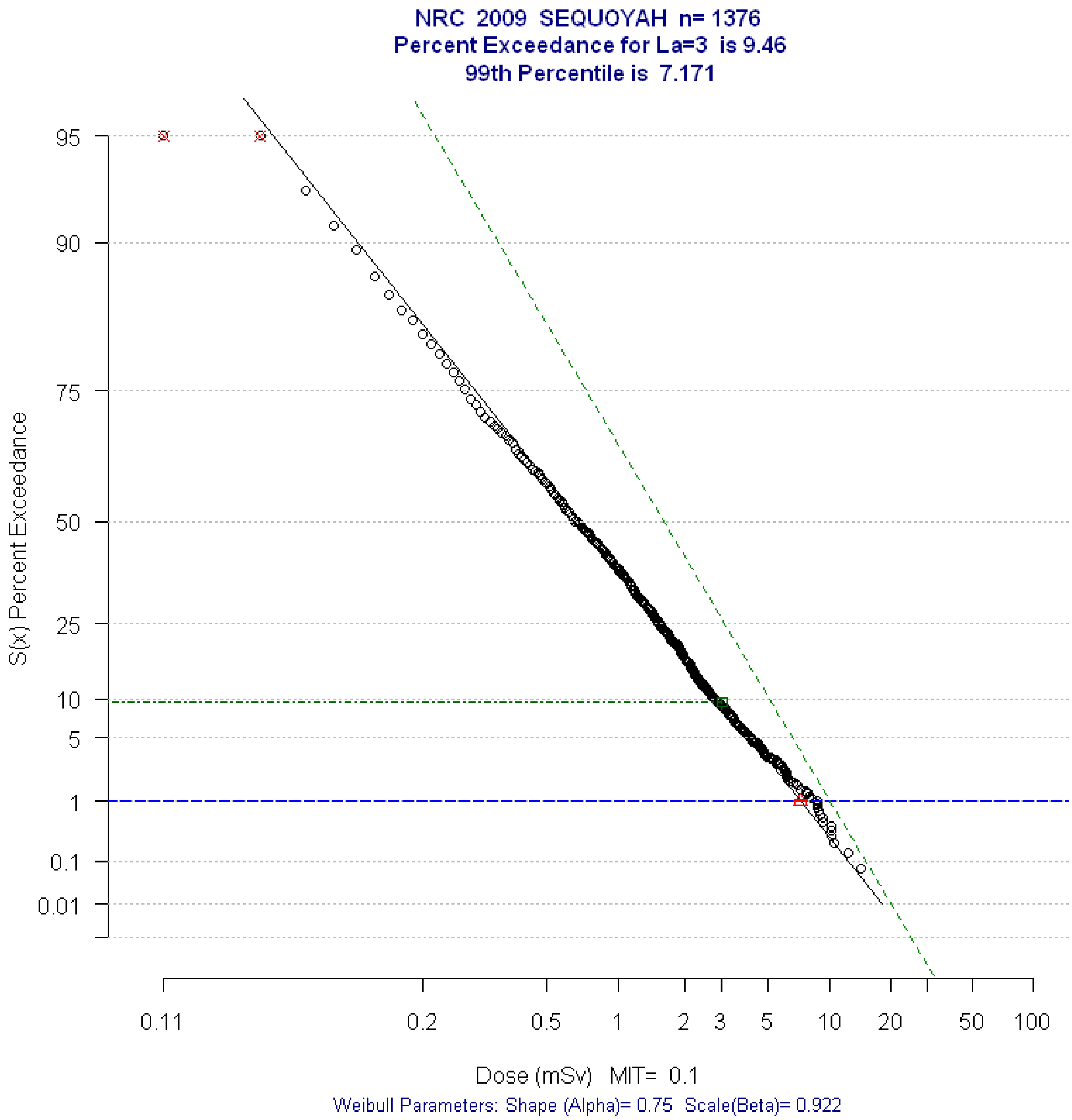

Figure C104: Weibull Probability Plot for Sequoyah.

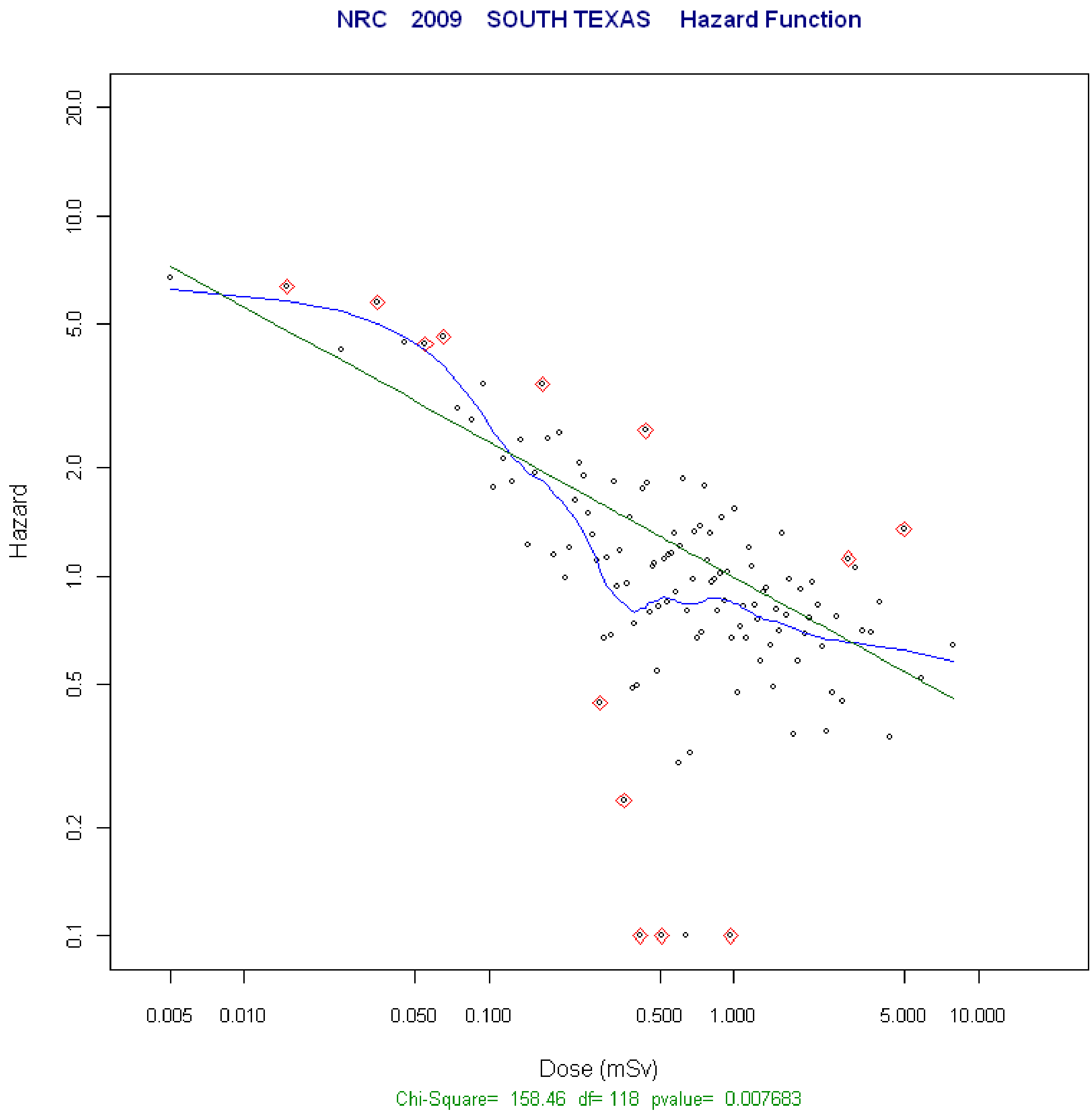

Figure C105: Weibull Goodness of Fit Plot for South Texas.

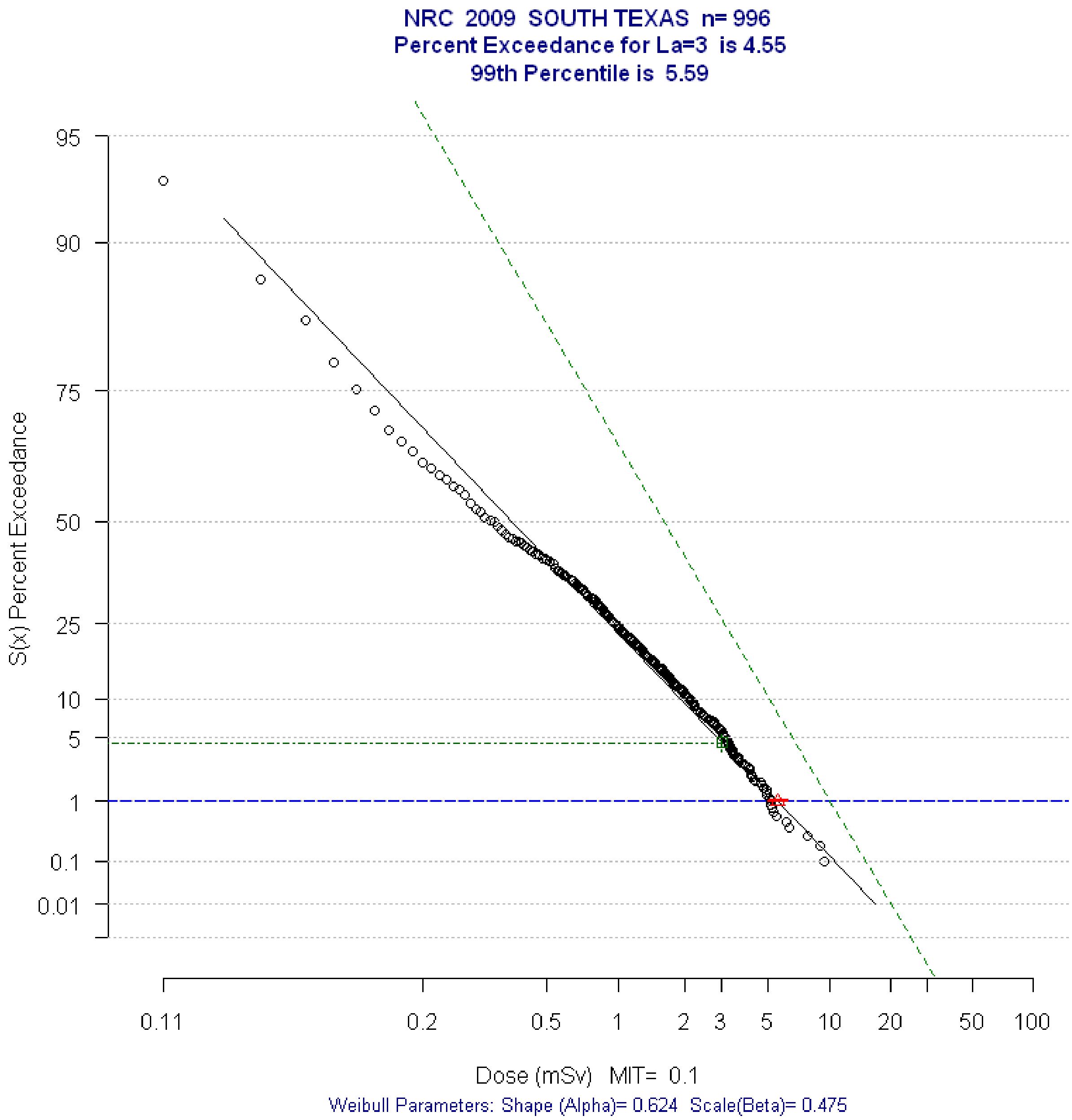

Figure C106: Weibull Probability Plot for South Texas.

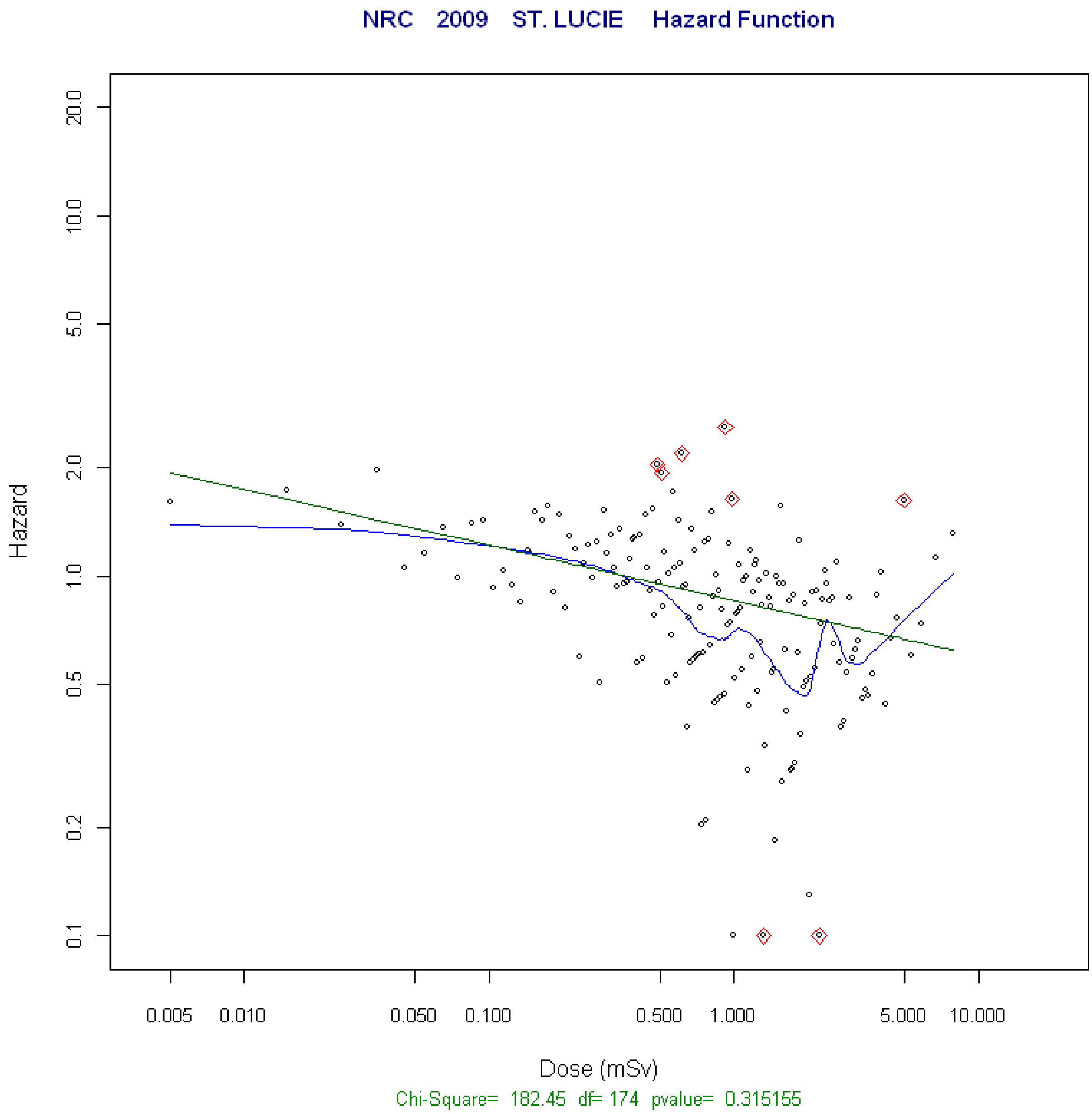

Figure C107: Weibull Goodness of Fit Plot for St. Lucie.

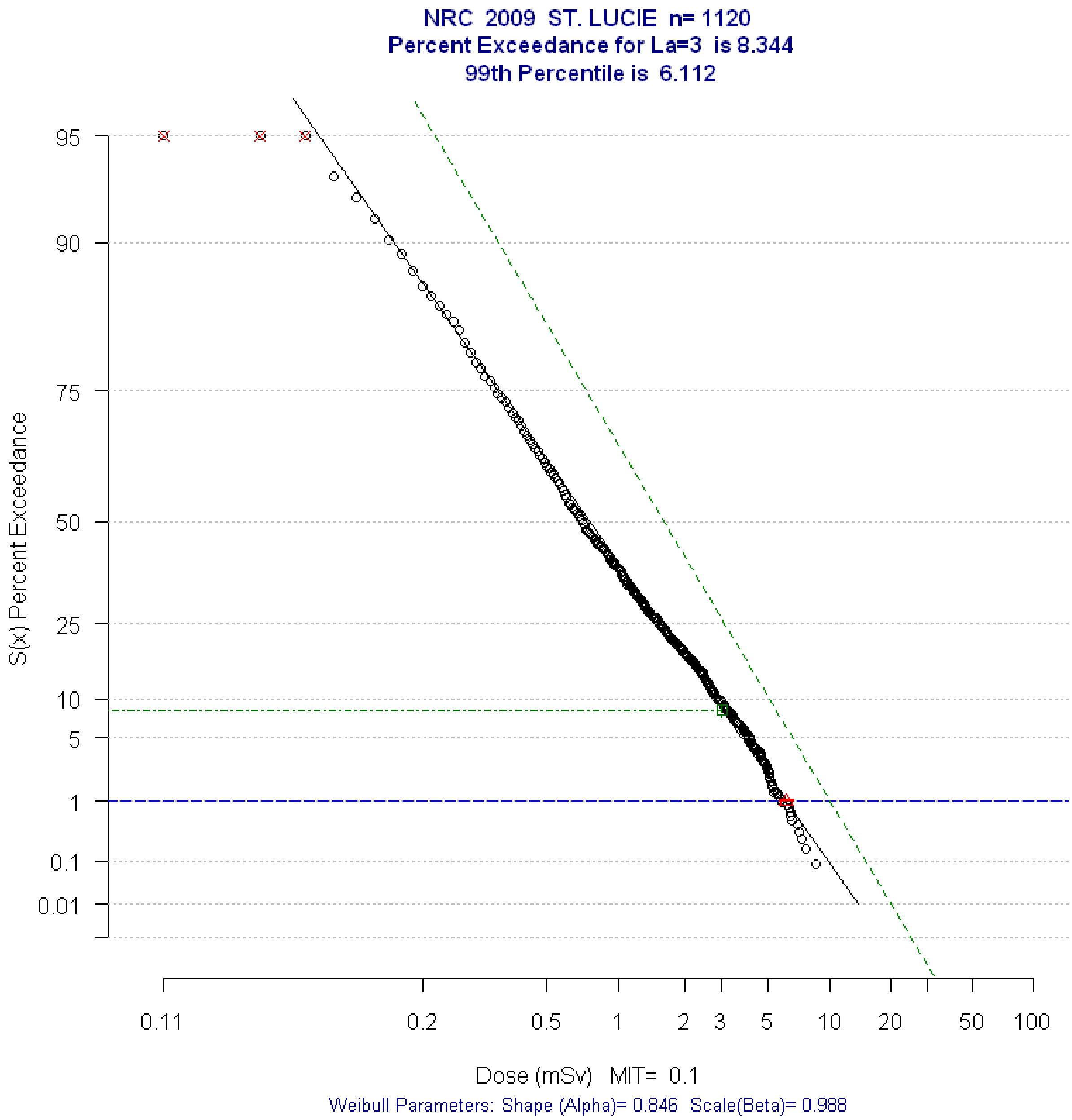

Figure C108: Weibull Probability Plot for St. Lucie.

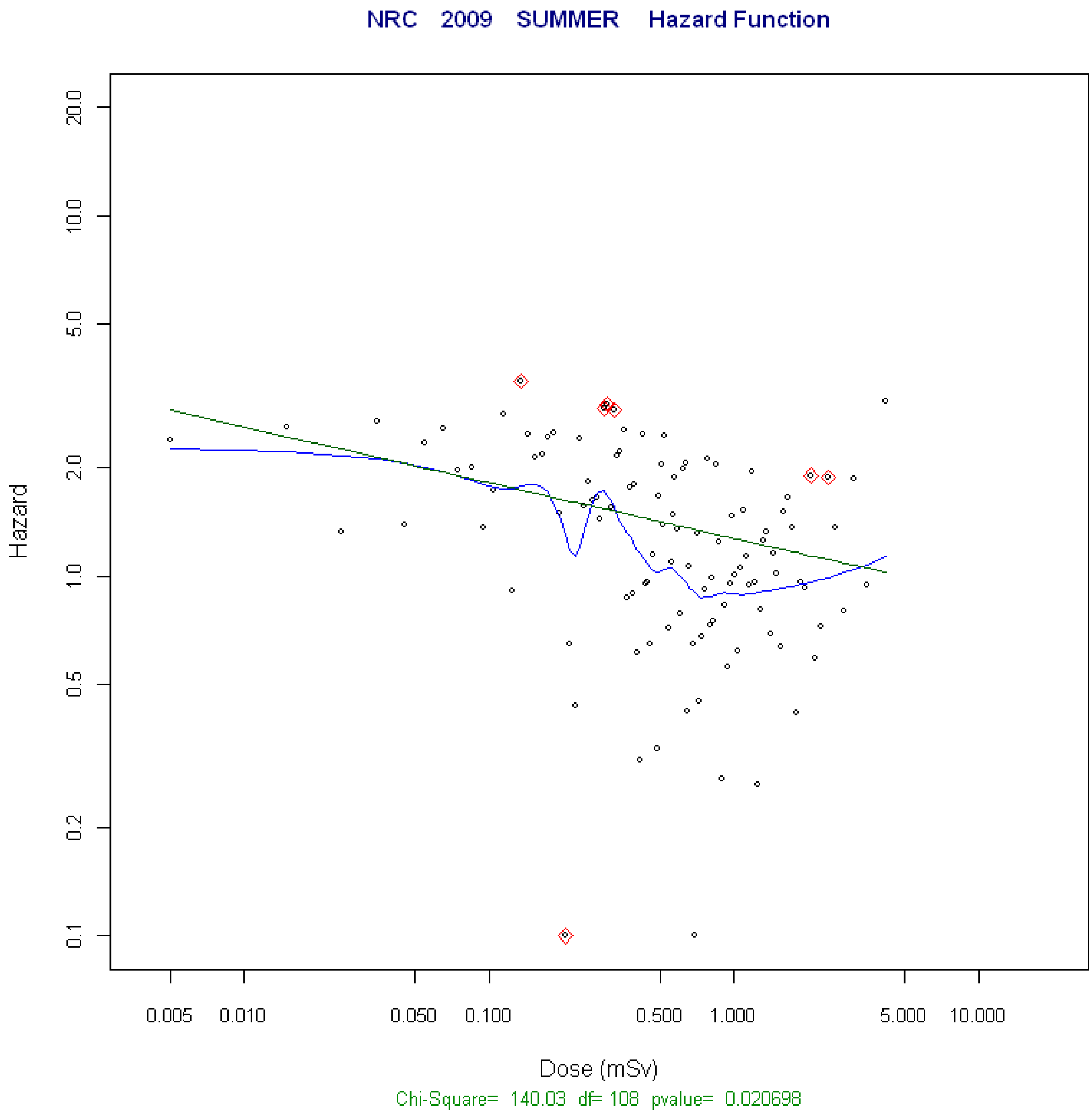

Figure C109: Weibull Goodness of Fit Plot for Summer.

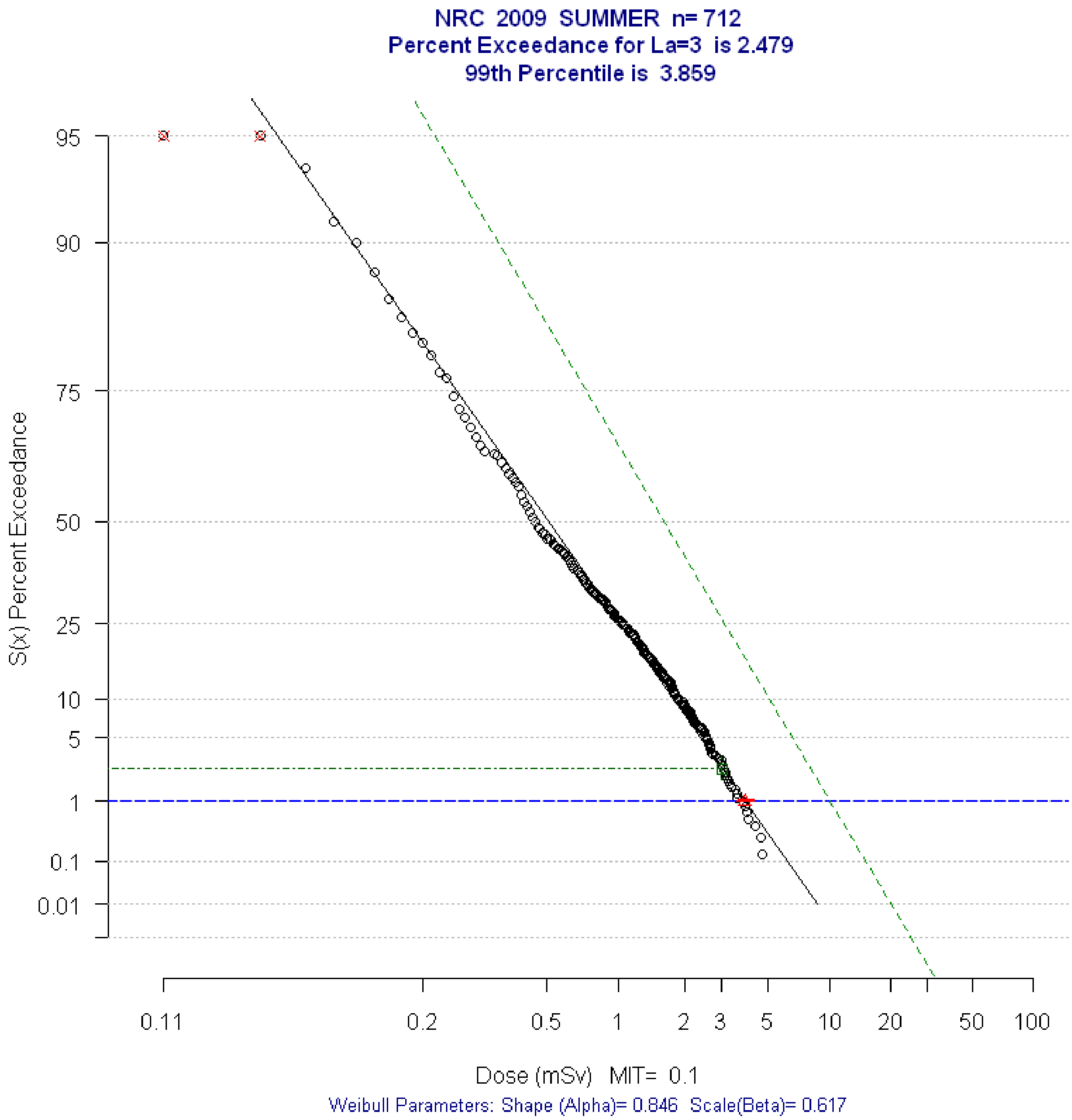

Figure C110: Weibull Probability Plot for Summer.

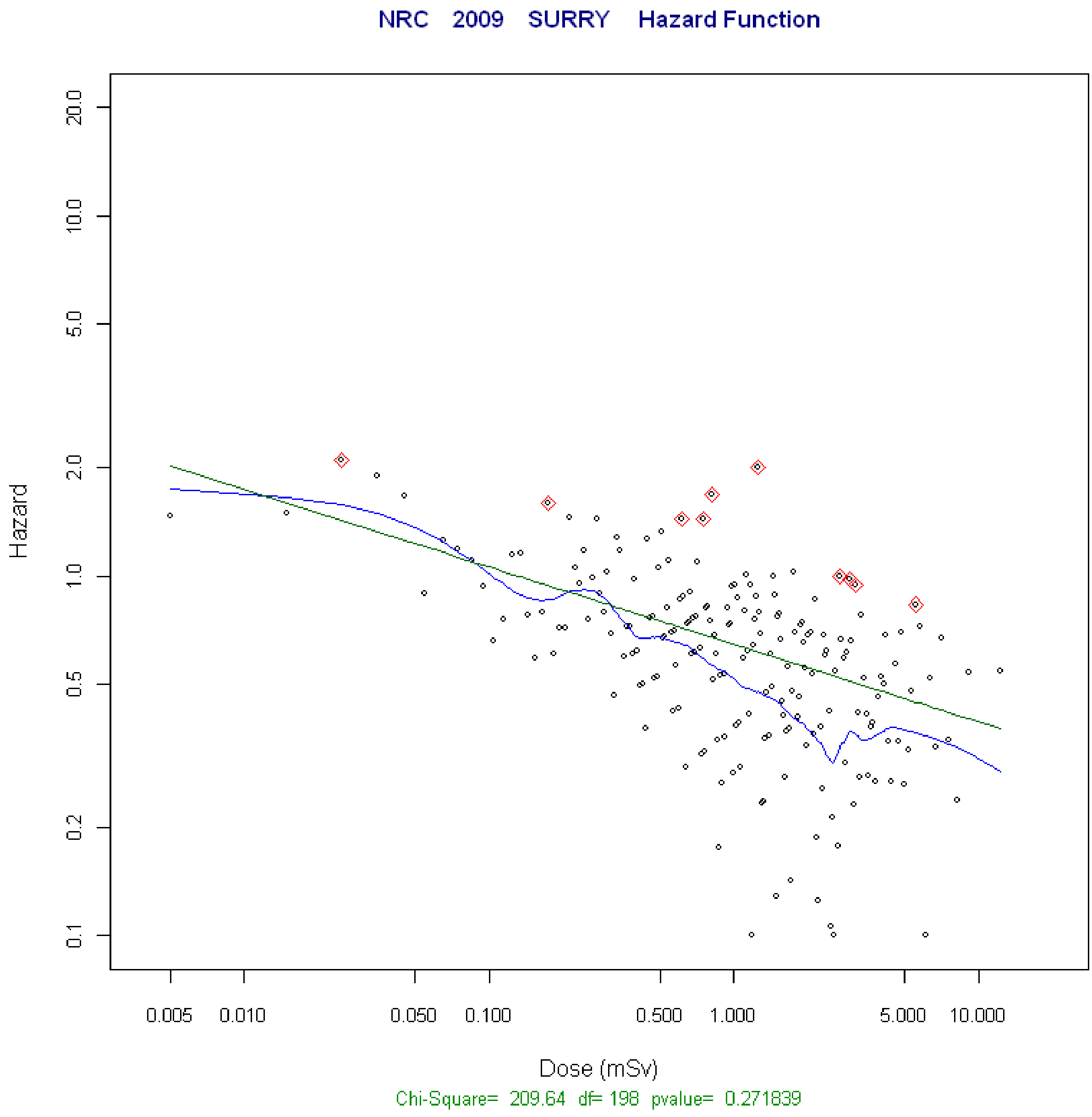

Figure C111: Weibull Goodness of Fit Plot for Surry.

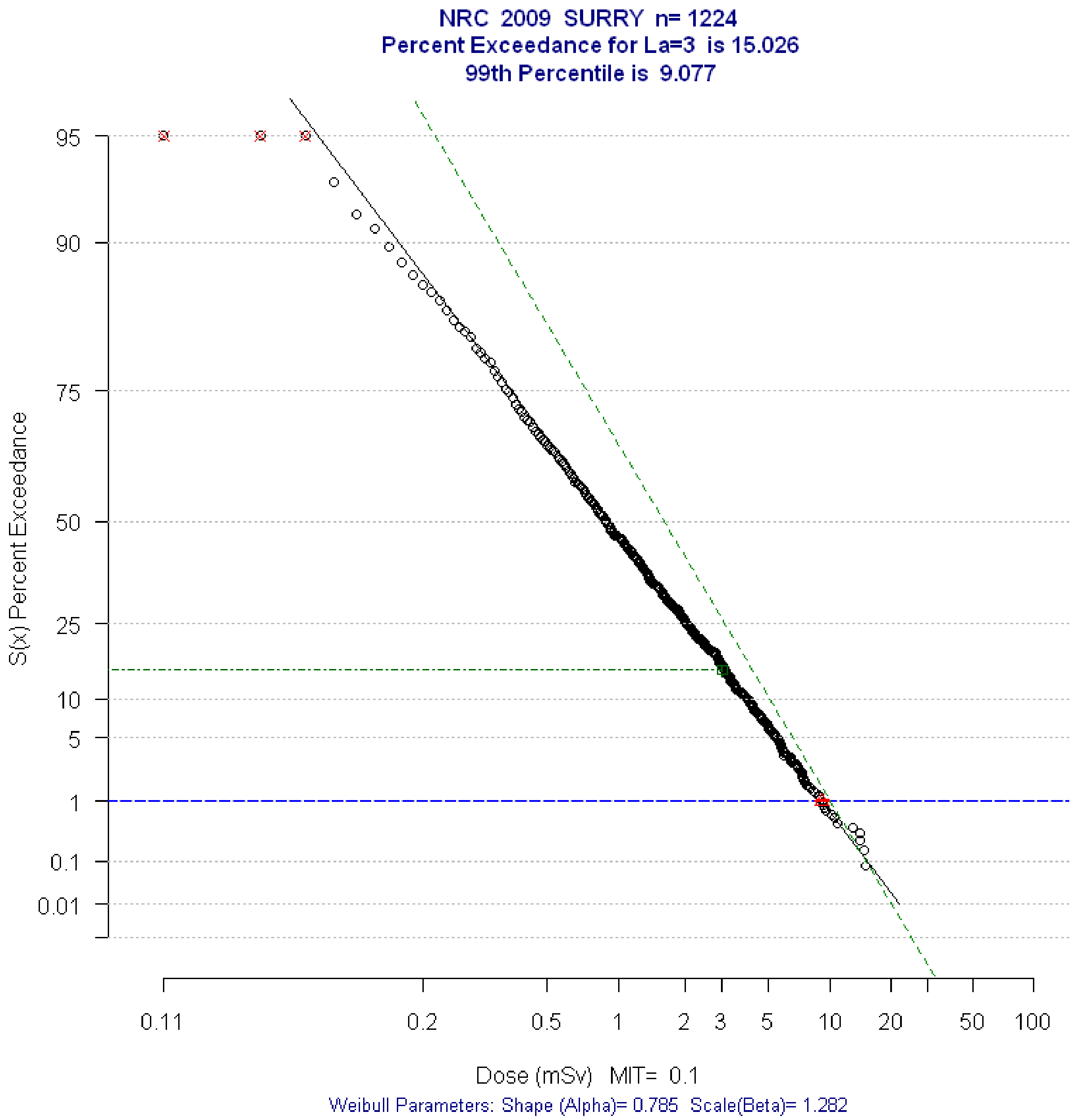

Figure C112: Weibull Probability Plot for Surry.

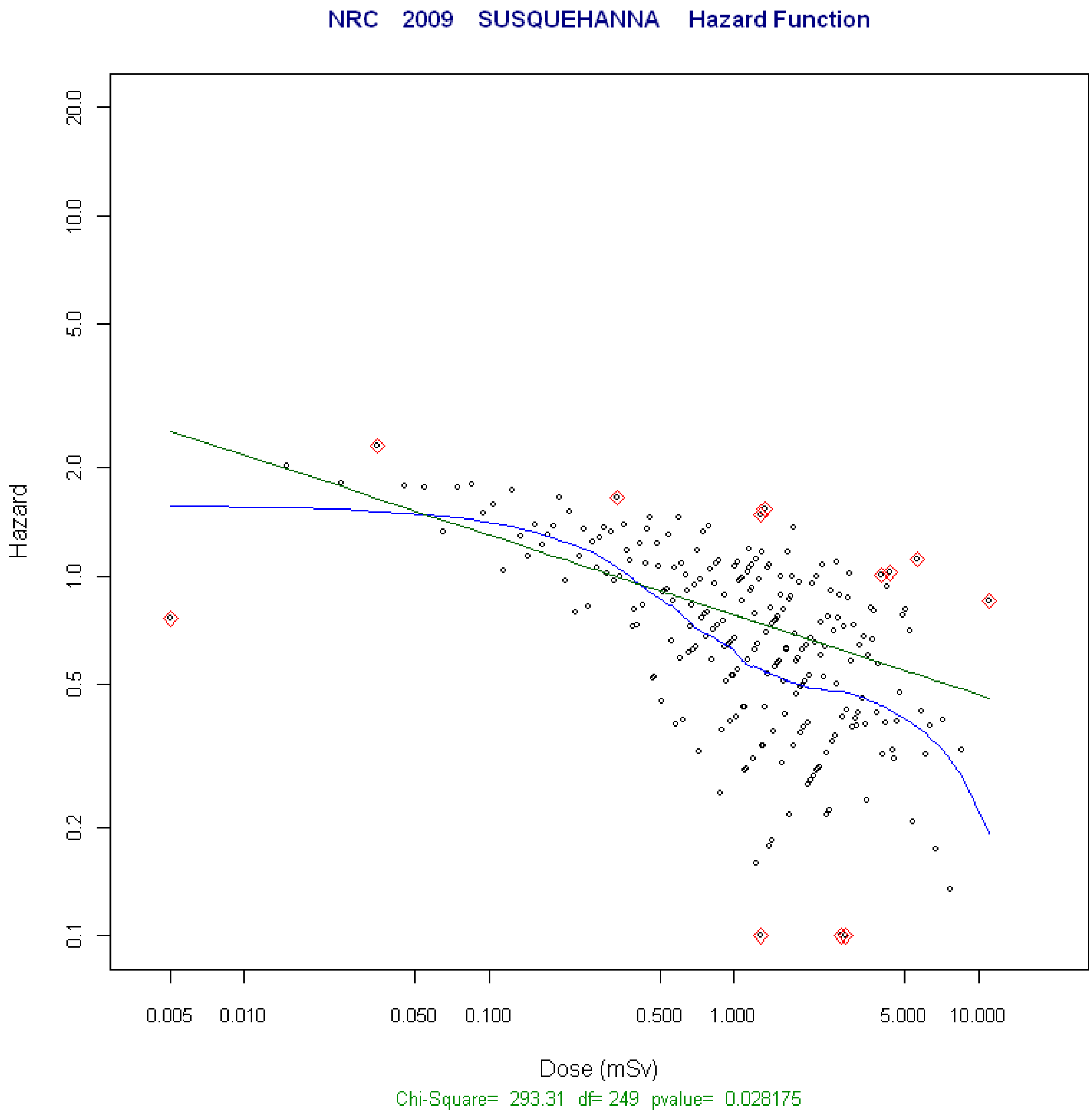

Figure C113: Weibull Goodness of Fit Plot for Susquehanna.

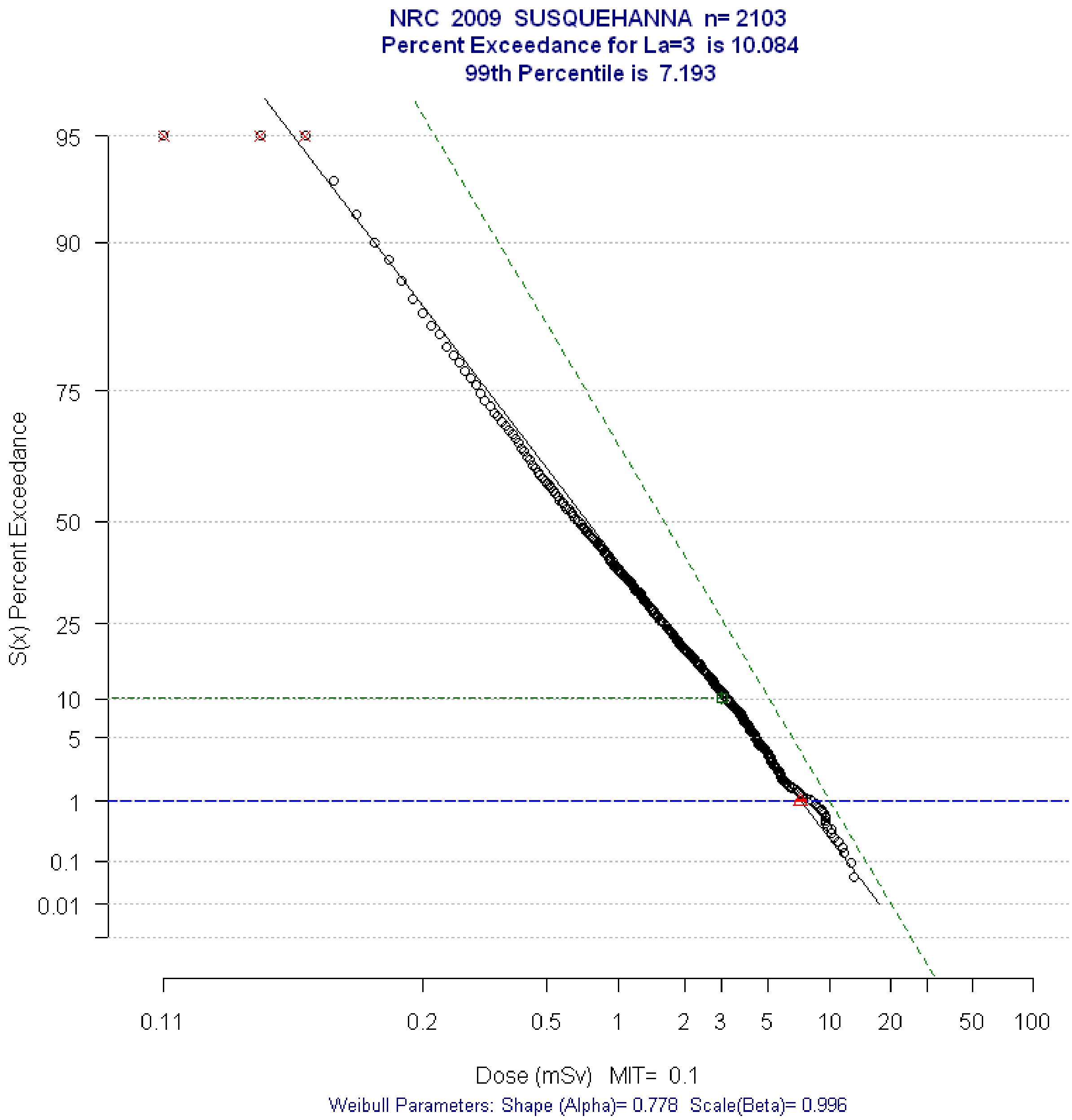

Figure C114: Weibull Probability Plot for Susquehanna.

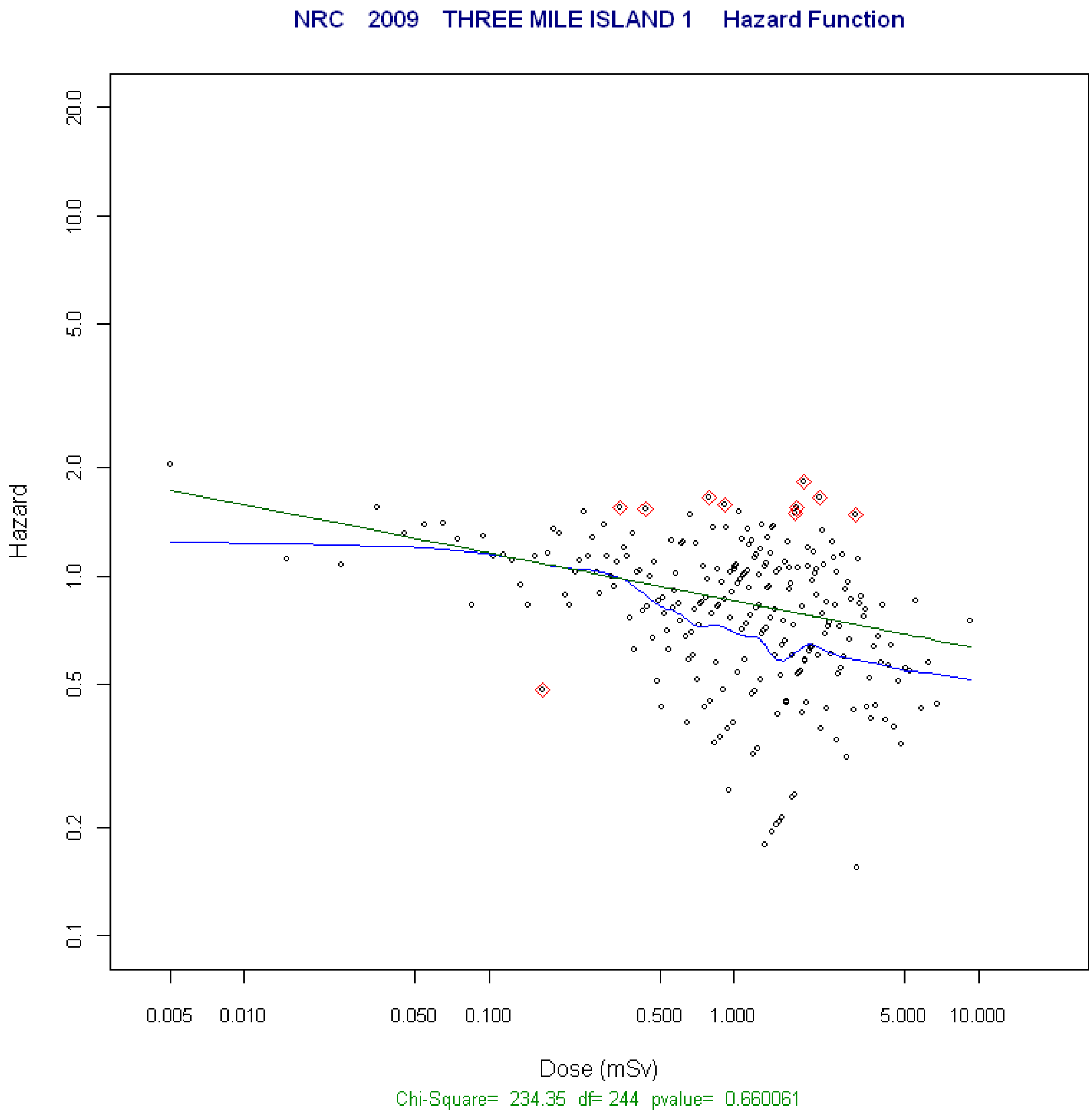

Figure C115: Weibull Goodness of Fit Plot for Three Mile Island.

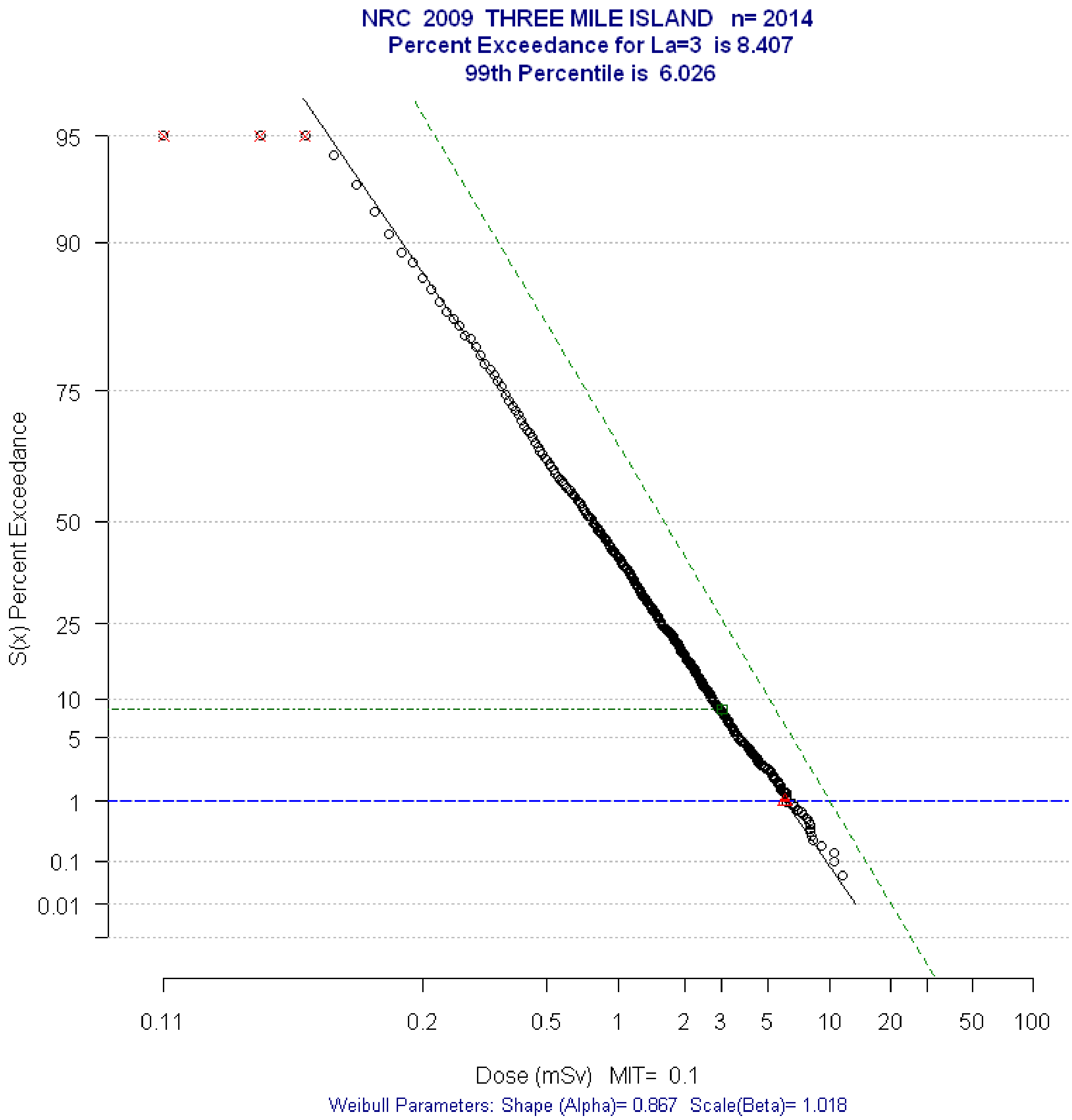

Figure C116: Weibull Probability Plot for Three Mile Island.

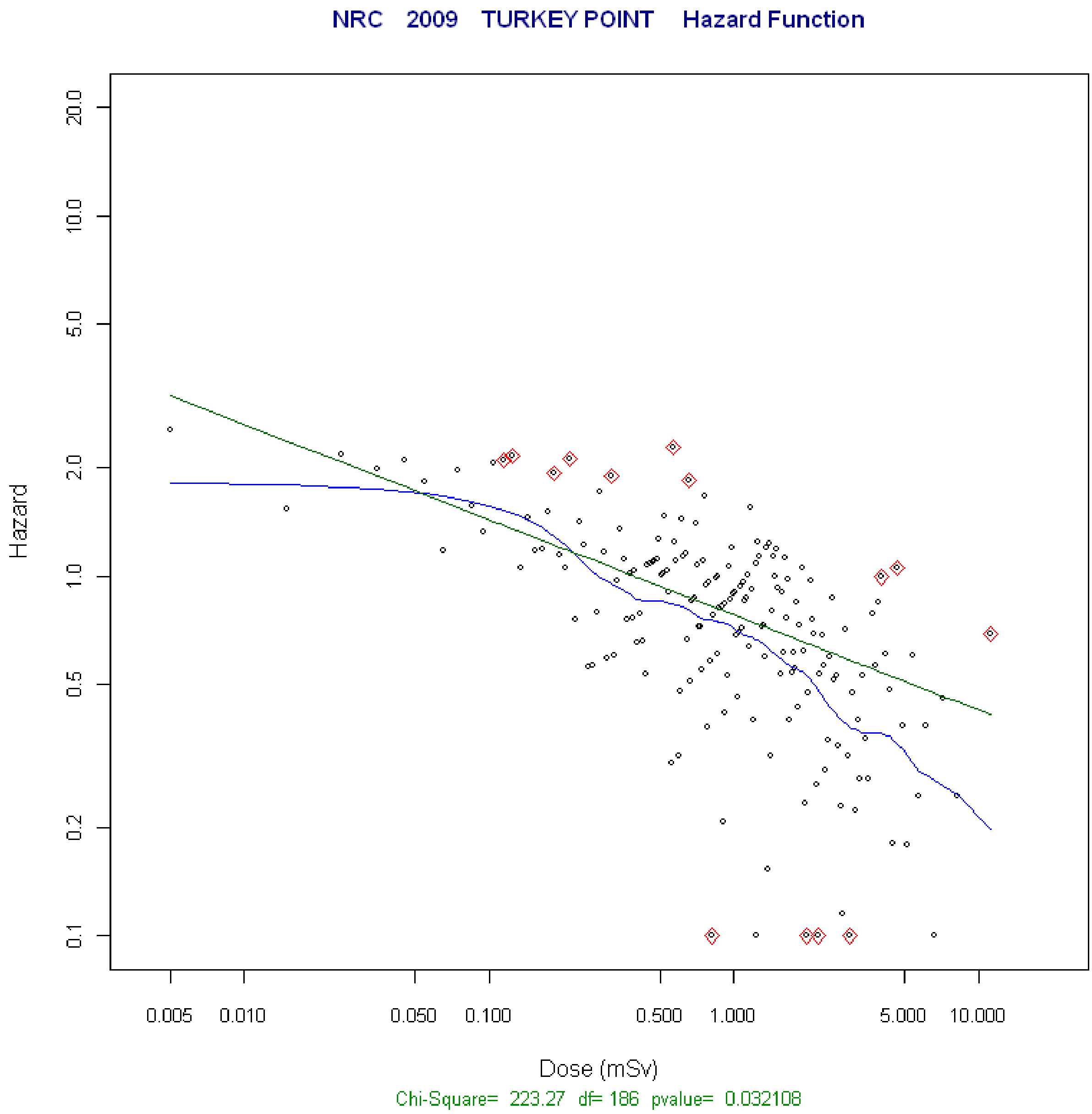

Figure C117: Weibull Goodness of Fit Plot for Turkey Point.

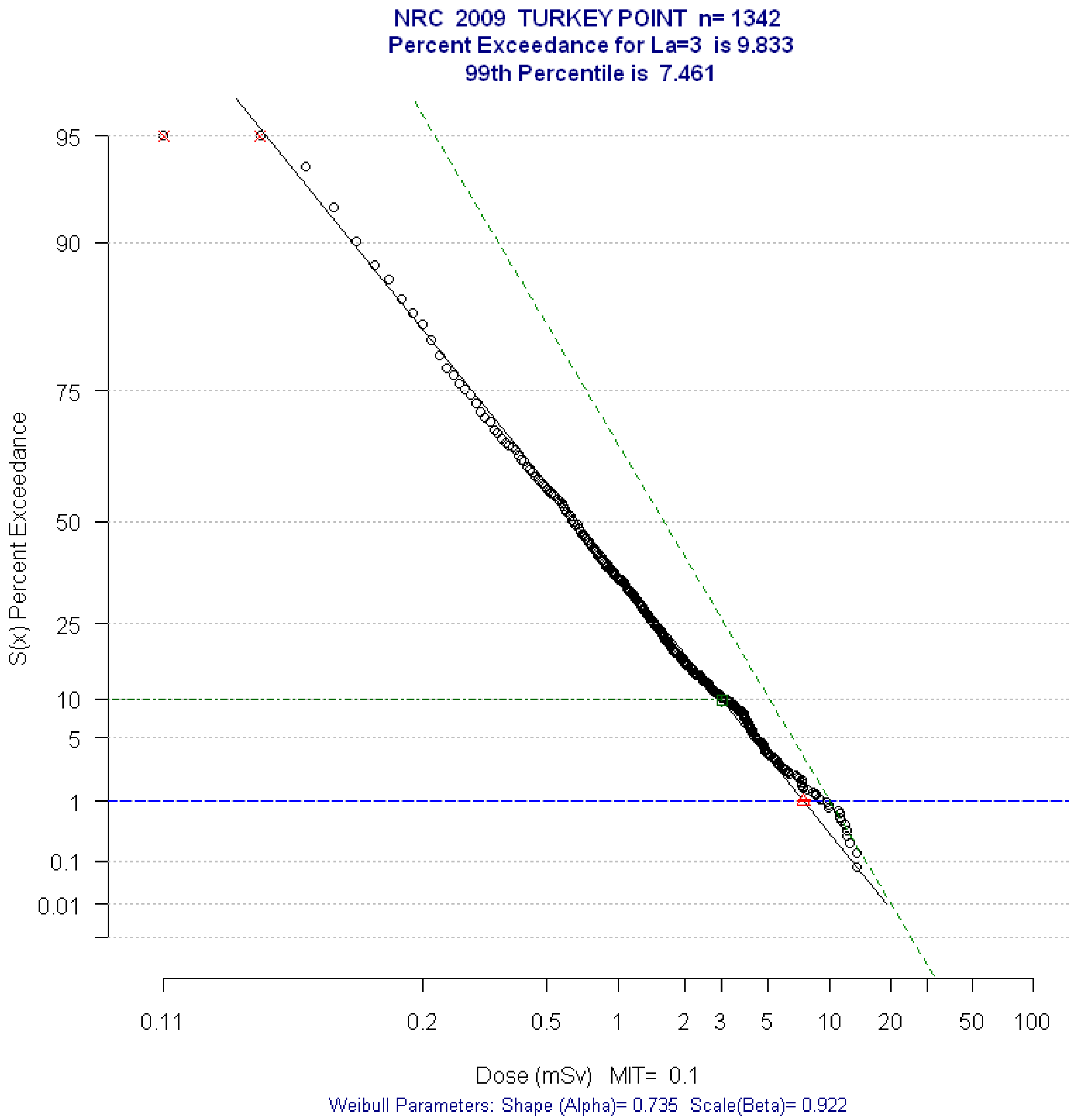

Figure C118: Weibull Probability Plot for Turkey Point.

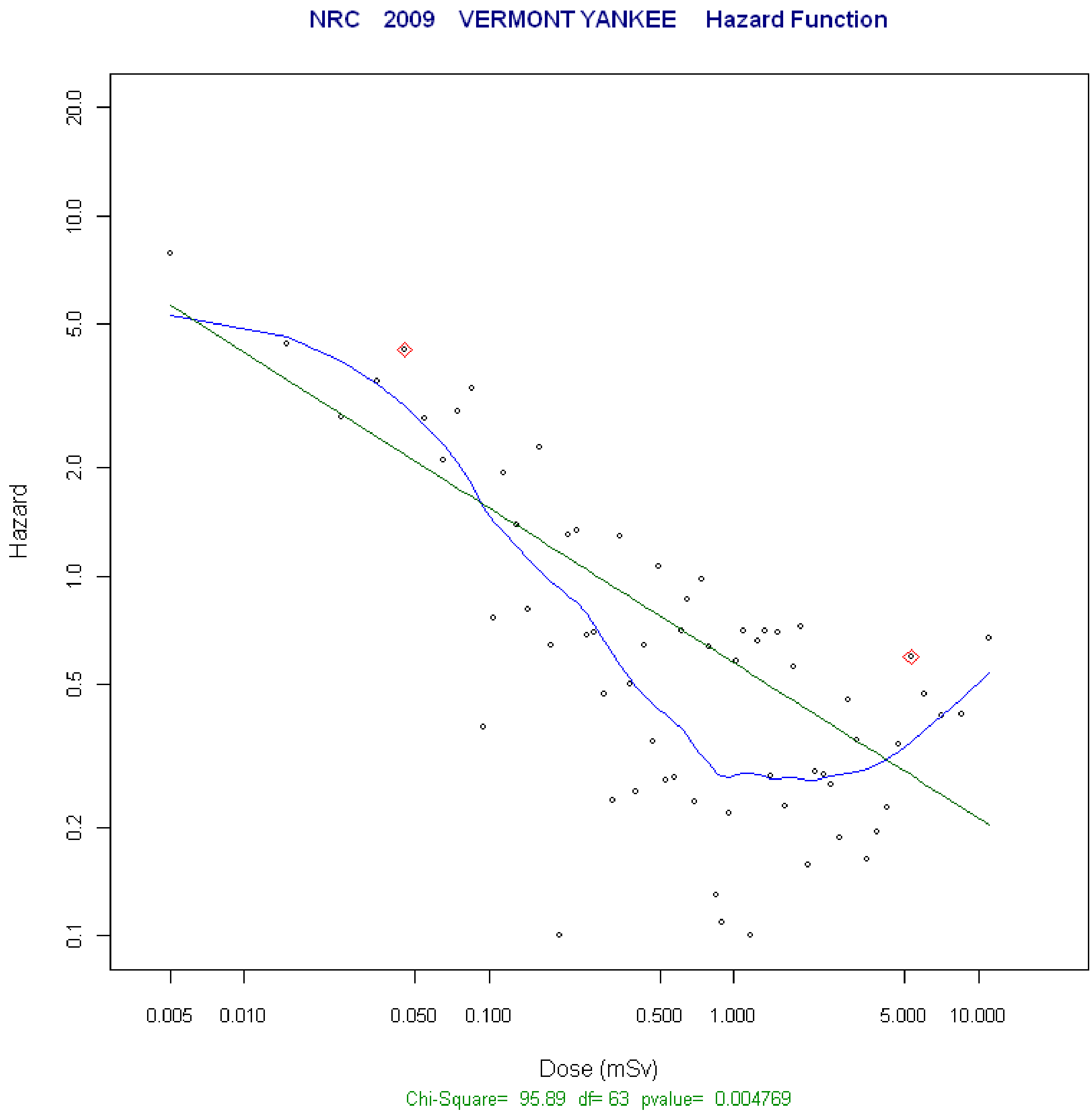

Figure C119: Weibull Goodness of Fit Plot for Vermont Yankee.

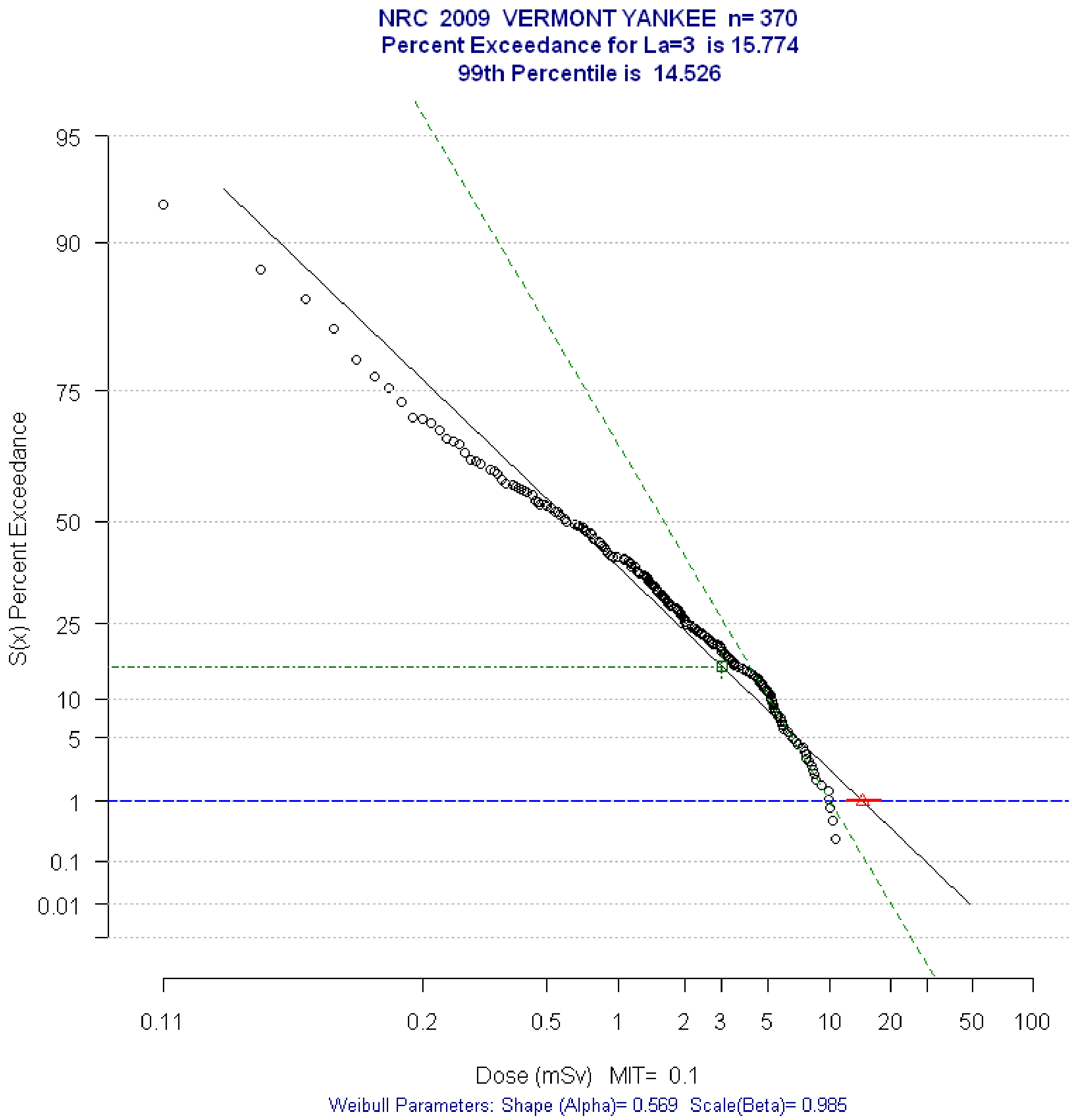

Figure C120: Weibull Probability Plot for Vermont Yankee.

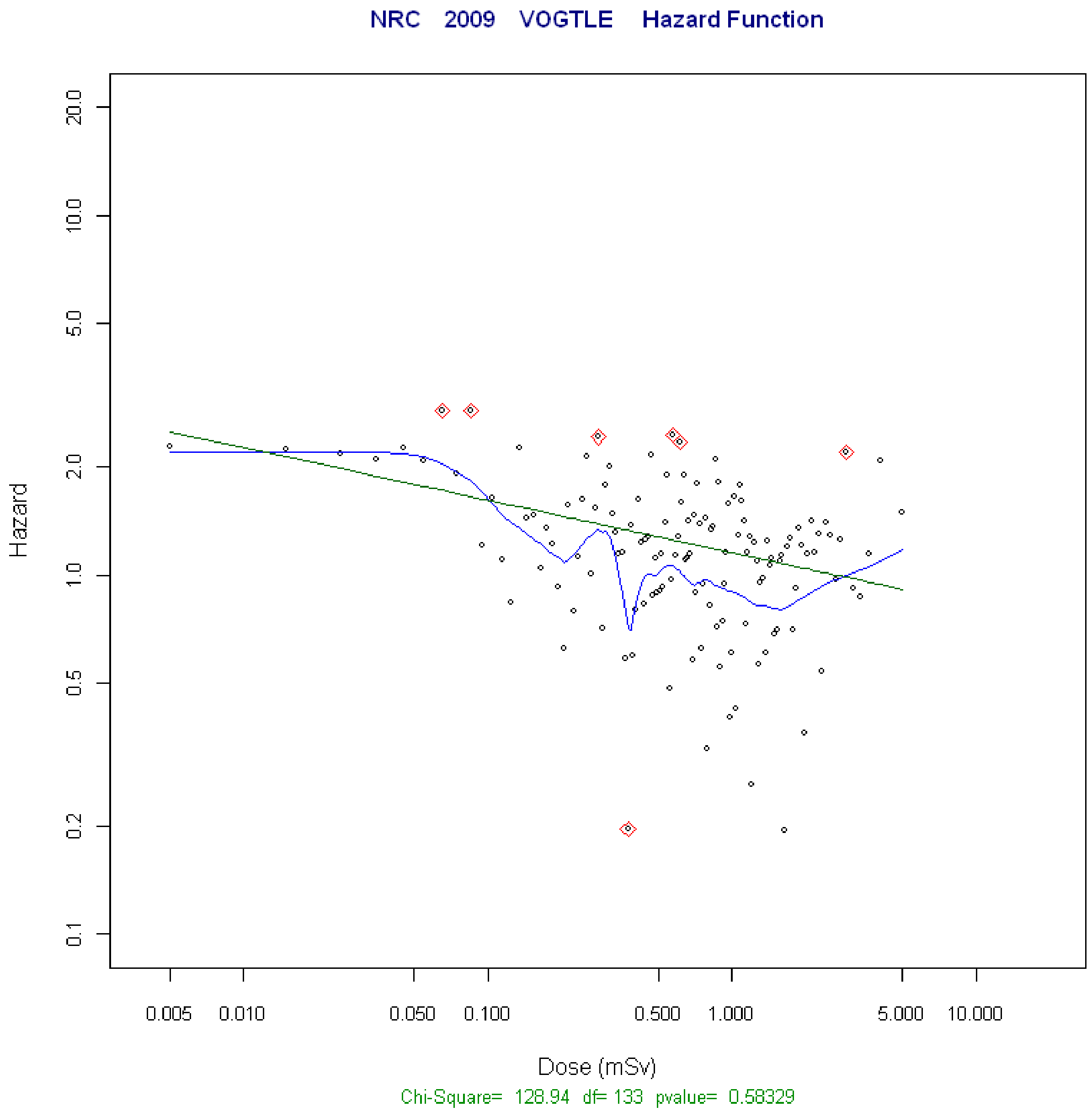

Figure C121: Weibull Goodness of Fit Plot for Vogtle.

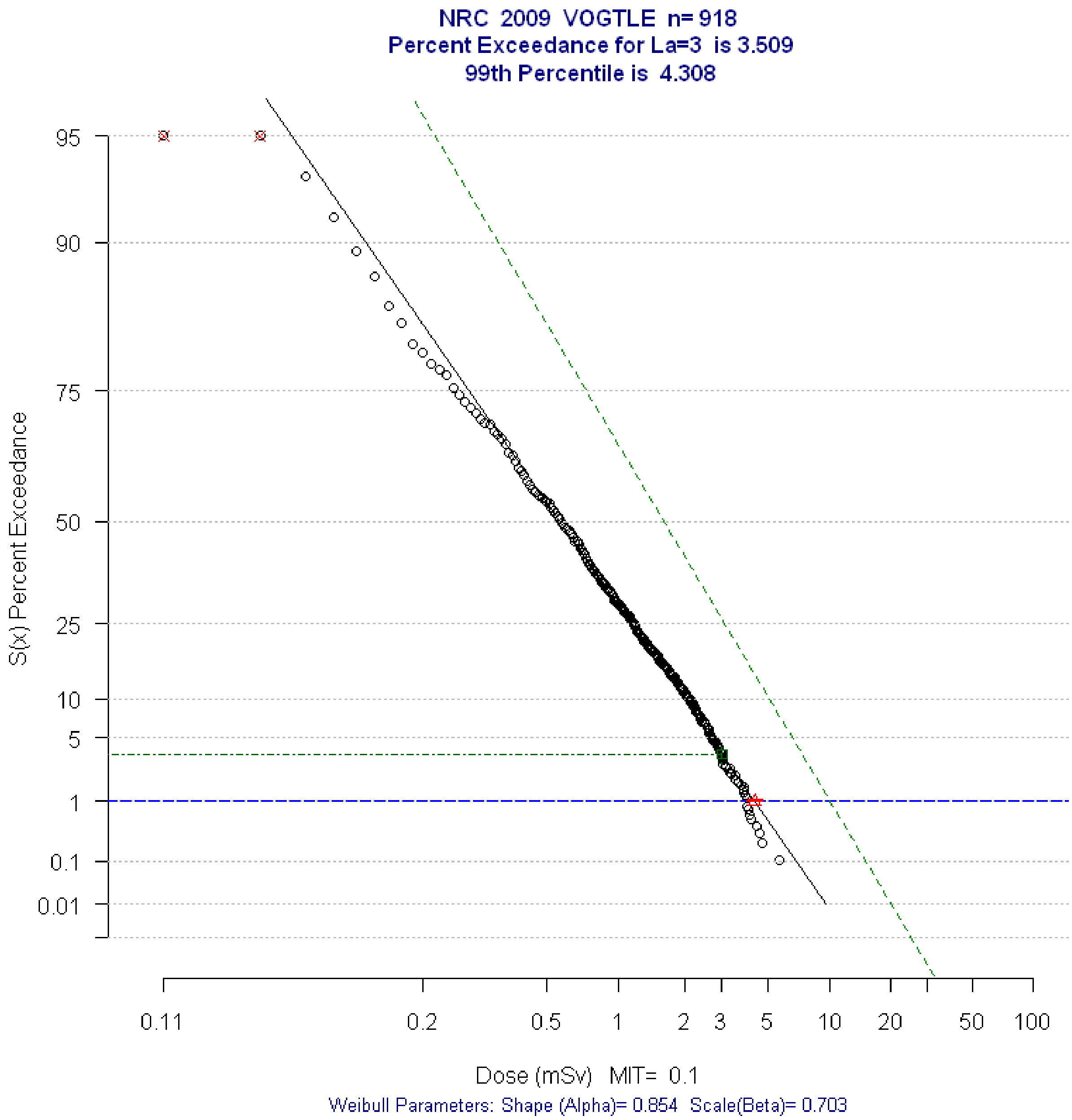

Figure C122: Weibull Probability Plot for Vogtle.

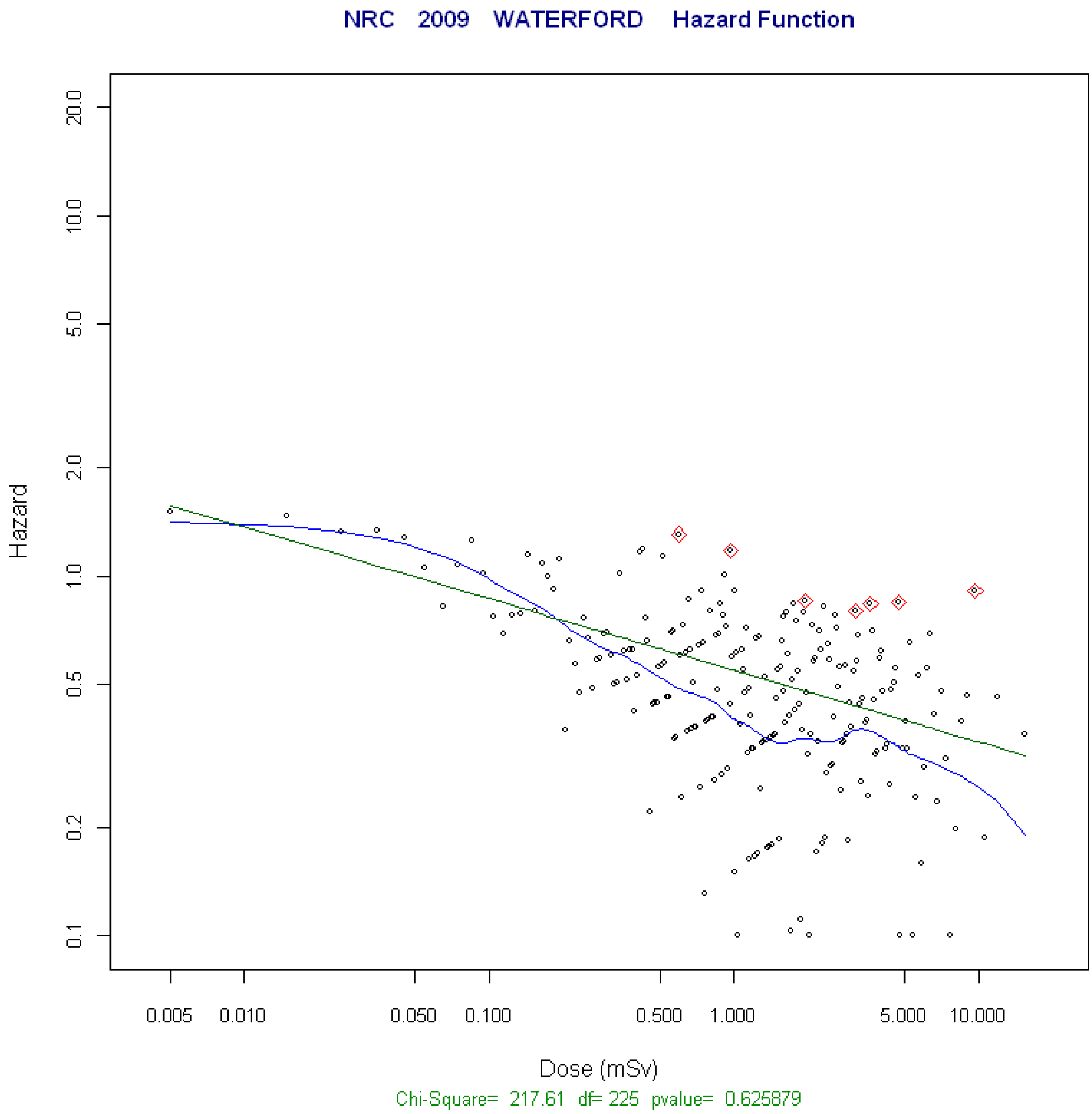

Figure C123: Weibull Goodness of Fit Plot for Waterford.

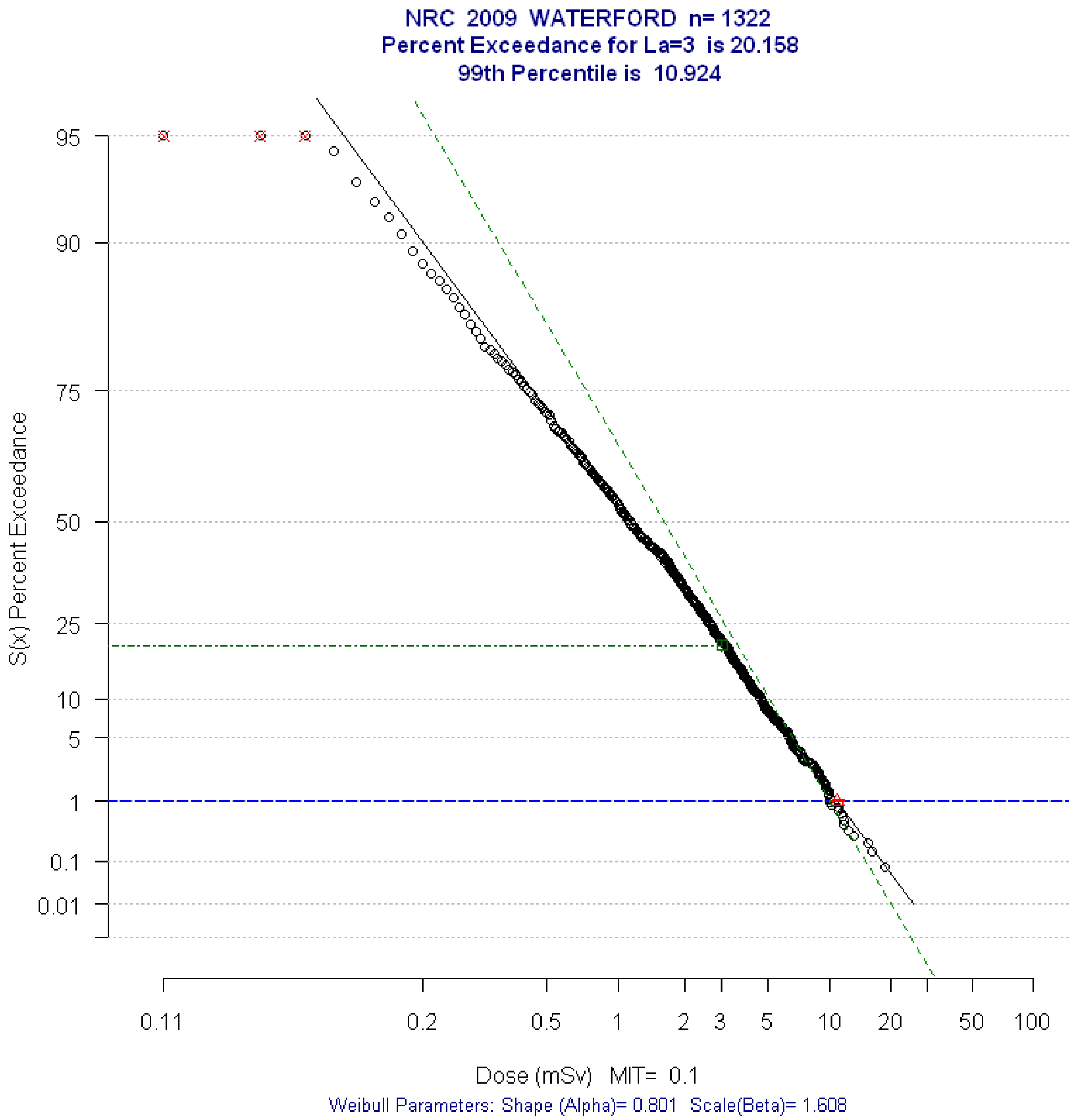

Figure C124: Weibull Probability Plot for Waterford.

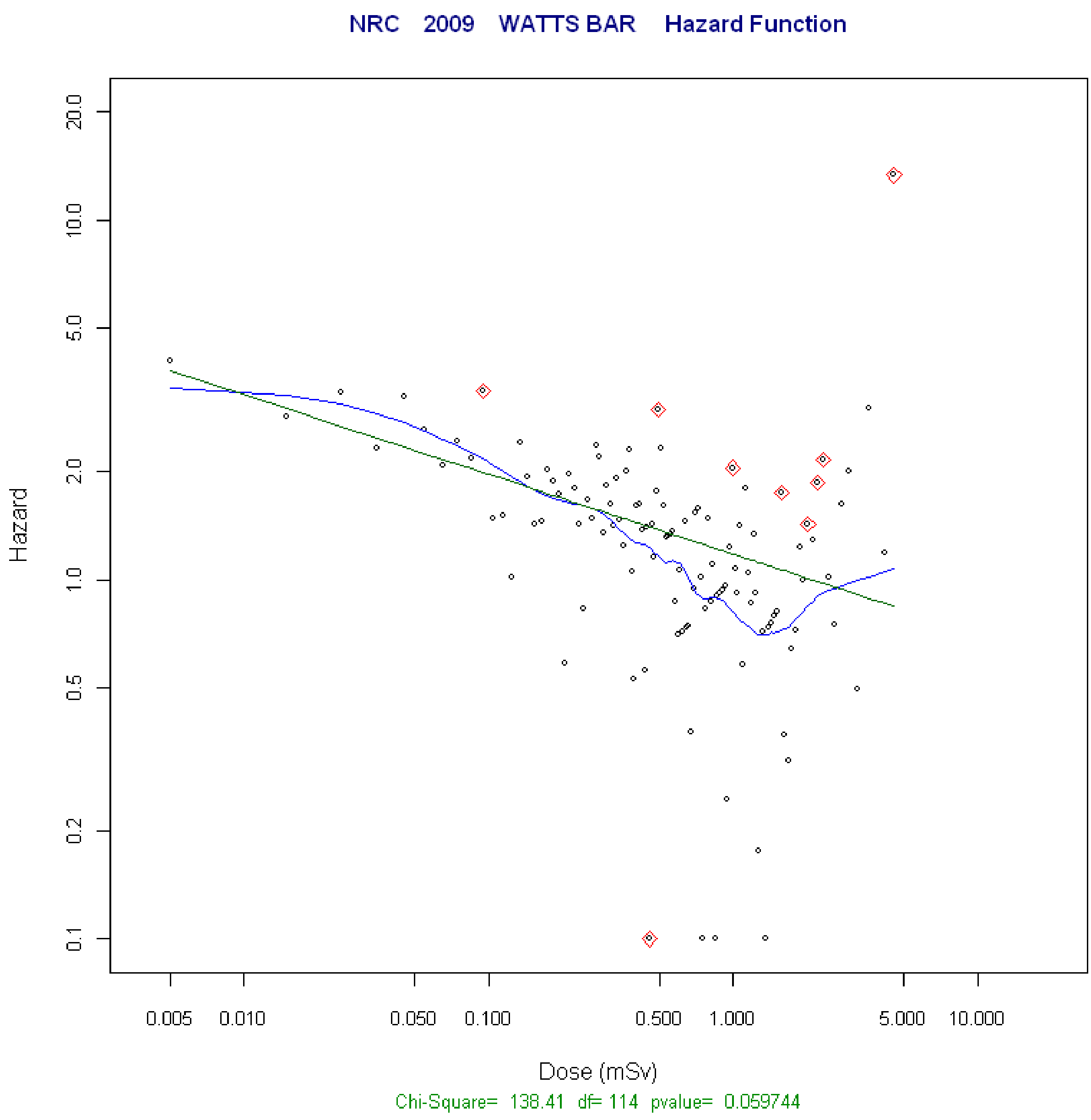

Figure C125: Weibull Goodness of Fit Plot for Watts Bar.

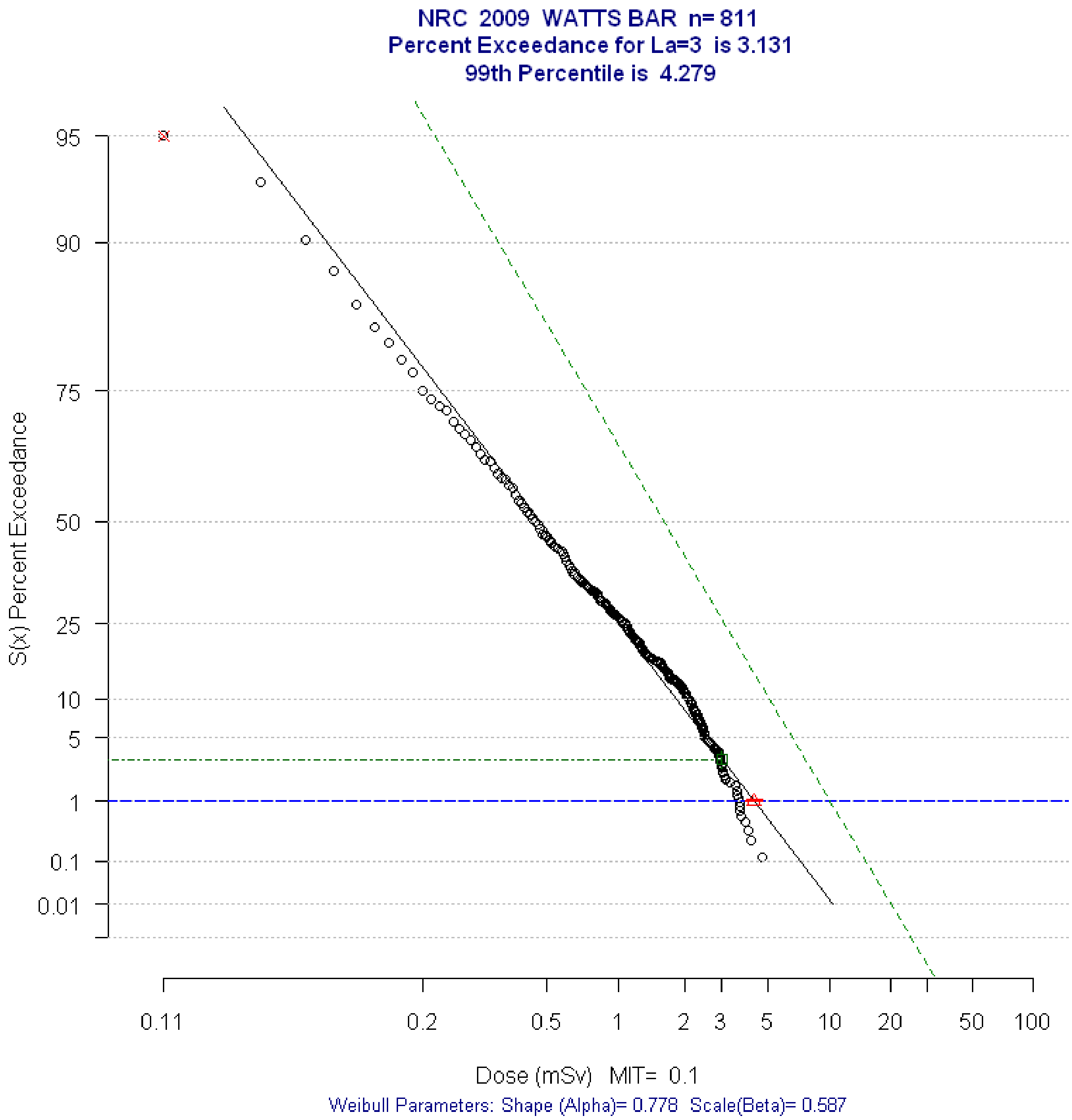

Figure C126: Weibull Probability Plot for Watts Bar.

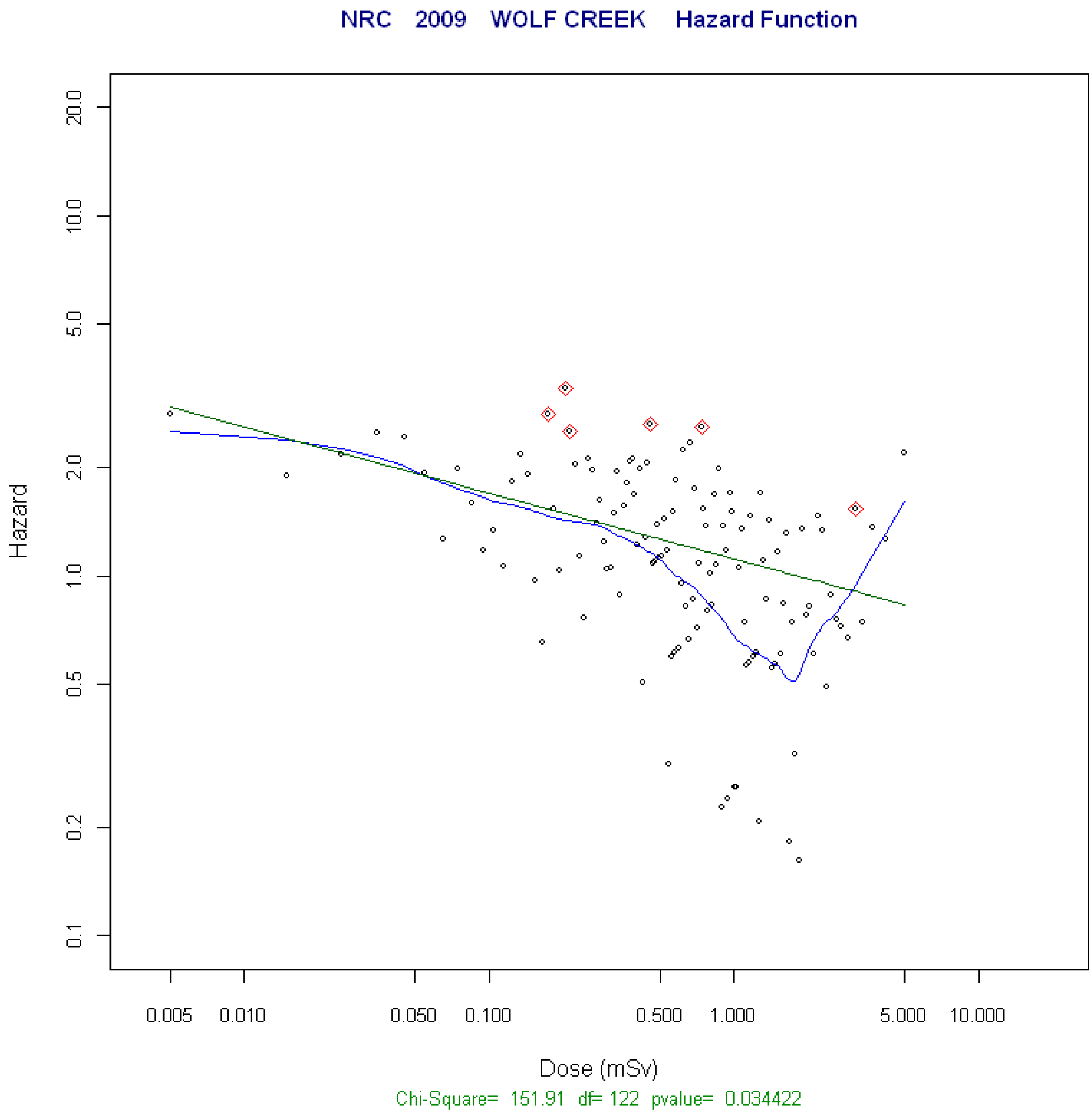

Figure C127: Weibull Goodness of Fit Plot for Wolf Creek.

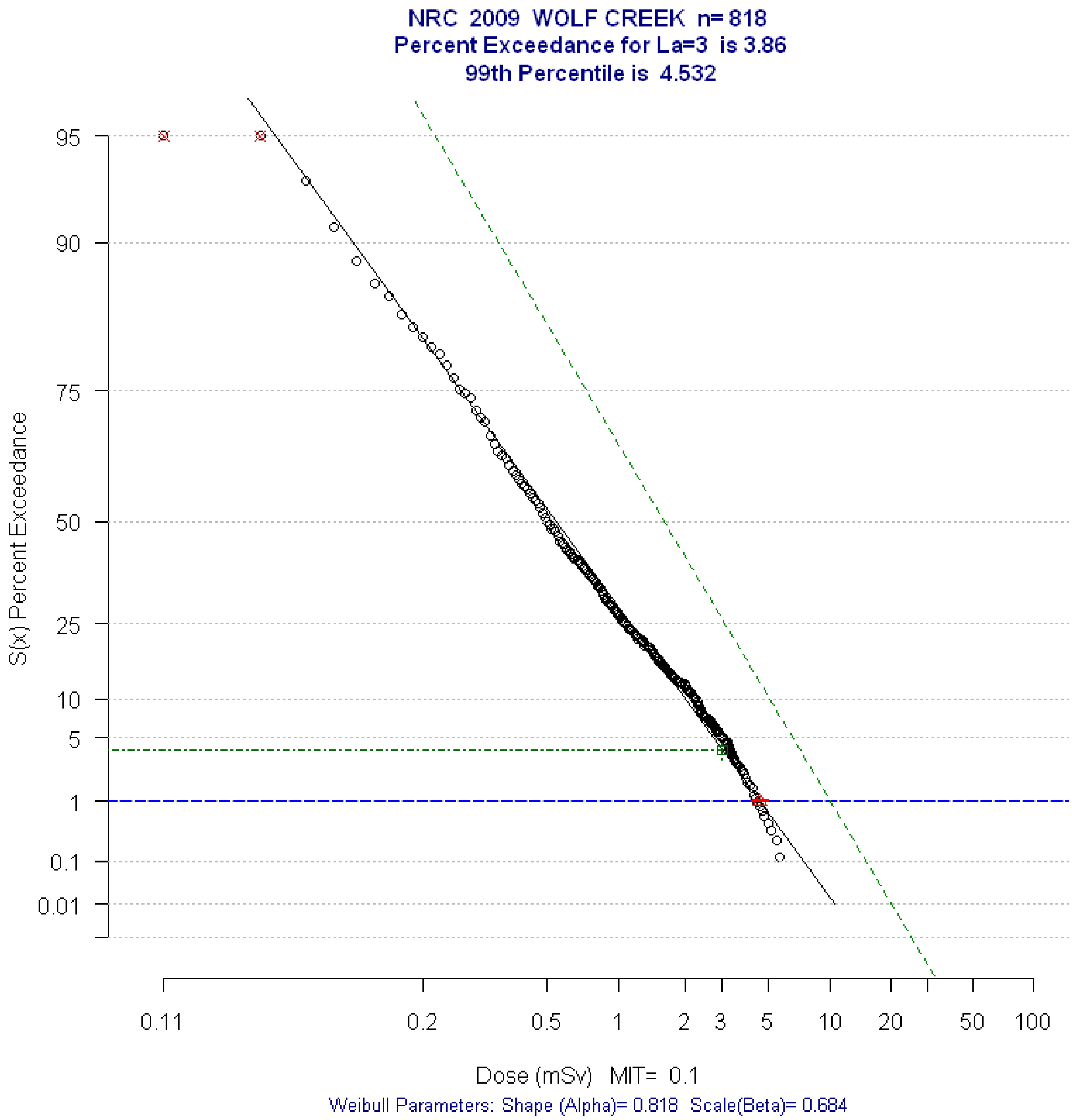

Figure C128: Weibull Probability Plot for Wolf Creek.