Using Weibull Distribution Analysis to Evaluate ALARA Performance

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Introduction – Who We Are

- Janice Watkins and Derek Hagemeyer of Oak Ridge Associated Universities (ORAU)
- Ed Frome, Consulting Scientist for Oak Ridge Institute for Science and Education (ORISE)
- Project work through ORISE
- Under contract to the U.S. Department of Energy and the U.S. Nuclear Regulatory Commission
- ORAU maintains the occupational radiation exposure databases for DOE (REMS) and NRC (REIRS).



Measuring ALARA

- ALARA is a fundamental philosophy of radiation protection codified in NRC and DOE regulations
- ALARA requires a *balance* between collective and individual dose optimization
- Current performance indicators give valuable but incomplete information
 - Collective dose,
 - Number of workers with measurable dose,
 - Average measurable dose,
 - Three-year average dose per reactor
- These are based on collective data and do not consider the distribution of dose to individuals



Our Goal

- To develop objective, data-driven statistically justifiable ALARA performance indicators
- Applicable to a variety of facility types
- In combination with existing parameters, provides a more balanced measure of radiation protection performance based on the way the dose is distributed among the exposed workforce



Weibull Distribution Analysis

Weibull

Flexible statistical distribution for describing positive data, especially when frequent lower values and rare high values

Proportion of doses > x
 S(X) = 1 - F(X) = exp(-[x/β]^α), α>0 (shape), β>0 (scale)

Definition of x Each worker's annual TEDE – MIT, where MIT fixed at 0.1 mSv

 Maximum likelihood Statistical method to select the shape and scale parameters for the particular Weibull that best matches a site's doses



Weibull Analysis Approach

- Weibull model fits to dose distributions
 Generally good since density function is asymptotic to y-axis when shape parameter < 1
- Performance indicators
 Generated from Weibull parameters estimates for the site
- R software functions

Written to calculate ML parameter estimates and performance indicators and to create Weibull plots

ALARA Performance Indicators

- Multiple ALARA indicators recommended
 - Shape parameter α
 - Slope of Weibull probability plot regression line (negative)
 - Fitted 99th percentile with confidence interval -- or
 - Percent exceedance with confidence interval
- Weibull probability plots
 - Provide visual evidence of ALARA effectiveness



Annotated Probability Plot



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All DOE Sites - 1999 and 2008



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All NRC Reactors - 1999 and 2008



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Comparison of NRC Licensees



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Using Collective Dose and Weibull Performance Indicators to evaluate ALARA among Sites



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Conclusions

- Objective performance indicators based on Weibull distribution analysis provide enhanced information for evaluating ALARA at a site
- Graphs demonstrate this approach is useful for comparing ALARA over time or among sites
- Analysis of dose distributions from a variety of sites establish the wide applicability of the Weibull approach



Further Research

- Evaluation of Goodness of Fit
- Expanded information for applying Weibull performance indicators
- Examination of Transient Worker effect
- Investigation into Experienced Worker effect



Goodness of Fit

- Statistical models require goodness of fit evaluation.
- Goodness of fit issues with respect to ALARA application of Weibull performance indicators:
 - Formal evaluation of goodness of fit based on Chi-square test.
 - Examination of plots to determine patterns in lack of fit.



Formal Assessment

- Basis: Chi-square test having null hypothesis that data fit the Weibull distribution.
- Procedure: Separate data into k bins.
- Test statistic: Sum over all bins of squares of residuals where residuals are (observed expected) / $\sqrt{(expected)}$.
- p-value: Based on Chi-square statistic with k-2 degrees of freedom.
- Conclusion: Any site having a p-value smaller than the critical value has statistically significant lack of fit and requires further evaluation.



Goodness of Fit Plots

- Method: Examine how close open circles are to green Weibull hazard line.
- Non-critical lack of fit: Low dose region.
- Flag raised: Rising blue curve (non-parametric smoother) covering dose intervals around important values, e.g. 10 mSv.
 - Were administrative criteria applied to pull individuals out of jobs with exposure potential when dose for year approached predetermined value?
- More effective ALARA practices: Actively maintaining each worker's dose as low as reasonably achievable throughout the year.

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Example - DOE Hanford 2009

- Information from goodness of fit hazard plot:
 - Points represent intervals used in Chi-square test.
 - p-value = 0.150 so not statistical evidence of lack of fit to Weibull.
 - Non-parametric smoother generally close to hazard line.
- Information from survival probability plot:
 - Points represent unique values in dose distribution.
 - Points generally close to Weibull line except for 6 (out of 1274) at high dose end and one at very low dose.





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Using Weibull Performance Indicators <u>PROCESS</u>

- Check value of shape parameter α: Site not effectively implementing ALARA if α > 1.
 - Exception to rule: α > 1 but very small 99th percentile along with percent exceedance near zero.
- Rank sites by fitted Weibull 99th percentile.
 - Table 2: DOE 2009.
 - Table 3: NRC 2009.
- Examine percent exceedance for additional information.



DOE Sites Listed by 99th Percentile, 2009





Using Weibull Performance Indicators Application to DOE 2009

- Question: Should sites be partitioned into quartiles by 99th percentiles?
- DOE 2009: Gap between first and second sites in highest quartile.
 - Pantex =5.141; LANL= 8.058.
- Alternative to partitioning into quartiles: Use 99th percentiles to identify clusters of sites.
 - Group 1: Sites that do not appear to be implementing ARARA effectively.
 - LANL, West Valley, ANL, and LLNL
 - Group 2: Sites that bridge between Group 1 and remainder of sites that do appear to implement ALARA effectively
 - Pantex, ORNL, and, based on percent exceedance, possibly Fermilab.



NRC Reactors Listed by 99th Percentile, 2009



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Using Weibull Performance Indicators Application to NRC 2009

- Group 1: Vermont Yankee, Palisades, and Perry.
 - High 99th percentiles and UCLs.
- Group 2: Cooper Station, Pilgrim, Columbia Generating, Millstone, Waterford, and Nine Mile Point.



Using the Plots to Assess Weibull Fit

- Sites with statistically significant lack of fit :
 - DOE: INL, LLNL, Pantex, and WIPP.
 - NRC: Brunswick, Cooper Station, LaSalle, Millstone, and Monticello.
- Management must decide whether to use Weibull performance indicators for ALARA evaluation.
- Analysis of Weibull plots substantial contribution to this decision.
- Detailed discussions of analysis for these sites in Proceedings paper.



Transient Worker Effect

- Transient workers: Monitored at more than one site during the year.
- Doses remain in separate site records for analysis of all NRC sites.
- When adjusted, transient worker doses from separate sites are summed.
- Adjusting for transient workers effects the Weibull results:

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





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Experienced Worker Effect

- Specialists trained to perform job tasks that involve potentially high exposure.
- Using experienced workers among these specialists promotes safety and results in lowest accumulation of collective dose.
- This practice can be an acceptable approach for supporting ALARA.
- Informal sensitivity analysis was carried out using several scenarios:
 - Scenario 1: Crystal River 2009 distribution
 - Scenario 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.
 - Scenario 3: Same as Scenario 2, with more individuals modified.

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One experienced worker





Several 'less' experienced workers



Results

- Each successive scenario experienced a small increase in the 99th percentile.
- Effect on 99th percentile of using less experienced workers shows this to be a somewhat less effective ALARA practice.

			99 th	99 th %	0/0	
Scenario	α	β	percentile	tile- ucl	exceedance	nx
1	0.802	1.128	7.682	8.212	11.897	1602
2	0.801	1.143	7.803	8.345	11.148	1595
3	0.802	1.156	7.864	8.410	12.386	1595





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Conclusions

- Use maximum likelihood methods to estimate Weibull shape and scale parameters for each site in the group.
- From site-specific parameters calculate fitted 99th percentile for performance indicator and percent exceedance as alternative performance indicator.
- Rank sites by 99th percentile and look for clusters of sites at high end.
- Perform Chi-squared goodness of fit tests to identify sites with statistically significant lack of fit to a Weibull distribution
- Consult Management to determine whether any operational issues affected dose distribution from sites with lack of fit.



Conclusions (continued)

- Use customized probability and goodness of fit plots to investigate patterns of lack of fit.
 - Is lack of fit substantial enough for the Weibull-based performance indicators to be rejected?
 - Are lack of fit contributions to the Chi-squared statistic concentrated in intervals from the very low dose range?
 - Are there values that appear to have been set administratively as an upper bound for an individual's dose?
- Weibull methodology reflected expected impact on ALARA performance indicators in transient and experienced workers analyses.





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Weibull Density Function for Scale Parameter of 0.5



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Details of Weibull Probability Plot

- Points (In x, -In(-In x))
- Regression line: solid black line
- Labels on axes adjusted
 - Horizontal: TEDE before MIT subtracted
 - Vertical: % exceedance for values of interest
- Fitted 99th %tile:
 - Intersection of blue horizontal dashed line with regression line
 - 95% CL indicated by horizontal red segment



Details of Weibull Probability Plot (cont.)

- Percent exceedance: Shown for 2.5 mSv
 - Intersection of green horizontal dot-dashed line with regression line
 - 95% CI indicated by vertical green segment
- Reference line for comparisons
 - Slanted green dashed line with slope = 1
 - Indicates boundary for 99% of doses being < 10 mSv

Research Objectives

Objective 1

Evaluate utility of Weibull distribution for assessing ALARA application to radiation exposed workers

Objective 2

Derive ALARA performance indicators based on Weibull distribution parameters

Objective 3

Design graphics that illustrate ALARA performance indicators and properties of site dose distributions



Weibull Plots for Goodness of Fit

- Purpose:
 - To visually examine patterns of goodness of fit .
 - To uncover dose ranges where lack of fit occurs.
- Plots for complementary information:
 - Customized Weibull probability plot based on survival function.
 - Goodness of fit plots bases on Weibull hazard function.
 - High hazard corresponds to low survival.
- Statistical details summarized in the following table.

