Failure Modes & Effects Analysis (FMEA)

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Need for FMEA's

Often the effects of a failure can have impacts of different severity with respect to economic impacts, environmental impacts, impacts on health and safety of humans, regulatory impacts or violations and impacts of public concern and censure. Risk concerns exist with regard to all of these potential impacts. The objective of an FMEA is to identify and quantify these risks in order to either avoid, or mitigate them.

FMEA is an acronym for **F**ailure **M**odes and **E**ffects **A**nalysis, and is a methodology for the assessment of 'risk', which is a combination of likelihood and consequences of failure. The goal is to provide a useful analysis technique that can be used to assess the potential for, or likelihood of, failure of structures, equipment or processes and the effects of such failures on the larger systems, of which they form a part, and on the surrounding ecosystem, including human health and safety. The environmental community often uses this type of process for conducting environmental risk assessments and engineers use this type of method to assess the risk of engineered systems. Mining companies can use this assessment method to evaluate the risk that their Closure Plans impose on the surrounding environment, workers and the public. This analysis methodology has been adapted for many applications over numerous industries including 'systems' approach and 'criticality' analysis.

Use of FMEA's for Risk Management

The FMEA provides the evaluators with the ability to perform a systematic and comprehensive evaluation of potential failure modes of the design/plan in order to identify the potential hazards. The technique is not limited to this but is applied as such in this instance. The FMEA can be used to evaluate the potential for failures of the Closure Plan measures that could result in Biological/Land Use Impacts, Regulatory Impacts/Censorship, Public Concern/Image and Health and Safety Impacts. A risk profile can be developed for each of these concern areas. Once the failure modes and measures with the highest risk have been identified, it is possible to consider mitigation or alternative designs to reduce risks. FMEAs are therefore an essential part of any risk and liability reduction program.

Evaluation of 'Risk'

Risk is a function of Likelihood and Consequence

The term 'risk' encompasses the concepts of both the likelihood of failure, or the 'expected frequency of failures, and the severity of the expected consequences' if such events were to occur. Because predictive risk assessment involves foreseeing the future, it is an imprecise art. There is a difference between the risk of a failure, and uncertainty in the estimate of that risk. There are also separate uncertainties associated with both the expected frequency and expected consequences.

Mine closure plans include complex natural and engineered systems involving geology, geotechnics, hydrogeology, hydrology, geochemistry, biology, ecology and social systems. Failure modes exist for each of these systems and as a result of interaction between these systems. Methods for failure risk analyses for geotechnical/geochemical/hydrogeological/biological engineered systems are in the early stages of development in comparison to failure risk analyses used in some other fields of engineering where the potential for failures have been more precisely determined from statistics of equivalent system performance or from probability analyses of deterministic systems. This lack is partly due to the heterogeneous nature of natural geological/geochemical/biological systems and partly due to the lack of any established databases for failures of components of such engineered/natural systems. Often the 'best' estimate of the likelihood of failure of such complex systems is made based on the opinion of suitably qualified and experienced professionals. In essence, such estimates are empirical values based on experience and informed judgement of the apprpriate 'expert' familiar with the design, operations and site conditions. The reliability of the estimate is substantially dependent on the available information, expertise, skill, experience and good judgement of the experts. The scope of the FMEA should be broad to cover the effects of relevant modes of failure, including engineered system failures and natural failures (avalanches, floods, droughts etc.). Factors, to account for the confidence in estimates of the likelihood and consequence, should be included to provide readers with an understanding of the analysts opinion of the reliability of the estimate.

Detailed Approach

This type of FMEA is a top down/ expert system approach to risk identification and quantification, and mitigation measure identification and prioritization. Its value and effectiveness depends on having experts with the appropriate knowledge and experience participate in the evaluation during which failure modes are identified, risks estimated, and appropriate mitigation measures proposed. It is therefore essential that the evaluation team include representatives who understand the geotechnics, hydrology, environmental impacts and regulatory requirements applicable to the engineered and natural systems and their surroundings, as well as the past history of the mine's design, construction, operation and performance.

An example of an FMEA worksheet including a few example failure modes is provided here in pdf form. This FMEA worksheet illustrates the methodology's structured approach for identifying failure modes leading to undesired events. This may be modified depending on the assessment objectives. The worksheet is organized in columns with the headings 'Mine Area/Component', 'ID', 'Failure Mode', 'Effect', 'Project Stage', 'Likelihood', 'Consequences', 'Level of Confidence' and 'Mitigation/Comments'. Each of these headings is described in the following sections.

Mine Area/Component

This column provides an area for a description of each area or component of the mine site is being evaluated. This can be an open pit, rock pile, spillway, dam, pipeline etc.

ID

This is a simple alpha-numeric code that makes ready, quick reference to specific failure modes for each component certain line items much simpler later on. For instance, often the alpha-numeric codes for each failure mode of each component are plotted within the Risk Matrix graphic (discussed further below) in order to provide a summary of the entire FMEA.

Failure Mode

A failure mode can be naturally initiated (e.g. an 'act of God' such as an earthquake which is greater than the design event) or it can be initiated by the failure of one of the engineered subsystems (e.g. instability of a dam) or result from operational failure (e.g. failure to close a valve releasing contaminating fluids). Because of the large number of potential failure modes that could be included in an FMEA, it is often necessary to confine evaluations to those that represent a significant risk. Failure modes can also be combinations of events where a small trigger event sets off a chain of events resulting in substantial or large consequences.

The examples provided in the worksheet relate to the generation of acid rock drainage from facilities such as open pit mine walls, tailings facilities and mine rock piles. Some of the failure modes are simply acts of nature (e.g. acidity generated from a pit wall) whereas others may be failure modes related to ineffective or inadequate control measures (e.g. inadequate blending of non-acid and acid generating materials).

Effects or Consequences

The assessment of the magnitude of the Effects (or Consequences) of specific failure modes should be based on evaluations or analyses of the systems responses following failure. Adverse effects may have physical, biological or health and safety consequences. It is often necessary to make first estimates of consequences based on a professional judgement of the anticipated impact of that failure. The examples related to acid generation provided in the sample FMEA worksheet would have an effect on the requirements for collection and treatment, or the appearance of contaminated seepage in unexpected areas. The classification of the severity of effects (i.e. the consequences) are discussed under the heading 'Consequences' below.

Project Stage

Some 'risks' have a different likelihood of occuring or a different consequence if they occur during operations (O) or post closure (PC). The column 'Project Stage' is included to indicate the time frame(s) in which the risk was considered. Some risks increase with the period over which the risk is assessed. I.e. the potential of a 100 year recurrence interval flood occuring is much greater during the long post closure period than it is during a, say, 10 year operating life of a mine. Risk of some facility failure (e.g. a spillway) may be greater post closure when there is not an operating staff to provide monitoring and maintenance. The time frame is also important when assessing risks to human health and safety where there are likely many more people at risk during operations than post closure.

Likelihood

The likelihood of the failure mode leading to the effects has been classified here using a 5 class system, ranging from not likely to expected (see Table 1). Two separate likelihood distributions have been adopted: one for safety consequences, and another for environmental and public concern consequences. The reason for this is that we have found that, in general, the public tolerance for safety consequences is much lower, and therefore the acceptability of risk of a safety event compared to an environmental event is lower. The number of classes, can be adapted to best suit a specific site.

Table 1. Likelihood of Risk

Likelihood Class	Likelihood of Occurrence for Safety Consequences (events/year)	Likelihood of Occurrence for Environmental and Public Concern Consequences

		(events/year)
Not Likely (NL)	<0.01% chance of occurrence	<0.1% chance of occurrence
Low (L)	0.01 - 0.1% chance of occurrence	0.1 - 1% chance of occurrence
Moderate (M)	0.1 - 1% chance of occurrence	1 - 10% chance of occurrence
High (H)	1 - 10% chance of occurrence	10 - 50% chance of occurrence
Expected (E)	>10% chance of occurrence	>50% chance of occurrence

Consequences

For each Effect, the consequence can be assessed separately in each of four different concern areas. For each concern area, there are various scales and thresholds that may apply, such as scales based on the severity of injury, community well-being, environmental impact, operational impact etc. The scales that we have found most applicable for mine closure assessments are provided on Table 2 below.

For mine closure purposes, the authors have found it useful to have separate consequence categories for each of the following concern areas:

1. Biological Impacts/Land Use
2. Regulatory Impacts and Censure
3. Public Concern and Image Impacts
4. Health and Safety

Regulatory impacts have been found to have a profound influence on risk. Changes in regulation or regulatory enforcement practices following failures, or perceptions of potential failures can have severe consequences. Public concern and activism following failures have also had severe impacts, including impacts on public company share value and abilities to permit new mines.

The consequence ranking, or severity, is typically also classified using a 5 class system. We have found ranking from negligible to extreme consequences to be effective and intuitive. The class intervals for each of the categories is outlined in table 2. Again, these are suggested classifications that have been found useful in the past, but could be adapted to best suit the site or plan being evaluated at the time.

Table 2. Severity of Effects

Consequences Severity	Biological Impacts and Land Use	Regulatory Impacts and Censure	Public Concern and Image	Health and Safety
Extreme	Catastrophic impact on habitat (irreversable and large)	Unable to meet regulatory obligations; shut down or severe restriction of operations	Local, international and NGO outcry and demonstrations, results in large stock devaluation; severe restrictions of 'license to practice'; large compensatory payments etc.	Fatality or multiple fatalities expected
High	Significant, irreversible impact on habitat (large but reversable)	Regularly (more than once per year) or severely fale regulatory obligations or expectations - large increasing fines and loss of regulatory trust	Local, international or NGO activism resulting in political and financial impacts on company's 'license to do business' and in major proceedure or practice changes	Severe injury or disability likely; or some potential for fatality
Moderate	Significant, reversible impact on habitat	Occasionally (less than one per year) or moderately fail regulatory obligations or expectations - fined or censured	Occasional local, international and NGO attention requiring minor proceedure changes and additional public relations and communications	Lost time or injury likely; or some potential for serious injuries; or small risk of fatality
Low	Minor impact on habitat	Seldom or marginally exceed regulatory obligations or expectations. Some loss of regulatory tolerance, increasing reporting.	Infrequent local, international and NGO attention addressed by normal public relations and communications	First aid required; or small risk of serious injury
Negligible	No measurable impact	Do not exceed regulatory obligations or expectations	No local, international, or NGO attention	No concern

Level of Confidence

There is uncertainty regarding both the likelihood of failure and consequence estimates based on a number of factors, including: lack of data; lack of system understanding; uncertain future operating conditions or uncertain maintenance; and, regional development post closure. Thus confidence in the risk estimates may range from low to high. It is useful to reviewers of the FMEA if the evaluation team provides their assessment of their confidence in any risk rating that they conclude.

We have found that a three interval classification system of low, medium and high confidence in the risk ratings is usually adequate and appropriate. Where there is low confidence in a high risk assessment value, this clearly indicates a need to further evaluate the risk in order to more reliably predict both the risk and the mitigation measures to reduce such risk.

Mitigation/Comments

For each of the risks, safeguards that are already in place through design or operating procedures can be listed (usually as a separate column). Safeguards act to prevent, detect, or mitigate a risk from reaching its worst results, and can be applied to both the failure mode and the resulting effects. The existing safeguards reduce the likelihood of the risk from occurring.

Similarly, if a particular failure mode and effect is rated a 'high' or 'expected' likelihood and a 'high' or 'extreme' consequence in any of the categories evaluated, additional mitigation measures may be sought to reduce this risk. In this manner, the FMEA worksheet can act as a template from which risk management measures or procedures can be prioritized.

Representation of Results

Given the likelihood and severity, a risk rating can be determined and displayed by plotting the results on a two dimensional risk matrix (see Figure 3a below). This procedure is often referred to as 'binning'. A failure mode which is 'expected' and would result in an 'extreme' consequence plots in the red 'bin'. The risk ratings are shown as colors alone, to indicate that this is not a mathematically precise representation of risk. The level of 'risk' increases moving from the bottom left to the top right. The warm colors (yellow through red) indicate failure modes with significant and increasing risk ratings. These are the failure modes in most urgent need of determination of mitigation measures. The cold colors (green through dark blue) indicate the failure modes with moderate to low risk.

For ease of communication, the alpha-numeric codes (ID) of the various failure modes can be plotted within the risk matrix easily flagging those ID codes with their associated risk ratings. The resulting plots are called 'Risk Matrices'. Separate matrices are plotted for each of the concern areas. The four risk matrices represent the 'risk profile' for the closure plan being evaluated. A typical profile is provided as Figures 3b to 3e. Comparison of these matrices indicates that for the example given, the matrix for Regulator Impacts and Censure has the highest risk ratings. These risk matrices (the risk profile) is an excellent tool for illustration to management, regulators and the public the risk profile for a project or its alternatives, as well as for planning risk management programs. In addition, the authors typically color-code the FMEA worksheet using the same color combinations as in the risk matrix, providing a tool with which the reader can scan a long list of evaluated risks and easily pick out those of most concern.

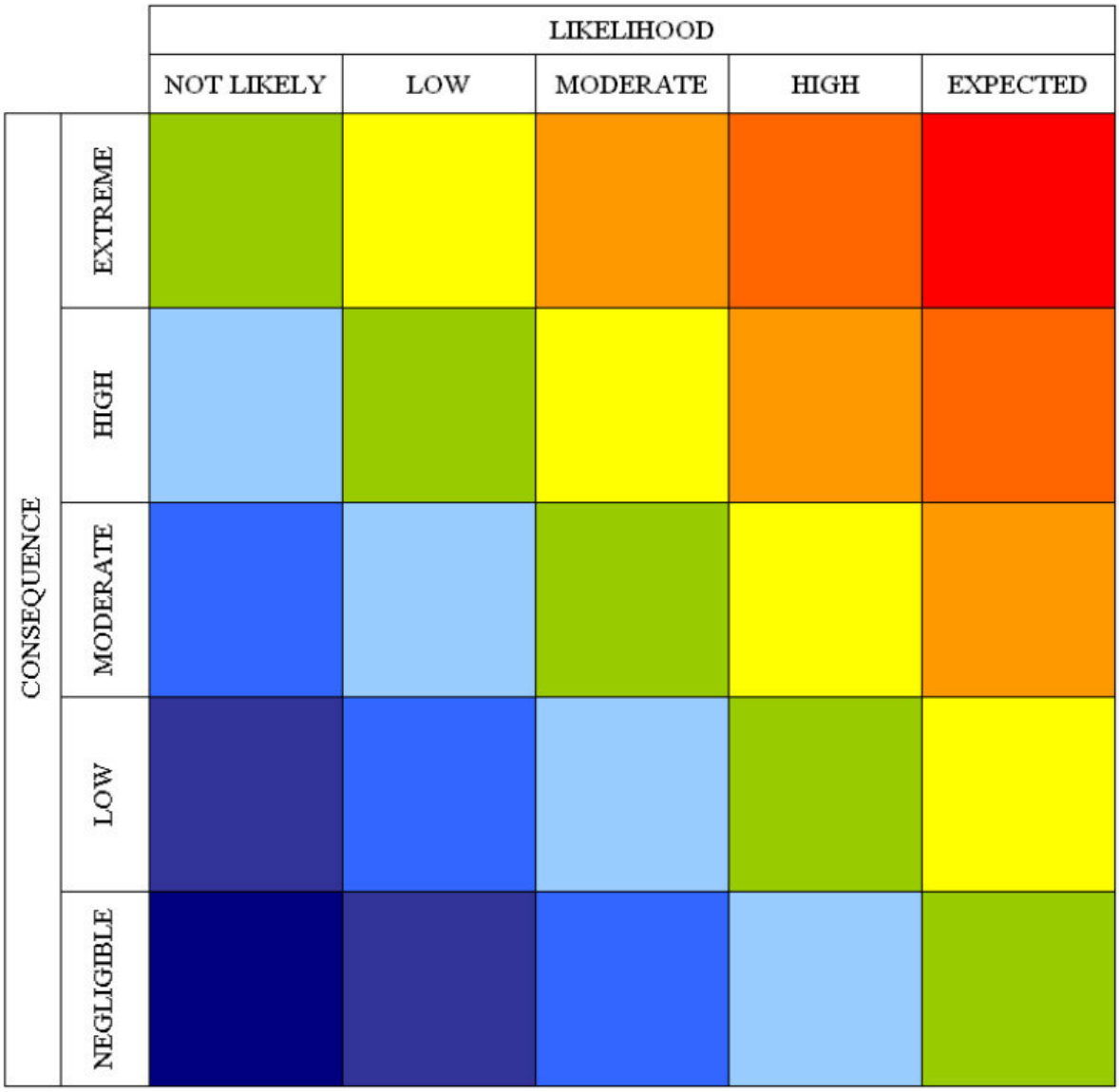

Figure 3a. Risk Matrix

CONSEQUENCE	LIKELIHOOD: NOT LIKELY	LOW	MODERATE	HIGH	EXPECTED
EXTREME	B14.1, B15.2, B16.2	A61.1, B14.1, B15.2, B16.2	A12.3, A61.2, A62		
HIGH		A41.7, A42.2, A101.3, B21.1, B31.5, B31.6, B33.6	B11.2, B11.3, B32.2	A55.1, B11.1, B15.1, B16.1	B21.2
MODERATE		A13, A22.2, A61.5, A81.6, B22.1, B23.1, B31.4, B33.4, B92.2	A21.1, A21.2, A22.1, A41.6, A52, A81.2, B12.1, B13.1, B13.2	A53.1, A55.2, A61.4, B12.2, B31.3, B33.3	A14.1, A41.8, A42.1, A92.1, B22.2, B23.2, B32.1
LOW	B17	A41.2, A41.4, A57, A92.2, A92.5, A101.2, A101.6, B14.2, B17, B31.2, B34.1, B37.1	A41.5, A63.3, A101.4, A63.5, B18, B31.1, B33.1, B36.1	A12.2, A41.1, A41.3, A53.2, A56, A61.6, A63.4, A71.1, A71.2, A81.4, A81.5, A92.3, B33.2	A11, A12.1, A14.2, A54, A61.3, A63.1, A63.2, A81.3, A92.4, A92.6, A101.5, A101.7, B34.2, B35.1, B36.2, B37.2, B53.2, B51, B52, B53, B71.1, B71.2, B94.2
NEGLIGIBLE		B41.1, B41.2, B41.3, B41.4, B85, B91.2, B91.3, B92.1, B93.1	A81.1, B92.3, B93.2, B93.3	B91.1	A91, B81.1, B81.2, B81.3, B81.4, B94.1

Figure 3b. Example Risk Matrix for Biological Impacts and Land Use

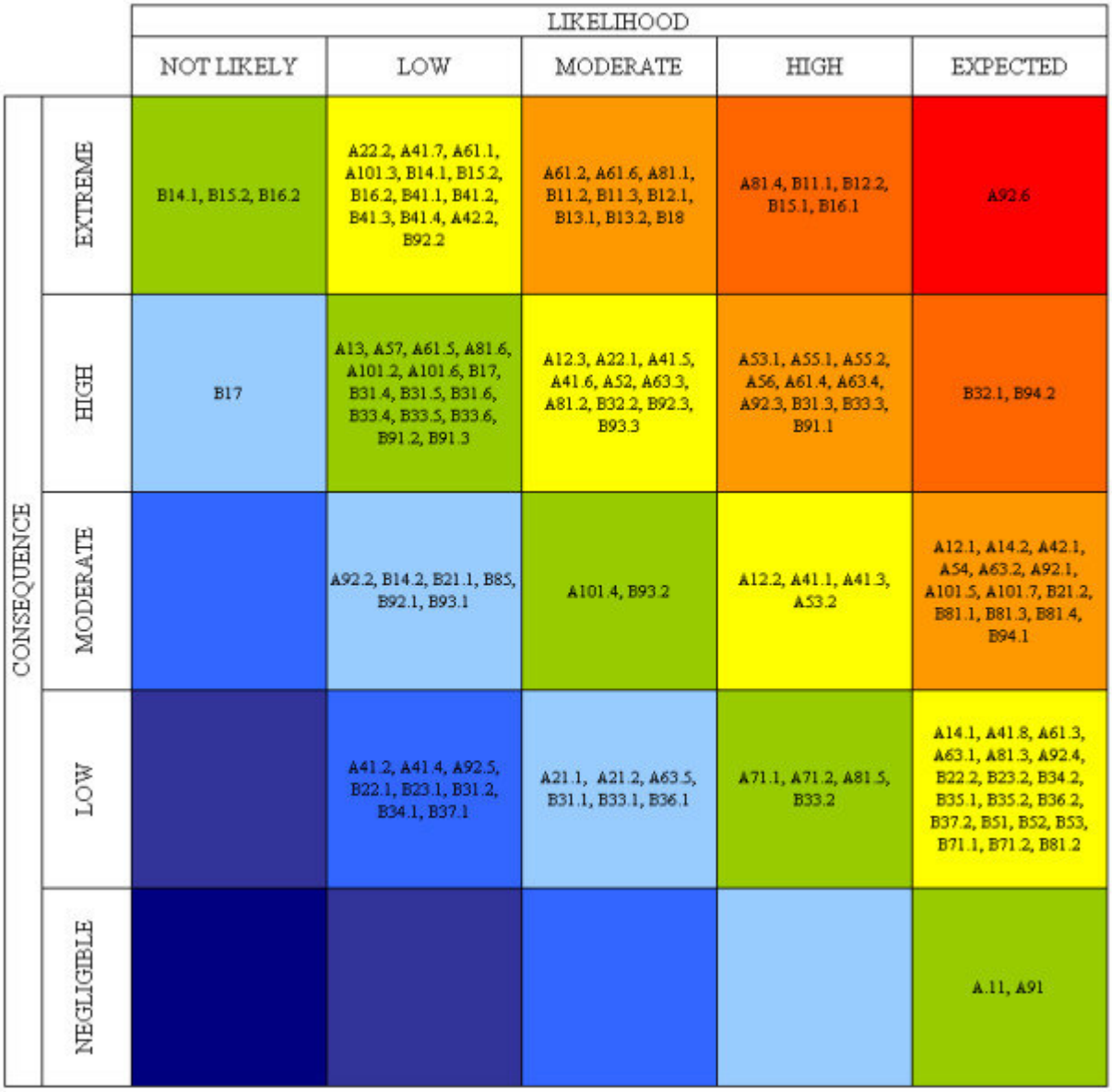

Figure 3c. Example Risk Matrix for Regulatory Impacts and Censure

CONSEQUENCE	LIKELIHOOD: NOT LIKELY	LOW	MODERATE	HIGH	EXPECTED
EXTREME	B14.1, B15.2, B16.2	A22.2, A41.7, A61.1, A81.6, A101.3, B14.1, B15.2, B16.2, B41.1, B41.2, B41.3, B41.4, B92.2	A61.2, A62, A81.1, A81.2, B11.2, B11.3, B12.1, B13.1, B13.2, B18	B11.1, B12.2, B15.1, B16.1	
HIGH	B17	A13, A57, A61.5, B17, B31.5, B31.6, B33.5, B33.6, B91.2, B91.3, B92.1, B93.1	A12.3, A41.5, A41.6, A63.3, B32.2, B92.3, B93.2, B93.3	A56, A61.4, A63.4, B91.1	A54, A92.1, B32.1, B94.2
MODERATE		A92.5, A101.2, A101.6, B14.2, B21.1, B31.4, B33.4	A22.1, A52, A101.4	A12.2, A41.1, A41.3, A53.1, A53.2, A55.1, A55.2, A81.5, B31.3, B33.3	A12.1, A14.2, A42.1, A63.2, A92.4, A92.6, A101.7, B22.2, B94.1
LOW		A41.2, A41.4, A92.2, B22.1, B23.1, B31.2, B34.1, B37.1, B85	A21.1, A21.2, A63.5, B31.1, B33.1, B36.1	A61.6, A71.1, A71.2, A92.3, B33.2	A11, A14.1, A41.8, A61.3, A63.1, A81.3, A101.5, B22.2, B23.2, B34.2, B35.1, B36.2, B37.2, B51, B52, B53, B71.1, B71.2, B81.1, B81.2, B81.3, B81.4
NEGLIGIBLE					A91

Figure 3d. Example Risk Matrix for Public Concern and Image

CONSEQUENCE	LIKELIHOOD: NOT LIKELY	LOW	MODERATE	HIGH	EXPECTED
EXTREME	B14.1, B15.2, B16.2	A42.2, A57, A81.6, B14.1, B14.2, B15.2, B16.2, B91.2, B91.3	A81.2, B92.3, B93.2, B93.3	A56, B15.1, B16.1, B91.1	
HIGH		A101.3	A12.3, A63.3, B11.2, B11.3, B13.1, B13.2,	B11.1	B81.1
MODERATE	B17	B17, B92.1, B92.2, B93.1	A63.3, B12.1, B18	A63.4, B12.2, B55.2	B81.3, B81.4, B94.1, B94.2
LOW		A13, A22.2, A61.5, A92.2, A92.5, B85	A101.4	A53.2, A55.2, A61.4, A61.6, A71.1, A71.2, A81.4, A81.5, A92.3	A14.1, A54, A63.1, A63.2, A81.3, A92.1, A92.4, A92.6, B51, B52, B53, B71.1, B71.2, B81.2
NEGLIGIBLE		A41.2, A41.4, A41.7, A42.2, A61.1, A63.5, A101.2, A101.6, B21.1, B22.1, B23.1, B31.2, B31.3, B31.4, B31.5, B31.6, B33.4, B33.5, B33.6, B34.1, B37.1, B41.1, B41.2, B41.3, B41.4	A21.1, A21.2, A22.1, A41.5, A41.6, A52, A61.2, A62, A81.1, B31.1, B32.2, B33.1, B36.1	A12.2, A41.1, A41.3, A53.1, A55.1, B31.3, B33.2, B33.3	A11, A12.1, A14.2, A41.8, A42.1, A61.3, A91, A101.5, A101.7, B21.2, B22.2, B23.2, B32.1, B34.2, B35.1, B35.2, B36.2, B37.2

Figure 3e. Example Risk Matrix for Health and Safety

The reader may also find of interest the Risk Analysis - Event Probability Assessment tool available on EduMine. This tool determines the number of events likely to occur during the lifespan of an operation such that probability of exceedance is limited to a specified value. It was created by Dr. F. Oboni who has also written an on-line course for EduMine called Risk Management in Mining that takes a slightly different approach to the FMEA described here.