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A Comparison of Risk Assessment Techniques from Qualitative to Quantitative

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I ABSTRACT

Risk assessment techniques vary from purely qualitative approaches, through a regime of semi-qualitative to the more traditional quantitative. Constraints such as time, money, manpower, skills, management perceptions, risk result communication to the public, and political pressures all affect the manner in which risk assessments are carried out. This paper surveys some risk matrix techniques, examining the uses and applicability for each. Limitations and problems for each technique are presented and compared to the others. Risk matrix approaches vary from purely qualitative axis descriptions of accident frequency vs consequences, to fully quantitative axis definitions using multi-attribute utility theory to equate different types of risk from the same operation.

This paper attempts to shed light on the basic issue regarding the demarcation between qualitative and quantitative risk assessment, and closes with an explanation of the author's "Top Ten Reasons to Not Quantify a Risk Assessment".

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II INTRODUCTION

The fundamental concepts of qualitative and quantitative are explained in a dictionary. Qualitative is defined as "of, relating to, or involving quality or kind." Quality has many definitions, including "peculiar and essential character; an inherent feature. Quality is a general term applicable to any trait or characteristic whether individual or generic." Quantitative is defined as "of, relating to, or expressible in terms of quantity, or involving the measurement of quantity or amount". Finally quantity is defined as "an indefinite amount or number". When applied to risk assessment, qualitative can be considered to produce a subjective and very limited relative sense of the risk only. Qualitative judgements may rank the risk from one scenario or group of scenarios to be greater than some other scenario or group of scenarios. When all the scenarios from a system are included in the ranking, the ranking can only be done subjectively.

In quantitative risk assessment, the risk from each scenario is estimated numerically, allowing the analyst to determine not only risk relative to all scenarios in the system, but absolute risk measured on whatever scale of units is chosen. These determinations can be made objectively using numerical scales. Semi-quantitative risk assessment may use some numbers, mainly in the form of broad ranges of frequency or consequence levels. These methods also determine relative risk to a limited extent, and may go farther than purely qualitative approaches by providing a measurement for how much more one scenario contributes over the next for certain comparisons only, though falling short of any absolute values.

III QUALITATIVE RISK MATRIX APPROACH

A purely qualitative risk assessment is basically task and/or hazard analysis with some relative judgements made in order to categorize the hazards. A task analysis studies each task in the operation. Potential hazards are identified, as well as potential accident initiators caused by the hazards. The accident initiators may be human error, equipment failure, or natural phenomena. Both the frequency and consequence of each accident scenario are then estimated on simple relative scales, such as Low-Medium-High. The risk for each scenario is the product of the frequency rating and consequence rating. In this example, the qualitative risk falls into nine distinct regimes or frequency*consequence pairs: Low*Low, Low*Medium, Low*High, Medium*Low, Medium*Medium, Medium*High, High*Low, High*Medium, High*High. Clearly the Low*Low region has the lowest risk, while the High*High region has the highest risk. The intermediate regions are more difficult to interpret because some regions are directly comparable and others are not.

The 3 by 3 qualitative risk matrix is shown in Figure 1, with arrows designating directions from lower risk regions to higher risk regions. The relative risk of each region is given by a numerical grade, with 1 being the lowest and 5 the highest. Some regions with the same numerical grade are denoted by prime (') and double-prime ('') to indicate that while they have the same relative risk level with respect to nearby regions connected by arrows, the risk of these regions is not necessarily equivalent, and may in fact be significantly different. The risk grade is only relative when applied to those regions directly connected by the arrows. For example, Medium*Low is risk grade 2 and is higher risk than Low*Low (grade 1), and lower risk than High*Low (grade 3). Then by inference, all the regions appearing in a consecutive chain from risk grades 1 to 5 can be compared directly. However regions not appearing in the same consecutive chain cannot be compared directly. For example, High*Low and Medium*Medium have risk grade 3 and 3' respectively, but there is no implied equivalence between them. The only information common to both is that they have greater risk than Medium*Low and lower risk than High*Medium.

Figure 1.
Qualitative Risk Matrix

Risk Levels are Relative to Regions Connected by Arrows

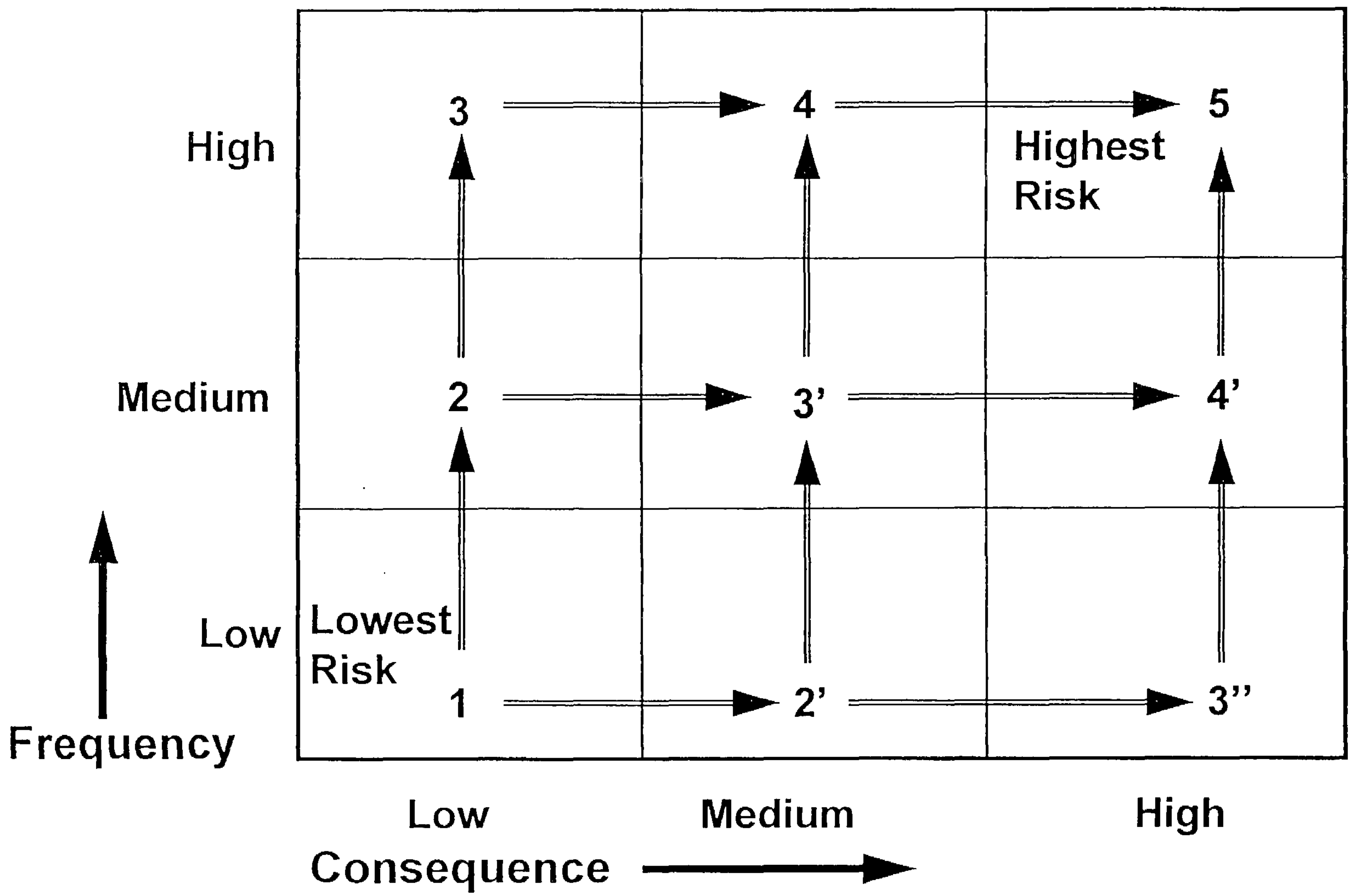


Figure 2 illustrates the six sets of five-link chains of possible comparative risk regions for the 3 by 3 risk matrix. Most regions appear in two or more chains, while the High*Low and Low*High corners only appear in one. The shaded regions in each set represent a chain of comparative risk regimes, with the arrows indicating the direction from low to high risk. Referring to the first example above, Set 1 contains the regions Low*Low, Medium*Low, and High*Low, allowing direct comparisons between them. However, referring to the second example above, High*Low and Medium*Medium do not appear together in any of six sets, and may not be directly compared.

In the EPA Technical Guidance for Hazards Analysis adopted by DOE-STD-3009-94 (Figure 3), the risk levels from the 3 by 3 matrix are grouped into three categories: Major Concern; Concern; and No Concern. Table 1 lists each region, the corresponding risk category from EPA, and the fundamental risk grade from Figure 1. The EPA grouping presents two types of logical inconsistencies. The first type of inconsistency places regions of different and directly comparable risk grade in the same group. Note the Major Concern Group equates risk grade 4 and 5, and the No Concern Group equates risk grades 1, 2, and one region of grade 3. The second type of logical inconsistency places regions which are not directly comparable in the same group. Note the Concern Group contains two risk grade 3 regions which are not directly comparable. The pitfalls that can be encountered from this type of grouping are demonstrated in Figures 4 and 5.

Figure 2.
Regions of Directly Comparable Risk

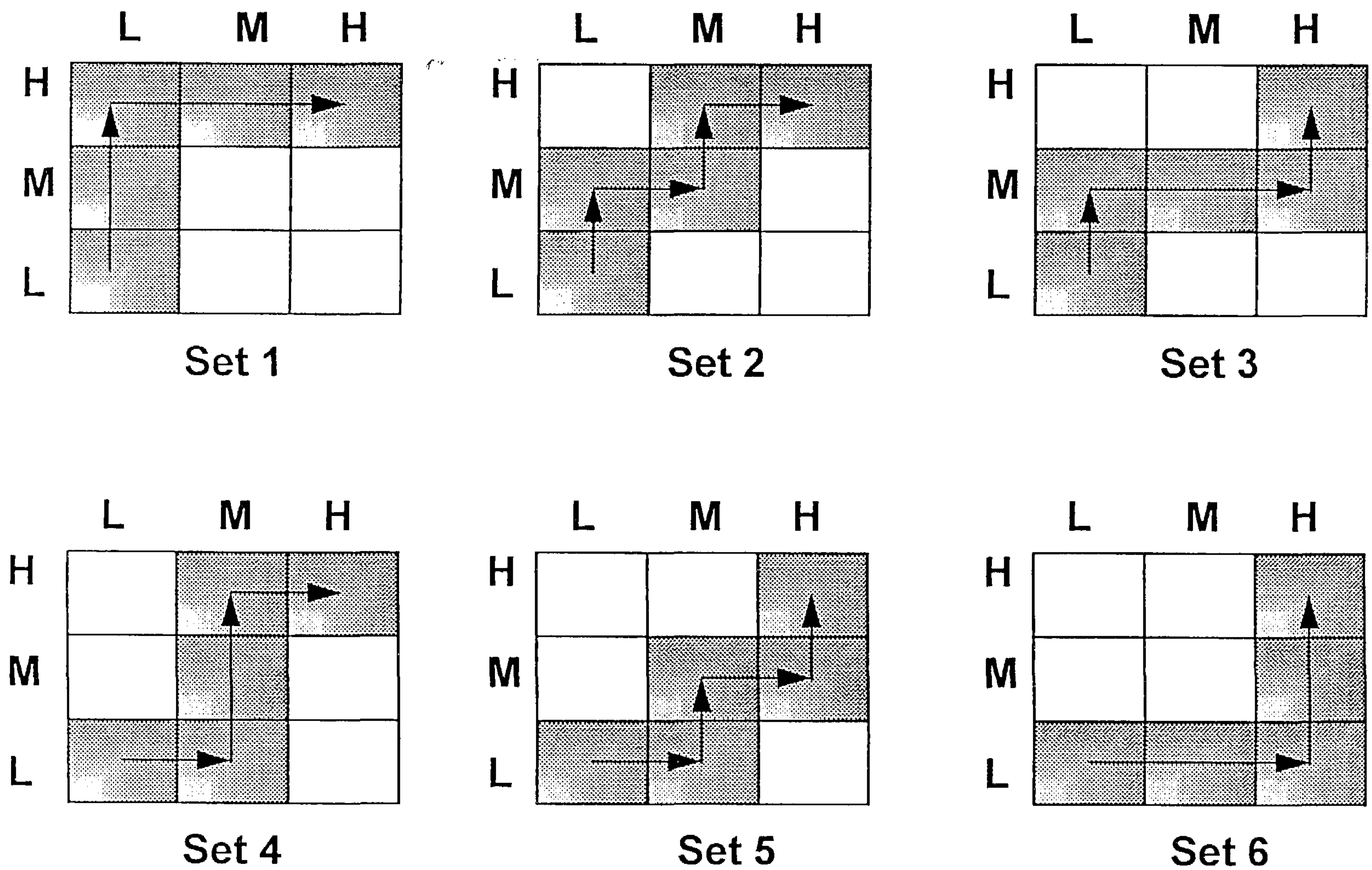


Figure 3. Qualitative 3X3 Risk Matrix from the EPA and DOE-STD-3009

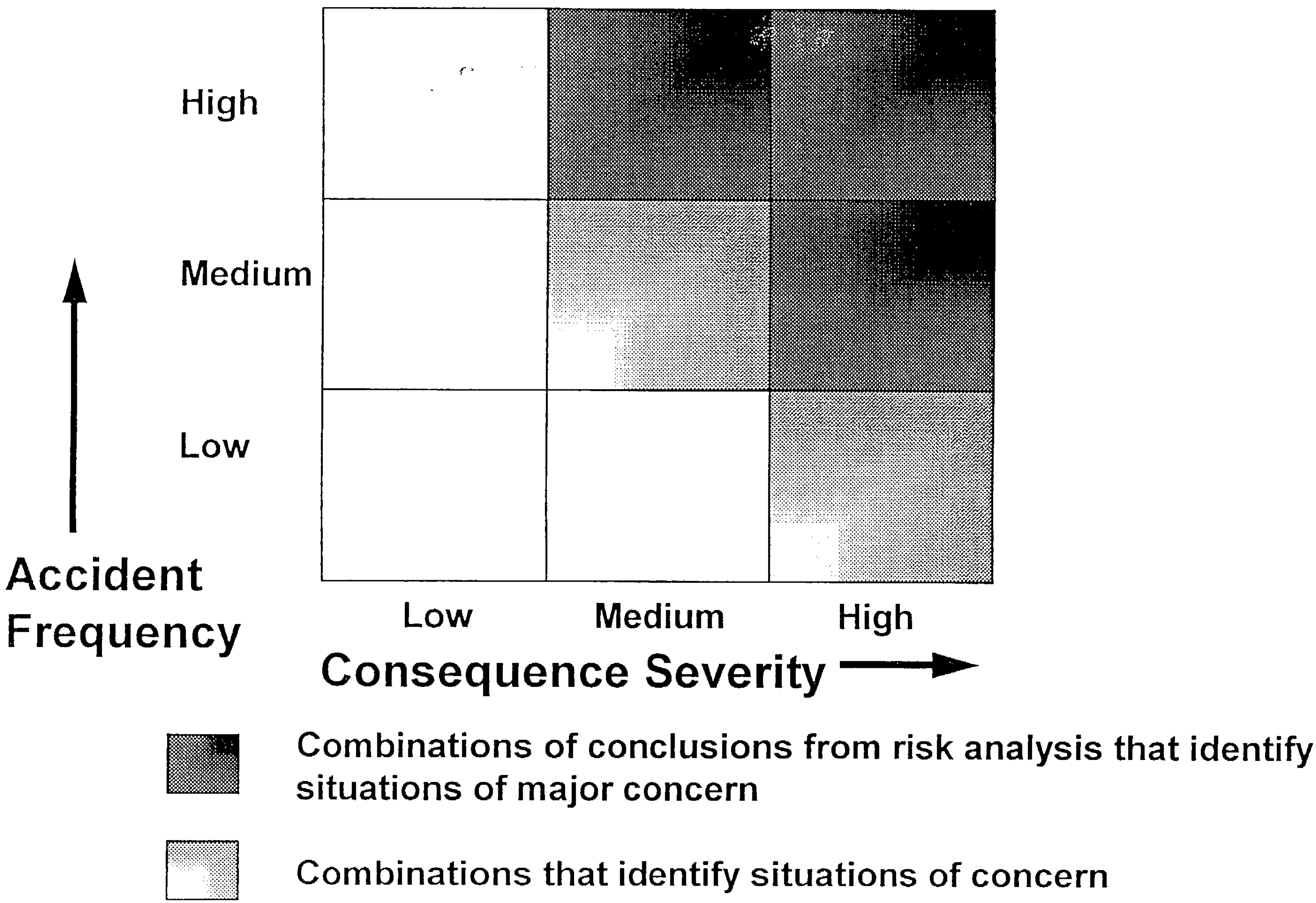


Table 1. Risk Groupings from EPA

Matrix Region	EPA Risk Grade	Figure 1 Risk Grade
High*High	Major Concern	5
High*Medium	Major Concern	4
Medium*High	Major Concern	4'
Medium*Medium	Concern	3'
Low*High	Concern	3''
High*Low	No Concern	3
Medium*Low	No Concern	2
Low*Medium	No Concern	2'
Low*Low	No Concern	1

Figure 4 shows an example of a quantitative 3 by 3 risk matrix, with a logarithmic frequency scale and linear consequence scale of unspecified units. The risk is given for each region in the matrix, as the product of the corresponding frequency and consequence values. In this case of drastically different scales, the frequency axis dominates the risk. Logical groupings might list the Major Concern Group as being High frequency; Concern Group as being Medium frequency; and No Concern Group as being Low frequency, all regardless of consequence level. Imposing a risk grouping system in advance, as is done in Figure 3, is inappropriate for this example.

Figure 5 shows a more realistic example of a quantitative 3 by 3 risk matrix, with logarithmic scales on both axes. In this example, there is a bias towards the consequence axis because that axis increases at a faster rate than the frequency axis. This example appears to be more amenable to using the EPA Groupings. However if applied here, we find that the High*Medium region is in the Major Concern Group

Figure 4.
Quantitative Example of 3x3 Matrix

Frequency Axis Dominates

Frequency ↑	Low 1	Medium 2	High 3
High 100	100	200	Highest Risk 300
Medium 10	10	20	30
Low 1	1 Lowest Risk	2	3

Consequence →

Figure 5.
Quantitative Example of 3x3 Matrix

Bias Towards Consequence Axis

Frequency ↑ / Consequence →	Low 1	Medium 100	High 10,000
High .1	.1	10	Highest Risk 1000
Medium .01	.01	1	100
Low .001	.001 Lowest Risk	.1	10

with a risk of only 10 units, while the Low*High region is in the Concern Group also with a risk of 10 units. While having equal risk these two regions would be are grouped apart. Even though these regions have different risk ratings of 4 and 3'' respectively as shown on Figure 1, and they cannot be qualitatively compared as seen in Figure 2, obviously they should be grouped together in the final risk ranking scheme for this quantitative example.

Figure 6 demonstrates a final example of a quantitative 3 by 3 matrix, where the scales were contrived to produce a risk result consistent with the EPA groups. In this case, all three regions in the Major Concern Group have higher risk than both regions in the Concern Group, which in turn have higher risk than all four regions in the No Concern Group.

Considering that groupings consisting of regions from different risk ratings are not logically consistent, and that groupings consisting of regions from the same risk rating are not logically consistent, one conclusion is clear. In general, logical groupings of regions of equivalent risk from the qualitative risk matrix cannot be found. It's a natural drive to organize that motivates the analyst to want to divide a 3 by 3 matrix into several groups (for example three) of regions each having different risk levels. In a general sense, it is true that some subjective notion of average risk for the Major Concern region of Figure 3 is greater than the average risk for the Concern region. However, there is no guarantee that every region of Major Concern has higher risk than every region of Concern, and similarly for the No Concern region. Therefore, it makes no sense to arbitrarily define such groups in advance for the purpose of having a methodology in order to apply to an actual risk analysis. The more logical alternative is to evaluate each accident scenario for the system being analyzed and place it on the risk matrix in whatever region is appropriate without any predefined risk acceptance levels or judgements. Then the analysts can define the risk acceptance levels by making subjective judgements based on the scenarios that fall in each region. Unfortunately,

Figure 6.
Quantitative Example of 3x3 Matrix

Example Matching STD-3009 Risk Ranking

Frequency ↑ / Consequence →	Low 1	Medium 500	High 10,000
High .1	.1	50	Highest Risk 1000
Medium .01	.01	5	100
Low .001	Lowest Risk .001	.5	10

this process leaves the analyst open to criticism for adjusting the acceptance levels to suit some hidden agenda. The analyst could be accused of following a process similar to Finagle's Law of Experimentation: "First draw desired curve, then plot appropriate data". This is a paradoxical problem with qualitative approaches.

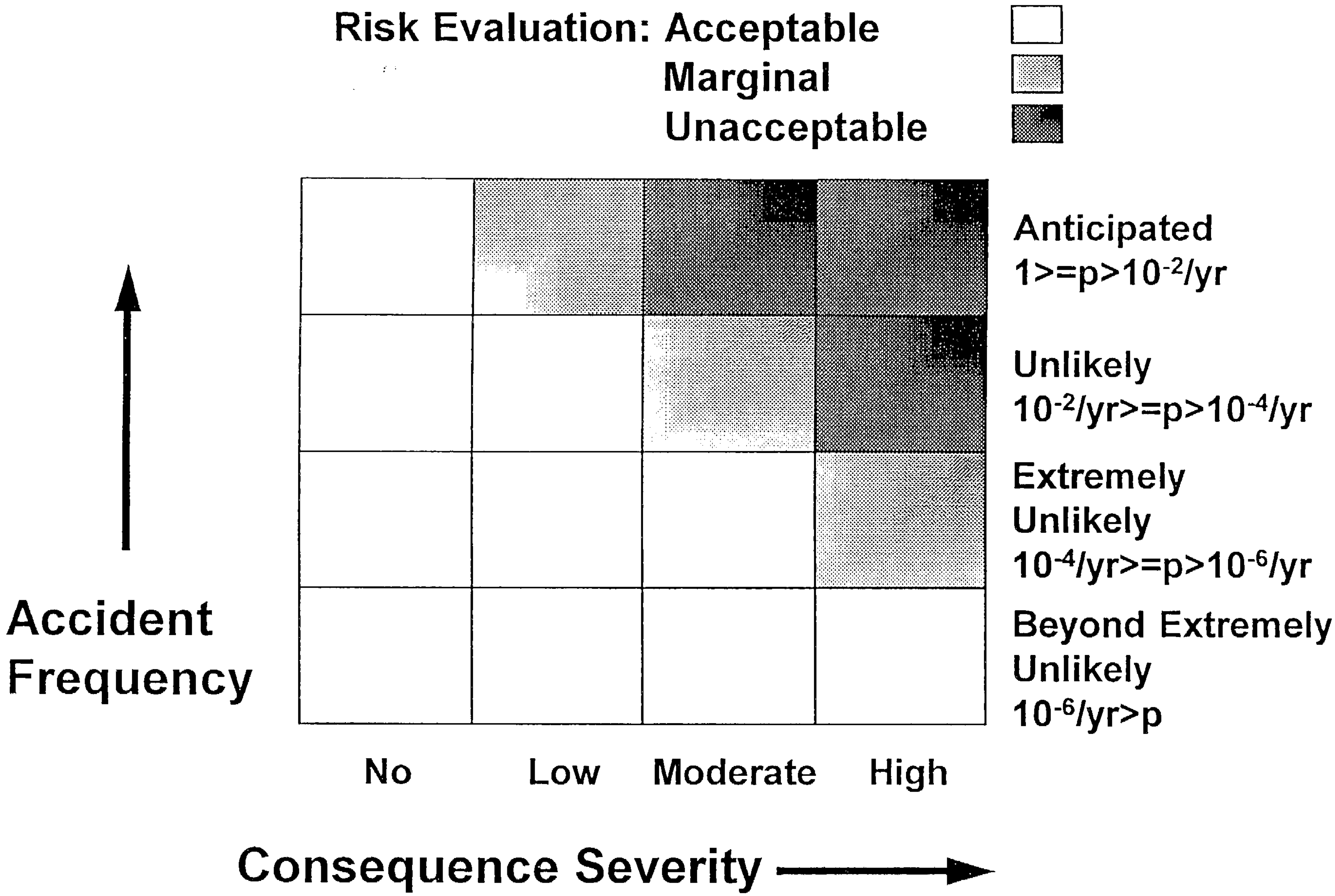
In summary, what has been shown through this series of examples is that logical groupings in the risk matrix can only be made after the quantitative scales are in place. There are no rigid requirements on how these scales are chosen. They should be dictated by the type of data available for the system being studied. For a purely qualitative risk matrix, no logical groupings of risk regions can be defined prior to performing the analysis. Only after all the potential accidents have been placed on the matrix can groupings then be made on a purely subjective basis.

IV SEMI-QUANTITATIVE RISK MATRIX

Few serious risk assessments actually use a purely qualitative approach, due to its limited usefulness. In an effort to enhance the usefulness of the comparative results, many semi-quantitative schemes have been tried. These are often referred to as qualitative methods, even though there is a quantitative foundation applied to either the frequency axis, consequence axis, or even both.

Figure 7 plots the semi-quantitative risk matrix described in DOE-STD-3009 Tables 3-3, 3-4, and 3-5. This approach uses a 4 by 4 matrix with broad quantitative bins for the frequency axis, while keeping the purely qualitative descriptions for the consequence axis. Three categories of risk are defined: Acceptable, Marginal, and Unacceptable. Even though the frequency axis is quantitative, the resulting risk for each region in the matrix is a mixed bag product of a numerical range and qualitative description, such as (10^{-4} to 10^{-6})*Low. Again, there are no direct comparisons possible between the risk of some regions, such as (10^{-4} to 10^{-6})*Low and ($< 10^{-6}$)*Moderate for example.

Figure 7
Semi-quantitative Risk Matrix from DOE-STD-3009



The same general rules for comparison exist with this matrix as with the simpler 3 by 3 qualitative matrices discussed previously. This implies that there is no logical consistent basis for making the arbitrary groupings shown in Figure 7. There is no basis to assume that the risks from each accident placed in the Unacceptable Group is greater than the risk from each accident placed in the Marginal Group. Similarly, there is no basis to assume that the risks from each accident placed in the Marginal Group is greater than the risk from each accident placed in the Acceptable Group. There is no objective logical way to compare accidents from different regions which are not connected directly by a chain of links from lower to higher risk similar to those described in Figure 2. Designations such as Acceptable, Marginal, and Unacceptable should only be made on a subjective basis after all the potential accidents are placed on the matrix. Figure 7 was meant to be used as a screening tool to decide which accidents are passed on to further analysis, such as an event tree / fault tree analysis. However, the danger of basing the screening arbitrarily upon the predetermined risk grouping is that it's quite possible some accidents selected for quantitative analysis will have lower risk than others which are screened out. This defeats the purpose of the screen.

V QUANTITATIVE RISK ASSESSMENT

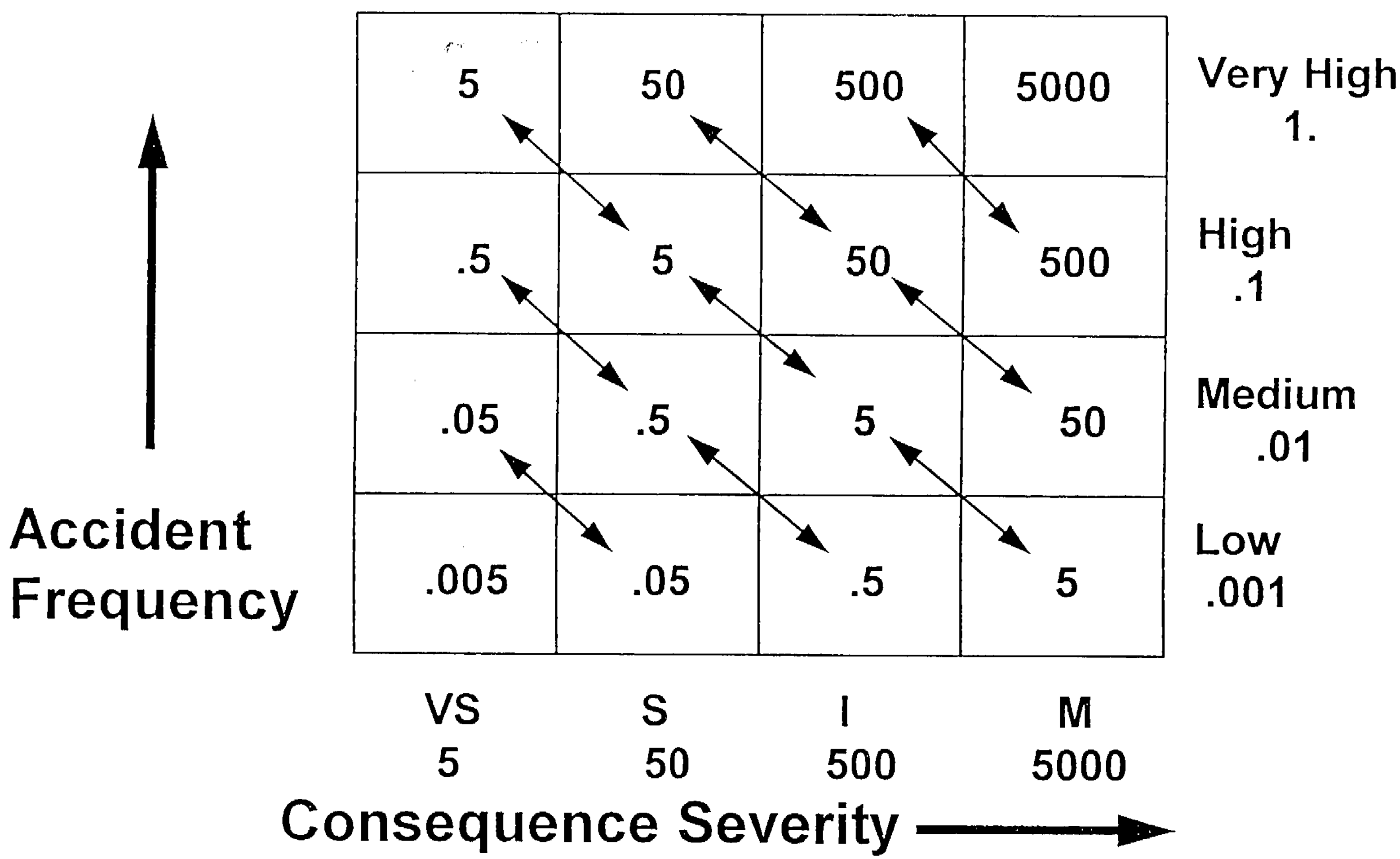
As we have demonstrated, objective decisions about screening can only be made if the screen is evaluated quantitatively. This does not imply that all scenarios must be analyzed with a quantitative event tree/fault tree analysis. By making the consequence scale quantitative, even if only in relative dimensionless units, relative risk can be calculated for all regions in the matrix.

An interesting example of a multidimensional quantitative screening matrix is reported in the DOE Nevada Operations Office as their Standards/Requirements Identification Documents (S/RIDS) Process Implementation Plan (1994). A three-dimensional quantitative matrix is used to examine the risk from operations. The first two dimensions make up a standard 4 by 4 matrix similar to Figure 8. The consequence severity levels are specified in relative units, and both axes increase logarithmically at one power of 10 per increment. The relative consequence units are tied to a qualitative description of each severity level that may include quantitative estimates as well. An example of the descriptions of severity levels for the consequence of Release of Radioactivity is: Negligible - public exposure of less than 1 man-REM; Low - Public exposure from 1 to 10 man-REM or minor injury; Medium - public exposure greater than 10 man-REM or injury; High - Acute injury or loss of life in the surrounding public.

The third dimension in the matrix handles different types of consequences. Nine categories of consequences are evaluated in this example: 1) Release of radioactivity; 2) Diversion of nuclear material; 3) Criticality; 4) Workplace hazard exposure (excluding radiation); 5) Radiation exposure; 6) Environmental releases; 7) Impact on DOE public image; 8) Impact on DOE budget; 9) Maintenance of mission capability. Each consequence category has a similar logarithmic scale, but different linear scaling factors are applied to each to discriminate between relative severity differences among the different categories. For example, Figure 8 may employ a scaling factor of 5 relative to some other consequence, which may have a baseline consequence severity ranging from 1 to 1000. Determining those scaling factors is a difficult subjective process in evaluating the tradeoffs between very different types of consequences. Once all the scales are defined, the relative risk of any scenario is then the sum of the risk value for all consequence categories.

Using this type of quantitative approach, each accident scenario will have a relative risk value associated with it. Then all scenarios can be easily compared and ranked. Objective risk acceptance criteria can be implemented, and screening determinations are facilitated for passing higher-risk scenarios on for more rigorous analysis.

Figure 8. Example of One Slice of the S/RIDS 4x4 Multidimensional Quantitative Risk Matrix



VS = Very Significant (Catastrophic)
S = Significant (Critical/Major)
I = Intermediate
M = Minimal (Negligible)

Figure 8 also highlights the position of regions of equal risk with diagonal iso-risk arrows. It's a natural misconception that such diagonal iso-risk lines will always appear like this. However, this is not true in general. This diagonal representation only exists in the case where the frequency and consequence axes both increase at the same rate. Simple iso-risk lines do not exist for any of the examples in Figures 4, 5, or 6. If pressed, one could define a skewed curve by interpolation. Of course, the concept of iso-risk lines does not even apply to the qualitative or semi-quantitative matrices like Figures 1 and 7.

VI THE TOP TEN REASONS TO NOT QUANTIFY A RISK ASSESSMENT

After discussing the merits of various types of risk matrices and the obvious advantage of a quantitative approach, this paper will close by presenting the author's top ten reasons for not quantifying a risk assessment. Note, there is no claim of independence among these somewhat facetious reasons.

Reason Number 10

Analysts are hung out to dry defending numbers.

Detractors will scrutinize and challenge every number used. Quantitative risk analysis is always controversial, and the analyst will be forever dealing with the controversy instead of dealing with the risk. Furthermore, the analyst who goes the extra yard to quantify, carries an "X" on his back marking the target. This helps one grow thick skin.

Reason Number 9

They bandy numbers around, leaving behind system insight.

No matter how careful the analyst is in presenting the work, the quantification presents a great temptation for anyone to grab onto the number of his fancy, and use it out of context or for purposes for which the analysis was not intended. A common example is grabbing the point estimate while ignoring the uncertainty distribution. Other examples include grabbing a point near the extreme of the uncertainty distribution, i.e. 99%, and using that to make ultra-conservative (useless) decisions. Another example is throwing around initiating event frequencies as actual accident rates, even though they may have been developed conservatively to envelop a range of accidents. A great deal of system understanding is built into the logic models of a risk assessment. It's important to focus on that understanding, and use the numbers to further that understanding. The numbers themselves are not the answer.

Reason Number 8

Numbers are easier to challenge than fuzzy concepts.

Qualitative analysis is fuzzy by its very nature. It's much easier to accept that fuzziness, like the risk is rated Unlikely*Moderate with few implications, rather than buy off on a risk rating of 50 units and be open to challenge, criticism, and comparison.

Reason Number 7

Quantitative analysis is too time consuming and too costly.

Detailed event tree/fault tree analysis can be a big job. However, a carefully done quantitative screening process with well thought out acceptance criteria will identify only the highest-risk scenarios, leading to a more efficient use of analytical resources.

Reason Number 6

Quantitative analysis is too uncertain.

Uncertainty is uncomfortable. Too often the point estimate gets all the attention, and there is no interest in "what you don't know". However, quantitative analysis lends itself to uncertainty calculations, giving an explicit and essential perspective on the point estimate. No mechanism has been devised to handle statistical uncertainty for a qualitative approach, as there are no statistics to play with.

Reason Number 5

Quantitative analysis requires more training.

Computer codes are extremely useful for quantitative analysis. Additional training is needed to handle functions like logic modeling, statistics, uncertainty analysis, and graphics interfaces. It's an investment in training that is well worth the time and effort.

Reason Number 4

Quantitative analysis requires data.

There is always a lack of good data, bad data, ugly data, or any other kind of data. Frequently the only data available comes from expert opinion or engineering judgement. However, even ugly data can provide valuable system insight. The power or computers can be tapped to perform a myriad of sensitivity studies just by varying the data. If you don't like my data, I'll run yours through the computer. Staying qualitative requires that known data be ignored, and there is no motivation to expend the effort needed to develop new data. Nothing is lost by incorporating data into the analysis, only additional system insight is gained. Finally, remember the statistician's proverb: "When tortured long enough, the data will confess".

Reason Number 3

What we don't know can't hurt us.

There is often resistance to turning over the rock of quantitative analysis because something unexpected might crawl out. Quantitative results can be threatening and compelling. It feels safer to keep one's head in the sand of a qualitative approach.

Reason Number 2

Qualitative results are good enough, so why bother with quantitative.

There is no reason to go beyond what is required for the purpose at hand, be that compliance with a specific order or regulation, application of a graded approach, or formulation of a risk management strategy. Considering the very limited usefulness found in the results from a qualitative analysis, it should be clear that those results are often not good enough. A quantitative approach can address the question of how much risk there is in the operation. It can provide numerical estimates of risk instead of some feeling like "the scenario is sorta credibly safe". It can be used to analyze the cost/benefit tradeoff of a risk reduction plan and address the perplexing question of: "How safe is safe enough?" The increased utility of quantitative results will easily justify the extra bother in many applications.

Finally, the Number One Reason Not to Quantify a Risk Assessment

Just what is a probability distribution, anyway?

The concept of probability is difficult to grasp and communicate. Even though we are surrounded by examples of probability, such as lottery picks and football betting pools, the misunderstanding and misuse of the principles provide a wall which blocks the jump from the fuzzy comfortable qualitative realm to the precise yet uncertain quantitative realm. The following example from a local newspaper demonstrates typical misunderstanding of the world of probability.

Longevity

"Take good care of you body. You're probably going to put a lot of miles on it.

Longevity tables used by the Internal Revenue Service say an individual retiring at 65 can expect to live another 20 years. If a couple retires and both are 65, chances are at

> least one of them will live another 25 years. What's more, you have a 50 percent chance of outliving your life expectancy."

Amazingly, half of us can expect to live longer than the other half! Which half do you belong to? That's another issue for quantitative risk assessment.

VII REFERENCES

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