Engineering considerations in the tolerability of risk

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1 Risk

In making judgements on tolerable levels of risk in industry, and in all spheres of life, it needs to be understood that every action gives rise to risk. Without risk, nothing can be done. Without risk, no economy could be advanced. There is a strong tendency to emphasize the risk at work, but persons who are not working are exposed to a different set of risks. Often persons who are not working face greater risks than persons who are working. Simply, in being alive, one is exposed to the risk of an accident, the risk of contracting a disease, and an extremely diverse variety of other risks. According to the Health and Safety Executive of the UK, it is not possible to have a state of zero risk, because "a state of zero risk does not exist".

Because zero risk is a physical impossibility, it is not possible to design for a state of zero risk in all engineering design. While the strategic target of achieving zero risk is laudable it does not provide any practical guidance to engineers as to what acceptable limits of risk should be. This causes a significant and real problem in the design for and the management of risk. Without meaningful guidelines, engineers, managers and the authorities often find themselves in disagreement. Thus, it has become essential to establish criteria for tolerable levels of risk and unacceptable levels of risk in order to design and manage engineering systems properly.

2 Perceptions of risk

Perceptions of unreasonable risk fall into two distinct categories. In one category, there are perceptions of unreasonably low levels of risk. In the other category, persons are willing to take unreasonably high risks.

3 Unreasonably low risk

The purpose of the following discussion is to show that unreasonably low perceptions of risk can be seriously misplaced. The consequence is that various authorities, and even governments, adopt policies, which cannot be put in place effectively.

The generation of electric power provides an excellent example of the public's unreasonable perception of risk. Worldwide, the public has an unreasonable fear of nuclear powered electric generating plants. The fear started with the fear of nuclear weapons, followed by fear as a result of the melt down of two nuclear reactors: Three Mile Island in the USA in 1979 and Chernobyl in the Ukraine in 1986.

The Chernobyl melt down is the only incident in which persons died: 28 soon after the meltdown, and 41 others much later due to radiation. This reactor was of a very early Soviet Russian design and did not have a containment structure. The Three Mile Island reactor was also of an early design, but did have a containment structure. No persons died and no radiation escaped. This incident should be seen as a success for safety.

There have been major advances in nuclear power technology and there are still prospects of further great advances. Modern nuclear plants are designed for a 50% chance of a melt down in 300,000 years. All modern plants have containment structures, which are designed to ensure that there will be no escape of radiation in the event of a melt down. Modern plants are designed for an operating life of 60 years. There are 440 nuclear plants operating in the world at present, all operating safely.

The extremely high levels of safety to which nuclear plants are designed come at high cost. The first cost of a nuclear plant is about double that of a coal-fired plant of equivalent generating capacity.

Table 1 shows fatal accident rates associated with power generating plants in the USA. The accident rate is stated as Fatalities per TeraWatt hour (TWh) of electric energy generated. The fatalities in nuclear plants were simple accidents. The Fatality Rate was much lower in Nuclear Plant than in Gas, Coal or Petroleum-fired Plant.

Table 1. Fatal Accident Rates per TWh of electric energy generated by plant in the USA.

Plant	Fatalities per TWh
Nuclear	0.001
Gas	0.01
Coal	0.04
Petroleum	0.05

The public opposed to nuclear power plant advocate renewable energy. This is done with total disregard for safety. Aside from Hydro-electric power, Wind Turbine Generators are the only form generating a significant amount of electric energy. The combined generating capacity of wind turbines in the USA is 3% of the total generating capacity, and in Germany it is 6% of total capacity. The USA and Germany each have some 20,000 turbines. The public seems to be completely unaware that wind turbine generators are extremely sophisticated machines. The main components, the vertical column, the turbine blades and the rotor shaft are subjected to highly variable forces as the blades rotate in a steady wind. As the wind speed varies, the variation in the forces increase with the result that these components are subjected to severe fatigue. The largest has a column 198m tall with blades 126m long. There are a number of sophisticated electrical and control systems.

The overall result is that wind turbines have a short design life of 15 years and require intensive maintenance. Many different types of problem arise, such as ice forming on blades and flying off putting the rotor out of balance, blades breaking off and fires that are exceedingly difficult to extinguish. Consequently, there are many fatal accidents. Statistics on fatal accident rates are poor. In one study the fatal accident rate for wind power was found to be 0.15 fatalities per TWh, more than 100 times that of nuclear power.

Within the mining industry there is also unreasonably low expectation of risk. However, as opposed to general public perceptions of risk, these expectations also arise at the very highest levels. The Chief Executive Officer of Anglo American Corporation has established a safety policy of Zero Harm. The Chamber of Mines, with an industry target of zero fatalities and injuries, has followed this safety policy. The Department of Mineral Resources (DMR) has followed suit with a vision of a fatality free industry.

Zero risk is a physical impossibility. However, it is sound policy to set targets for improving safety, but these targets have to be achievable and reasonably practicable.

4 Unreasonably high risk

The purpose of the following discussion is to show that the general South African population is not risk averse and tends to take unreasonably high risks.

The very high levels of road-related fatalities show that the South African population as a whole willingly takes unreasonably high risks.

Table 2 compares road related fatalities in South Africa in 2007 with those in the UK and the USA for the year 2008. It needs to be taken into consideration that there are many more registered motor vehicles in the UK and the USA, especially in the USA, and that the population in the USA is about seven times greater than that in South Africa.

Table 2. Comparison of Road Related Fatalities in South Africa, the UK and the USA.

Country	All Road Fatalities	Driver Fatalities	Pedestrian Fatalities
South Africa	14,920	4,283	5,272
UK	2,538	1,257	572
USA	37,261	19,220	4,378

The road related fatalities in South Africa are radically higher than those in the UK in all categories. Bearing in mind that the population and the number of registered vehicles are much higher in the USA than in South Africa, the fatality rates are much higher in South Africa than in the USA. The Driver Fatalities in South Africa show that South African drivers are willing to take very high risks. The pedestrian fatalities show that ordinary South Africans are willing to take extremely high risks.

The willingness of South Africans to take risks is also a problem in mining. Mining related fatalities are mainly caused by accidents so that there is a similarity between mining related fatalities and road related fatalities.

It is of interest to compare the risk of fatalities in mining with the risk of fatalities in motorcar accidents. In mining in South Africa the risk of a fatality is usually stated as the number of fatalities per million man-hours worked. Following the same approach, then the number of fatalities per million hours of motorcar usage can be estimated as follows:

In 2007, there were about 5 million registered motorcars. If all registered motorcars were driven for an average of 1 hour per day, then the number of hours that motorcars were used in a year would be 1,825 million hours per year. In 2007, the number of motorcar drivers killed was 2,481. This is equivalent to 1.36 motorcar drivers killed per million hours driven. Statistics for the number of passengers killed in motorcars are not available, but if taken to be half that of drivers, then the number of persons killed in motorcars is 3,720 in a year. (Note that for all motor vehicles, many more passengers were killed than drivers). Thus, the number of persons killed in motorcars (drivers and passengers) is about 2 per million hours of motorcar usage.

In the years 2004 to 2008, the average number of fatalities per million hours worked was about 0.2 for all mining in South Africa, and 0.3 for gold mining in South Africa. Using a motorcar in South Africa is much more risky than working in a mine.

The willingness of South Africans to take risks is a serious problem for the mining industry. The law requires that employers and all employees are obliged to ensure that "the workplace was safe, as far as reasonably practicable". This applies through the design stage, commissioning, operation and decommissioning of a mine. Sometimes employers have unreasonable expectations such as calling for unreasonably fast rates of mining. Sometimes inappropriate decisions are made that result in the workplace not being as safe as far as reasonably practicable. Sometimes employees take unreasonable risks such as not wearing safety belts when required to do so, not installing support according to mine standards or blasting before all the required support has been installed. The DMR also has responsibilities in this regard and sometimes makes wrong decisions such as closing mines after a fatal accident. When mining recommences, workplaces are often less safe than they were before the closure because regular safety maintenance procedures have not been possible.

5 Assessment of risk

In assessing risk, a distinction needs to be made between two forms of risk, namely, voluntary and involuntary risk. As an example, persons travelling in an aircraft take a voluntary risk while persons on the ground are exposed to an involuntary risk in the event of a crash. Also, the number of persons exposed in a single event and the frequency with which events occur need to be taken into account.

Risks in different engineering industries can differ greatly with the result that the risk to the public and to employees can differ greatly. In civil engineering, the failure of a large dam could expose thousands of people living down stream to an involuntary risk. In nuclear power engineering, the main risk is the escape of radioactive substances into the surroundings exposing the public to involuntary risk. In chemical engineering, the common risks are the escape of toxic substances and fires, which expose the public and employees to risk. There are many types of chemical plant each of which requires different control measures. In mining, there are opencast and underground mines, which can be shallow or deep. There are soft and hard rock and narrow seam and wide seam mines, each of which requires its own set of design considerations. However, the public is not exposed to significant risk from mining. Employees are exposed to voluntary risk. Also, it is exceptional to have an accident in which many employees might be killed. This makes the assessment of risk in mining much less complicated.

The quandary of determining limits on tolerable risk is not new. Design guidelines for the safety of the public were first developed for large dams, following a sequence of dam failures that cost many lives. The nuclear industry developed the fault/event tree methodology for reducing the risk to tolerable levels in the design of nuclear plants. These methods are commonly applied in the design of chemical plants to limit risk to tolerable levels. Reference 1 describes the many approaches that have been considered for assessing tolerable risk.

Figure 1 presents the fatality guidelines developed in the UK for major industrial hazards in the form of an F-N diagram. F represents the frequency of occurrence of N or more fatalities in a year and N represents the number of fatalities in a single event, for example, the failure of a dam or the crash of an airliner. These criteria were the result of the major hazards transport study conducted by the Health and Safety Executive (HSE) in the UK. The vertical axis on this graph is the annual rate of occurrence, F, of N or more fatalities. Of particular note is the zone defined as negligible. The frequency of 1x10-4 for a single fatality comes from a comparison with the Age Specific Death Rates (ASDR) of males from all causes in the USA, Figure 2, where the lowest ASDR is a little more than 0.1 per 1000 per annum at the age of 10 years. This therefore implies that, should the fatality risk to a worker be limited to within 1 in 10,000 per annum, he will not be exposed to a significantly higher risk than death due to other causes. This is a very conservative number and does not represent the fatality risk due to natural causes of the age group at work. A more realistic figure and generally accepted within industries is 1 per 1,000 per annum.

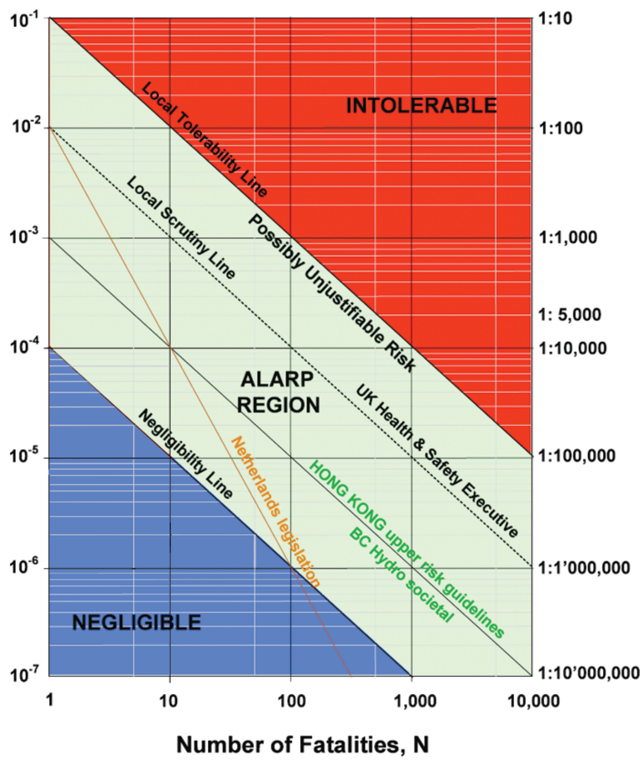

Figure 1 F-N diagram. F, along the vertical axis, represents the frequency of occurrence of N or more fatalities in a year and N represents the number of fatalities in a single event.

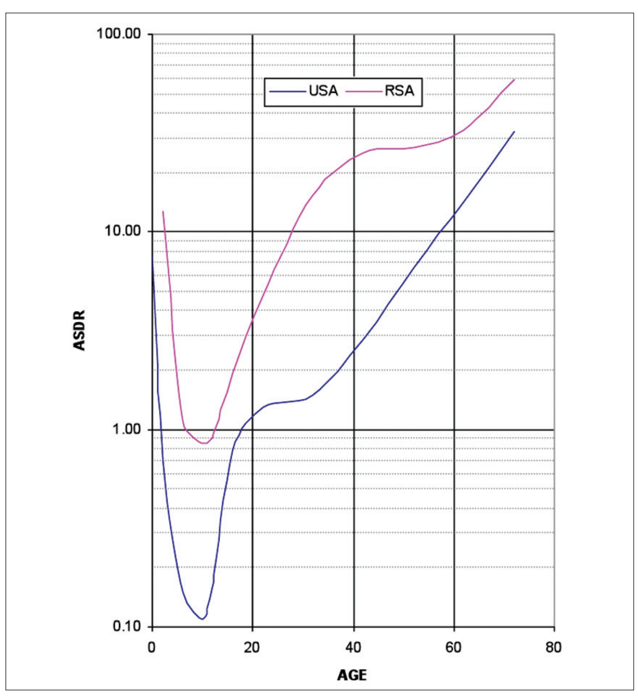

Figure 2 Age Specific Death Rates for males in the USA and South Africa. Deaths per1000 in a year at a particular age.

For fatal accidents in industry in which no more than a few people are killed per accident, the criteria that have been adopted in most advanced countries can be summarised as follows:

- Cumulative Fatal Accident Rates (FAR) lower than 0.1 per 1000 per annum are in the negligible range.
- Cumulative FAR lower than 1 per 1000 are in the tolerable range. This rate is lower than the ASDR for persons employed in industry in the USA. Such rates are considered as being As Low As Reasonably Practicable (ALARP).
- Cumulative FAR lower than 10 per 1000 are tolerable in special circumstances. Some countries do not accept this level.

For mining, the F-N diagram is the most suitable approach for defining tolerable risk. It has the great advantage that it defines negligible, tolerable and intolerable levels of risk and defines a range in which the risk is As Low As Reasonably Practicable (ALARP). The F-N diagram is based on the ASDR in the USA. Figure 2 also shows the ASDR for males in South Africa in 2006. These rates are very much higher than those in the USA. For South Africa, the lowest ASDR from all causes also occurs at the age of about 10 years, but the ASDR is much higher than that in the USA, almost 10 times as high. At the age of 40 years it is approximately 25 per 1000 per annum, which is 250 times higher than the negligible level. In South Africa, applying the tolerable FAR criteria for advanced countries should be seen as being extremely conservative.

From a mining perspective, it is important to note that these figures apply to persons exposed to the risk in their workplace and therefore the accident statistics should be calculated independently for each working environment.

Mining is widely regarded as being dangerous and it is relevant to assess how well the industry is limiting fatal accidents. The average fatal accident rate from 2004 to 2008 was 0.2 per million man-hours worked for all mining. This is equivalent to 0.4 fatalities per 1000 employees per annum. For gold mining, the fatal accident rate was 0.3 per million hours worked, equivalent to 0.6 fatalities per 1000 employees per annum. Rockbursts are regarded as being particularly dangerous. Over the period, 2004 to 2006, the fatal accident rate of employees exposed to rockbursts in stopes was 0.3 per 1000 per annum. In recent years, the fatal accident rates for nearly all types of accident were well within the ALARP range.

6 Risk and the law

Of greatest relevance to the South African mining industry in determining acceptable levels of risk is the Mine Health and Safety Act, No. 29 of 1996 (MHSA), which requires that the employer (the holder of the mining permit), ensures that the working environment at a mine is healthy and safe as far as is "*reasonably practicable*". The words "*reasonably practicable*" are defined in section 102 of the MHSA as meaning "**practicable having regard to**:

1. the severity and scope of the hazard or risk concerned;
2. the state of knowledge reasonably available concerning that hazard or risk and of any means of removing or mitigating that hazard or risk;
3. the availability and suitability of means to remove or mitigate that hazard or risk; and
4. the costs and the benefits of removing or mitigating that hazard or risk".

Regarding 1, the South African mining industry is mature so that the severity and scope of hazards and risks are well recognised.

Regarding 2, at all times in it's history the industry has been active in addressing hazards and risks. Between 1960 and 1990 the industry conducted an intensive research and development programme, which led to a major advance in knowledge and the development of techniques for mitigating the hazards and risks. Since 1990 there has been ongoing research, which has been little more than an extension of some of previous work. A stage has now been reached where a completely fresh approach to research and development is required to address unresolved questions.

Regarding 3, many methods and techniques are available but these have been introduced to a limited extent.

Regarding 4, it is nearly always possible to do better, but this may come at unreasonably higher cost.

In this context, mines are required to strive continually for improvement in their safety performance.

It is important to note that the Act requires only that reasonable precautions, and not all precautions, be taken.

7 Risk reduction

In circumstances where the state of knowledge concerning an existing risk or of mitigating the risk and the means to remove or mitigate risk are inadequate, it becomes necessary to conduct a research programme or a development programme to reduce the risk.

Research is a slow and costly process, which usually takes about a decade. Development follows research and is a still slower and more costly process, which can take longer than a decade. A successful development may take a very long time to implement.

Difficulties in implementation have been the greatest stumbling block in introducing new methods or techniques with the result that many new developments have been introduced to a limited extent. It is worth giving a number of examples to illustrate the variety of problems that have arisen. Compressed air powered rockdrills with integrated silencers have been developed, but there has been difficulty in getting them accepted because the operators perceive them to be much less powerful as they are not as noisy. Water powered rockdrills are much more powerful than compressed air drills and can drill much faster. On introducing them on some mines, the number of drill operators was reduced. The operators were then expected to drill more holes per shift, which required these remaining operators to do more work. Also, the reduction in the number of operators was seen to be loss of jobs so that the operators strongly resisted the introduction of the drills. The persons responsible for introducing the drills should have seen the benefit as being reduced time to complete drilling so that other tasks, such as installing support, could commence sooner and that the exposure of the drill operators to hazards at the face would be reduced. Another example is rapid yielding hydraulic props that were introduced on a grand scale. Some 400,000 props were purchased, only 100,000 were in operation at the faces, 100,000 were in maintenance or were being transported to or from the workshops and 200,000 were unaccounted for. Application of the props was discontinued because the employers regarded the cost as being completely unacceptable. In recent years, contractors have introduced rapid yielding props very successfully. They are being used in the most difficult circumstances, such as in the mining of remnants, with great benefit. The contractors own, install, advance, maintain and monitor the props all at reasonable cost. When new methods are to be introduced, they have to be very carefully planned. The first obstacle to be addressed is the natural phenomenon of resistance to change. All employees involved have to be properly instructed on the objective and the benefits of the change. The new method has to be introduced on a limited scale, in an area where it has the best chance of working and away from other activities. The operation of the method has to be carefully explained and demonstrated to all involved. This should include maintenance personnel. Only once the new method has been shown to be fully effective at acceptable cost should it be introduced in other areas and then very gradually. Full-scale implementation of a new method on a mine may take a whole decade.

A fresh research programme aimed only at the generation of knowledge could lead to application within a decade, but a fresh research and development programme aimed at developing new equipment or methods could take many decades to reach full implementation and few existing mines would benefit. Implementation is usually costly so that low grade or old mines cannot afford to introduce new technical developments. However, many methods and techniques, resulting from the industry's intensive research and development prior to 1990, are available and could benefit existing mines if properly implemented. Some of these techniques can be introduced at lower overall cost so that even old mines could benefit.

All engineering enterprises have a design life. In order to ensure that the level of risk on which the enterprise was designed is achieved, the system has to be properly maintained throughout the design life. Once the design life has been passed, the risk will increase. If the enterprise is to continue after it has reached its design life, higher levels of maintenance will be required at higher cost. To illustrate the sort of problems that arise, consider the compressed air network on an old mine. The pipelines are very long and are usually badly corroded so that there are many leaks resulting in very poor compressed air pressures. In turn, this results in very poor rockdrill performance, which makes it necessary to increase the number of drill operators. Thus the overall exposure of operators to hazards at the face is increased. To make matters worse, the rock pressures at faces in old mines are usually much higher so that the risk of rock falls and rockbursts are much higher. Also, the cost of generating compressed air in terms of the rock broken is very much higher. In situations such as these alternative technologies should be introduced.

Geological irregularities give rise to the largest hazards. It is important to have knowledge of the presence of geological irregularities in advance of mining. In particular, it is essential to have advance knowledge of the presence of faults so that mining configurations can be adapted to avoid the problems caused by faults. An improved method for detecting the presence of faults is required.

7 Reduction of fatal accidents

Risks in mining exist. Reducing fatalities in mining is a matter of how employees face the risks.

Most fatalities in mining are as a result of accidents. In many ways accidents in mining are similar to road accidents. It was argued in the section on **Perceptions of Risk** that South Africans seem to be willing to take great risks. This mentality also exists in mining. Not all, but many employees, from the most senior to the most junior employees, seem to be willing to take risks. If mine fatalities are to be reduced significantly in the short term, it is essential to change this mindset. A number of mines are addressing this and are achieving excellent safety records, even below the internationally accepted negligible level.

In the presentation on the laws relating to safety in mining, it was made clear that it was the duty of the employee to take reasonable care of his own safety and the safety of others. Unfortunately, a pattern has emerged in which the DMR stops mining operations for a period after a fatal accident. This is counter-productive in two ways. First the DMR and the trade union leaders publicly criticize the owners or the senior employees, which leaves the junior employees with the impression that it is the responsibility of others to ensure safety, and that they are not responsible for their own safety and that of others. Second, when operations recommence after a stoppage workplaces are often less safe than before the stoppage.

Regulation is not a particulary effective way of reducing fatalities. Usually regulations affect the employer and the most senior employees rather than all the employees, many of whom continue without regard for new regulations. Road safety regulations have not proved to be very effective in South Africa.

In summary, if mining fatalities are to be reduced significantly in the short term, it is essential to change the attitude of all employees towards safety. In the longer term, it is possible to reduce risk by improving knowledge or introducing improved mining methods.

9 Recommendation

Fatal accident rates in mining in South Africa are already in the ALARP range. If targets are to be set for improved safety, then it is suggested that the level be set at a cumulative rate of 0.1 fatalities per 1000 employees per annum, equivalent to 0.05 per million man-hours worked. This is the level that has been accepted by advanced countries as being negligible. This target should be considered to be particularly cautious when considered against the background of risk levels in South Africa.

10 References

10.1 Much of the information referred to in this analysis was taken from various sites on the Internet. Some of the sites where Statistics South Africa, U S Census Bureau, Chamber of Mines Reports, Electric Power Generation, Drive Alive and the like. Some of the information is based on the author's personal knowledge and some is based on unpublished privileged information.

1 Economic Activity and Societal Risk Acceptance. Rolf Skong and Monika Eknes, Strategic Research, NO-1322 Hovik, Norway.