Increasing Thermal Rating by Risk Analysis

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Abstract—It has long been realized that the thermal ratings of overhead transmission lines when computed deterministically, are typically conservative, resulting in underutilization of conductors. A probabilistic method to assess thermal capacity based on risk is presented in this paper. We address the potential impacts of thermal overload, the stochastic model of conductor temperature, and the quantitative risk which indicates the average “danger” of an overload. The continuous, short-time, and long-time thermal ratings are calculated using the risk of thermal overload. This method can provide technical justification for increased thermal capacity for a transmission line and an evaluation of risk for the given operating conditions.

Keywords—transmission, thermal ratings, risk, impact, probability, temperature, sag, annealing.

1 Introduction

Every conductor used in power system transmission circuits has an associated ampacity or current limit, which is called the thermal capacity or thermal rating. This current-carrying capacity is limited by the conductor’s maximum design temperature, which determines the maximum sag of the conductor, and the rate of annealing, hence the cumulative loss of tensile strength of the conductor. Normally, the thermal rating is deterministically calculated by assuming specific values of ambient conditions [1, 2].

It has long been realized that this rating is conservative and results in under-utilization of conductors. This fact is of particular importance in a competitive electric energy market because here, agents seek to fully utilize equipment so as to maximize transmission capacity, achieving greater economy via long distance energy exchange.

There are generally two techniques that have been utilized to overcome this problem; a) dynamic methods and b) probabilistic methods. Dynamic thermal ratings (DTR) [3, 4, 5, 6] are computed from real time meteorological measurements rather than fixed values. They vary as a function of time, depending on variation in ambient conditions. However, a significant problem with a dynamic line-rating system is equipment cost [7]. So, there is also a growing interest in using probabilistic methods [8, 9, 10], which account for the variability and stochastic nature of the ambient conditions, without requiring real time meteorological measurements.

In this paper, we develop a new method which combines probability and impact calculations to provide the risk of operating a conductor at a certain current level. The risk, which indicates the expectation of the consequence associated with thermal overload, may be effectively used to make decisions regarding the line loading. This approach for computing risk of thermal overload complements the method proposed in [11] to compute the risk of transient instability.

2 Impact of Thermal Overload

The conductor’s steady state temperature is determined by the thermal balance between the heat gains and losses in the conductor. This behavior, in ANSI/IEEE Standard 738 [1], is expressed by the thermal balance equation, given as

\[ I^2R(\theta) + Q_s = Q_r(\theta, \theta_a) + Q_c(\theta, \theta_a, u) \]  

(1)

Here, \( I^2R \) is the Joule (resistance) and solar heating gain, respectively, \( Q_r \) and \( Q_c \) are the heat loss by radiation and convection, \( \theta, \theta_a \) and \( u \) are conductor temperature, air temperature and wind velocity, respectively.

The flow of more current through the conductor results in an elevation of the conductor temperature which may bring about both mechanical and electrical effects. Three primary factors must be considered when defining the thermal limit of a power line [12]: sag, loss of strength, and limitations of the conductor fittings. It has been found that properly designed and selected fittings are not a limiting factor for the thermal limit [13]. Hence, only the significance of sag and loss of strength are considered.

2.1 Sag

The thermal expansion caused by the increase of temperature can result in the line dropping beneath its safety clearance. Under certain conditions, this may cause flashover to the ground, resulting in a ground fault, outage of this circuit, and weakening of the system with the possibility of cascading events. This was the case in the well known July 2, 1996 WSCC outage where a 345-kV line sagged and touched a 15-ft-high tree [7]. Hence, the impact, which depends on whether flashover occurs, is a function of line temperature. The limiting condition for sag is that line temperature should not exceed a limiting temperature for which the line sags through all of the designed safety mar-
gins, as specified by the National Electrical Safety Code [14].

We express the temperature corresponding to this limiting condition as \( \theta_L = \theta_{MDT} + M_s/K_s \), where \( \theta_{MDT} \) is the maximum design temperature at which a designed safety margin \( M_s \) is maintained, and \( K_s \) is the sagging coefficient which represents the increasing sag due to the temperature rising by \( 1^\circ C \). We then express the impact of sag as

\[
I_sag[\theta] = \begin{cases} I[Fault] & \theta > \theta_L \\ 0 & \text{otherwise} \end{cases}
\]

where \( I[Fault] \) is the impact (or financial cost) corresponding to an outage of the overloaded circuit. This impact is dependent on operating conditions, and its quantification requires analysis by power flow and stability simulation. Generally, however, if a circuit is so heavily loaded that it sags and flashes over, it is likely that the impact of its outage will be substantial.

The safety clearance by Code [14] is specified large enough so that under most conditions, the probability of occurrence for a flashover is extremely small. However, when weather conditions are extreme (high ambient temperature and little wind) or during an emergency short-time overload when current is very high, this probability increases and risk of sag can be substantial.

### 2.2 Loss of Strength due to Annealing

Annealing, the recrystallization of metal, is a gradual and irreversible process when the grain matrix established by cold-working is consumed causing loss of tensile strength [17]. When fully recrystallized, the metal would be in the softened state as it was before cold working. Whenever the line's remaining strength decreases to the tensile load, it indicates the end of service life, and thus replacement of the line is required. So the conductor's expected total life is the amount of time for the conductor strength to reach the tensile load, under the condition that the conductor operating temperature is always maintained at its maximum allowable temperature. For instance, the projected or anticipated total life of the conductors in New York state is 25-40 years [6]. But a higher annealing rate caused by higher operating temperatures will accelerate this process and therefore reduce the lifetime of the conductor.

Conductor strength reduction as a function of conductor temperature and time are illustrated in Figure 1. The expressions to describe this phenomenon are presented in references [16, 17, 18]. The rate of strength loss varies with conductor operating temperatures, as illustrated by these curves.

When the conductor operating temperature is higher than the maximum allowable value (\( \theta_{MDT} \)), the annealing rate is greater than that for which it was designed, and therefore the conductor’s expected life is decreased. The annealing impact of thermal overload is proportional to this decrease of expected life. We compute the decrease in expected life as the difference between the overload time interval \( \tau \) during which time the conductor operates at a temperature \( \theta > \theta_{MDT} \), when conductor strength reduction is \( \Delta S(\theta, \tau) \), and the expected time \( t \) required to lose this same amount of strength at the design temperature \( \theta_{MDT} \). We denote this decrease in expected life as \( \Delta t = t - \tau \).

When computing risk for continuous operation at an elevated temperature \( \theta > \theta_{MDT} \), we have that \( t = t_e(\theta_{MDT}) \) and \( \tau = \tau_e(\theta) \) so that \( \Delta t \) is given by

\[
\Delta t = t_e(\theta_{MDT}) - t_e(\theta)
\]

where \( t_e(\theta) \) is the remaining conductor life for conductor continuous operation at \( \theta \), during which time the conductor strength reduces from the present strength to its tensile load, and \( t_e(\theta_{MDT}) \) is the expected remaining conductor life for continuous operation at \( \theta_{MDT} \), when the same amount of strength (denoted as \( \Delta S = \Delta S(\theta_{MDT}, t_e) = \Delta S(\theta, \tau_e) \)) is lost.

When computing risk for temporary operation at an elevated temperature \( \theta > \theta_{MDT} \), \( \Delta t \) is given by

\[
\Delta t = \begin{cases} t_e(\theta_{MDT}) - t_e(\theta) & \Delta S < \Delta S_c \\ t_e(\theta_{MDT}) - \tau_e(\theta) & \text{otherwise} \end{cases}
\]

where \( t_e(\theta) \) is the temporary overload time interval at the operating temperature \( \theta > \theta_{MDT} \), during which time the tensile strength reduces by \( \Delta S_c(\theta, \tau_e) \), \( t_e(\theta_{MDT}) \) is the time required for the same amount of strength reduction when the conductor operates at the design temperature \( \theta_{MDT} \).

In both cases, the annealing impact of thermal overload is then given by

\[
I_{annal}[\theta] = \begin{cases} \frac{\Delta t}{t_0} \times C_t & \theta > \theta_{MDT} \\ 0 & \text{otherwise} \end{cases}
\]

where \( C_t \) is the cost of re-conductoring the circuit, and \( t_0 = t_e(\theta_{MDT}) \) is the expected remaining conductor life.

\[\text{Fig. 1. Illustration of loss of life by strength reduction curves}\]

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1 Exact calculation of sag is given by references [15, 16].

2 If the temperature (\( \theta \)) or temporary overload time (\( \tau_e(\theta) \)) is so high that the conductor's strength “quickly” decreases to its tensile load within the time \( \tau_e(\theta) \), the problem degenerates to the continuous case.
2.3 Composite Impact of Thermal Overload

The composite impact of thermal overload is the summation of the sagging impact (I_{sag}) and the annealing impact (I_{anneal}) under the temperature $\theta$. It is acceptable to add them in computing risk because, as we will show in the next section, they are conditioned by the same probability.

3 Risk Analysis

3.1 Risk Expression

Risk, which is the mean impact of an event, is the product of the event’s probability and its impact. For our case, the event is thermal overload, i.e., temperature of conductor being greater than the permissible value, and the risk is the expectation of costs that may result. Given the current $I$, we may compute thermal overload risk as the probability of the temperature being greater than $\theta_{MDT}$, times its related impacts, i.e.,

$$ R[I] = \int_{\theta > \theta_{MDT}} P[\theta|I] (I_{sag}[\theta|I] + I_{anneal}[\theta|I]) \, d\theta $$  (4)

Here, $\theta$ is the conductor temperature which is influenced by $I$ together with the ambient conditions, $P[\theta|I]$ is the probability density function (pdf) of $\theta$ given $I$, and $R[I]$ is the risk regarding the line loading.

3.2 Probability Distribution of Conductor Temperature

Because of the uncertainty of ambient conditions, the probability density of temperature $\theta$ is governed by the joint probability function of ambient conditions.

3.2.1 Continuous Loading

For the continuous loading case, given the current, the probability of conductor temperature being $\theta$ is the summation of the joint probability of all ambient conditions $\mathbf{z}$ such that the temperature determined by them under the given current $I$, by the steady-state thermal balance equation (1), is $\theta$, i.e.,

$$ P[\theta|I] = \sum_{\mathbf{z}} P[\mathbf{z}] \quad \forall \mathbf{z} \in \{ \mathbf{z} : \theta_{\mathbf{z}, I} = \theta \} $$  (5)

3.2.2 Short Time Emergency Loading

When an increase in current occurs suddenly in a conductor, the conductor temperature does not rise instantaneously because of the heat capacity of the conductor. The time required at each current level for the conductor temperature to reach the steady-state level is approximately 60 minutes [13]. This time delay depends on the specific heat capacity of the conductor, the weight, and also the ambient weather conditions. The time-temperature characteristics of ACSR is expressed [5] as a first-order differential equation, according to

$$ P \frac{\partial \theta}{\partial t} = I^2 R(\theta) + Q_s - Q_t(\theta, \theta_a) - Q_e(\theta, \theta, u) $$  (6)

where $P = 4.186(453.6)(C_1W_1 + C_2W_2)$ is the heat capacity of the conductor, $C_1$ is the specific heat capacity of aluminum, $W_1$ is the weight per unit length of aluminum, $C_2$ is the specific heat capacity of steel, $W_2$ is the weight per unit length of steel, and $\theta$ is the instantaneous conductor temperature.

When the conductor reaches its steady state temperature, i.e., $\frac{\partial \theta}{\partial t} = 0$, this equation degenerates into the equation (1) as shown in Section 2.

Given a short time emergency (STE) overload, which is much higher than the continuous rating, the maximum conductor temperature does not necessarily reach a level determined by the steady-state thermal balance equation (1) during the short time interval $\tau$. Therefore, to determine conductor temperature following a short time overload, one needs to consider the line temperature prior to the overload, and the temperature increase during the time interval $\tau$. Equation (7) provides the probability of the conductor temperature, given a short time overload current $I$ during the time interval $\tau$.

$$ P[\theta|I] = \sum_{\mathbf{z}} P[\mathbf{z}] \quad \forall \mathbf{z} \in \{ \mathbf{z} : \theta_0 + \int_0^\tau \frac{\partial \theta_{\mathbf{z}, I}(t)}{\partial t} \, dt = \theta \} $$  (7)

Here $\theta_0$ is the conductor temperature just prior to the short time overload.

By screening out the redundant $\mathbf{z}$ that results in the conductor’s steady-state temperature being less than $\theta_{MDT}$, and then performing integration of (6) from 0 to time $\tau$, the stochastic differential equation (7) can be solved with reasonable computational effort.

3.2.3 Long Time Emergency Loading

It may be of interest to sustain an overload for time periods greater than 1 hour, e.g., for 3 to 4 hours. In this case, the dynamic behavior of conductor temperature is negligible, since this time frame is longer than that of the time-temperature transient period. The probability expression is then the same as that for continuous loading, as treated in Section 3.2.1.

3.3 Distribution of Ambient Conditions

The temperature of the line is influenced by the ambient conditions, but detailed analysis of the thermal mechanics is beyond the scope of this paper. We only consider the three major factors: ambient temperature, wind speed and solar radiation. The random behavior of air temperature $\theta_a$ and wind speed $u$ are modeled as Normal and Weibull distributions [8, 10] respectively, as in (8), where the optimal parameters of distribution functions can be obtained using point estimation [19] from historical data.
\[ P[\theta_a|\mu, \sigma] = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(\theta_a - \mu)^2}{2\sigma^2}} \]
\[ P[u|\gamma, \beta] = \frac{1}{\beta} u^{-\gamma - 1} e^{-u/\beta} \]

Here, \( \mu, \sigma, \gamma \) and \( \beta \) are the scale and shape parameters for both distributions.

The solar radiation is assumed constant, since its influence is relatively small. Therefore, the vector \( \bar{z} \) used in (5) and (7) consists of the air temperature \( \theta_a \) and wind velocity \( u \).\(^4\) The joint distribution of \( \bar{z} \) is the product of the distribution functions of \( \theta_a \) and \( u \), which is

\[ P[\bar{z}] = P[\theta_a|u] \times P[u] \]

If the correlation between \( \theta_a \) and \( u \) is negligible, then

\[ P[\theta_a|u] = P[\theta_a] \]

in equation (9).

4.3 Short Time Emergency Rating

We also use the equal risk criterion in determining the short time emergency (STE) rating. Here, the STE rating is also higher than the normal rating because of the much-reduced impact of annealing. Furthermore, it is higher than the LTE rating because the dynamics of conductor temperature are effective in this time frame and, for the same current level, the 1 hour temperature level is always lower than the steady-state level which is used for LTE and normal ratings.

5 RESULTS

The example consists of a 1000 ft. "Drake" conductor 705 kcmil 26/7 ACSR, and for every 1°C temperature increase, the sag of the line increases by 0.8%. The conditions of Table I are typically used to compute the deterministic capacities.

\begin{table}[h]
\centering
\caption{Deterministic Conditions}
\begin{tabular}{ll}
Ambient air temperature (\( \theta_a \)) & 40°C \\
Wind velocity (\( u \)) & 2.0 ft/s \\
Maximum design temperature (\( \theta_{MBT} \)) & 100°C
\end{tabular}
\end{table}

The line ratings, by the deterministic method of IEEE standard [1], are listed in Table II.

\begin{table}[h]
\centering
\caption{Example of Conductor Ratings by Deterministic Method}
\begin{tabular}{ll}
Rating (A) & \\
Normal (100°C) & 992 \\
LTE (115°C, 3hrs) [6, 12] & 1140 \\
STE (125°C, 15min) [6] & 1310
\end{tabular}
\end{table}

5.1 Distribution of Ambient Conditions

The ambient conditions are not always so severe. Suppose that the mean and standard deviation of air temperature and wind speed around this conductor, according to historical data, are as listed in Table III. Their probability density functions by (8) are shown in Figure 2. We see that air temperature of 40°C is beyond four standard deviations of its mean, so that its probability is less than 10^{-4}.

\begin{table}[h]
\centering
\caption{Distribution of Air Temperature and Wind}
\begin{tabular}{lll}
mean & standard deviation & \\
air temperature, °C & 15 & 6.3 \\
winds velocity, ft/s & 3.5 & 1.3
\end{tabular}
\end{table}

For the long transmission line, the ambient conditions tend to vary along the line length. However, if we assume that the statistical description of this variation is uniform along the line length, i.e., the probability that a particular ambient condition happens at one location is the same as

\footnotesize{\(^4\)More variables may be included in the vector \( \bar{z} \) if desired for use in more detailed models.}
Figure 2. Probability density function of ambient conditions

The probability that this condition happens at another location (not necessarily at the same time), we can still use the statistics at one location to describe the weather distribution along the entire line. Otherwise, we should use the data collected at the location where the ambient conditions are statistically more extreme.

5.2 Distribution of Conductor Temperature

Conductor temperature is a function of current as well as ambient conditions (see (1) and (6)). Even when the line carries its deterministic limiting current, its temperature is typically below its maximum design value $\theta_{MDT}$. Figure 3 shows that conductor temperature varies from $11^\circ C$ to $138^\circ C$ with different ambient conditions when continuous limiting current (992A) flows through the line. We see that only for very high temperature and very low wind speed, does the temperature exceed $\theta_{MDT} = 100^\circ C$.

Figure 4. Distribution of Conductor Temperature, $I = 992A$

5.3 Risk of Continuous Loading

Combining the distribution of temperature with its potential impacts, the risk for various current levels is calculated by (4). The results are shown in Figure 5, where the sagging impact is assumed much higher than that of the conductor's annealing. It can be seen that the potential damage, when carrying current between 992 to 1200A, is mainly due to the conductor's annealing, which is not very high and only associated with the line itself. For the current levels beyond 1200A, the increasing probability of system-wide impact caused by line flashover makes the risk rise significantly.

Figure 5 also shows that the risk of the deterministic continuous rating is not zero, since the ambient condition could be more severe than that of the deterministic $40^\circ C$.

5 We choose 100 times of the single line re-conducting cost as the flashover impact, which depends on the importance of the conductor in the whole system.

6 The value of risk is normalized by the line re-conducting cost.
air temperature. Because this small amount of risk has been accepted implicitly in the industry, we will use it to identify ratings associated with temporary overload.

5.4 Risk of Temporary Overload

For the temporary overload, higher current can be transmitted through the line without significant risk, because the elevation of the temperature is not sustained, and for short time overload, the temperature does not rise so fast to reach the maximum design temperature.

5.4.1 Risk of Long Time and Very Long Time Emergency Overload

As mentioned before, the time period of overload can be extended to any length of time, less than the expected life, through risk analysis. Figures 6 and 7 show the iso-risk contours for the long time and the very long time emergency (LTE, VLTE) overload which lasts from hours up to 90 days. Figure 6 indicates that for the LTE overload, the composite risk at 0.005 is dominated by the sagging risk since the equivalent risk of annealing only occurs at a much higher current level. This is in contrast to the VLTE case, shown in Figure 7, which indicates that as the length of overload time increases, the risk of annealing becomes dominant and approaches the risk of continuous loading.

Fig. 7. Very Long Time Emergency Rating (up to 90 days)

5.5 Ratings based on Risk Analysis

5.5.1 Continuous Rating

The continuous rating is obtained directly from Figure 5, and it depends on the prescribed risk level. If one would accept a risk of 0.01 (which means 1 percent of the cost to re-conductor this circuit, or equivalently, one percent of the life loss compared with the designed one), then the continuous limiting current would be 1028 A. This risk is about 2 times as high as that incurred when the deterministic limit of 992 A is used.

Since the acceptable lower risk of continuous loading is mainly caused by the annealing effect, the decision for the continuous rating can be determined by the annealing risk only, unless one selects a high risk which falls in the region of sagging, as indicated by Figure 5.

5.5.2 Long Time Emergency Rating

Since the risk of deterministic continuous rating is implicitly accepted, the same amount of the risk associated with the temporary overload should also be acceptable. This is so called the "equal risk criterion" which is used to decide the long time and short time ratings. Based on this criterion, one may guarantee that the temporary ratings are as safe as the deterministic continuous loading.

The long time ratings can be determined by the iso-risk contours of Figure 6 and 7. They are 1225 A for the LTE rating and, for the VLTE rating, below 1225 A depending on the number of days. These ratings are useful during system recovery or for short term energy exchange.

5.5.3 Short Time Emergency Rating

The Short Time Emergency (STE) rating (within 60 minutes), also based on the equal risk criterion, ranges between 1225 A and 1700 A, as indicated in Figure 8. This would be useful during emergency periods. The limiting factor for STE rating is the impact of sag rather than the annealing in the continuous and very long time ratings.

From Figure 8, the deterministic 15-minute STE rating goes beyond the risk-based rating. That means operating on this deterministic STE rating for 15 minutes does not ensure the same safety as the normal loading. It will result in a higher expected cost.
Fig. 8. Short Time Emergency Rating based on Risk of Thermal Overload

6 CONCLUSION

A systematic approach to measure the risk associated with the thermal overload is presented in this paper. This method provides a new objective guideline to determine the conductor's normal, LTE and STE ratings. The different contributions for the thermal risk of the sagging and annealing in the different time frames are also presented. The increased line ampacity and the time duration, with the quantitative risk is helpful for the operator to trade off the benefits and costs in the competitive utility environment. The risk function can also be included, along with a benefit term, in the optimization functions to obtain the optimal decision for power system operation.

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BIography

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Discussion

Vincent T. Morgan (CSIRO Telecommunications and Industrial Physics, Sydney, Australia): The authors are to be commended for focusing attention on the risks of increasing conductor ratings ever higher. I have always been puzzled why a small risk of failure is implicitly accepted in the design of some line components, e.g., towers, but the regulations of most countries insist that the risk that an overhead conductor will sag below a limiting value must be zero. The authors have proposed that the long-time and short-time emergency ratings should be based on the equal-risk criterion, taking the implicit risk for the normal rating as reference. The authors show that this risk for a Drake ACSR conductor with the conditions of 992 A, 40 °C ambient and 2 ft/s crosswind is 0.005. However, if these conditions were to exist, in conjunction with high solar radiation intensity, the operating utility would be bound by the regulations to reduce the current to ensure zero risk.

The probability density functions assumed for ambient temperature and wind speed in Fig. 2 are idealistic curves. In actual conditions, they may vary significantly [A, B]. The combined effects of ambient temperature, wind speed and direction, and the intensity of global solar radiation can be obtained by measuring the temperature of a conductor carrying a constant current [C]. The probability density function of such a distribution may vary significantly from the non-normal distribution shown in Fig. 4, due to the non-normal pdfs of the individual meteorological distributions [D].

In (1), the wind direction has to be included, as well as the wind speed, in calculating the convective loss, since the angle of attack of the wind depends on the wind direction and the azimuth of the line. Is \( u \) the actual wind speed or the crossflow velocity?

The authors have chosen the flashover impact to be 100 times that of the cost of reconductoring a single line. This appears to be a subjective assessment. The impact of the loss of strength of a conductor on a vital line may even be greater than that of the line flashover.

Presumably, the units of the ordinate in Fig. 8 should be minutes, rather than amperes.

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J. Stephen Barrett and Yakov Motlis (Ontario Hydro, Toronto, Canada): The authors make a statement that three primary factors must be considered when defining the thermal limit of a power line: sag, loss of strength, and limitations of the conductor fittings. However, the elaborations of each of these factors in the paper are difficult for the experienced line engineer to reconcile with decades of line engineering practice and concepts of risk.

The authors state in Section 2 that, "properly designed and selected fittings are not a limiting factor for the thermal limit". Although this may be the case for new lines (almost by definition of "properly designed"), it may not be true when operating older lines above their maximum design temperature \( \theta_{MDT} \) [1], which is the subject of much of this paper.

Transmission lines are often designed with a clearance safety margin \( M_g \), or buffer, in addition to the legislated minimum ground clearance. This buffer is meant to compensate for errors and uncertainties in clearance computations and line construction. The authors advocate using this buffer to allow an emergency operating temperature limit \( \theta_L \) that is higher than the continuous maximum design temperature \( \theta_{MDT} \). It should be noted that any benefit derived from using this buffer is not a benefit of probabilistic rating, since it can also be realized with a deterministic rating method. It is dangerous to simply use the buffer to increase line rating, without first determining the actual state of the line by means of a condition survey.

Safety standards specify "absolute" minimum ground clearances that must be maintained. It is standard practice to use a deterministic method of computing conductor temperature in order to meet the standard. This involves using ampacity parameters that will all tend, statistically, to overestimate the conductor temperature. Even design engineers sometimes do not recognize that there is still risk attached to such methods, leading them to believe, incorrectly, that deterministic methods are inherently "safe", while probabilistic methods are not. In Sections 4.1-4.3, the authors employ the "equal risk criterion" to ensure that their probabilistic method incurs no more risk than any chosen deterministic method. This ought to be a persuasive concept, regardless of how uncomfortable an engineer may be with the idea that he has always been accepting some level of safety risk.

The example in Section 5 uses a sag-temperature coefficient of \( K_s = 0.6^\circ°C \). If a 2 ft. buffer can safely be used up, this produces an emergency operating temperature \( \theta_L \) that is 40°C higher than the continuous maximum design temperature \( \theta_{MDT} \).

It is important to mention that the sag-temperature coefficient \( K_s \) varies for different ranges of conductor temperature. A single run of a sag-tension computer program was performed with "Drake" conductor: ruling span 1000 ft (304.5 m), tension 5000 lb. (4.45 kN or 16% RTS) @ 16°C, no ice or wind. For the range from 38°C to 93°C, \( K_s = 0.7^\circ°C \). For the range from 93°C to 149°C, however, \( K_s = 1.4^\circ°C \). A multi-span sag-tension program may be required to obtain accurate values of \( K_s \) for each span.

The expected total life of a conductor is described in Section 2.2 as "the amount of time for the conductor strength to reach the tensile load". It is not clear which tensile load the authors
have in mind, but it is apparent that they wish to relate the life of a conductor to the possibility that it will break. The danger that a conductor will break, however, actually decreases with annealing. The Rated Tensile Strength (RTS) of an unannealed conductor is based on an assumed breaking strain of 1%. Fully-annealed EC grade aluminum breaks at approximately 20% strain, and the steel core breaks at approximately 4% strain. If the aluminum were to be partially annealed so that its breaking strain would also be a few percent, this would allow the conductor, in most cases, to be stretched to the ground by a heavy ice load without breaking.

The authors have not addressed the question of how to keep track of the state of the line as the conductor anneals and undergoes various weather loads. This involves short- and long-term creep of partially annealed conductor, about which almost nothing is known.

The paper considers the impacts of sag and annealing to be independent effects of temperature, as indicated by Eqn. 4. This is not the case. In fact, the most serious consequence of annealing is not that it makes the conductor more likely to break, but that it increases sags. Strength loss, then, is not the real issue. The most noticeable effect of annealing is the increase of creep, and therefore sag, at normal operating temperatures. The short-term creep during design ice & wind loads or heavy ice loads, will also be accentuated in an annealed conductor. Annealing of the aluminum will cause the steel core to sustain additional tensile load and permanent elongation during ice and wind loads. This results in larger high-temperature sags above the birdcaging temperature. By means of a condition survey, the state of the conductor, including its birdcaging temperature, can be inferred from the change of strain since installation of the conductor. This computation includes the effect of compressive stresses in aluminum [2,3], which can increase the high temperature sags above the birdcaging temperature. In older transmission lines, the birdcaging temperature may be as low as approximately 85°C.

The creep of stranded conductors can be computed by sag-tension programs with a reasonable degree of accuracy, as long as annealing is not a consideration. This is because an enormous amount of creep testing has been undertaken on unannealed conductors and aluminum wires. There is almost no data available, however, on the creep of partially-annealed or fully-annealed aluminum, and it will take a major research effort to obtain such data. Considering the present state of knowledge about annealing, it does not appear that it should be included in risk assessment in the way that it has been in this paper.

Rather than using historical data for weather parameters, as advocated in Section 5.1, it is possible to measure statistical distributions of how much the weather parameters on-site deviate from values measured at an off-site weather station [4]. This would allow use of the authors’ method with data from an off-site weather station.

REFERENCES


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T. O. Seppa (The Valley Group Inc.): This report combines interesting mathematical analysis with questionable assumptions and an insufficient understanding of the design and operation of real transmission lines. The authors should thoroughly re-examine the validity of their conclusions, ask advice from practicing engineers and then decide if their conclusions can guide the reader to operational decisions which are dangerous.

Transmission lines are subject to three types of risk. Annealing risk results in a replacement costs and is quantifiable. There is a reliability risk, which results in service interruption. The cost of reliability risk is difficult to quantify. For example, what is the impact of July 2, 1996 outage, that caused a blackout of large portions of the western U.S.? Finally, there is a safety risk. The safety risks are absolute, and set the total ceiling on risk analysis. The upper limit of financial risk analysis is reached when public is endangered and engineers go to jail.

Transmission line safety is governed by NESC, which sets clearance limits which are absolute. These clearances depend on line sag. Operating the lines knowingly for any period of time in violation of these limits is subject to severe economic and criminal sanctions. What is an acceptable risk of a 500kV line flashover to a schoolbus? Economists and academics may debate this point, but no self-respecting engineer will accept this as a possible consequence of economic gain.

There are so many technical errors in this report that the space allows only for comments of the most significant ones:

1. All lines are clearance-limited. They may not be operated to this limit, but there is a maximum NESC allowable sag. Very few lines are annealing limited. For example, the "Drake" conductor used in the examples loses - for a 500 hour exposure - less than 0.5% strength at 130°C and less than 3% at 150°C. In general, ACSR conductors with more than 7% of steel are not subject to annealing. The vast majority of lines in the U.S. are not and will never be subject to annealing, because the majority of lines are sag-limited to temperatures less than 100°C.

2. The authors treat safety margins as if there were unnecessary "fat" in the line design. Nothing could be further from truth. Most line designs contain error sources, which
become significant in high temperature operation. Two papers presented at IEEE 1998 WPM [1,2] identify error sources which each amount to 2-3 ft. higher sags than anticipated at temperatures at or above 100°F. Together, these errors may result in line sags which are up to 5 ft. more than anticipated. The safety buffers also depend on utility specific line design and erection practices. Instead of casually suggesting that “line temperature should not exceed the limiting temperature for which the line sags through all of the designed safety margins, as specified by the NESC”, a responsible designer will add safety buffers to assure that the clearances specified by NESC will not be violated.

3. The authors postulate a simplified ambient model, and assume normal and Weibull distributions for temperature and wind speed. They omit two important variables, wind direction and solar radiation. The effect of solar radiation can vary from zero to 20°F, while the assumed perpendicular wind results in a cooling effect which is 2.5 times higher than a parallel wind. A more realistic assumption would have been to use a distribution of “effective” wind, which usually follows a Rayleigh-distribution. The difference is very large.

4. The authors treat the variables as independent. Weather variables are not independent. Wind speed generally exhibit a diurnal pattern. Usually, wind speeds at daytime are higher than at nighttime, although reverse cases also exist. On some lines, the daily ambient pattern counteracts load effects (e.g., when strong afternoon winds coincide with high loads), while on other lines, high loads can coincide with morning/evening calm periods. Furthermore, use of average annual temperature is essentially meaningless, as lines are either summer or winter peaking. For summer peaking lines the line current has a strong positive correlation with ambient temperature.

5. As a chairman of the IEEE WG on “Thermal Aspects of Bare Overhead Conductors and Accessories”, I must accept partial blame for the ill-chosen deterministic conditions of Table I of the report. It has been copied directly from the sample calculations of the IEEE 738-93 program diskette! During our discussion of this standard, one of the members suggested that we write on the top of this screen “Do not use these programs unless you know what you are doing”. Perhaps we should put that statement in the new IEEE 738-98 version.

There are no “typical” conditions for using deterministic capacities. At some locations, daytime wind speeds are much higher than the 3.5 ft/sec median assumed by the authors. For example, in California, summer daytime median effective wind speeds in transmission line corridors vary from 15 ft/sec to 3.5 ft/sec while nighttime median wind speeds vary from 5 ft/sec to 1 ft/sec [3]. In many sites in the U.S., nighttime winds can be less than 1 ft/sec for prolonged periods. The only deterministically safe wind speed assumption is zero wind. Thus, the assumed ratings of Table II are not necessarily acceptably safe.

6. Why have we not had more safety violations if ratings such as those of Table II are not safe? This is because the past safety record of lines operated by integrated utilities is not a good model of the lines in the future open access network. In the past, most lines were only rarely operated at or near their static rating, because there was no economic justification for high temperature operation. Temperatures of over 90°F in lines designed for 100°F typically occurred for less than 1-2 hours per year.

In the open access network, the situation is dramatically different. Today, it is not uncommon to find lines which operate in excess of 80% of their static rating several hours each week. Service interruptions of such lines are common. They are either caused by excessive sag or failures of splices - disregarded by the authors as “not a limiting factor”.

Finally, some blame for this report lies in the present IEEE review process. That this paper was not referred for review by the T&D Committee shows the lack of engineering judgment in the responsible committee.

Today’s stripped-down utilities are already making enough mistakes which jeopardize safety and reliability and justify their mistakes by the economics of competition. Some lines are now “upgraded by memo”! IEEE reports should not sanction this process. Vestigia terrae.


Manuscript received June 12, 1998.

M. FOTOUI-FIRUZABAD AND R. BILLINTON (Power Systems Research Group, University of Saskatchewan): The authors are to be commended for their contribution to a significant topic which has been of interest for many years [1]. Deterministic techniques are inconsistent and cannot incorporate the variability and the stochastic nature of influential factors. The probabilistic behavior of air temperature and wind speed are considered in the paper to calculate the risk associated with the continuous, short-term and long-term thermal ratings. Such a formulation is a necessary and important step in power system planning and operation. We have the following comments on which we would appreciate reading the authors opinions and clarifications.

The authors noted in the introduction that the thermal rating is deterministically based which is conservative and results in under-utilization of conductors. Deterministic methods are in general inconsistent and unreliable and using them can lead to very different probabilistic risks. With regard to transmission line ratings, these techniques could also lead to over-utilization of the conductor and therefore result in a higher risk. A more consistent and realistic method is one based on probabilistic methods. This is dependent on the probability distribution associated with the relevant parameters. The analysis conducted in [1] was based on actual hourly ambient temperatures, wind velocities and solar radiation records.

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The risk of operating a conductor at a certain current level is calculated by the probability of reaching a specific temperature multiplied by its impact. For example, the impact associated with sag has been defined as the financial cost corresponding to an outage of the overload line. Outage of a transmission line will result in overload in other line(s) or require appropriate load curtailment. Would the authors indicate whether the cost associated with the customer load interruptions have been considered?

It has been stated in Section 5.2 that a comparison must be made between the incremental risk and the incremental benefit incurred due to increasing the line rating. Did the authors conduct any optimization in this regard in which additional benefit can be achieved only up to a certain value of risk?

The thermal rating has been calculated assuming that the mean and standard deviation of air temperature and wind speed are identical along the line considering that the statistical descriptions of these variations are uniform. Under this assumption, at which particular location on the line the ambient conditions be monitored to accommodate this assumption in practice, the ambient conditions are different along the line, especially for a long transmission lines. Would the authors please indicate that how this assumption impacts on accuracy of the results. In addition, the wind direction for calculating conductor temperature has been recognized as a significant parameter. Would the authors indicate that how can this factor be included in the proposed probabilistic technique?

The equal risk criterion is used to determine the thermal ratings associated with the long and short time emergency ratings. An identical preselected risk has been considered for the conductor’s normal, long and short-term emergency ratings. Do the authors think a lower specified risk should be selected for the conductor’s STY compared to that of LTE for the sake of system security?

There is always a degree of uncertainty in predicting the system load, and therefore there is no specific line current value. In addition the line load may have a positive or negative correlation coefficient with the ambient conditions depending on the line and location. Would the authors indicate that how this factor effects the risk calculation and how it can be included in the analysis?

Once again we would like to congratulate the authors on an interesting paper. Their comments regarding these issues will be appreciated.


Manuscript received August 12, 1998.

Hua Wan, James D. McCalley, and Vijay Vittal:

1 Using Risk Analysis for Conductor Ratings

We understand that the risk concept introduced in this paper makes some experienced engineers feel uncomfortable, because they feel we are persuading people to increase ratings beyond what has been traditionally accepted.

Traditional acceptance of line ratings, and indeed of other equipment and system limitations, has been influenced by the fact that system stress, as confirmed by Mr. Seppa's comment 6, occurred infrequently. Since risk was rarely very high, there was little incentive to evaluate it, and it was satisfactory to handle uncertainty in identified limits by applying margin. The philosophy underlying this approach is that uncertain risk should be avoided. However, it neither requires nor motivates an interest in measuring risk to improve the decision making. We think a better approach is to first quantify the risk in order to make the decision.

The objective of this paper is not to advocate taking high risk. Rather the objective is to show how to quantify the risk in order to provide a view of the uncertain world, how risky it is, and how to prepare for it. An individual decision-maker should make his/her own decision regarding how much risk to take.

As Dr. Barrett and Mr. Motlis said in their discussion, "Even design engineers sometimes do not recognize that there is still risk attached to such (deterministic) methods, leading them to believe, incorrectly, that deterministic methods are inherently 'safe', while probabilistic methods are not...." The risk exists, and we have provided an effective method of quantifying it.

The approach used in our paper is illustrated in Figure 1. Of course, there could be refinements to each component. Nevertheless, we constructed a complete picture of how to perform risk analysis associated with conductor loading, and we believe this picture is appropriate for use in the industry. It is worth noting that most discussers' suggestions are directed at refining individual blocks of Figure 1, but not at reorganizing them.

We are appreciative of the valuable comments and advice provided by the discussion. The following sections are our response to their comments.

![Figure 1: General Idea of Risk-based Conductor Thermal Overload Assessment](image)

2 About probability assumption of ambient weather

The concern about the probability functions assumed in the probabilistic analysis was mentioned by each of the discussers. As Dr. Morgan suggested, "The probability density function of such a distribution may vary significantly from the near-normal distribution ... due to the non-normal PDFs of the individual meteorological distributions." "A more realistic assumption would have been to use a distribution of 'effective' wind, which usually follows a Rayleigh-distribution," as Mr. Seppa said. Dr. Barrett and Mr. Motlis also suggested use of on-site information of weather parameters. Dr. Fouki-Firuzabad and Dr. Billinton noticed that "[the probabilistic method] is dependent on the probability distribution associated with the relevant parameters."
To obtain a "true" or "near-true" probability distribution is a continuous task for both statisticians and engineers. A better estimation of the distributions obviously provides better information for the decision-maker. However, one typically has to make the decision before all facts are completely known. This means one is unable to obtain all the knowledge (moments) of the true distribution function but rather only a limited set of moments or even only a mean value. Even if we obtained a "perfect" function to describe the historical statistics of weather completely, whether it would fit the future condition is still questionable. The near-normal distributions, which are assumed in the paper, capture two moments of probability functions.

For our risk analysis, a particular form of probability function does not influence the method used in computing the risk, which is the expected value of impact. Using computers, the expected value can be computed from any distribution function, even if there is no analytical form for the function. The numerical result of the expected value, an integral, through discrete summation can be obtained from any form of distribution functions, which is either continuous or discrete. The reference [1] has a formula to compute the expected value, and [2] provides numerical methods to compute an integral.

Mr. Seppa suggested that a Rayleigh distribution is a more realistic assumption. We agree with him that in some cases, it could be. However, as a special case of the Weibull distribution with the parameter $\gamma = 2$ in the Equation (8) of our paper, the assumption of Rayleigh distribution may limit our risk analysis from incorporating a generic probability distribution.

Dr. Barrett, Mr. Motlis, Dr. Fotahi-Firuzabad and Dr. Billinton suggested good ways to obtain on-site or actual weather information. This may improve the accuracy of estimating future conditions. Nevertheless, as in our paper, future conditions must still be estimated. One alternative we are considering is using this prior information of probability distribution to compute the posterior probability distribution when new information is obtained. In this way, the estimated probability function can be updated based on new observations [3].

We respond to the issue of dependence between weather parameters in a similar way. If the decision-maker can obtain simultaneous records of air temperature and wind, then their correlation can be included via Equation (9) in the paper. However, although this is an improvement on the estimation of the distribution function, it does not change the method used to perform the risk calculation.

It is true that the ambient conditions are different along a long transmission line, therefore we do not assume the same condition along the line at the same snapshot of time. We do assume the weather statistics are the same along the line. If this assumption does not hold for a particular transmission line, then the spatial distribution of the statistics must be considered.

3 About Thermal Model

Regarding the integration of wind direction and other factors into the thermal model, we agree with Mr. Seppa and Drs. Morgan, Fotahi-Firuzabad and Billinton that some of these factors may have significant influence on estimating conductor temperature.

The thermal model we use is suggested in an IEEE Standard [4]. It is assumed the wind is perpendicular to the conductor, which means the $u$, in eq. (1), is the crossflow velocity. If the decision-maker needs a more accurate model other than the relatively simplified model of [4], reference [5] and others provide detailed presentation of these thermal models which incorporate wind direction, wind turbulence, height of conductors, and so on. The distribution functions of these factors then have to be estimated to compute the pdf of conductor temperature and subsequently perform the risk analysis.

We do account for the effect of solar radiation. We assumed it to be constant using the IEEE [4] sunshine period from 10am to 2pm, which is considered to be a conservative assumption.

It is of interest that the paper [6] by Dr. Chisholm and Dr. Barrett indicated that "the ampacity models of House and Tuttle and IEEE provided reliable predictions of conductor temperature when the site weather data were used." The IEEE model is the one that we used in our study.

We do not argue which thermal model is better. Rather, we accept whatever model is recommended by the industry for use in our risk analysis.

4 Annealing Impact

It is a fact that the strength of conductor decreases because of annealing. The reduction of strength has been modeled by researchers as in [7] and [8]. This at least gives us a danger that the conductor breaks when its strength reduces below its tensile load. However, with the increase of sag due to permanent creep or other factors, the conductor's tensile load also decreases. This may result in the case that "the danger that a conductor will break, however, actually decreases with annealing" as addressed by Dr. Barrett and Mr. Motlis. We think the method through the strength-reduction curve correctly characterizes this danger, as long as the tensile load of the line is accurately modeled.

Dr. Barrett and Mr. Motlis provide a more detailed description of the conductor annealing. For a refinement of our annealing impact, the correlation between annealing and sag can be introduced. A reduced tensile load instead of constant tensile load in Figure 1 of the paper can be used to calculate the loss of life, where the reduction of tensile load depends on the additional elongation of the conductor due to creep and other factors.

5 Sag-Temperature Model

We use a simplified linear sag-temperature model when determining the sag based on the conductor temperature. However, we noticed the sophisticated nature of conductor sag/annealing early in our work, and as a result, we suggested a relatively detailed sag model, besides the linear approximation, in the footnote 1 of the paper. These models and the one suggested by Dr. Barrett and Mr. Motlis in their discussion consider the sag due to permanent creep and other factors. Some of them can be found in [6], [9] and [10].

These alternative models incorporate more factors, such as average stress in conductor, permanent inelastic elongation
(creep), conductor heating pattern, etc, to determine conductor sag. A refinement of the sag-temperature model can be considered to incorporate more of these factors. As in the model used in [9] by Dr. Barrett et al, the total conductor strain can be expressed as the sum of thermal strain, slack, elastic strain, setting strain and the creep strain. The sag is then determined by solving a parabolic function based on this total strain.

Above all, the model can be improved and there are some alternatives. But we can accept whatever model is recommended by the industry. Therefore, again, we consider Dr. Barrett and Mr. Motlis' comments contributing toward refining our method, but not fundamentally changing it.

6 Sag Impact, Clearance issues

Mr. Seppa, Dr. Barrett and Mr. Motlis criticize the treatment of safety margin when computing the sag impact. We perceive there are two sources for this criticism: (1) misunderstanding of our treatment, (2) disagreement on handling uncertainty. We address these two issues in what follows.

6.1 Our Treatment of Safety Margin

We did not suggest to use up or violate the safety margin added by the line designer. We only argue that the impact is zero when line sags within this margin, which is still above the NESC requirement.

• The requirement of NESC is NOT violated.

Mr. Seppa indicated, "a responsible designer will add safety buffers to assure that the clearance specified by NESC will not be violated" yet if a line does sag into the safety margin, but does not violate the NESC clearance requirements, there is no impact from the sag. It is only if NESC violation occurs do we have impact. Our analysis reflects this fact.

• The possibility of flashover is extremely small.

Even though the line sags beneath the NESC requirement, whether a flashover occurs still depends on:

(a) the occurrence of a sufficiently high underlying activity,
(b) a sufficiently high voltage surge on the transmission line, and
(c) the insulation of the remaining air gap breaking down under this voltage surge due to bad weather conditions.

Reference [11] indicates that the possibility of simultaneous occurrence of all these events is extremely small. Reference [5] shows the joint probability of these events is of the order of $10^{-8}$ or less, which is lower than the risk of a person being killed by a natural phenomenon, such as a lightning strike ($p=10^{-5}$), or by an aircraft ($p=10^{-7}$). This is not said in order to advocate loosening NESC requirements but rather to justify the claim that we do not underestimate the risk of sag.

• Use of high consequence for sag impact

We did not explicitly address "safety risk". However, the impact of sag, Equation (2) in the paper, does account for it in that this impact is given as 100 times the reconducting cost (see footnote 5). The implication of having such a high impact corresponding to sag is that our calculations will reflect

significant risk even when the likelihood of flashover is extremely small.

For the question raised by Drs. Foutzi-Firuzabad and Billinton in their discussion, the overload in other line(s) is not explicitly quantified by the method in the paper, rather the impact of these "N-2" events are given by the relative estimation as described in the previous paragraph. Regarding inclusion of load curtailment, we consider that this would occur as a result of intentional operating action in order to avoid the sag risk. Thus, it is not a direct impact, but rather a result of a decision that would be much based on comparing its cost with the resulting risk reduction.

6.2 To treat the error source probabilistically

We all know that there are error sources in mathematical models and therefore some uncertainty exists regarding calculations made with these models. One way to handle this uncertainty is to add a "safety buffer" or "margin". The problem with this, however, is it tends to be chosen intuitively, without measurement and quantification of the uncertainty driving its need. In contrast, we advocate probabilistic treatments of uncertainty in the model input parameters so that we can obtain statistical information about the calculated sag, in terms of expected value and standard error. This provides the basis for a more informed decision regarding line ratings. Generally, we advocate this approach for identification of all equipment or system limitations.

7 Clearance-limited vs. Annealing-limited line

Mr. Seppa suggests that "all lines are clearance-limited". However, whether clearance or annealing is the limiting factor depends on how the transmission line is designed. Suppose that a particular designer adds a very large safety buffer above the NESC required clearance. In this case, the risk associated with sag will be small relative to the risk associated with conductor damage and loss of life. We have included the annealing impact in order to account for this possibility.

8 Fittings and Other Impacts

If the overhead line fittings are the limiting factors of line thermal rating, its impact can be estimated by the cost of fitting replacement and service interruption.

9 Correlation between line current and weather

This may be an important issue for planning; however, in the case of identifying ratings and the operating risk, we assume the current is specified, and therefore we do not consider the statistics of line current. However, the consideration of the correlation should be reflected in the estimated probability distribution of ambient conditions, i.e., the distribution parameters of weather is conditional values given a specified line current.

10 Risk/Benefit Tradeoff

Drs. Foutzi-Firuzabad and Billinton raised a question of whether we conducted any optimization in determining the risk/benefit tradeoff. The answer is no. However, we agree that use of an optimization procedure as suggested would be
an appropriate method to employ. Application of this method would entail identification of the line current where the incremental risk is exactly compensated by the incremental benefit. The solution to this first order condition gives the solution to the optimization problem.

11 Equal Risk Criterion

The "Equal Risk Criterion" we proposed in the paper is one of several decision-making criteria [3]. There are many other strategies. They are either deterministic or probabilistic, and conservative or aggressive. This criterion is entirely based on the expected (or average) cost. It can not guarantee the true cost will be exactly the same as this expected value, and the deviation from this expectation may be significant in the short-term. If the decision-maker feels it necessary to include variance from the expected value in the decision criterion, then he/she may choose other criteria such as augmenting the expected value with its standard deviation, etc. We are still working on different criteria in the decision-making area.

12 The numbers used in examples

As Mr. Seppa emphasized in his discussion, people have to do their own homework to determine what their maximum design temperature is, what their weather conditions are, what kind of line it is, etc. Probably we should write a note on the top of the paper, "Use your own data." The example is only for illustrating the method, just like the example in the IEEE standard. Neither the IEEE nor we limit the method by the particular numbers used in the examples.

13 Heavy loading issue

In response to Mr. Seppa's comments about today's increased line loadings, indeed, it is exactly this that largely motivates our work. When there was no economic justification for high temperature operation, there was little or no need to measure the risk of doing so. Now, since equipment utilization has increased so dramatically, it is imperative that we quantify the risk in order to provide a basis for decision making. If the "danger" associated with poor operating practices cannot be stated in clear and understandable terms, then it is likely that it will be ignored, which is what Mr. Seppa's final paragraph suggests is already happening.