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THE EFFECT OF REPETITIVE SWELLS ON METAL-OXIDE VARISTORS

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Abstract — *Neither the effects of repetitive swells on metal-oxide varistors, nor the natural occurrence of swells have been documented in the literature. The paper briefly describes a laboratory system capable of generating arbitrary swells and applying them to test varistors. A statistical experiment on five lots of varistors has been performed and preliminary results are reported. Effects of amplitude, duration, and number of swell occurrences are assessed, using as a criterion the change in varistor nominal voltage from before to after the swell sequence.*

MOTIVATION FOR A SWELL EFFECTS STUDY

Metal-oxide varistors, introduced in the early seventies, are used extensively as the basic nonlinear element in surge arresters built for electric utilities and in 'surge suppressors' for end-use protection at utilization voltage levels. These devices operate by diverting the surge currents away from sensitive loads and, in combination with the source impedance of the surge, limit the voltage across their terminals by a 'clamping' action. Thus, the prime function of the varistor is to offer a low (but not zero) impedance to surge currents, resulting in power being dissipated in the bulk material. For surges of short duration, the peak power can be high but the total energy deposited in the material during one typical surge event remains low enough to keep the material from reaching excessive temperatures.

Another power system disturbance involves a temporary overvoltage at the power frequency, with amplitudes ranging from a modest increase in the rms value of the line voltage to slightly less than twice the system voltage. The term 'swell' was proposed to describe this type of disturbance, and has now received acceptance in the U.S. engineering community [ANSI/IEEE C62.41]. Occurrences of swells have not been documented as much as occurrences of surges, but some data are now being collected and published [Hairabedian, 1992]. A question then arises on the possible effect that these small but long swells could have on varistor life, compared with the effect of short but large surges.

It is known that conducting high-peak current surges can cause a progressive degradation of the varistor material. Manufacturers of electronic-grade varistors have recognized this process, and publish "Pulse Rating" charts describing the permissible stress [Harris, 1990]. These pulse rating charts present a set of permissible values of the amplitude, duration, and number of occurrences of surges that will not produce a change of more than 10% in the varistor nominal voltage (the voltage corresponding to a 1 mA dc current).

Figure 1 shows a typical Pulse Rating chart, with pulse duration, pulse amplitude and number of allowable pulses before the varistor reaches the criterion of expended rating, that is, a 10% change in characteristics. The surges are understood to be repeated events with cooling between repetitive surges. The surge duration covered by the charts provided by the manufacturers ranges from 20 to 10 000 µs, and amplitudes from a few amperes to a few kiloamperes.

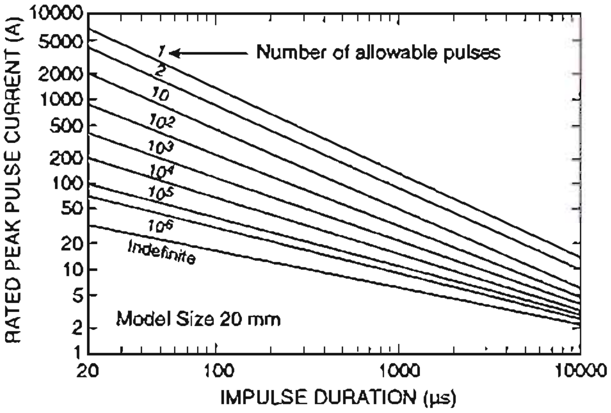

Figure 1
Pulse Rating chart for 20-mm dia. metal-oxide varistors

Armed with this information, designers can select a varistor size commensurate with the expected level of surges in the application of interest [Martzloff, 1985]. Nevertheless, anecdotes of unexplained varistor failures occurring in the absence of accurately documented high-energy surges are sometimes heard.

One of several possible explanations would be that varistors selected with a relatively low clamping voltage will be subjected to greater stress than varistors with a relatively higher clamping voltage when swells occur in the power system [Martzloff & Leedy, 1987]. The effect of repetitive swells on the durability of varistors is not discussed in the information provided by manufacturers.

Therefore, we speculate that an aging mechanism, perhaps similar to that characterized by the pulse rating charts, might be induced by the stress associated with repetitive swells applied during the lifetime of a varistor. Rather than identifying the aging mechanism itself — a task we leave to those versed in varistor physics or ceramics — we seek to establish an empirical but predictable relationship

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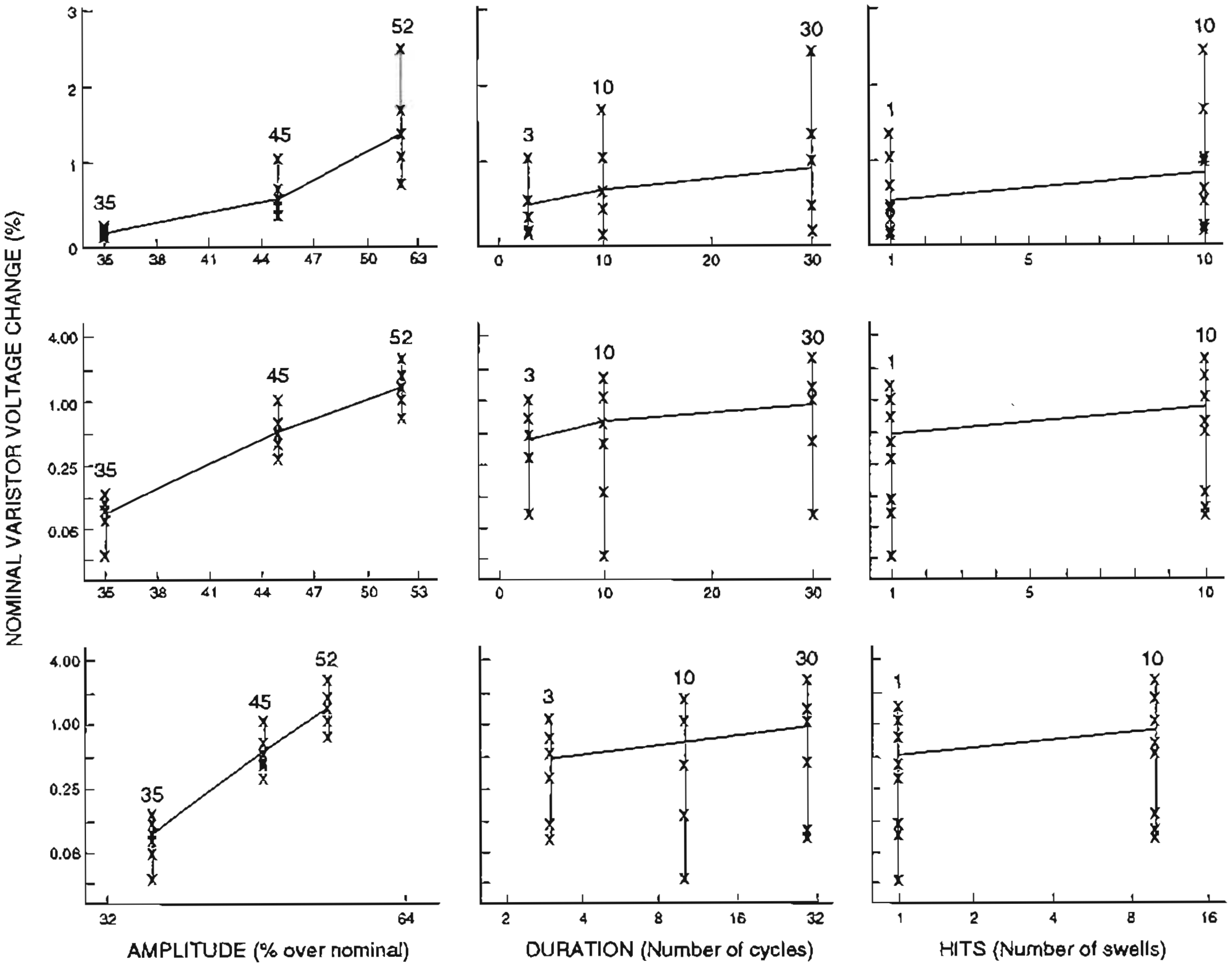

Figure 5
Plots of nominal voltage change versus factors (first row), log [voltage change] versus factors (second row) and log [voltage change] versus log [factors] (third row)

The fourth assumption is required only for performing statistical inference (such as hypothesis tests, confidence intervals, ...). From the first row of plots in Figure 5 we can see that the second assumption is violated. Variation in nominal voltage change is not constant, in fact it increases as amplitude or duration or number of swells increases.

There are several ways to correct this problem. One particularly effective way is to identify a transformation of the y's such that the transformed y's have constant variation. When the variation in y increases as x increases, a log transformation of the y's often yields transformed data having constant variation. The second row in Figure 5 gives plots of the log (y) versus the three factors. The log (y) clearly satisfies the assumption of constant variation better than the original y's. From this second row of plots we observe curvature in the plot of y versus amplitude and y versus duration (there were only two settings of number of swells, so curvature, even if present, cannot be detected). A second use of transformations is to simplify the relationship between the y's and x's. The bottom row gives plots of log (y) versus the log (x). We see that log (y) is now a linear function of log (x_1) and log (x_2). These plots lead us to postulate the following empirical model

$$y^* = \beta_0 + \beta_1 \log x_1 + \beta_2 \log x_2 + \beta_3 \log x_3 + \varepsilon \qquad (2)$$

where $y^* = \log(y)$. (For lots C and E, $y^* = \log(y+0.1)$, since a few small negative values were recorded.) The term ε represents the combined effect of all x's that affect y, but have not been included in the model, and is called a "random error" term. By taking the exponential of both sides of equation (2), we obtain equation (3), a power model in the original units,

$$y = \beta_0^* \, x_1^{\beta_1} \, x_2^{\beta_2} \, x_3^{\beta_3} \, \varepsilon^* \qquad (3)$$

where

$$\beta_0^* = e^{\beta_0} \tag{4}$$

and $\varepsilon^* = e^{\varepsilon}$. We fit the model (2) using least squares regression.

Note that this postulated model is linear in the log (x). It is entirely possible that a better model is obtained by including cross-product terms. We considered such models and concluded that they were not an improvement over model (2). The details in performing such tests can be found in [Neter, 1990].

The fitted model is given in equation (5)

$$\hat{y}^* = b_0 + b_1 \log x_1 + b_2 \log x_2 + b_3 \log x_3 \tag{5}$$

The terms b_0, b_1, b_2 and b_3 are least squares estimates of the parameters β_0, β_1, β_2 and β_3, respectively. The term $\hat{y}^*$ is the y value predicted by the fitted model at x_1, x_2 and x_3. The values $y^* - \hat{y}$ are called residuals. The model is then validated by a thorough graphical analysis of these residuals. Residuals without structure indicate a satisfactory model. This analysis was performed for each lot, see [Neter, 1990] for details on this type of analysis. The least squares estimates for the fitted model (5) for each lot are given in Table 2.

Table 2
Least square estimates for model (5) for five lots

LOT	Response variable	b_0	b_1	b_2	b_3	Residual standard deviation
A	log(y)	-13.4	3.09	0.09	0.29	0.46
B	log(y)	-12.04	2.98	0.08	0.18	0.19
C	log(y+0.1)	-24.55	5.99	0.28	0.29	0.31
D	log(y)	-27.48	6.86	0.17	0.22	0.31
E	log(y+0.1)	-18.77	4.48	0.25	0.28	0.35

In Table 2, the residual standard deviation is given for each fitted model and indicates how closely the model predicts the original data. We observe that the coefficient of amplitude (b_1) is substantially larger than that for duration or number of swells.

Once the empirical model is validated, we can interpret it. An effective way of interpreting such models is by contour plots. A contour plot displays "traces" (contours) which have equal values of the response, y, as a function of two x variables. Since we have three x variables, we generate contour plots for each setting of a third variable. Since x_3 (number of swells) has only two settings, 1 and 10, we generate two contour plots, one for each setting of x_3. Figure 6 gives two such plots for lot D.

The contours of nominal voltage change are plotted over the experimental region (amplitude 35 to 52% and duration 3 to 30 cycles). The maximum nominal voltage change contour over this region for 1 swell is 1.18% and for 10 swells is 1.95%. These fall well short of the desired change of 10%. The shape of the contour lines indicate that nominal voltage change increases more rapidly when amplitude is increased rather than duration (or number of swells) and therefore, to reach 10% nominal voltage change most rapidly, we should increase the amplitude.

The swell generator, however, has an upper limit of 15 A peak for the current it can deliver. For some specimens with low I-V characteristic, this limit is almost reached with a 52% voltage level and, therefore, the amplitude cannot be increased.

Since we are interested in applications of one to thousands of swells, we need to increase swell duration if the criterion of 10% change is to be reached after only a few swells. Informal tests were run at longer swell duration to determine the duration required to identify the point at which a 10% change occurred or the varistor burned out. This point was identified and a second experiment was planned in this region.

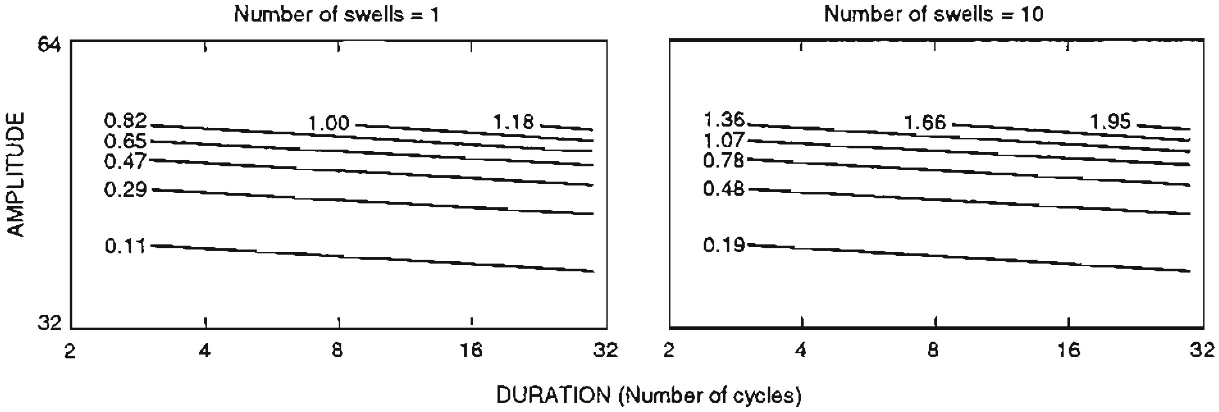

Figure 6
Contours plots of amplitude versus duration with nominal voltage change contours for 1 and 10 swells

Since nominal voltage changed very little at 35% amplitude, this setting was dropped, and a third setting of number of swells (30) was added. Also, the duration now depends on the number of swells. For example, 30 swells of 600 cycles each could be too severe and 1 swell of 6 cycles too mild. A 2x3x3 full factorial design with two controls was planned for each lot, similar to the first series, but with the new settings, as shown in Table 3.

Table 3
Factors and settings for the second experiment

Amplitude (% Above nominal)	Hits (Number of swells)	Duration (Number of cycles)
45	1	60
		180
		600
	10	18
		60
		180
	30	6
		18
		60
52	1	60
		180
		600
	10	18
		60
		180
	30	6
		18
		60

Tests on new varistors from the same five lots were performed with the new settings shown in Table 3. A thorough statistical analysis is currently underway. However, inspection of the test results already provides interesting information.

First, the point of failure, which was not reached in the first experiment, was reached for three lots. Several varistors failed in short-circuit mode, indicating that the new settings might be within range of significant change.

Second, none of the five sets of lots had degradation close to 10%. Most varistors tested degraded less than 2%, while a few completely failed. A graphical analysis of the data for one lot indicates that the failures that did occur were for settings of long duration and high amplitude (Figure 7). However, no quantification of this apparent phenomenon has been done at this time. In the discussion below, we offer some speculation on what may be the cause of this behavior.

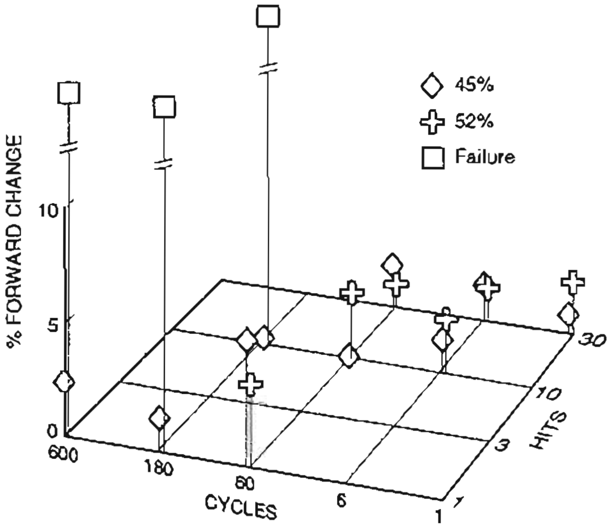

Figure 7
Three-dimension plot of failure distribution for two swell amplitudes: 45% and 52% - shifts and failures

DISCUSSION AND DIRECTION OF FUTURE WORK

Test results

The results obtained in the two experiments reported here are the beginning of a more comprehensive series of experiments from which more general conclusions will be drawn. Nevertheless, we can make several observations that will guide us toward the next series.

From the first experiment, we obtained statistical confirmation that the most powerful factor for change is the amplitude of the swell (the high value of coefficient b_1 in Table 2). Given the nonlinear response of the varistors, we can expect this finding. The other two factors, duration of the swell and number of swells, were found quite smaller and of comparable magnitude.

This statistical finding that duration and number of swells have comparable effect must be reconciled with intuitive expectations. We would expect a difference in the behavior of varistors exposed to a few long-duration swells versus varistors exposed to many short-duration swells. We can readily accept that the longer the swell, the higher the temperature reached in the body of the varistor [Martzloff & Leedy, 1987]. To validate this expectation, we applied a sequence of 10 swells of 60 cycles each (a total of 10 seconds), allowing the varistor to cool between swells. That test is illustrated in the profile shown in Figure 3. The highest temperature rise of the surface was less than 10 °C, and the actual temperature returned to room temperature before application of the next swell. Then, we applied to the same varistor, with the same swell amplitude, an uninterrupted swell of 10 seconds. In that second test, the temperature rise at the surface reached 45 °C.

Varistor aging considerations

Not knowing the physics of varistor aging, we can speculate that the internal temperature of the varistor body (higher than the measured surface temperature) plays a dual role in the process. On the one hand, the accumulation of small temperature rise events — repetitive 'benign' swells — may be the aging mechanism that we are attempting to accelerate by our laboratory tests. On the other hand, a single, large temperature rise caused by a large swell may launch a thermal runaway of the varistor, without involving much aging.

Examination of the plot of Figure 7 shows two distinct behaviors of the test varistors. Among those that failed catastrophically, two were exposed to a single long duration swell, one failed during a sequence planned for 10 swells. The data stored by the computer include all the swell history for each application; by searching through the records we will be able to pinpoint the time of failure within one exposure to the swell(s) and refine the statistical analysis.

Looking at the pattern of voltage changes for varistors that did not fail, we see only a maximum of 4% for one, the rest being less than 2%. That behavior may be genuine aging, as opposed to catastrophic failure caused by thermal runaway. These varistors might have aged further if a greater number of swells had been applied.

Our software system includes the acquisition and storage for time, voltage, and current. From these data, the total energy deposition (joules) and total charge transfer (coulombs) are computed for each swell. A statistical analysis of these parameters might reveal a stronger correlation for one of those energy or charge parameters, pointing toward a hypothesis on the nature of the effect.

In summary, increasing the amplitude of the swells could produce faster aging, as long as the temperature rise during a single swell will not reach the thermal runaway threshold. Increasing the duration of the swell does bring the varistor quickly to this threshold. That situation could point toward short swells of high amplitude, but our system does not produce these high swell currents. Furthermore, a 1-cycle (16 ms) swell current amplitude of more than 10 A begins to look very much like a 16-ms *surge*, a stress defined on the long time range (10 000 μs) of the pulse rating chart of Figure 1.

Therefore, our next direction will be toward increasing the number of swells. We will apply those amplitudes and durations in the ranges used during the second experiment that did not produce failure, but substantially increase the number of swells and observe whether the changes increase beyond the present 2-4% range.

An alternative approach might be to accelerate the process by conducting the experiment at higher ambient temperatures, on the assumption that some Arrhenius-type relationship could be found. The manufacturers' data show such a relationship for aging under exposure to rated line voltage [Harris, 1990]. However, to make this demonstration, several ambient temperatures must be applied to allow extrapolation, introducing the risk of modifying the failure mechanism. Therefore, with the limited resources available at this point of the investigation, we prefer conducting the experiments at room temperature, rather than introduce one more variable in the process.

ACTION ITEMS

Just as we are seeking new knowledge on the effects of repetitive swells on varistors, we clearly need to find out more about the occurrence of swells in practical applications. When the two bodies of information will have matured, then it will be possible for application engineers to consider the aging effects of swells, as they do now for the pulse ratings. Therefore, we can define an agenda for future work, inviting the surge-protection engineering community to participate:

1. Characterize swells as they occur in power systems

- How often do swells occur?
- How long are these swells?
- How large are these swells?

Several organizations are currently conducting surveys of power quality on low-voltage power systems. Some of these have been published [Hairabedian, 1992], while others remain unheralded or proprietary. In the past, emphasis was often given to characterization of surges. More recently, characterization of harmonics has become a subject of intense interest. To these disturbances, we now add swells as a subject that needs more attention, in view of the anecdotes of varistor failures. Sharing information on the data collection is a must, if the situation is to be corrected.

2. Conduct further experiments on aging caused by swells

- Increase the number of swells in a sequence
- Investigate acceleration by ambient temperature
- Extend the range of specimen collection
- Correlate aging with joules and coulombs

We intend to conduct further research on these items, but also invite other researchers to join in the quest, and share the results.

3. Investigate the physics of aging caused by swells

As non-specialists in this field, we refrain from making any suggestion, but invite a dialogue with interested parties.

4. Combine, share, and recommend

These three areas of research, if pursued aggressively, reported candidly, and shared openly, will serve as the basis for a new consensus on varistor applications.

CONCLUSIONS

1. Applying swells produced by a computer-driven system is a practical method for subjecting varistors to repetitive swells under controlled conditions.

2. The factors that affect the varistor response are the amplitude of the swell, the duration of the swell, and the number of swells experienced in the life of the varistor.

3. It seems that failure by thermal runaway occurs quickly when amplitude or duration settings are large. Failure caused by gradual aging (the 10% limit quoted by industry) appears to require a larger number of swells than those applied in our current experiments.

4. These results suggest an agenda for additional research. We encourage all interested parties to contribute and share new information on the subject.

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Eric S. Lagergren is a mathematical statistician at the National Institute of Standards and Technology (NIST), Gaithersburg, MD. He received his M.S. and Ph.D. degrees in Applied Statistics from the University of California at Riverside and has prior work experience at Eastman Kodak Company and IBM. He has been a member of the NIST staff for four years promoting the use of experiment design in ceramic superconductor development, ceramic powder milling and size measurement and temperature measurement of hot-rolled aluminum. His specialties include experiment design, quality engineering and linear models.

François D. Martzloff is an electronics engineer at NIST. After undergraduate studies in France, he obtained an M.S., E.E. at Georgia Tech in 1952 and, twenty years later, an M.S., I.A. at Union College. After 29 years with GE, he joined the National Institute of Standards and Technology. His early professional experience included the design of high-voltage fuses and high-voltage bushings. He changed to semiconductor technology, then to transients measurement and surge protection. A Fellow of the IEEE, he has contributed a number of papers and led the development of several standards on surge characterization and surge testing.

Mark E. Parker is an electronics technician at NIST. He has been with the Electronic Instrumentation and Metrology Group for the past 8 years where he contributes to the development and characterization of ac voltage and current sources, and of measuring devices. He was responsible for the design and implementation of the hardware and the software of the swell system, as well as performing the tests.

Susannah B. Schiller is a mathematical statistician at NIST. She received her M.S. degree in Statistics from the University of Illinois, and has been a member of the NIST staff for five years. At NIST, her focus has been on designing and analyzing experiments for Standard Reference Material certification. In addition, she was a member of the NIST Power Quality Committee, providing the data encoding, analysis, and graphical display of data in a recent survey of NIST power quality. She has also organized a tutorial lecture series on statistical methods, which promote a high standard of statistical practice by NIST scientists and engineers.