

Achieving Effective Alarm System Performance: Results of ASM[®] Consortium Benchmarking against the EEMUA Guide for Alarm Systems

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ABSTRACT

The Abnormal Situation Management^{®1} Consortium has recently completed a series of studies related to effective alarm management practices for the refining and petrochemicals industry. These studies related directly to the alarm system performance guidelines published in the Engineering Equipment and Materials User Association's (EEMUA) Publication No. 191. Results from 37 unique operator consoles indicate that the EEMUA recommendation for average alarm rate during normal operations (i.e., less than one alarm per 10 minutes), while not universally demonstrated, is achievable today. Our study found that about one-third of the consoles surveyed were able to achieve this recommended alarm rate guideline for normal operations and about one-quarter more consoles were achieving the EEMUA "manageable" level of 1 to 2 alarms per 10 minute period. However, the EEMUA recommendation for peak alarm rates following a major plant upset (i.e., not more than 10 alarms in the first 10 minutes) appears to be a challenge, given today's practices and technology. Only 2 of the 37 consoles came close to achieving the alarm rate guideline for upset conditions. This suggests that to achieve alarm system guidelines for upset conditions, more advanced site practices and alarm-handling technology (e.g., dynamic or mode-based alarming) are required. In studying the relationships between the observed alarm rate performance and other metrics collected, along with anecdotal information gathered (a subset of which is included here), we conclude that there is no "silver bullet" for achieving the EEMUA alarm system performance recommendations. Rather, a metrics-focused continuous improvement program that addresses key lifecycle management issues is most appropriate.

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1. INTRODUCTION

In an informal survey of industry practice that was conducted at the 2001 Honeywell Users Group meeting, only 30% of the 20 refining and petrochemical companies surveyed reported "Doing Quite a Bit" for alarm management, whereas 50% of those companies reported "Just Starting", and the remaining 20% reported "Doing Nothing or Little". Taken together with results of a Health & Safety Executive (HSE) survey (HSE, 2000) that showed an approximate average alarm rate of 5 alarms per 10 minute period, the conclusion one might draw is that very few operating sites would be achieving the Engineering Equipment and Materials User Association (EEMUA) recommendations for average alarm rate in its Publication No. 191 document (EEMUA, 1999). This document defined some aggressive alarm rate recommendations that need to be confirmed as being attainable. These recommendations included:

- An average of less than 1 alarm per 10 minute period for steady-state operations, and
- Less than 10 alarms per 10 minute period following a plant upset

Following the publication the EEMUA alarm rate recommendations, there were questions on whether these recommendations were appropriate, particularly for the recommendation of not more than 10 alarms per 10 minutes following an upset condition. Reising, Downs, and Bayn (2004), as part of another ASM study, concluded this recommendation appears to be supported by human cognitive capabilities (more accurately, the limits associated with human cognitive capabilities). Two different modeling analyses were conducted, and both analyses suggest that EEMUA recommendation for upset conditions is a very reasonable guideline, with respect to human performance limitations. Based on video-recorded observations of operators responding to upset conditions in high-fidelity simulator training, they were able to code various response behaviors, the frequency of those behaviors, the average time for those behaviors, and derive an averaged probabilistic time estimate needed to respond to an alarm at approximately 49 seconds. This result, taken together with past research on human mental workload that suggests not taxing people for more than 80% of the time available (Parks & Bouchek, 1989), suggests that – with today's alarm management practices and alarm system tools -- an operator requires approximately 1 minute per alarm, on average, during alarm burst conditions.

The Abnormal Situation Management (ASM) Consortium recently completed a series of studies to benchmark the performance of alarm systems in ASM members' facilities, primarily throughout North America. The objectives for this work were to:

- (i) assess whether members were achieving the EEMUA recommendations for alarm system performance as well as to
- (ii) relate that performance to contextual metrics such as plant complexity, degree of alarm rationalization, nature of plant operation, and so on.

In the ASM study, alarm system metrics (e.g., alarm rate average, alarm rate distribution), system configuration metrics (e.g., total number of control valves, total number of configured points, etc.), alarm system maintenance metrics (e.g., percent of total alarms from Top 10 Worst Actors, average number of standing alarms) as well as

general information (e.g., process type, DCS type, frequency of monitoring average alarm rate, extent of alarm rationalization) were all collected to achieve these two objectives.

We present the results of this data collection effort below, along with anecdotal information about successful alarm management initiatives, and conclude the paper with suggestions on how to best focus alarm management resources.

2. STUDY APPROACH

The ASM benchmarking study was conducted in two phases. In Phase I, the participating ASM members agreed upon the set of metrics, duration of the data collection periods and committed to providing at least 3 months of data to Honeywell for each console in the study. A console was defined as representing a portion or area of a plant that was typically operated by a single console operator under normal plant conditions, even if that console had multiple workstations (i.e., keyboards).

Honeywell collated and analyzed the information and presented the anonymous results back to the Consortium members. In addition to the alarm rate performance collected for each console, three broad areas of metrics were also collected, so as to better relate the alarm rate performance data to other potential factors. Each of these broad areas had specific metrics; the three areas were:

- General descriptive data (e.g., type of unit, type of DCS, extent to which the console was rationalized, extent to which worst actors were tracked, etc.)
- Alarm system configuration data (e.g., total number of configured alarms, alarm priority distribution, total number of points, etc.), and
- Alarm system maintenance data (e.g., average percent of the total alarms that the top 10 worst actors make up, average number of standing alarms, average number of disabled alarms, etc.).

In Phase II, participating members once again agreed on the set of metrics and were asked to provide additional console data and provide anecdotal information about and lessons learned from their alarm management initiatives and practices; this latter information then could possibly be used to examine potential critical elements that might explain the varying alarm performance results.

While the majority of the metrics collected in each phase remained identical, a few metrics were revised in Phase II. For example, some of the general descriptive metrics in Phase II were revised in attempt to get more objective values for those metrics. The data sets for consoles participating in Phase I were also re-categorized by the original contributors on these revised general descriptive metrics so that both the Phase I and Phase II data sets could be combined for more thorough analyses.

The combined phases collected a total of 90 sets of monthly data from 37 unique consoles. There were 22 unique consoles from Phase I -- each with three months of data submitted -- and 15 new, unique consoles from Phase II -- each with just one month of data submitted. Three consoles appeared in both phases, which account for the 40 entries in the following result figures.

3. STUDY RESULTS

The data collected from the two phases of the ASM study are combined in the following discussion of results. First, the benchmarking results against the alarm rate recommendation for normal operations are presented. Second, the results of peak alarm rate for non-normal operations are discussed. Third, this section concludes with a discussion of a multivariate regression analysis that investigated possible relations between the average alarm rate and other influencing metrics.

3.1 Average Alarm Rate for Steady-State Operations

Figure 1 presents the monthly overall average alarm rate for the 40 console data sets. Each bar represents the lowest, average and highest monthly average alarm rate for a single console that submitted 3 months of data. Single points represent consoles in the second phase that were only required to submit one month of data. On the right hand side of the chart is a scale representing the 5 alarm performance categories described in Table 1 below.

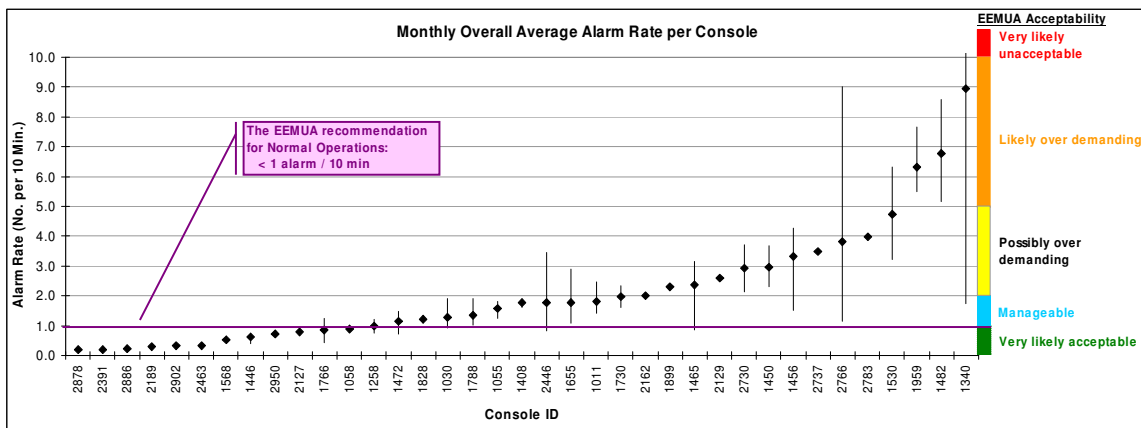


Figure 1: Monthly overall average alarm rate per console. Consoles that submitted three months of data show the low-average-high monthly values with bars present.²

The overall average alarm rate for each month was calculated for the entire month of data for a given console and included all modes of plant operation (normal, planned off normal, abnormal and emergency), not just steady-state operations. Participants stated that removing or filtering out non-steady-state modes would be prohibitive, given the state of the art in alarm system tools circa 2001-2003. Because the EEMUA acceptability categories were meant to categorize alarm rates for normal plant operation, the consoles in the ASM study that had non-normal operation during the month will be biased on the high side against the true steady-state average alarm rates.

² The last three digits of the console identification number were randomly generated and randomly assigned to the various consoles. The first digit of the identification number (either 1 or 2) specifies which phase of the ASM benchmarking study data was reported. Three consoles participated in both phases (446, 730, and 766).

Average Alarm Rate in Steady-state Operation, per 10 minute period	Acceptability Categorization
More than 10 alarms	Very likely to be unacceptable
More than 5 but less than 10	Likely to be over-demanding
More than 2 but less than 5	Possibly over-demanding (see Note 1)
1 or more but less than 2	Manageable
Less than 1 alarm	Very likely to be acceptable

Note 1: This range was categorized by ASM study team in absence of range categorization in EEMUA Publication No. 191

Table 1: Acceptability categories for average alarm rate in steady-state operations, as outlined in EEMUA Publication No. 191 (adapted from Figure 42, p. 105)

The monthly overall average alarm rate across both phases of the ASM study was 2.3 alarms per 10-minute period, compared to the British Health & Safety Executive study of 5 alarms per 10-minute window that led to the EEMUA guidelines document (HSE, 2000). The median monthly average alarm rate was 1.77 alarms per 10 minute period, meaning that over half of the consoles were at "Manageable" or "Very likely to be acceptable" average alarm rate levels.

There are two caveats to be considered when interpreting the results presented in Figure 1. First, as was stated above, because these data points may contain modes of operation other than steady-state, these might be considered "conservative" estimates of the actual steady-state alarm rates for the consoles participating in the ASM study. Second, while the reported average alarm rates might be conservative estimates for the participating consoles, these same rates probably do not reflect the general performance across all consoles of the ASM member companies, or presumably the industry as a whole. The ASM members acknowledged that the data collection process did not represent the full range of performance at their faculties and that, typically, better performing consoles were better represented because alarm rate performance data was more readily available from these consoles.

Regardless, based on the average alarm rates reported in Figure 1, one may conclude that the EEMUA recommendation is an achievable target for which to strive.

3.2 Averaged Peak Alarm Rate for Non-Normal Operations

In addition to characterizing the acceptability of various average alarm rate values, EEMUA (1999) also characterizes the acceptability of various peak alarm rate values following major upsets. Table 2 presents this characterization below. The ASM study team, in an effort to understand better how consoles were performing against these acceptability categories, asked participants to report the percent of the time for a month spent in additional categories (see the legend in Figure 3). Two new categories were: (i) 1-10 alarms/10 minute period, and (ii) > 100 alarms/10 minute period. In addition, the EEMUA category of 20-100 alarms/10 minute period was broken into three separate categories: 21- 30 alarms/10 minute period, 31-50 alarms/10 minute period, and 51-100 alarms/10 minute period.

Number of alarms displayed in 10 minutes following a major plant upset	Acceptability Categorization
More than 100 alarms	Definitely excessive and very likely to lead to operator abandoning use of the system
20-100	Hard to cope with
10-20	Possibly hard to cope with (see Note 2)
Under 10	Should be manageable – but may be difficult if several of the alarms require a complex operator response

Note 2: This range was categorized by ASM study team in absence of range categorization in EEMUA Publication No. 191.

Table 2: Acceptability categories for peak alarm rate following a major upset, as outlined in EEMUA Publication No. 191 (adapted from Figure 45, p. 107)

Figure 2 presents the averaged peak alarm rate distribution for each console to examine how much of the time each console was experiencing a specific alarm rate (see the legend in Figure 2). This contribution chart in Figure 2 was generated by averaging values across each console's set of three month data, if applicable, for the Peak Alarm Rate Distribution intervals (e.g., "% with < 1", "% with 1-10", and so on). The "% of 10 minute periods" for the various alarm count intervals are plotted on a Log scale to highlight those periods in which there were peak alarm rates and increased operator workload.

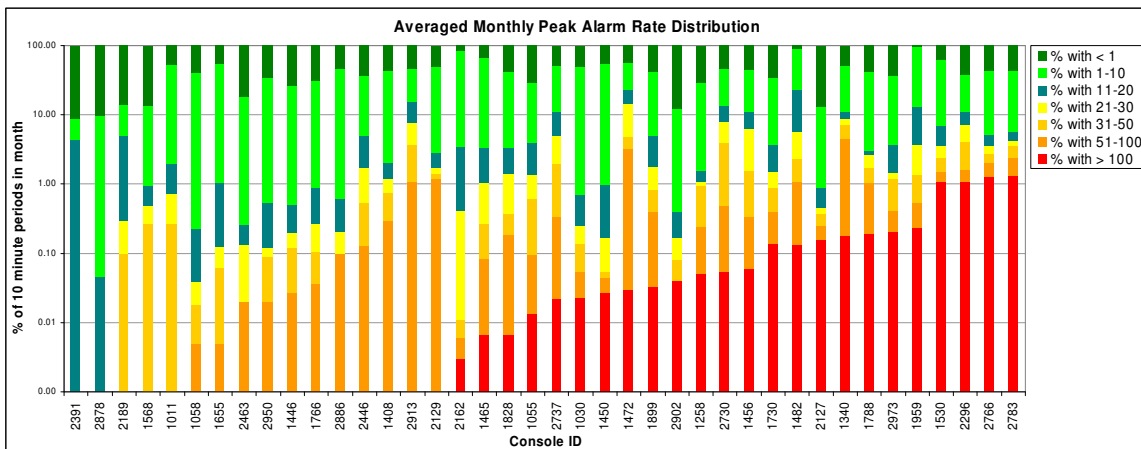


Figure 2: Monthly average peak alarm rate distribution per console. Bars for consoles that submitted three months of data show the averaged value -- across the three months reported -- for each peak alarm rate category.³

Figure 2 shows that no console was able to meet the peak alarm rate recommendation of less than 10 alarms per 10 minute period for the duration of their data collection

³ Care is needed in interpreting the Log-plotted results. As a general rule, bar lengths can not be compared between consoles (e.g., Console 2878 has 9.5% for 1-10 alarms and the associated, green bar looks as long as Console 1730's 1-10 alarms bar, which is actually representing 34.0%).

timeframe. Only two (2) consoles were able to come close to this recommendation; these two consoles had ten minute periods with 11-20 alarms but did not have periods in which the peak alarm rate exceeded 20 alarms. The remaining 35 unique consoles (95% of the unique consoles in the studies) had peak alarm rate periods with 31-50 alarms per 10 minute period, with 24 of those consoles (65% of the unique consoles in the studies) reporting at least one occurrence where the peak alarm rate periods exceeded 100 alarms per 10 minute period.

While the two best consoles (consoles 2391 and 2878) did not indicate 10 minute periods exceeded a peak alarm rate of 20 alarms during their respective data collection timeframe, it is not possible to assess whether these consoles' peak alarm rate performance was due to superior performance or due to the fact that they did not experience significant process upsets in that timeframe. To that end, our data collection methodology was insufficient insofar as we did not collect alarm rate data specifically tied to plant upsets. The only conclusion that can be drawn from the current data set is that this latter EEMUA recommendation alarm rate performance is a challenge with today's technology and practices.

3.3 Relating Average Alarm Rate for Normal Operations to Benchmarking Metrics

One of the observations made by ASM members about EEMUA Publication No. 191 is that the recommendations for alarm rate performance are devoid of context. That is to say, the recommendations for 1 alarm per 10 minute period during steady-state operations and not more than 10 alarms in the first 10 minutes following an upset are not accompanied with statements about expected level of automation to support those recommendations, the size or operations complexity of the unit being considered, the number of control loops or total number of points in the unit, and so on.

The ASM study did analyze whether there were strong linear correlations between the average alarm rate for normal operations and many of the other general, configuration, and maintenance metrics collected. Not surprising, few -- if any -- strong bivariate correlations existed between any one of the other metrics and average alarm rate. In light of this, a multivariate best subsets regression was performed to investigate the relation that multiple, potentially influential metrics might have on the average alarm rate for normal operations. This would allow the consideration of multiple relations with average alarm rate simultaneously, as opposed to the single comparisons allowed by the bivariate correlation analyses. Intuitively, such an analysis is more reasonable, given the multiple tactics being employed at sites to address alarm management issues.

While the ASM study did collect over 30 different metrics for each console, in addition to the average alarm rate and peak alarm rate data, the ASM study team identified fourteen potentially influential metrics for inclusion in the multivariate regression analysis, based on the results of the bivariate correlation analyses and their collective industry experience (Reising & Montgomery, 2005). The fourteen potential metrics included:

- the total number of configured alarms for the console
- the percent of configured emergency priority alarms out of all configured alarms on the console

- the percent of configured high priority alarms out of all configured alarms on the console
- the percent of configured low priority alarms out of all configured alarms on the console
- the percentage of points rationalized on the console
- the total number of control valves for the console
- the total number of configured alarms per control valve on the console
- the total number of analog inputs for the console
- the degree of modal alarming on the console (i.e., the number of strategies that dynamically change alarm settings based on either process conditions or operating mode)
- the control sophistication of the console (a qualitative rating based on the presence of multivariate predictive control on the unit and the number of emergency shutdown systems for the console)
- the frequency of monitoring the top ten worst actors on the console
- the frequency of monitoring the average alarm rate
- the frequency of monitoring the peak alarm rate distribution
- the average number of standing alarms on the console

An "optimal" set of variables for the best subsets regression resulted in the best model, although the selection of the optimal set was somewhat subjective, given that the R^2 only changed slightly after subsets of eight predictor variables. This resulting optimal model was selected as the lowest-order model with $R^2 > 53.0$, which was the point where R^2 improved only incrementally as additional predictor variables were considered. The plotted residuals for this model followed a normal distribution on a Normal Probability Plot, and there was no obvious pattern in a scatter plot of the residuals, both suggesting the assumptions of regression analysis were being met.

The resulting equation for the Best Subsets regression contained the following factors (presented in the relative order of weighting):

- The *degree of rationalization* had a negative coefficient, meaning that as more points on the console were rationalized, the average alarm rate decreased.
- The *frequency for monitoring average alarm rate* had a positive coefficient, meaning that the more frequently monitored consoles also had the higher average alarm rates. This was a surprising result and the lack of a negative correlation suggests that simply having a monitoring program is not sufficient. Rather, supporting work processes (e.g., a worst actors program) need to be in place to take advantage of monitoring programs.
- The *degree of control sophistication* had a negative coefficient, meaning as control sophistication increased, the average alarm rate decreased.
- The *frequency for monitoring Top 10 worst actors* had a negative coefficient, meaning that as the worst actors were more frequently identified, the average alarm rate decreased.
- The *average number of standing alarms* had a positive coefficient meaning that the average alarm rate increased with an increase in the average number of standing alarms.

The actual values for the constant term and coefficients from the Best Subsets regression equation are not presented because we do not believe these values can be used to "predict" an expected average alarm rate. Our purpose for the regression analysis was not for predictive purposes, but rather to explore the relations between various potential influencing factors and the average alarm rates observed. In addition, this model only accounted for approximately 50% of the variance in the average alarm rate data. The conclusion to be drawn from the regression results are that good alarm system performance requires a battery of techniques and practices, from alarm rationalization upfront, to ongoing maintenance activities such as addressing worst actors. And there are other influencing factors not captured in our data set that account for the other 50%. One of the limitations in our study, which might account for some portion of that other 50%, was that we did not ask participants to quantify:

- how proactive or reactive their operators were in running the plants.
- how well equipment was maintained or how hard the unit was being pushed against its limits.
- the quality of the alarm rationalization efforts or how long it had been since the rationalization was complete.

4. ANECDOTAL SUCCESS STORIES

In addition to collecting alarm system performance data, the ASM study also asked participants to provide anecdotal success stories around their alarm management initiatives, including how those initiatives impacted their average alarm rate performance. The following discussions highlight several points that will be called out in the Conclusion section of this paper.

4.1 Success through Alarm Rationalization

Two separate pairs of units of similar manufacturing processes were compared on alarm system performance at Site A. The two newer units had approximately 40% more tags than their comparable older units. The two newer units were considered fully rationalized with respect to alarm configuration while the older units were reported to have very little, if any, rationalization completed.

For the three-month data collection period, the older units were reasonably steady (i.e., no trips, just normal furnace swings), whereas the newer, rationalized units had a complete plant trip in the first month of the collection. When comparing the older comparable units to the new comparable units, Site A found:

- The newer units had an average alarm rate at approximately the EEMUA recommendation of 1 or less alarms per 10 minute period when considering steady-state operations
- The older units (with no trips) had up to 7 times the average alarm rate per minute when compared to the new units of the same type (with trips)
- The older units (with no trips) had up to 20 times the average alarm rate per minute when compared to the new units of the same type if the month with a trip for newer units is excluded (no trips)

- The older units had 2-3 times the number of alarm bursts when compared to the new units of the same type (with trips), where alarm burst is defined by the EEMUA definition of more than 10 alarms in a 10 minute period.

4.2 Success through Addressing Worst Actors

Site B, which was about to embark on an alarm rationalization process, was able to reduce its average alarm rate by nearly 40% by doing a "batch-wise" worst actors review⁴ and addressing the most troublesome points through either elimination or repair. Most of the improvements ended up addressing problems introduced in the original engineering of the alarm system including status alarms (alarms indicating a non-critical status changes) and duplicate alarms (alarms for the same measurement or condition). The plant is now operating regularly within the EEMUA "Manageable" average alarm rate benchmark of <1 alarm per 5 minutes (see EEMUA, 1999, Figure 42, page 105 for these benchmarks). Further improvements are expected following the completion of the rationalization process.

Site C, which has over 10 operating consoles, had been doing alarm rationalizations for the last 10 years, but still had high average alarms rates relative to the EEMUA recommendations. This site was able to reduce its average alarm rate by about 75% over a 6 month period by implementing software tools and supporting work processes to routinely monitor alarm rates and address alarm worst actors. Approximately 30% of the consoles experienced much better performance over this period while another 30% experienced noticeably better performance. (The rest of the consoles remained about the same because they already had low alarm rates.) Following this improvement, the number of consoles achieving the EEMUA "Very likely to be acceptable" average alarm rate benchmark (<1 alarm/10 min) doubled to approximately 65% of the site's consoles, and the number of consoles achieving the EEMUA "Manageable" average alarm rate benchmark (<1 alarm/5 min) or better increased to 80+% (see EEMUA, 1999, Figure 42, page 105, for these benchmarks). The site, however, still suffers from high alarm rates following major plant upsets and is now using its alarm metrics monitoring infrastructure to learn how dynamic alarming could reduce/eliminate alarm flood situations.

4.2 Success through Alarm Rationalization and Addressing Worst Actors

Site D, which had a number of operator consoles, was able to reduce its average alarm rate by approximately 33% following an alarm rationalization project. This was despite the fact that the number of configured alarms actually increased by nearly 20% as a result of the alarm rationalization project.

In the following year, monthly worst actors monitoring led to another 33% reduction in the average alarm rate. In the second year following its initial alarm rationalization efforts, continued monthly worst actors monitoring helped the site achieve an additional ~20% average alarm rate reduction for an 86% reduction overall.

Part way through its third year of worst actors monitoring, Site D achieved another 8% average alarm rate reduction and was experiencing only ~6% of the alarms it

⁴ "Batch-wise" is meant to connote a review of one large block of historized alarm data at a time, in contrast to continuously reviewing the worst actors each week or month.

experienced before initiating its alarm management improvement efforts. This achievement is particularly noteworthy because the site has added ~15% more configured alarms since the initial alarm rationalization work. These additional alarms are mainly due to additional facilities that have been installed at this site.

The site now consistently operates below the EMMUA "Manageable" average alarm rate benchmark of <1 alarm per 5 minutes on all of its consoles, and half of these consoles operate below the EMMUA "Very likely to be acceptable" benchmark of <1 alarm per 10 minutes (EEMUA, 1999, Figure 42, page 105).

5. CONCLUSIONS

Our objectives in the ASM study that benchmarked alarm system performance against the EEMUA recommendations (EEMUA, 1999) for was to (i) determine if these recommendations were being achieved, and (ii) relate these alarm system performance results to other characteristics and metrics of the consoles themselves. From our study results, we believe that the EEMUA recommendation for less than one alarm per 10 minute period for normal operations is achievable. However, the recommendation for not more than 10 alarms in the first 10 minutes following a major upset appears to be more difficult to achieve. Only two of the 37 consoles in this study came close to meeting that recommendation, which suggests that today's practices and technology are insufficient for achieving that level of performance. Our study results indicate that more sophisticated alarm handling techniques (Campbell Brown, 2002), such as dynamic alarming and/or alarm suppression, will have to be applied for alarm flood situations so that this recommendation can be achieved. In addition, the application of such advanced alarm handling techniques will require more explicit consideration of alarm flood situations during the alarm rationalization process.

While our study did not have strong bivariate correlations between average alarm rate and various other metrics, the multivariate regression suggests there are alarm management activities that will have an impact on average alarm rate performance, such as alarm rationalization, improved control strategies, and addressing worst actors. In addition, common sense tells us that good and superior alarm rate performance should be supported by ongoing maintenance (i.e., lifecycle management) practices, such as following sound alarm system design practices, routinely monitoring alarm system performance, and investigating alarm system performance following major upset conditions (beyond the root cause incident investigations often conducted for regulatory compliance).

There is no "silver bullet" or "one shot wonder" for good alarm management. The most successful sites will likely approach alarm management as an ongoing, continuous improvement activity, not unlike preventive maintenance or total quality management programs. However, based on our anecdotal reports above and the improvement roadmap recommended in the EEMUA guide (see "Roadmap," page xii), we would strongly recommend addressing alarm worst actors on a regular basis as the best action a site with limited resources could take to improve its alarm system performance.

6. ACKNOWLEDGEMENTS

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