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Original Article

Development of a Leading Performance Indicator from Operational Experience and Resilience in a Nuclear Power Plant

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ABSTRACT

The development of operational performance indicators is of utmost importance for nuclear power plants, since they measure, track, and trend plant operation. Leading indicators are ideal for reducing the likelihood of consequential events. This paper describes the operational data analysis of the information contained in the Corrective Action Program. The methodology considers human error and organizational factors because of their large contribution to consequential events. The results include a tool developed from the data to be used for the identification, prediction, and reduction of the likelihood of significant consequential events. This tool is based on the resilience curve that was built from the plant's operational data. The stress is described by the number of unresolved condition reports. The strain is represented by the number of preventive maintenance tasks and other periodic work activities (i.e., baseline activities), as well as, closing open corrective actions assigned to different departments to resolve the condition reports (i.e., corrective action workload). Beyond the identified resilience threshold, the stress exceeds the station's ability to operate successfully and there is an increased likelihood that a consequential event will occur. A performance indicator is proposed to reduce the likelihood of consequential events at nuclear power plants.

1. Introduction

Every nuclear power station is subject to daily organizational stresses, which result from the cumulative strain of routine operation, maintaining regulatory and operating requirements, and supporting long-term reliable operations. In addition, operational conditions are periodically changed to accommodate safe refueling, perform shutdown maintenance activities, and restart for another cycle. The impact of these strains varies depending upon the age of the plant.

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One must also consider unexpected operational events that result in work that goes beyond normal plant operations, regulatory compliance, and typical maintenance activities. These conditions result in periods of time when individual and organizational workloads increase significantly, raising the likelihood of errors, which in turn, further increase personnel workloads.

"Safety culture" emphasizes the importance of developing and maintaining a strong Problem Identification and Resolution Program [1], typically referred to as a Corrective Action Program (CAP) where all incidents, risk significant or not, are to be reported. The term "safety culture" was first used in INSAG's 1988 "Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident," [2] where it is described as "that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance". All nuclear power stations in the United States have a Problem Identification and Resolution Program as required by regulation.

A plant's CAP is provided to employees, who use it to identify problems or issues and to record them in a problem report, formally known as a condition report (CR). The events that trigger these reports serve as sources of organizational stress, as they represent additional scopes of work beyond those required for maintaining regulatory compliance and reliable plant operation. Increasing numbers of CRs accompanied by CRs with high severity levels indicate that organizational resilience levels are being exceeded. Here, we define resilience as the intrinsic ability of an organization to adjust its functioning prior to, during, or following changes and disturbances, in order to sustain required operations for the current conditions of the plant [3].

Some condition reporting programs are considered "low-level," as the threshold required for generating a CR is very minor (e.g., editorial errors in procedures or minor errors in design drawings). Low-level CR programs are characterized by having high levels of granularity as criteria for the identification of a situation requiring the generation of a CR (i.e., thousands of items are identified in a single year covering virtually all plant organizations). Alternatively, some condition reporting programs are considered to be "high-level," as the generation of a CR must meet a certain, high criteria (e.g., only plant hardware issues are considered). Generally, most United States plants are characterized as low-level condition reporting programs, such that each typically generates in excess of 10,000 CRs each year.

The fact that even minor incidents reported in low-level condition reporting programs can combine with others and cause an accident brings forward the concept of high reliability organizations (HROs), which include nuclear power generation plants, naval aircraft carriers, air traffic control systems, and space shuttles. Studies of HROs have challenged the postulations of Perrow's Normal Accident Theory [4], in which he insists that "normal" or system accidents are inevitable in extremely complex systems. He states that given the characteristics of the system involved, multiple failures that interact with each other will occur, despite efforts to avoid them. He continues to say that operator error is a very common problem, many failures relate to organizations rather than technology, and big accidents almost always have very small beginnings. Such events appear trivial to begin with before unpredictably cascading through the system to create a large event with severe consequences.

HROs, and specifically nuclear power plants (NPPs), are complex, but have nonetheless maintained exceptional safety records over a long period of time. According to Weick et al [5], HROs are learning organizations characterized by a set of cognitive practices that enable people to work safely and eventually create mindfulness and reliability. These practices involve constantly tracking and investigating small errors, resisting oversimplification, sensitivity towards current operations, and committing to resilience.

HRO research can be said to represent a focal shift in safety research, from a focus on failure to a focus on success. The HRO perspective represents a valuable addition to safety research, and we believe that combining the HRO perspective with data that is readily available, specifically from the CRs contained in the CAP database, provides the necessary elements to produce a resilience curve and an associated resilience threshold. This can be applied at NPPs in order to identify areas where human errors are more likely to result in consequential events, to reduce human error rates, to consider organizational interaction factors, and to develop a leading performance indicator.

The application of resilience engineering is relatively new to the nuclear industry, but it has been used in general aviation, offshore oil and gas production, safety science, and healthcare, among others, and it has provided a substantial body of knowledge and experience [6–10]. In particular, Woods et al [10] compared the demand-stretch model of an organization with the stress–strain curve and resilience property from materials science. This prior work is largely qualitative, whereas here we present a quantitative application.

Section 2 describes the data used. Section 3 identifies the sources of stress and strain and presents the methodology used to develop the resilience model. Section 4 presents the resulting organizational resilience curve and threshold. Section 5 shows the application of the resilience threshold to develop a leading performance indicator to predict situations where the likelihood of consequential events is increased. Section 6 contains the conclusions and describes future work.

2. NPP operational data

We propose the use of the CAP database to evaluate human and organizational performance. Other studies have examined licensee event reports (LERs) to evaluate human performance, types of events, etc. [11–13]. These studies provide valuable ways of looking at the historical events. We believe that the inclusion of all plant specific events (LERs plus all the other events reported in the CRs) increases the statistical validity of the data and enables the specific and detailed study of a plant's operating experience and organizational behaviors.

In this study, the CAP database from an operating plant was analyzed to test the database's ability to yield measurable results with regard to assessing organizational resilience. Ten years of CRs (2005–2014) were analyzed, yielding not only interesting tendencies and insight into resilience, but also a basis for the construction of leading organizational performance indicators at NPPs.

In order to begin to understand the information contained in the CRs, as well as the complex interdepartmental relationships in HROs such as NPPs, it is necessary to define the most important administrative units, known as organizations, as well as the extent of their responsibilities in everyday activities.

A simplified flow diagram is shown in Fig. 1, which outlines a typical process used for planning, executing, and completing a work package. A work package can be considered an organizational activity that involves manipulating plant equipment or other hardware. The work package contains the necessary prerequisites, approvals, work steps, and hardware parts (consumables) that will be necessary to complete the activity on a component or set of components. The flow diagram shows the types of activities during which the events that are the focus of this paper occur. That is, when a problem (e.g., unplanned equipment failure) or a necessary work activity [e.g., preventive maintenance activity (PM)] is identified, there are many opportunities for organizational errors. These errors can occur based on the organizational programs and procedures necessary to authorize and perform work on plant equipment. Since the actions recommended to resolve these errors are combined with other organizational work activities associated with low-level CR programs not directly associated with plant hardware, it can be seen that organizational workloads can vary greatly, as well as be significantly affected by the quantity and scope of CRs.

As shown in Fig. 1, a work order (WO) is written to trigger the work process. If the work is emergent or unplanned, a work planner "walks down" the job per the WO and develops draft work instructions, which are then reviewed and finalized. A work package is then prepared and planned. This package is reviewed and approved and is issued to the appropriate maintenance discipline. The package is scheduled per the work scheduling process, and when the scheduled workday arrives, the working discipline retrieves the package, gathers parts, materials, tools, etc., and begins the process of completing the activities required and described in the work package. The operations organization ensures that the proper equipment clearance tags are hung so that the equipment to be worked on is isolated, such that work can be performed safely. Maintenance for the working discipline (e.g., mechanical, electrical) begins by obtaining work start approval from operations (i.e., operations releases the equipment to maintenance), a pre job briefing is typically held between maintenance and operations, then the working discipline is released to perform the work. After the work activities are completed, a post maintenance test is performed to ensure the equipment operates correctly and, if the test is passed (i.e., results are acceptable to operations), then maintenance releases the equipment back to operations. Then, if applicable, the work process activities continue to obtain the necessary final reviews and approvals (e.g., engineering reviews) and the package is closed and archived. Follow-on activities include entries made in equipment history logs, as well as other monitoring processes (Probabilistic Risk Assessment risk profile, maintenance rule, equipment history, etc.).

This organizational process is performed thousands of times during an operating cycle and is also performed during planned and unplanned plant outages. This paper analyzes the errors that occur during these processes, and demonstrates how this constant tracking becomes the data feedstock used to produce methods that can become part of the solution for the plant to minimize similar errors, and most importantly, to avoid consequential outcomes (e.g., plant trip, inadvertent actuations).

As part of the effort to determine the organizational factors that lead to an event (CR), a detailed review of the CAP data made it possible to better understand which plant organizations have greater exposure to consequential errors, given the number of CRs generated that identify that organization as the responsible party for resolving the condition described in the CR. Also, through analysis of the actions that are generated after the occurrence of an event, the creation of the CR, and the subsequent investigation, we gain more insight into

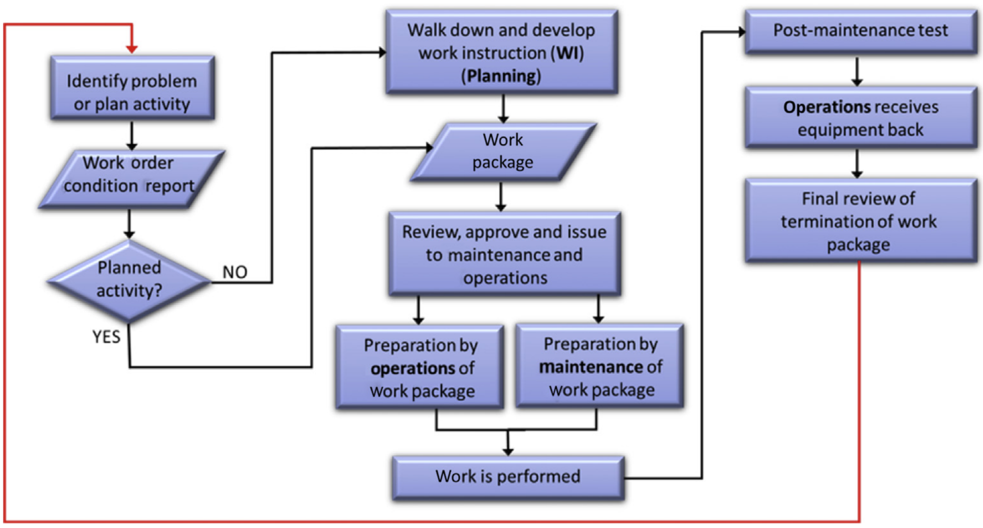

Fig. 1 – Typical organization process flow of work activities at a nuclear power plant (NPP).

the total organizational workload and how the organizations work together, or at times, do not work together to produce conditions of low resilience and higher likelihood of consequential events. The time series of the events provides insight into the cyclic behavior, particularly controlled by the outages. This can be used for predictive purposes and is presented in the next sections.

2.1. *Operational data time series*

One way to observe the operational experience at the plant is to plot the events that occur at the plant over time. This graph is presented in Fig. 2, using data from the operating NPP. In this graph, the events are plotted by level of severity, the red [significant condition adverse to quality (SCAQ)—a condition adverse to quality that, if uncorrected, could have a serious effect on safety or operability. Based on Nuclear Quality Assurance-1 Standard issued by American Society of Mechanical Engineers, ASME NQA-1-1994.] representing the most significant contributor to risk, next the gray (condition adverse to quality on a station level, CAQ-L1), and finally the green (condition adverse to quality on a department level, CAQ-L2). Although the more severe (red) events are plotted on an exaggerated scale—on the right side of the graph, with between zero and four SCAQs a month—this does not detract from the fact that the peaks in the number of events frequently coincide for all severity levels. Presumably, we will have more events during cold shutdowns, refueling, and outages, because there is an increased amount of maintenance work, more people at the plant, especially contractors, and the peaks in Fig. 2 illustrate this.

Fig. 3 plots the events per month, but for only the period 2007–2008, allowing the relationship between the different CR severity levels to be observed in greater detail. In particular, the first and last peaks (April 2007 and October 2008, respectively) for this period show that the peaks of all three severity level CRs coincide. Despite the fact that we see dips (i.e., lower total number of CRs), we can also observe that they, too, generally follow the same trend. In other words, in periods where the total number of CRs is low, the three highest severity level CRs are also at minimums. This may seem to be an obvious conclusion; however, the severity level of a single CR is independent of the number of CRs generated. It is determined by predefined criteria, and therefore a CR's severity level is not related to the absolute number of CRs generated. Thus, based on Fig. 3 we can conclude that there is a correlation between the number and scope of open CRs and the likelihood of occurrence of a more severe CR, up to and including the most severe, an SCAQ. In addition, it is important to mention that even when the red peak (SCAQ) is not above the green (CAQ-L2), we are still seeing significant results, remembering that the scale is different. There may be only one significant event, as in April 2008; however, the three types of events are aligned, occurring simultaneously. This means that as more events of less severity occur, it is more likely that significant events may occur.

Fig. 4, which shows events per week, includes the least severe events (condition not adverse to quality, CNAQ) in blue and locates the SCAQs by red dots. The higher red dots represent occasions when there were two SCAQs in 1 week. The importance of the CNAQs is their large number, and while they can be events that do not affect components, they sometimes generate as many as 2,000 activities on top of the already large amount of work that each department must accomplish.

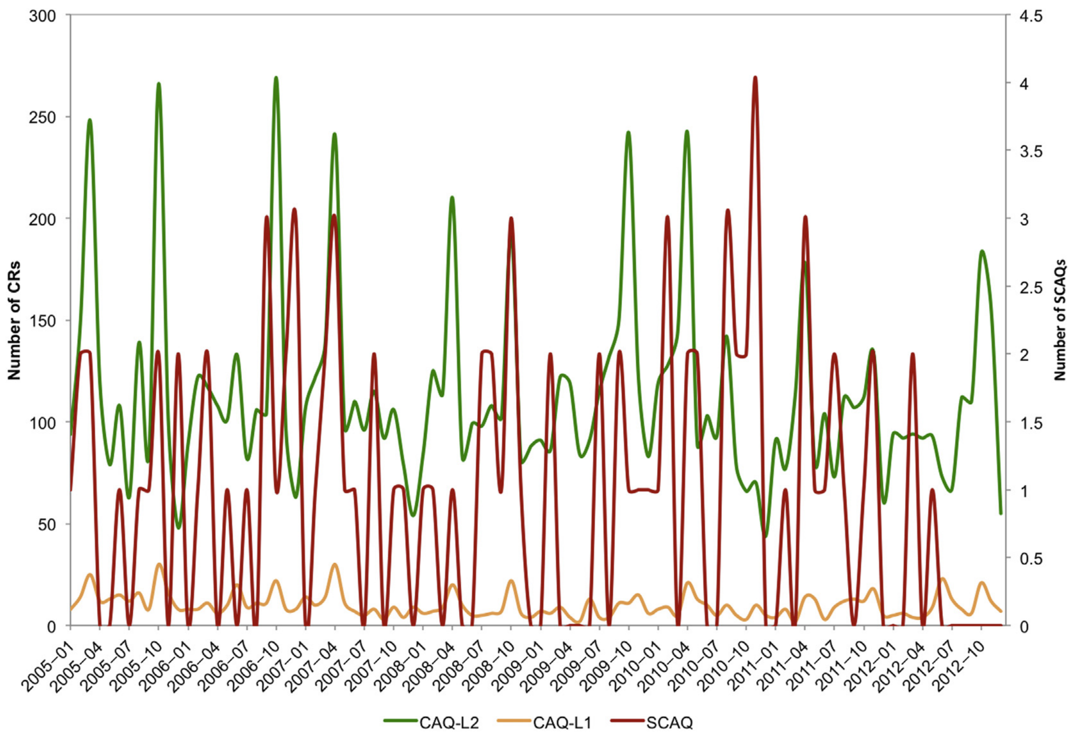

Fig. 2 – Events 2005–2012. CR, condition report; SCAQ, significant condition adverse to quality.

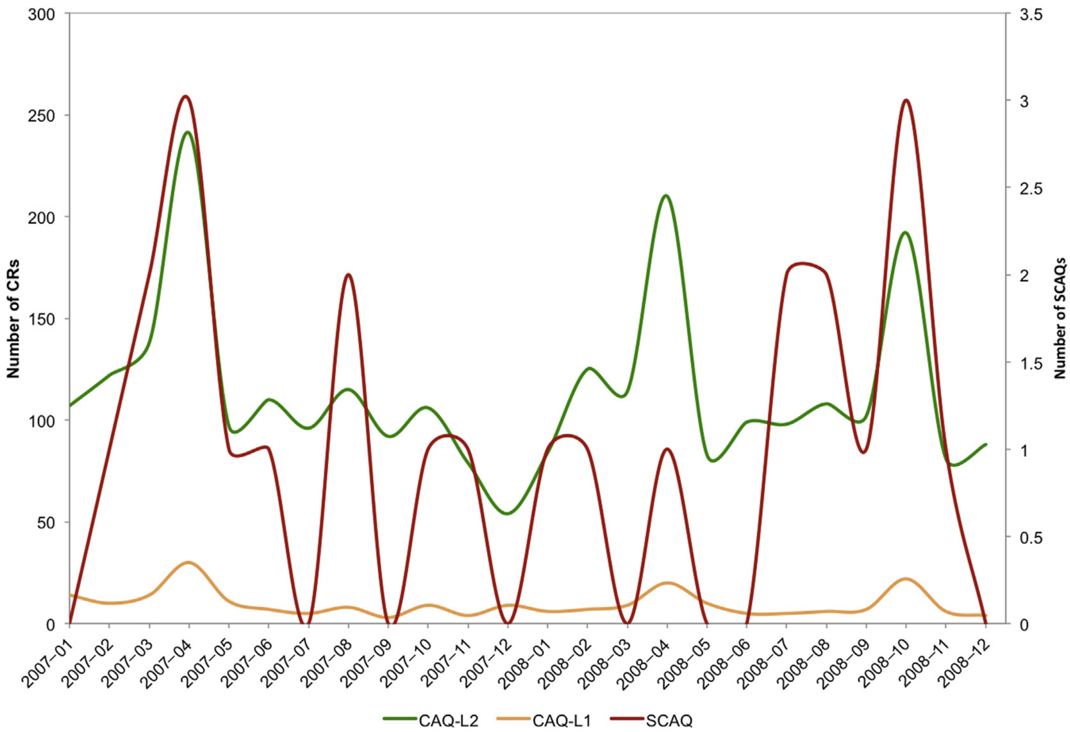

Fig. 3 – Events 2007–2008. CR, condition report; SCAQ, significant condition adverse to quality.

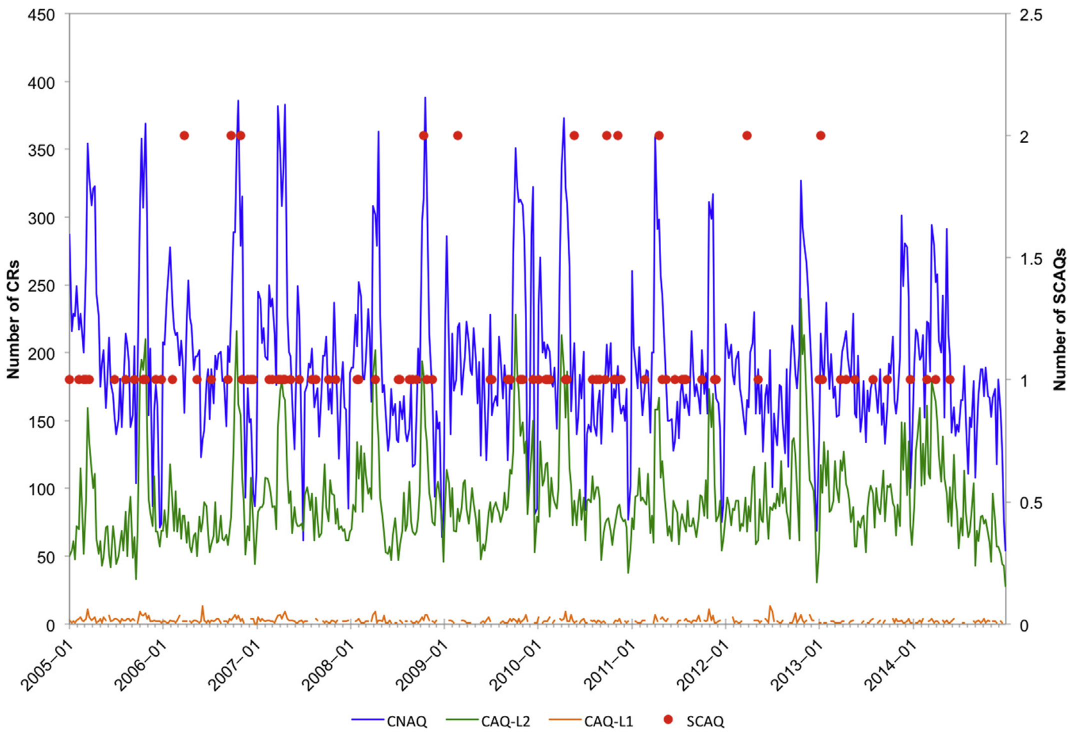

Fig. 4 – Events per week, 2005–2014. CNAQ, condition not adverse to quality; CR, condition report; SCAQ, significant condition adverse to quality.

2.2. Tools developed from time series

From the CAP database, we can develop a simple planning tool, as presented in Fig. 5. The cumulative frequency curve was developed for determining the probability of an SCAQ occurring given the number of CRs accumulated since the last SCAQ.

Although this is a simplified approach for developing an indicator (a more complete approach is presented later), this curve can be used to determine the position of the station relative to overall workload, which has been shown to be correlated with the likelihood of the occurrence of an SCAQ. In fact, performance indicator thresholds could be established to indicate when a management barrier or other compensatory action may be implemented in order to reduce the likelihood of conditions meeting SCAQ criteria. In the case of this particular plant, for example, before there have been 5,000 CRs since the last SCAQ, an organizational barrier or other actions (e.g., increased equipment performance reviews and monitoring) should be implemented in order to reduce the probability of the next SCAQ occurrence. While this can be helpful, the plant requires more insight into how the organizational factors influence the failures in human performance, in order to select the proper barrier to implement. An analysis of causal factors of the events and methods for choosing effective barriers is discussed by Nelson and Martín del Campo [14]. Also, in order to comprehend how plant processes and activities affect organizational factors and the resultant stress and strain they impose on station personnel, the inter- and intradepartmental factors are discussed in the following section.

2.3. Interdepartmental factors

As part of the effort to better understand the organizational factors and human performance events that cause station level events, a detailed review of the CAP database was performed. It is the best source of empirical data for records of events at all levels and across all organizations, and a thorough analysis enables one to understand which plant organization identified the problem and the organizations responsible for correcting the problem. The number of CRs generated with an organization being identified as responsible, either as the identifier (i.e., generating a CR) or as the owner of an action within the CR, gives important insights into station procedural and process functions that result in specific plant organizations being more at risk for causing or responding to station events. In addition, through analysis of the actions that are generated after the occurrence of an event, we gain more insight into how the organizations communicate and work together or, at times, do not work together.

Fig. 6 presents the distribution of CRs among the station departments for all the severity levels. In 10 years, more than 121,000 CRs were created by 169 organizational functions (it is recognized that some organizational functions may be shared among different station departments). In this data survey, the procedures development function (labeled "Procedures" in the figures) is the leading generator of CRs. Procedures are recognized as being part of the cause, as well as the resolution. Since the procedure writing function affects all activities at a station, it does not seem unreasonable that this function produces and receives the maximum number of actions.

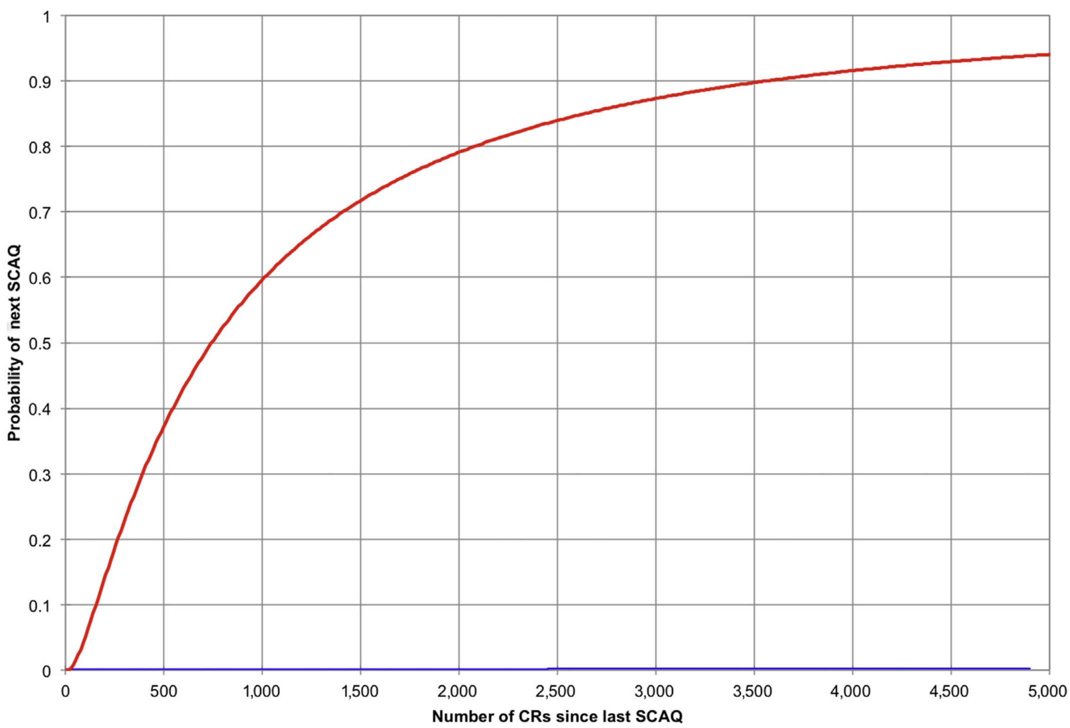

Fig. 5 – Probability of a significant condition adverse to quality (SCAQ) given number of events since last occurrence. CR, condition report.

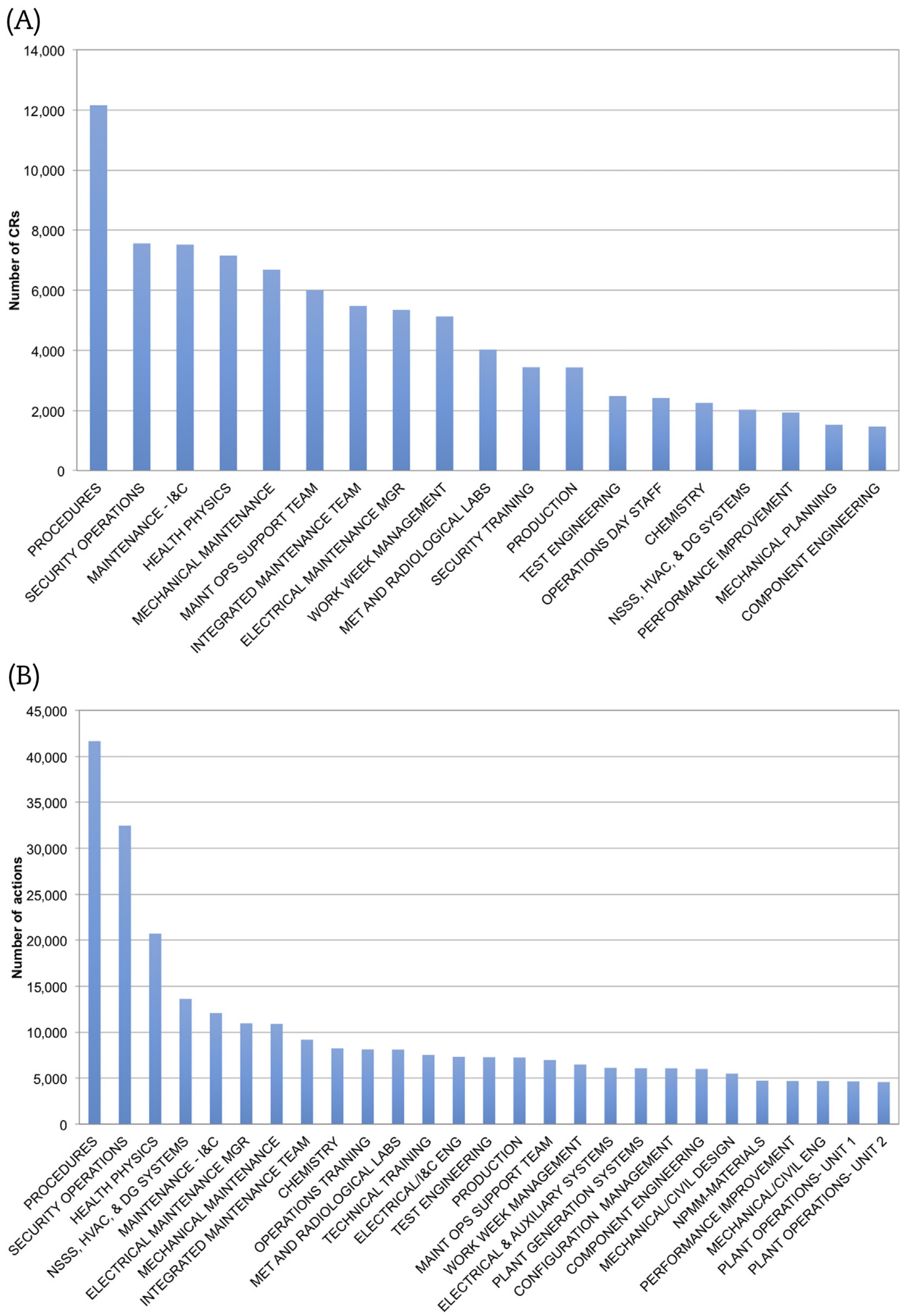

Fig. 6 – Departments. (A) Creating condition reports (CRs) 2005–2014. (B) Receiving actions 2005–2014. DG, Diesel generator; I&C, Instrumentation & Calibration; HVAC, Heating Ventilation and Air conditioning; LABS, Laboratories; MAINT, Maintenance; MET, Metrology; MGR, Manager; NPMM, Nuclear Purchasing and Material Management; NSSS, Nuclear Steam Supply System; OPS, Operations.

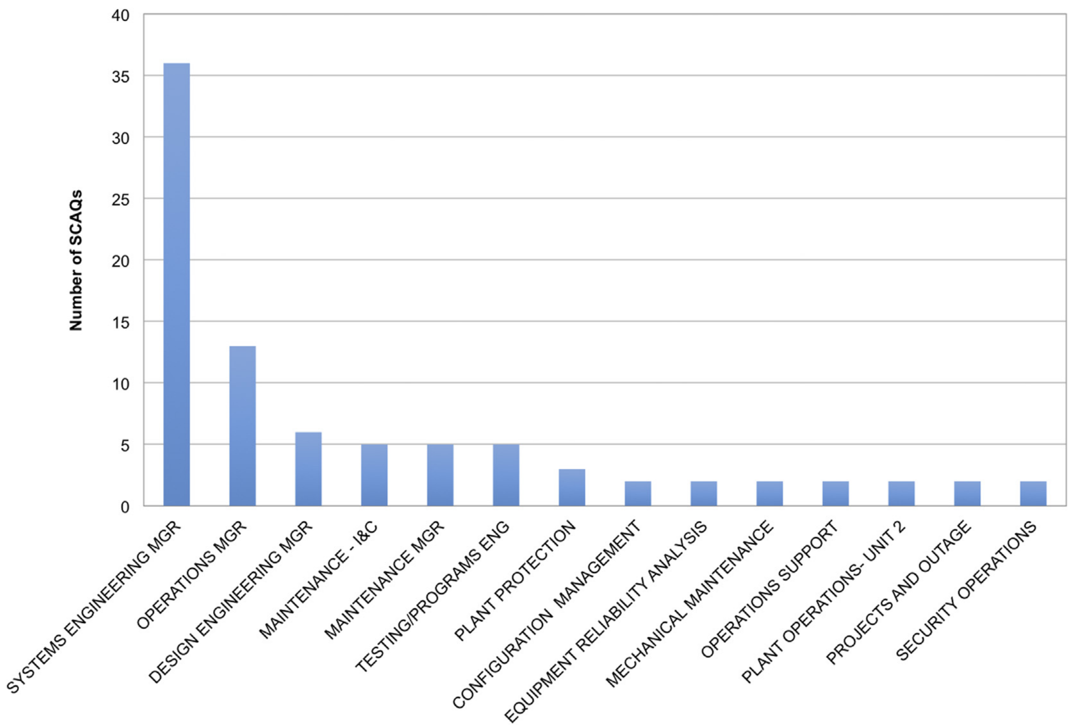

Fig. 7 – Number of significant conditions adverse to quality (SCAQs) for departments responsible for more than one SCAQ. ENG, Engineering; I&C, Instrumentation & Calibration; MGR, Manager.

During this 10-year period, there were more than 400,000 actions generated, 106 SCAQs, and seven plant trips.

However, the procedures function does not play a role in generating the most significant events in the 10-year period. As shown in Fig. 7, the organizational functions that have caused two or more SCAQ events fall under the responsibility of the engineering, operations, and maintenance departments. That is, procedures are responsible for the majority of the CRs, but not the SCAQs.

The actions for other organizational functions received after an SCAQ was generated are shown in Fig. 8A and the number of actions for the SCAQ owner in Fig. 8B. The observation is that the CR owners assigning actions add considerable strain on the individual departments, which in turn can increase workloads. In Section 3, this is shown to increase organizational stress.

It is difficult to describe organizational responsibilities and authority relations in simple statements. Plant organizations have specific functions and associated products (e.g., create procedures, perform maintenance), but they must also perform a variety of administrative activities. These activities include job-specific qualification and certification training, access authorization, emergency response organization participation, outage related assignments, etc. It is possible, through interviews and an extended set of observations over many different organizational activities, to begin to understand the number and complexity of interdepartmental relationships, as done by Schulman [15]. We have found, as Schulman [15] found in his qualitative study at Diablo Canyon, Nuclear Power Plant, San Luis Obisbo, CA, USA, "Where error, oversight, or failure had foreseeable consequences that threatened individual or environmental safety, the administrative procedures were likely to be most elaborate and the interdepartmental interactions most intense". The process in this study is to determine the responsibilities, interactions, successes, and failures through analysis of the reports included in the CAP.

3. Materials and methods

Due to a similarity between cognitive systems engineering and how organizations adapt, and engineer resilience into their organizations, we propose a new method that provides organizational stress and resilience insights with respect to their relationship to plant performance. Using the 10 years of CAP data, the correlation is examined between increasing organizational demands and the likelihood of consequential events (i.e., plant trips, equipment clearance order error, component trips, inadvertent actuation of safety injection, etc.).

In this regard, it is anticipated that new and different insights into how organizational activities that support or facilitate work processes (i.e., soft processes) can and do result in both direct and indirect changes to equipment performance and reliability (i.e., hard impacts). A correlation was observed between the demand on an organization and the level of risk at the plant. This concept, which relates the resilience to the demands over time, is presented in Fig. 9. In this figure, we can observe that the demand on the plant can be thought of as the

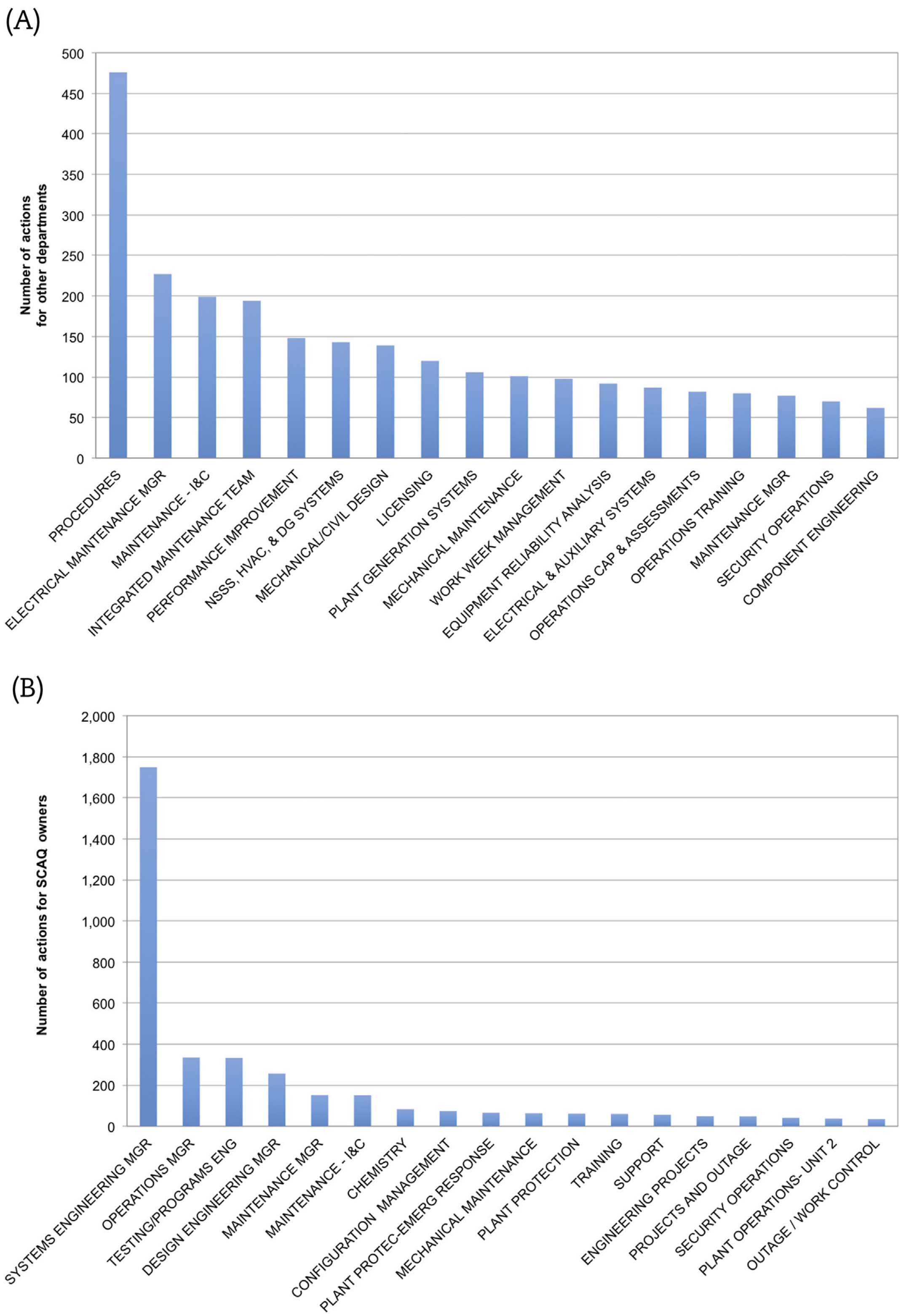

Fig. 8 – Actions. (A) For others from significant conditions adverse to quality (SCAQs). (B) Generated for SCAQ owner. DG, ; ENG, Engineering; I&C, Instrumentation & Calibration; HVAC, Heating, Ventilation and Air conditioning; MGR, Manager; NSSS, Nuclear Steam Supply System.

stress placed on the organizational capacity, and this is related to the risk that exists at the plant due to all of the ongoing activities. The resilience can be thought of as the organization's ability to cope with the risk and bounce back from increased risk (i.e., strength) [16]. However, if the stress reaches a resilience threshold, the plant will become brittle and not be able to adapt. In this case, the failure point is reached when an SCAQ occurs.

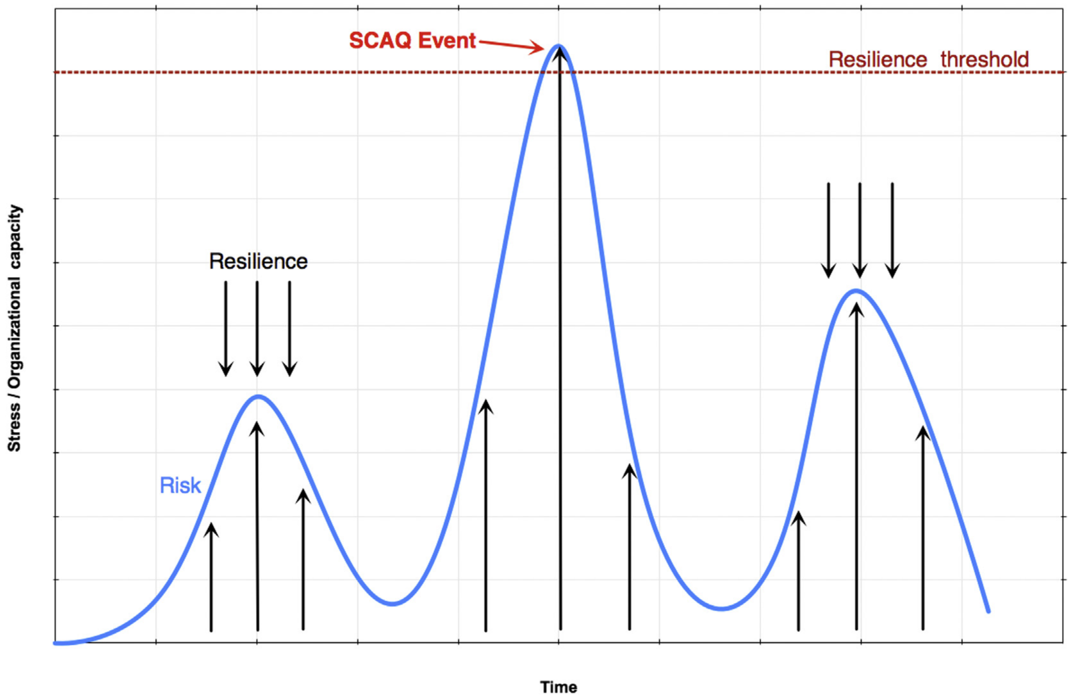

Fig. 9 – Organizational stress over time. SCAQ, significant condition adverse to quality.

3.1. *Organizational stress and strain curve*

One way to characterize and measure an organization's resilience can be based on an analogy from the field of materials engineering, the stress–strain curve (Fig. 10). A stress–strain curve is created by stretching (straining) a material and measuring the resulting load (stress). The area under the linear (uniform) portion of the curve is called the resilience, the energy the material is able to absorb before deforming permanently. Materials that are brittle break along this linear region, without any yielding (permanent deformation). These terms and concepts correlate well with the basic finding in cognitive systems engineering that demand factors are critical [16,17]. Thus, the hypothesis is that to characterize a cognitive system of people and machines, one should examine how that joint system responds to different amounts of work activities. It is interesting that the two fields use similar language, resilience, and brittleness, to characterize how an organization "stretches" as demands increase.

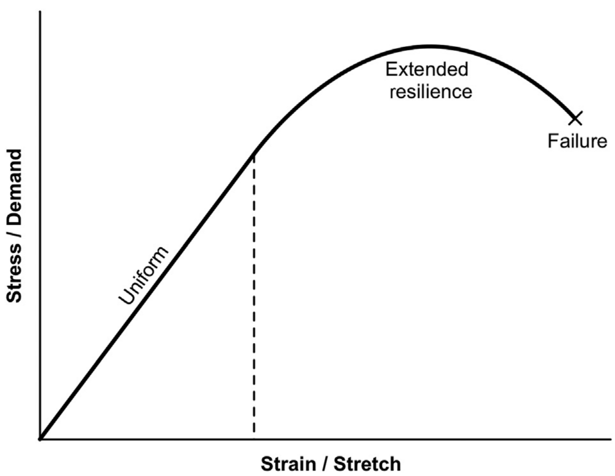

Fig. 10 – Basic demand-stretch or stress–strain curve.

3.2. *Organizational resilience curve methodology*

The methodology is data-based and includes consideration of human error and organizational factors because of their large contribution to consequential events.

Step 1. Gather CRs and work activities (i.e., actions, PMs and WOs) per month from the CAP database, covering a period of 10 years. The outage history is needed for the same period of time. Within the category of severe events (SCAQs), the consequential events (main turbine trips and reactor trips) should be highlighted.

Step 2. A scatter plot is developed with stress on the y-axis and strain on the x-axis, to develop the resilience curve. The stress is represented by the number of open CRs. The strain is the number of activities (i.e., WOs, PMs, and open actions).

Step 3. Develop the equation for the resilience curve, with a breakpoint defined as the resilience threshold. The resilience threshold is the point where main turbine and reactor trips begin to appear.

Finally, this equation can be used to calculate where the plant is on the resilience curve at any time, as well as to predict where it will be in the next months, if no changes are made in the organization. When the stress factor (the number of CRs and the sum of the different work activities that are in process) approaches the resilience threshold, a barrier should be installed, that is, some additional compensating actions should be implemented by the station organization to reduce the likelihood of failures in human performance and potentially avoid a consequential event. These failures in human performance are not only due to human errors, but also process and procedural complexities, as well as management decisions that impact plant performance. These organizational processes and decisions can have both direct and latent effects on plant equipment and can encompass all types of engineering, maintenance, and operations programs. For example, testing and maintenance frequency decisions should be based on historical data and the significance of the equipment to nuclear safety and reliable plant operations. Therefore, a surveillance testing interval of every 6 months may be too infrequent to detect the onset of corrosion, and should be modified given the historical data.

4. Results and discussion

We can plot the strain as the number of PMs, CAP actions, and other WOs completed per month, which corresponds to an ever-present base level activity load for the plant organizations. The open actions are summed, since these increase the organizational strain level of the station. The stress is related to the number of CRs opened or remaining open in the month. Fig. 11 presents the resulting organizational resilience curve for the plant used for this pilot study. The red squares represent plant trips, the point of exceeding the resilience threshold—the ability to absorb malfunctions in performance and maintain performance to some standard of performance (e.g., online power generation). The shaded area indicates the area where an increased likelihood of a plant trip is found, and the base of this trapezoid is the perpendicular line that indicates where this increase in likelihood begins and is defined as the resilience threshold. At this point, it is assumed that the organizational elements and their interactions with plant equipment through planned and unplanned work result in more failures that cause consequential events (e.g., plant trips).

4.1. *Application*

Based on this resilience curve, a method of anticipating consequential events was developed in the form of a leading performance indicator, using fuzzy logic. This provides the ability to monitor organizational demands against the increasing probability of a consequential event over time. Performance indicating alerts and thresholds are then proposed to provide awareness and recognition of "challenges" to organizational stress levels and resilience limits. This is shown as an increase in the probability of consequential events versus work activities, with thresholds associated with specific levels of risk (i.e., likelihood of plant trips). As noted earlier, the key premise is that increasing organizational demands, as recorded in the CAP database, reflect equipment or process problems that, in turn, increase the likelihood of a consequential event. As organizational demands increase, the organizational resilience limit is approached and the likelihood of the occurrence of a consequential event increases up to the point that a probabilistic prediction of the next consequential event can be made. This approach bases itself on plant-specific operating experience and history; specifically, the number of consequential events and the demand on the organization. Thus, this indicator can predict the need to take

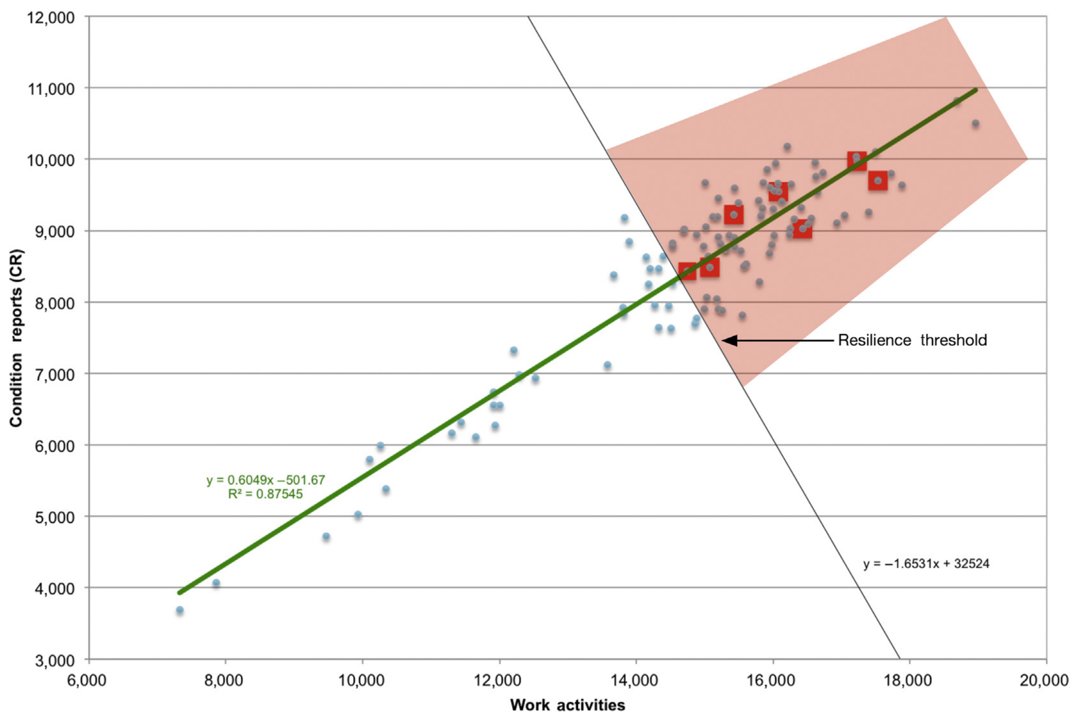

Fig. 11 – Organizational resilience. The shaded area contains the plant trips and majority of consequential events.

action in order to avoid causing significant events; in this case, implement a barrier to protect the plant from such an event.

4.1.1. *Performance indicators*

There are three types of performance indicators used in the nuclear industry: lagging, current, and leading. Lagging performance indicators provide information about a selected parameter (e.g., human performance) as reflected in events that have occurred in the past. For example, the Nuclear Regulatory Commission (NRC) Human Factors Information System database [18] lists the LERs, examinations reports, and inspection reports associated with human factors that were reported during each year for each plant. Analysis of these events can help to determine categories of human performance-related errors. Counting the number of occurrences in each error category provides the basis for a lagging indicator of human performance. According to Reason's [19] model, lagging indicators are measures associated with the unwanted consequences of unsafe acts, such as those described in LERs and significant event reports.

Current performance indicators provide information on selected parameters based on current conditions. For example, most nuclear plants have the voluntary Problem Identification and Resolution Program reporting system that is part of the CAP, as described earlier. Those items flagged as involving human performance can be placed in error categories and counted. The current performance indicator in this example is the number of items in each error category. According to Reason's model, current performance indicators are measures associated with the occurrence of unsafe acts, such as acts that are self-reported by workers, whether or not there was a significant consequential event.

Leading performance indicators provide information about developing or changing conditions and factors that tend to influence future human performance. This same concept holds true for plant performance as well, since equipment or component events can provide information about developing or changing conditions that influence future plant performance. According to Reason's [19] model, the leading indicators would be associated with the causes of unsafe actions, particularly the workplace and organizational factors. There have been efforts to develop leading performance indicators in the nuclear industry, such as EPRI's human performance assistance package [20]. The Electric Power Research Institute (EPRI) systems were piloted at three nuclear plants in the US, and a concern that was presented in the final report of the pilot study [21] was the inability to create a mapping from a leading indicator to an outcome, which is one of the intentions of the model in this paper.

The development and use of leading performance indicators of human performance is a reasonable expectation given the volume of data being collected on a continuous basis in the nuclear industry. A structured approach to analyzing the data is presented here in order to establish a useful focus on available proactive, or leading information and intelligence. Ready access to these ideas is fundamental for any organization in order to avoid consequential events. While the lagging and current performance indicators are fairly well understood and used, the leading performance indicators have been more challenging and, thus, have not yet been used to their fullest potential. The approach to developing leading indicators in this paper is to establish a resilience threshold and monitor when the stress factor approaches this threshold, which will indicate when measures should be taken to reduce the likelihood of occurrence of a consequential event.

4.1.2. *Approach for developing a leading performance indicator*

In order to develop a leading performance indicator from the resilience curve (Fig. 11), a fuzzy logic approach [22] was chosen, because the data support approximation rather than precision; however, a mechanism is needed to convert this rather imprecise data to a crisp performance indicator. Several studies have introduced the fuzzy set theory (FST) approach for performance assessment of health, safety, and environment in organizations [23,24]. These studies show important reasons to use FST: reduction of human error, creation of expert knowledge, and interpretation of large amounts of vague or highly varied data.

The CAP databases used in United States nuclear plants prove to be appropriate for the use of FST for similar reasons. They have a preponderance of human error related events (most minor, but some significant and consequential). They identify implemented CAP corrective actions and lessons learned, which are the primary plant mechanisms for authorizing changes to virtually all station processes to improve performance. They also function as the primary repository or data warehouse for identifying, assigning, and scheduling work related activities for almost all station activities, whether or not they are a baseline function or an added CAP function. In this regard, CAP programs represent an excellent barometer of the time-dependent "pressure" an organization is exposed to, relative to activities defined in normal (routine) job functions and those that represent additional scopes of work with due dates resulting from problems or issues captured by the CAP process.

In our case, the fuzzy inference system uses the amount of work activities and CRs as input and the if/then rules are applied to calculate the consequences of exceeding the resilience threshold, that is, the increased likelihood of plant trips. While the focus is on plant trips as being the consequential event of measure, it is important to mention that a large percentage of the other consequential events occurred above the resilience threshold value as well. These other non-plant trip consequential events include: 85% of the SCAQs, 80% of the significant component trips, and 80% of the equipment clearance order problems.

MATLAB's Fuzzy Logic Toolbox (version 2.1.1; The MathWorks, Inc., Natick, MA, USA) was used to create and edit a fuzzy logic system. The required parameters are encoded in fuzzy representations, and the interrelationships between them take the form of well-defined "if/then" rules following the following steps. (1) Membership functions are built for the two inputs (CRs, work activities) and also for a single output called plant trip. The linguistic labels "low", "medium", and "high" were used to "fuzzify" the functions, based on normalized distribution of the values ≤50%, 50–75%, and >75%; corresponding to ≤8,480, 8,480–9,400, and >9,400 CRs/mo. Fig. 12 shows the distribution. (2) Five fuzzy if/then rules are defined to determine the likelihood of a plant trip occurring in the short term, given the quantity of CRs and activities. These rules effectively define

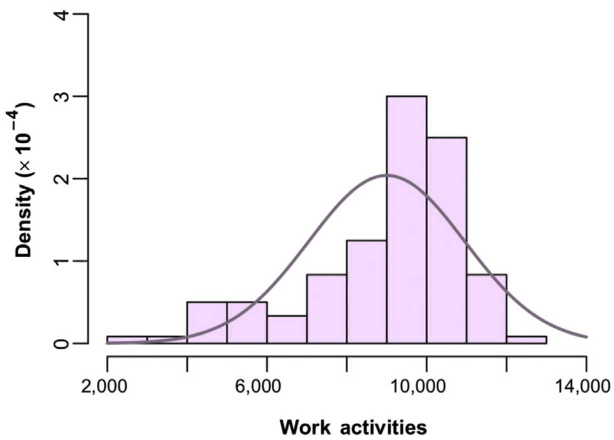

Fig. 12 – Normal distribution of condition reports (CRs).

the shaded area in Fig. 11, although the last two include the area above and to the right of the point of the first plant trip, but with less weight since there is no evidence at this time. (i) If "CRs" is <low> and "work activities" is <low> then "plant trip" is <low>. (ii) If "CRs" is <medium> and "work activities" is <medium> then "plant trip" is <medium>. (iii) If "CRs" is <high> and "work activities" is <high> then "plant trip" is <high>. (iv) If "CRs" is <high> then "plant trip" is <high>, weight = 0.5. (v) If "work activities" is <high> then "plant trip" is <high>, weight = 0.5. (3) Apply implication method: to formulate the mapping from a given input to an output, the AND method with the *prod* (product) operator is utilized, and the last two rules are assigned a weight of 0.5, due to less evidence obtained from the data. (4) The aggregation method *sum* is used to aggregate the output. (5) The output is "defuzzified" using the centroid calculation in order to obtain the likelihood of a plant trip given varying combinations of numbers of CRs and work activities.

Fig. 13 shows the surface graph of the likelihood of a plant trip occurring in the short term as a function of the number of CRs and work activities obtained with this system. The general objective is to evaluate the conditions where the likelihood of a plant trip increases by varying the values for CRs and work activities. The red squares again represent the plant trips.

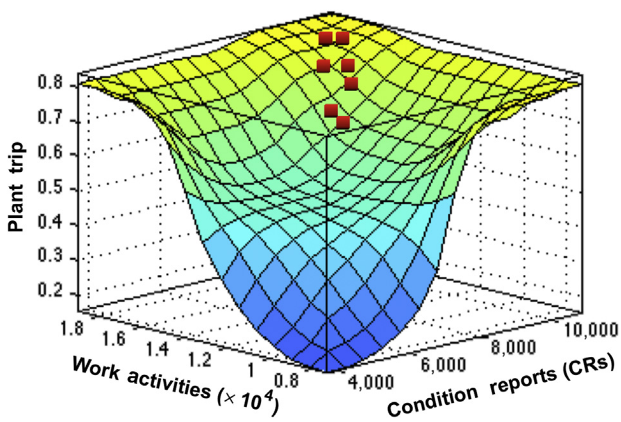

Fig. 13 – Likelihood of next plant trip as a function of condition reports and work activities in the surface viewer of the Fuzzy Logic Toolbox.

In order for a performance indicator to be useful, it should be uncomplicated (measurable) and straightforward. For this reason, the results acquired from the inference system are laid out in tabular form in Fig. 14.

If station personnel were to track their location on Fig. 14, the indicator would notify station leaders when plant and organizational stresses are increasing beyond an "alert" level, developed through the inference process described above. For stress levels in the white band, there is a 25–40% conditional likelihood that a plant trip would occur in the short term (within the next month). The X's indicate the color band for each of the plant trips over 9 years (2006–2014); the first plant trip occurred in the yellow band; however, the remaining six all occurred in the orange band (2 in 2007, 2008, 2 in 2010, 2011, and 2013). There were no plant trips during 2009, 2012, and 2014. Those time periods are associated with the white and light green color bands, which further adds verification of the indicator's validity.

This performance indicator could be further enhanced through identifying a "required action" level where management-directed compensatory measures could be taken based on examination of the current plant and organizational status or performance relative to significant plant and organizational functions. The leading indicator presented here is analogous to a thermometer type or heat index performance indicator. It should create awareness in management and station personnel, leading to further internal examinations when stress levels are exceeding predefined limits. It should also lead the plant management and personnel to further examine current plant conditions for vulnerabilities of a plant trip. The use of the white band region could be assigned as the "alert" band and the yellow region could be designated as the "required action" band. The alert band indicates the appropriate time to begin to reduce strain on the plant (reduce work activities, such as PMs, WOs, and/or CAP actions) or implement measures or barriers to effectively address current station vulnerabilities and increase the resilience threshold. The required action band indicates the region where immediate development and implementation of identified stress reducing

Work activities	Open CRs	Likelihood of next plant trip[a]
> 18,901	> 10,801	> 85%
15,001 – 18,900	7,981 – 10,800	65 – 85%
11,001 – 15,000	7,261 – 7,980	40 – 65%
10,101 – 11,000	6,211 – 7,260	25 – 40%
7,381 – 10,100	3,791 – 6,210	10 – 25%
≤ 7,380	≤ 3,790	< 10%

2006 2007 2008 2009 2010 2011 2012 2013 2014

Fig. 14 – Conceptual performance indicator. [a]Conditional likelihood in the short term.

actions and/or actions to reduce current plant vulnerabilities are required to be implemented and monitored.

It is important to note that with this leading performance indicator, actions taken to return to lower regions may not be conducive to the intent of CAPs (i.e., to identify and correct problems). Thus, in that regard, this indicator's value is in its ability to predict when increased likelihoods of plant trips could occur, which in and of itself, represents the involuntary reduction in resilience since the plant trip changes both plant and organization to an outage frame of mind (i.e., other work stops and focus is solely on returning the plant back to at-power conditions). However, by predicting conditions whereby increased plant trips are more likely to occur based on plant specific operating history, there is an opportunity for organizations to pause and make an assessment of current conditions and in so doing, re-scope and reprioritize activities to increase resilience (e.g., free up critical resources that may be currently committed to less significant activities or reschedule work activities to more appropriate time frames). This leading indicator is intended for this purpose, and if implemented by nuclear plant organizations, can provide an important cue to perform a "resilience examination".

4.2. *Conclusions*

The conclusion of this research is that it is possible to monitor organizational stress levels and implement compensating actions before the plant organization and equipment reach the point where undesirable events (e.g., plant trips) occur. Organizational performance improvement is a generic concern at commercial NPPs, and the approach described in this paper provides a method to improve organizational performance beyond that currently achievable with event reporting and CAP monitoring, through the evaluation of organizational stress levels and associated resilience levels, leading to the development of a proposed leading performance indicator. It has been shown here that the CAP database can be used for many purposes including how to (1) describe organizational factors between and within departments; (2) calculate the probability of an SCAQ given the number of CRs reported since last occurrence; (3) detect when the station is at risk of exceeding its resilience; and (4) develop an organizational performance indicator.

We have also shown that the CAP databases are proper candidates for the use of FST, due to the scope and high variability (i.e., uncertainty) of items captured in CAP processes that, at some level, are all contributors to overall organizational and plant performance levels.

We have found, as did Hollnagel and Fujita [25], that resilience engineering provides a way to identify the capabilities that a complex sociotechnical system must have to perform acceptably in everyday situations, as well as during accidents. Applying the cognitive system engineering analogy to organizational resilience, we were able to build a stress–-strain curve to relate the station's stress (i.e., CRs) to the strain (i.e., work activities) that allows the station to continue to operate successfully. The station's CRs that are accounted for in this report are both "soft" CRs in terms of the process activities required to operate and maintain an NPP and the "hard" CRs in terms of the equipment and component issues that place further demand on organizational performance and that can also generate consequential plant events.

Thus, the organizational performance can be characterized by a strain and an associated stress, which indicate levels of organizational resilience. The strain is defined as the sum of the preventive maintenance, WOs, and open CAP actions. Organizational strain is seen to increase before, during, and just after an outage, but can also have peaks during at-power times. The stress is measured by the number of CRs, which is the plant's mechanism for identifying events, errors, and other failures across almost all plant processes. An organization's resilience is its ability to withstand these stresses and strains and still satisfactorily perform activities. The point where the stress and strain result in consequential events, such as a plant trip (i.e., the "breaking point"), is the resilience threshold.

This paper provides a method for measuring and analyzing stresses in term of the likelihood of consequential events based on plant specific operating experience. These parameters form the technical basis for developing a leading organizational resilience performance indicator. Since SCAQs represent times when demand on the organization (i.e., stress) exceeds its resilience limits, we use the occurrence of a plant trip as the consequential event of concern. Thus, when the stress factor exceeds the resilience threshold, it is more likely that a plant trip will occur. The performance indicator presents a conceptual color band arrangement representing the increased likelihood of a plant trip based on the stress factor. When the stress factor approaches the resilience threshold, additional barriers and other provisions should be considered for implementation.

When a particular problem is identified and resolved, the solution, represented by a corrective action or set of actions, does not always remain effective over long periods of time (i.e., years). The continual monitoring, application, and communication of the described process is necessary to assure that the resilience performance indicator continues to provide useful and timely information. Because change and adaptability increase resilience, the process will be improved by continual or periodic updating. Reductions in consequential events at the plant level over a period of time will be the key indication that either organizational stress has been reduced to more acceptable levels, or that organizational resilience has been increased due to increased organizational capacities and capabilities.

Processing the operational data daily or at least weekly will provide a regular update of the stress factor and the resilience threshold and produce a more accurate leading performance indicator for preventing consequential events.

Conflicts of interest

All authors have no conflicts of interest to declare.

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