Characterization of resilience in Nuclear Power Plants

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Abstract: An emergency operation system in a nuclear power plant consist of operators, human-machine interface, procedures, and the interactions among these elements working together to respond to incidents. The complexity of dynamic systems such as nuclear power plants poses a challenge for safety as it can be a source of deviations from normal behavior during system operation. NPP control rooms consist of many elements that result in complex interactions between them. Resilience is the ability of a system to recover from a disturbance, so that it can sustain required operations under both expected and unexpected conditions.
Nuclear power plants must anticipate the operating risks caused by either the hardware, human, or organizational failures in order to be resilient. The ability of NPPs to monitor the current status of the system, anticipate possible problems, react appropriately to events, and learn from past incidents is a measure of success hence the resilience. Although the significance of resilience has been stressed in the literature, there is a lack of adequate literature attempting to analyze system resilience. To achieve a practical an insightful understanding of the EOS resilience complexity, this paper aims at characterizing resilience attributes based on the existing literature.

Keywords: Resilience, emergency operation system (EOS), resilience attributes

1. INTRODUCTION

A nuclear power plant is a safety-critical organization whose main objective is to control hazards and risks that can lead to release of radioactive elements to the environment. There has been a significant improvement of safety designs as well as risk analysis tools and methodologies of nuclear power plants over the past few decades. The first safety design concept in a nuclear power plant was based on defence in depth philosophy which relies to a great extent on multi-level physical barriers and engineered safety features to protect the workers, public and the environment should an accident occur. The next significant safety analysis concept that was introduced was classical probabilistic safety assessment (PSA) which was hardware oriented. Human reliability analysis followed thereafter after it was recognized that human errors contributed to major accidents, e.g. Three Mile Island accident. The history of nuclear power plants illustrates a shift of emphasis in the safety considerations from a technical perspective to human factors and broader issues connected to organization and management [1].

Conventional safety analysis methods such as PSA have several limitations [2,3,4]: 1) they primarily focus on technical dimension, 2) the analysis are linear and sequential, 3) they are dominated by static models, 4) they do not take a systemic view into account, and 5) they focus primarily on why accidents happen and not how success is achieved. Insights from research and failures in complex systems have also demonstrated that safety is an emergent rather than a resultant property of systems, therefore it cannot be predicted by considering only the constituents parts of a system. New approaches to risk analysis for NPPs are needed to complement the conventional approaches [3].

Nuclear power plants being safety critical organizations have had low number of accidents and this has weakened the ability to learn from experience. Thus resilience is needed to increase the system’s ability to cope by enhancing anticipation for both expected and unexpected events. The study of a nuclear power plant safety can be further improved by characterizing NPP EOS resilience to gain an understanding of the various resilience attributes.

2. THEORETICAL BACKGROUND

2.1 Resilience Engineering

A resilient system is defined by “its ability effectively to adjust its functioning prior to or following changes and disturbances so that it can continue its functioning after a disruption or major mishap, and in the presence of continuous stresses" [5]. A study of a nuclear power plant emergency operation demonstrated that for system operations to be successful, more than procedure guidance is required and that in some incidents some degree of adaptability from the operators is needed [6,7]. The studies further shows that problems occur when operators fail to adapt plans and procedures to the situation. The adaptive capability to such situations is a measure of system resilience. Another study investigating the possibilities of operating crews to act flexibly in situations where procedures cannot be applied showed that expertise gained from training and teamwork effectiveness is important when the unexpected strikes [8]. A framework was proposed to analyze micro-incidents during nuclear power plant operation [9]. In this framework, micro incidents were defined as complex with four basic properties: singularity, unpredictability, importance, and pertinence to the situation. The findings indicate that to achieve a resilient performance the operators cannot rely only on the formal organizational constructs such as procedures, local adaptation by operators is necessary to solve plant problems.

A mathematical optimization model proposed for measuring resilience categorized resilience characteristics into two: inherent or adaptive. Inherent refers to resilience under normal operating conditions and adaptive refers to the use of a different strategy in crisis situations [10]. Adaptive capacity of a system is not static; the time dimension is important. Recovery time of the system after a disturbance should be taken into account when measuring resilience [11].

2.2 The safe Regulation Model

The safe regulation model shown in Figure 1 was developed by EDF research and development team to explain the impact of organizational factors on the operation of safety-critical systems such as nuclear power plants [5]. Three safe regulation phases are defined in this model; stabilisation, interruption, and stabilisation (post interruption stabilisation).

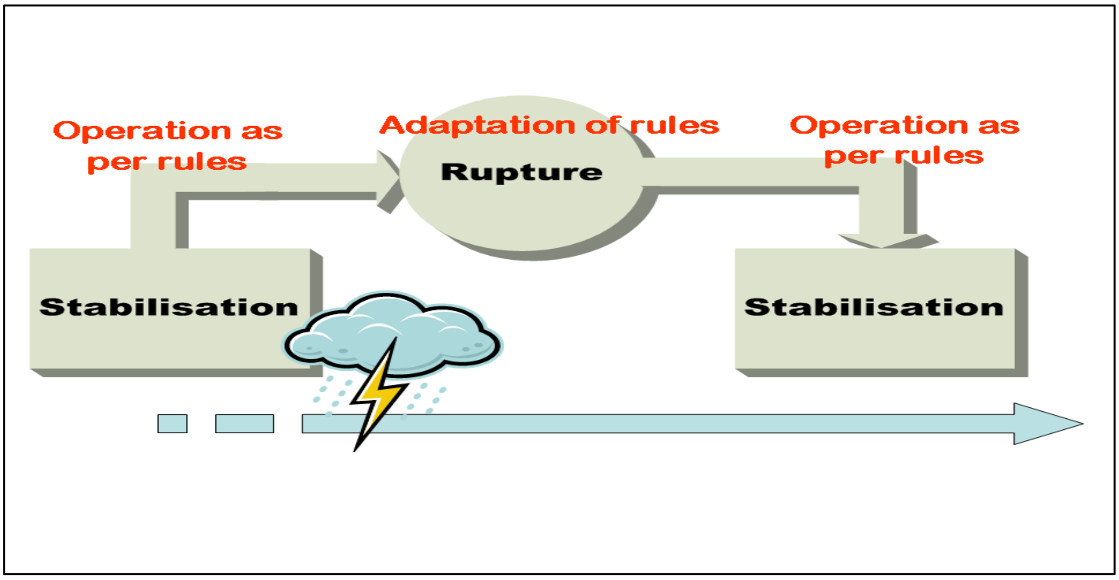

Figure 1: Safe Regulation Model [5]

3. EOS RESILIENCE MODEL (MRS)

EDF Research and Development Human Reliability team suggested five resilience attributes in their model of resilience in situation (Figure 2). The five high level resilience attributes are anticipation, adaptation, collective functioning, robustness, and learning organization.

3.1 Anticipation

A resilient system must be able to anticipate disruptions and their consequences. According to MRS, prescription, human resource, human machine interface, training, safety culture, and experience of the employees contribute to anticipation attribute. Resilient systems gauge their ability to anticipate using the following patterns [12]:

- Ability to recognize that adaptive capacity is falling/deteriorating,
- Ability to recognize that buffers or reserves become exhausted,
- Ability to recognize when to shift priorities across goal tradeoffs,
- Ability to navigate changing interdependencies across roles, activities, levels, and goals, and;
- Ability to recognize the need to learn new ways to adapt.

3.1.1. Prescription

Prescription consists of procedures used by the operators and collective rules such as task allocation and delegation rules. In a nuclear power plant, the operators have procedures to guide them in all modes of plant operation. While it is clear that the procedures give important support in accident operation, the degree of adequacy varies according to the characteristics of the actual situation during the team's operation. Licensees and applicants should ensure that all operators receive training on the use of EOPs prior to their implementation [13]. If an accident deviates from the procedures, the operators need to use their expertise in assessing the situation and eventually adjust the operation.

Emergency Operating Procedures (EOPs) are plant procedures that direct operators' actions necessary to mitigate the consequences of transients and accidents that have exceeded the set limits [13]. Procedures can be symptom based or event based; emergency operating procedures are mostly symptom based. Event-oriented EOPs require that the operator diagnose the specific event causing the transient or accident in order to mitigate the consequences of that transient or accident [13]. Symptom-based EOPs provide the operator with guidance on how to verify the adequacy of critical safety functions and how to restore and maintain these functions when they are degraded. Symptom-based emergency operating procedures are written in a way that the operator need not diagnose an event, such as a LOCA, to maintain a plant in a safe condition. The following limitations are related to strict application of procedures [14].

- Procedures do not take into account the individuals' variability in experience, attitude, and perceptions of the risk activity,
- It's not possible to guarantee the correct use of procedure during an emergency,
- The application conditions are not always well defined due to uncertainties: contingencies can turn the procedure inadequate depending on the actual conditions of the plant,
- In many cases procedures are developed by the system designers in a country different from where the system will be installed; different social aspects such as culture, and the language of the country that the plant has to operate may lead to wrong use of the procedure, and;
- Procedures generally refer to ideal situations, previously modeled by system designers which in most cases differ from the actual situations.

3.1.2. Human resource

Human resource refers to the way that the organization hires and assigns tasks to personnel.The organization should ensure that the main control room (MCR) team size is adequate to completely handle all of the scenarios under normal, abnormal, and emergency conditions. Team size should be determined with respect to both staffing requirements originating from the size of the task, as well as teamwork requirements originating from task complexity and uncertainty [15].
Task analysis can also be used to determine the staffing level by identifying the specific tasks needed to accomplish human actions, the information, control, and task support required to complete those tasks [16]. A task analysis report has detailed narratives of what personnel have to do including analyzing the alarms, information, controls, and task support needed to accomplish the task. The task analysis forms the baseline data upon which to allocate roles and responsibilities [17].

Table 1: Task Considerations [16]

Topic	Example
Alerts	- Alarms and warnings
Information	- Parameters (units, precision, and accuracy) - Feedback needed to indicate adequacy of actions taken
Decision-making	- Decision type (relative, absolute, probabilistic) - Evaluations to be performed
Response	- Actions to be taken - Task frequency and required accuracy - Time available and temporal constraints (task ordering) - Physical position (stand, sit, squat, etc.) - Biomechanics - Movements (lift, push, turn, pull, crank, etc.)
Teamwork and communication	- Coordination needed between the team performing the work - Personnel communication for monitoring information or taking control actions
Workload	- Cognitive - Physical - Overlap of task requirements (serial vs. parallel task elements)
Task support	- Special and protective clothing - Job aids, procedures or reference materials needed - Tools and equipment needed
Workplace factors	- Ingress and egress paths to the worksite - Workspace needed to perform the task - Typical environmental conditions (such as lighting, temp, noise)
Situational and performance shaping factors	- Stress - Time pressure - Extreme environmental conditions - Reduced staffing
Hazard identification	- Identification of hazards involved, e.g. potential personal injury

3.1.3. Human Machine Interface (HMI)

Human machine interface includes alarm system, indicators, controllers, operator support systems, and ergonomics. Human Machine Interfaces (HMI) is the primary mechanism through which personnel interact with the system during plant operation. HMI support the delivery of nuclear plant safety functions through detection, diagnosis, decision-making, and action. Nuclear power plant operation is a safety-critical organization where ultimate diagnosis and execution of tasks decisions lies with the operators. Thus it is important to provide a reliable decision support through effective supervisory control operator interfaces. Advances in digital technology have resulted to more application of automation for plant control. The systems in use now are advanced and more flexible because the personnel interact with plant at varying levels. Examples of advanced HMI include computer-based procedures, computerized operator support systems, intelligent agents that perform information processing tasks for operators in an autonomous manner, visual displays, and advanced Controls that combine multiple control methods [18]. When HMI performance is degraded, two main scenarios can be envisioned [19]: If the HMI is capable of returning to the initial nominal performance the system is resistant. If the HMI is capable of recovering from a disturbance and stabilizing at another functioning level; the system can be defined is resilient.

3.1.4. Safety culture

The term safety culture was first introduced by IAEA following their analysis of the nuclear power plants accidents at Chernobyl, Ukraine in 1986 [20]. The identification of poor safety culture, as a contributing factor to accident, led to a large number of studies investigating safety culture in many high hazard industries. There is no universally accepted definition for safety culture, however, majority of research studies commonly describe it as including norms, rules, and behaviours that are presented with respect to safety, as well as characteristics, beliefs, and values that are exhibited in an organization [21]. Safety culture is that assembly of characteristics and attitudes in organizations and individuals establish that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance [22]. The most important safety culture attributes are; communication, learning culture, management commitment to safety, problem identification, roles and responsibilities, and technical knowledge [23].

3.1.5. Training

Training refers to the knowledge and experience imparted to the personnel by the organization. The content, scheduling, and the frequency of the training should be considered when establishing a training program. Training operators is important in ensuring safe and reliable operation of nuclear power plants. Training programs enable the plant personnel have the knowledge, skills, and abilities needed to perform their roles and responsibilities.

Teams can learn from the repetitive simulations of various types of environments that may be confronted in a naturalistic setting. Simulation can establish effective learning environments that enhances team problem solving expertise [24]. The number of serious accidents recorded in NPPs is low therefore training through simulation provides the teams with skills to handle emergency scenarios. Simulator studies are of great importance in testing the applicability of the procedures.

Table 2: Implications of simulation for training (25)

Skill	Implications for Training	Source
Information Processing skills Encoding Storage Retrieval	- Simulation can provide a shared environment which fosters similar templates - Similar experiences within a simulation can enable team members to have consistent knowledge organizations that lead to the development of common goals	[26] [27]
Situation awareness Cue recognition Template recognition	- Simulation is an excellent environment in which to receive practice - Simulation can provide many more trials than would be possible in a natural setting - Simulation can highlight specific patterns	[24] [28] [29]

Problem solving skills Domain specific skills	- Simulation can provide a safe setting to practice problem solving in complex dynamic environments - By providing multiple practice opportunities, simulation can accelerate team member proficiency - Opportunities for feedback can be established in simulation environments	[24] [30] [28] [27]
Monitoring Detecting faults Metacognition	- Simulation can be used to provide examples of normal system states. - Team members are able to practice self-regulating behaviors within a simulation environment	[24] [31] [32]

3.2. Adaptation

Adaptation is the ability to detect deviations from expected or unexpected paths and to readjust operation accordingly [33]. A resilient system responds to regular and irregular threats in a robust, yet flexible, manner. Emergency operation system stability therefore relies on dynamic and adaptive strategies to unanticipated situations. System verification strategies and reconfiguration approaches contribute to the adaptive capability of an EOS. Reconfiguration process involves stopping wrong rules, selection of adequate procedure, crew negotiation to adapt new rules, and validation of the new rules by a person with in-situation delegation of control regulation [5].

A theoretical framework for team adaptation shows that high performing teams adapt to the following: (a) decision making strategy, and (b) behaviour and organizational structure to the demands of the situation in order to achieve effective team performance [34]. Cooperation and trust are required to enable the team members engage in adaptive behaviour. Team trust among team members is increasingly recognized as important in applied research, especially because of the interdependence required in dynamic tasks [35]. Trust is important especially during validation of rules during system reconfiguration because the team share and commits to ideas in a decision-making and help each other in solving problems.

3.3. Robustness

Robustness of an EOS is the ability to carry out the required operation strategies and monitor them to ensure they are correctly applied. Tasks execution strategy and system control affect the robustness capability of the system. Execution involves information selection and the related operator actions. Operator actions can be done in series or in parallel depending on the procedure instructions. The operators need feedback information about the actual state of the controlled process for situation awareness purpose and satisfy their safety management objectives [19]. Human machine interface system supports interaction between the operators and the environment to aid in detection and interpretations of the plant process and this enhances system robustness.

The operator obtains information directly from the process system or processed information through the HMI. The tasks included in the information acquisition are collecting process parameters data, grouping the information, noting the necessary information, and recognizing required parameter values [36]. Diagnosis of the plant condition is done by either human operator or automation. Once the diagnosis has been performed, the operators select the response guided by the emergency operating procedures.

Execution of the various control tasks are done either by human operator or automation. The implementation of the selected response can also be done by automation with the consent of the human operator [36].

Table 3: The information required for monitoring or verifying automation activities [36]

Process Stage	Information	Example
Information acquisition	The process of raw measurements from process system, in terms of how the raw measurements are being processed	The calculation of the difference between SG level of each SG is shown, including the readings from all channels of the interested parameters
Plant Diagnosis	The process of how the diagnosis is made	The logic or steps of how the diagnosis result is achieved, for example for a loss of feedwater, the corresponding parameters and the set points, such as steam flow, SG level, etc. are shown, as well as the criteria of coming to the conclusion during diagnosis
Response Selection	The basis of response selection (the criteria that resulted in the particular response to be chosen)	The diagnosis result and the goal that needs to be achieved to deal with the diagnosis are shown
Response Implementation	The basis of implementation	The reason for the implementation, for example when automation reduces the feedwater flow through economizer valve, the HSI should be able to show the reason why the automation acts such way, along with the diagnosis result and the selected procedure to support the basis of implementation

3.4. Collective functioning

Nuclear power plant control room crew performs the plant operational tasks collectively. The operating tasks includes monitoring the system, detecting and receiving information, interpreting and assessing situations, diagnosing symptoms, making decisions, and task execution. The resilience of complex systems such as NPPs emerges in the core of team coordination and cooperation processes [37]. Communication and collective management of the situation determines the team collective effort. Communication is an important means of exchanging information between individuals during a group activity which is a prerequisite for good teamwork by establishing a shared mental model [38]. Communication is a cornerstone for teamwork and it becomes very critical especially during abnormal and emergency conditions. Communication influences attitudes, behaviours, and builds commitment and ownership [39]. The importance of communication has been stressed in reports of previous major incidents. In nuclear industry, a study in Japan showed that about 13% of incidents involving human error were caused by written communication and about 5% were caused by verbal communication [40]. A study carried out in Germany showed that 10% of 232 operational events were caused by communication problems [41]. Standardized communications among operators is fundamental as it can increase the sureness of the communications and reduce the possibilities of confusion, misunderstanding, or errors [42]. In a nuclear power plant MCR, the amount of conversation is significantly reduced by using computer-based procedures instead of conventional paper-based procedures, because information can be shared easily through computer screens [43].

Collective management of the situation involves spontaneous sharing of information among team members, co-ordination for action or diagnostics, validation of information or action with someone, collaboration, co-operation, close inter-monitoring of activity, and recap of rule points to be applied.

Teamwork defines how operators interact with each other in order to exchange information, coordinate actions, and maintain social order [24]. Team work deficiencies have attributed to incidents in nuclear power plants for example radioactive release accident from the Biblis nuclear power plant, Germany, in 1987 [44]. Team coordination is an important characteristic of teamwork and is the process of planning, scheduling, integrating, and allocating resources and responsibilities for coordinated tasks.The taxonomy of team skills shown in Table 4 provides a framework to identify the team skills required to be developed and aid in investigating teamwork mishaps [45].

Table 4: Nuclear team skills taxonomy [45]

Category	Elements	Definition
Building situation awareness	Develop understanding	Analyzing and sharing the information in order to develop an accurate model of the problem or task
	Anticipation	Forward planning to identify and discuss contingency strategies
	Maintain overview	Retaining abroad picture of a task or situation without becoming involved in the details
	Performance monitoring	Observing the activities and performance of other team members
Team focused decision making	Analytical decision making	Gathering and integrating information from team members, selecting the best solution, and evaluating the consequences
	Procedure following	Following written procedures.
	Intuitive decision making	Associating cues in the environment to appropriate corrective actions and making a decision
	Initiative	Using judgment to make decisions and carry out tasks without needing to be told what to do
Communication	Assertiveness	Communicating ideas and observations in a manner which is persuasive to other team members
	Information exchange	Exchanging information clearly and accurately between team members
Coordination	Adaptability	Reacting flexibly to changing requirements of a task or situation
	Supporting behavior	Giving help to other team members in situations in which it was thought they need assistance
	Team workload management	Prioritizing and coordinating tasks and resources
Collaboration	Leadership	Directing and coordinating the activities of, and motivating other team members, assessing team performance, and establishing a positive atmosphere
	Cooperation	Two or more team members working together on a task which requires meaningful task interdependence without any leadership
	Followership	Cooperating in the accomplishment of a task as directed by a senior team member

3.5. Learning organization

A Learning Organization is an organization that continuously monitors its environment for changes, and learns from and adapts to these changes. Organizations are seen as learning through processes that create new knowledge or modify existing knowledge [46]. The effectiveness of learning from experience depends on which events or experiences are taken into account, as well as on how the events are analyzed and evaluated [8]. Learning orientation can lead to a favorable culture for innovation, behavior improvement, and capability of individuals so that the organization can effectively respond to changes in its environment [47]. A learning organization creates an atmosphere where workers freely report concerns and the management responds to these concerns appropriately.

Learning organization is determined by factors such as knowledge management, telling stories by actors, in-situation learning, simulations, and learning from internal and external events. Learning from accidents is to extract, put together, analyze, and also to communicate and bring back knowledge on accidents and near-accidents, from discovery to course of event, damage, and cause to all who need this information" (as defined by Swedish Centre for Lessons Learned from Accidents). The six basic quality criteria for experience feedback are; initial reporting, selection methodology, investigation, dissemination of results, preventive measures, and evaluation [48].

Simulation produces situations as close as possible to the future reality and aims to create future work scenarios by using future operating means (interfaces, procedures, and operators) to impart experience and emergency coping skills to operators [49]. Learning is also a direct in-situation feedback, and the team plays an essential role in this by mutual assistance and cooperation mechanism in case of an incident [5]. During incidents, the less experienced members learn from their more experienced colleagues enabling the team to cement collective experience.

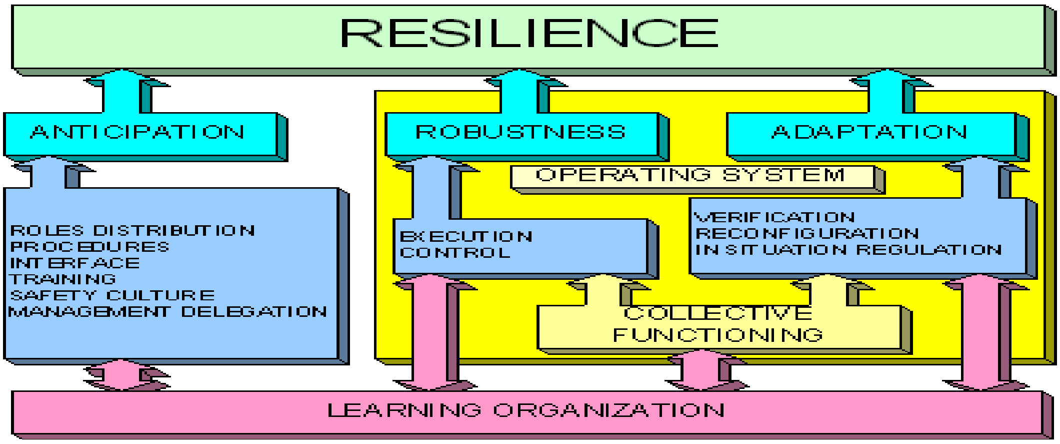

Figure 2: Model of resilience in situation [50]

4. Discussion

This paper is based on resilience engineering, which a new paradigm for safety management of complex systems. Traditional safety approaches such as PSA are inclined toward how accidents happen but not how success is achieved, they are linear and sequential, and they treat systems as static, and focus mainly on technical aspects. Safety is not being free of acceptable risks but the ability to succeed during expected and unexpected conditions. Resilience approaches address this limitation by treating safety as an emergent property of a system and evaluating the system's ability to adjust to its functioning status after disturbance. The nuclear domain being a strongly procedure guided environment is characterized by small number of accidents; hence flexibility during emergency situations that fall outside the procedures is critical for system success. Resilience engineering takes into account not only the technical dimension of the system but also human and organizational factors.

Resilience attributes are likely to deteriorate with time due to changes in the system environment. Although incident reduction measures may initially improve system safety, the absence of incidents decreases situational awareness of the system [51]. For ultra-safe systems such as nuclear power plants, continued elimination of errors, incidents, and breakdowns may lead to decrease in safety and hence the resilience [52]. Safety improvement programs can be expensive and often do not show immediate results leading to less emphasis on safety and adjustment of the goals of the safety program. A history of operations without incidents often leads to growing complacency which also results in decreased safety goals. To assure continued preparation to operators against expected and unexpected events, a certain level of incidents is tolerable. Responding to incidents provides the organization with the desire to adapt and therefore increases the resilience of the system. It is also the responsibility of the organization to evaluate the EOS resilience periodically to assure system success during expected and unexpected conditions.

5. Conclusion

This paper analyzes and characterizes resilience attributes to improve understanding of the EOS resilience dynamics of complex systems such as nuclear power plants. By improving understanding of resilience attributes, it may provide insights to new resilient strategies that the management can adapt

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The main conclusion is that EOS resilience analysis approach can supplement traditional safety approaches to help in addressing their inherent limitations. This approach focuses on how success is achieved in a dynamic environment such as a nuclear power plant. With rapid growth in technology, large socio-technical systems such as nuclear power plants have become so complex that the established safety analyses methods have become inadequate. The characterization may help managers and employees to correct or expand their understanding on resilience.

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