Investigating the stress issue of plant personnel under the extreme condition based on the lessons learned from the Fukushima accident

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1. Introduction

It has been reported that, in NPPs, the human performance average contribution to risk during events is 62% [1]. Therefore, during NPP severe accidents, the humans' actions role is critical for the wellbeing of human and the environment. In addition, human role provides resilience toward safe conditions when automatic systems fail [2]. On the whole, to achieve this resilience, human performance must be optimized. However, high stress level is a challenge during emergency operation and accidents[3], [4]; which has been proven to contribute to degradation in human performance.

Recently, Fukushima accident has uncovered the insufficiency of human performance under extreme conditions [5], and stress was a significant factor during extreme conditions. A previous study found that, during Fukushima, 41.7% of workers experienced near death conditions, 26% witnessed plant explosion, 29% major property loss, and 66.8% evacuated their homes, 5.8% and 17.3% of workers have a family members or colleague, respectively, who had died during the earthquake or the tsunami. All of which increased the workers' stress during the accident management.

Stress issues seem to have attention in the nuclear industry only during the design stage of the control room. However, apparently in Fukushima, many stressors were experienced, led to much high levels of workers' stress, and no measures were taken to accommodate for that stress during the accident; heightened stress levels and lack of accommodation for them definitely contributed to severity of the accident propagation.

In stress research, very few studies investigated stress of human experiencing multiple stressors under real extreme conditions [6]; most of studies simulated one or two stressors.

Thus, the Fukushima accident provides the most recent case of humans experiencing real extreme stress conditions, with multiple stressors, during NPPs emergency operation. Therefore, it provides the latest data source for stress research, and for improving plant safety and accidents management.

This paper aims to contribute to stress research and to improve nuclear safety. Particularly, to investigate stress issues under real extreme conditions with existence of the multiple stressors affecting human performance by studying stressors led to increase workers' stress during Fukushima accident; to point out stressors during Fukushima, draw strong conclusions and lessons in perspective of stress, find possible remediation, and accentuate stress as a contributing factor in Fukushima accident; which updates the stress studies with data from real extreme condition, and provide substantial lessons learned from the Fukushima accident to avoid reoccurrence of the same problems.

2. Stressor, stress, and human error

In order to review stress, a literature review was done of references that studied stress in a variety of fields, including: nuclear, medical, aviation, and military. The specific purpose of this review was to extract stressors, and their effects on human performance.

Since 1936, when Hans Selye has defined stress for the first time, many researchers have studied and performed experiments on stress. Consequently, stress has different definitions; the latest definition was provided by Stokes and Kite [7] in 2001 as "an agent, circumstance, situation, or variable that disturbs the 'normal' functioning of the individual".

Many studies have discussed human performance degradation during high stress levels [6]–[12]. Others studies effects of one or two stressors on human performance.

In this paper, stress is considered as an independent variable correlated by all stressors that degrade human performance directly, and increase stress as shown in Fig. 1; such consideration gives more attention to the problem, and provides a better basis for analysis, remediation of stress, and further studies.

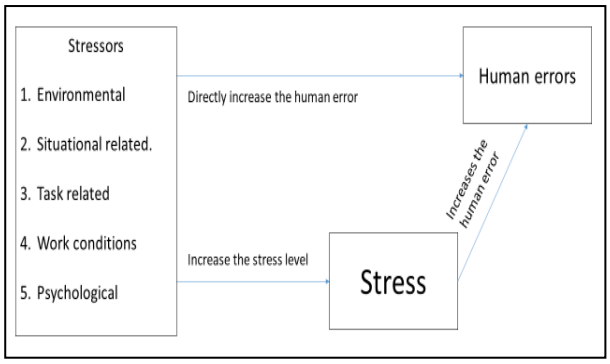

Fig. 1. Stressors, stress, and human error relation.

In addition, the summary of stressors found from prior studies is shown in Table I.

Table I: Summary of stressors from literature review

Category	Stressors
Environmental	Lighting, noise, vibration, heat, cold, and air quality.
Situational related	Novelty, and uncertainty.
Task related	High workload, and time pressure
Work conditions	Night shift, long work hours, lack of sleep, sustained attention, and fear of committing errors.
Psychological	Threat, frustration, anxiety, anger, anticipation, boredom, fatigue, external life stressors, and loss of control.

3. Reanalysis on Fukushima accident

This section shows the summary of extracted data from review of Fukushima accident, including accident reports, different publications on Fukushima, and workers witness statements. In addition, it discusses the possible effects on human performance during the Fukushima accident, based on extracted data, and literature review. Lastly, it discusses the possible remediation of workers' stress during extreme conditions obtained from lessons learned from Fukushima, and from other risky industries.

3.1 Method

The stress prior research results were used as a basis to collect data from Fukushima accident; results include summary of stressors, and possible effect on human performance. Consequently, different Fukushima accident documents, which discussed human performance or include workers' narratives, were reviewed in order to extract data related to stress; such references might help for the difficulty in performing a stress questioner for workers during Fukushima accident. Stressors are categorized into several categories as shown in Table II and Table III; stressor is a factor which increases the worker's stress and leads to human performance degradation. Moreover, stressors can directly contribute to human error as shown in Fig. 1. Possible effects are different human performance degradations associated with stress.

Accordingly, stressors, possible effects, and possible remediation are summarized and discussed in order to draw conclusions and lessons learned from Fukushima that should be considered in order to avoid stress related issues in the NPPs.

3.2 Results and discussions

Plenty of stressors took place during the Fukushima accident, but those mentioned in this section are documented in reports and studies on Fukushima accident.

The collected stressors during the Fukushima accident, as presented in Table II and Table III, are categorized into environmental, situational related, task related, work conditions, and psychological. In addition, it is assumed that communication impairments are a stressor as it may contribute in more complex task, time pressure, and lack of information.

Table II: Summary of stressors during the Fukushima accident

	Reference [13]	**References** [5], [14]
Environmental	Darkness,	Darkness[14].
Situational related (Novelty)	The lack of previous experience. Lack of nuclear accident training to subcontractors.	Inadequate severe accident management provisions against multiple failures [14].
Situational related (Uncertainty)	Uncertainty of workers' roles during the accident. Lack of information about important plant parameters. Lack of information about actual working situation. Lack of information about radiological situation of operational areas and workers' dosage. TEPCO hided some information.	Ineffective and unavailable procedures for the crisis [5], [14]. Lack of information available on the existing systems [5]. Lack of information about actual working situation [5]. Lack of information about radiological situation [5]. Unavailable instrumentation and control [14].
Task related (complexity)		
Communication	Ineffective communication of information to the subcontracted workers.	Ineffective communication between the On-site Emergency Control Centre (OECC) and on-site personnel [14].
Work conditions	Limited availability of measuring devices on-site. Inadequate supply of water and food. Shortage of staff. Lack of dosimeters and protective equipment. High levels of radiation. Individuals overdosed. Daily lives in home at night after being exposed to radiation.	Lack of tools [5]. Uncovered manholes, and cracks and depressions in the ground [14]. Falling debris, debris from the tsunami, rubble due to the explosions, respirators and protective clothing obstruction, high levels of radiation [14].
Psychological	Threats, fear of life, worries about families, mental fatigue, anxiety and frustration, Health hazards.	Surprise, worries about families, threats, mental fatigue, disbelief, fear of life, sacrifice decisions, loss of control feeling [5]. Health hazards [14].

Table III: Summary of stressors during the Fukushima accident

	Reference [15]	**References** [2], [16]–[19]
Environmental	Darkness, high ambient dose rates (ADRs), noise, heat, and high air humidity, dehydration and heat stroke, wearing full protective suits without cooling.	Darkness[2]. Darkness, dust [18].
Situational related (Novelty)	New and unexpected events occurred repeatedly.	Inadequate knowledge and training related to severe accidents [17]. Failure to expect the unexpected [17]. Lack of site employees' knowledge or training about subcontractors' responsibilities [17]. The situation was completely unpredicted [19].

		Operators' unfamiliarity of I&C [18]. Lack of previous experience [18].
Situational related (Uncertainty)	Unclear roles and responsibilities of the supervisory bodies. Lack of information about important plant parameters. Lack of information about actual working situation. Lack of information about radiological situation of operational areas and workers' dosage. Unavailable instrumentation. Unreliable information.	Ineffective and unavailable procedures or guidance for the crisis [2]. Uncertainty of prime responsibility for safety and decision making between stakeholders [19]. Uncertainty of workers' roles during the accident [18]. Unavailable instrumentation [18]. Lack of information about actual plant situation. Ineffective emergency procedures [18]. Unavailable feedback of operators' actions [18].
Task related	Parallel tasks in different units.	Time pressure due to rising radioactivity levels [18]. Complexity of the system' action could affect another action sequence' [18].
Communication	Poor communication between the plant and the outside world.	Difficulties in workers' communications with management [2]. Inefficient communication between government experts and operators through regulatory body [19].
Work conditions	Restricted access to systems and rooms, falling debris, highly radioactive debris, damaged doors, flooded buildings and plants, risk of explosion, and high exposure to radiation. Individuals overdosed. Local emergency center was not adequately protected against radiation. Lack of dosimeters and protective equipment. Inadequate supply of food. Lack of sleep.	Navigating around falling debris, open manholes, risk of explosion, flooded with radioactively contaminated water, and loss of DC and AC power [2]. Offsite and onsite infrastructure destruction [2]. High levels of radiation [2]. Contaminated environment [18]. Tsunami evacuation [16].
Psychological	Worries about families, death of family members, deaths of several workers in the plant, health hazards, loss of control feeling, mental fatigue, over-tiredness, and state of shock after earthquake and tsunami.	Near-death experience, witnessed plant explosion, colleague deaths, major property loss, and home evacuation [16]. Panic after earthquake and tsunami, loss of control feeling, anticipation of bad scenarios due to poor feedback, fear of life, and worries about families and surrounding population [18].

The environmental stressors include high air humidity, heat, high radiation levels, noise, dehydration and heat stroke, and dust.

The situational related comprise the novelty (lack of knowledge, training and experience) including: lack of previous experience of similar situations, inadequate severe accident management provisions against multiple failures, new and unexpected events occurred repeatedly, lack of nuclear accident training to subcontractors' workers, lack of site employees' knowledge about subcontractors' responsibilities, and unfamiliarity of operators with I&C.

Other situational related stressor is the uncertainty including:

1. Failure to expect due to unavailable or ineffective procedures, inadequate knowledge and experience, unavailable feedback. 2. Lack of information about: actual plant conditions due to unavailable indicators, actual working situation, and radiological situation of operational areas and workers' dosage. In addition, TEPCO hid some information as subcontractor workers complained. 3. Uncertainties of roles and responsibilities, including: the uncertainty of workers' roles during the accident, and uncertainty of prime responsibility for safety between the contractors, operator, regulator, and the government.

The task related stressors including: high workload, time pressure, fatigue due to high vigilance for a long time. Other task related stressor is the accident complexity which includes the ineffective communications: 1. between contractors, operator, regulator, and the government; 2. between the plant and the outside world; 3. information to subcontractor workers, 4. and anti-earthquake building isolation; 5. Between the on-site emergency control center and on-site personnel. Other complexities were due to the numerous important actions prioritization, and simultaneous actions.

The work conditions related stressors includes: lack of dosimeters and protective equipment, respirators and protective clothing burden, loss of electricity, health hazard for staff, scarcity of water and food, shortage of staff, individuals overdosed, and lack of sleep. Other work conditions related to the restricted access due to damaged doors, falling debris and its radioactivity, flooded building and contaminated water, the risk of explosion, darkness, uncovered manholes cracks and depression in the ground, and crowded control room.

The last category is the psychological stressors include: anxiety and frustration, over-tiredness, big responsibility, anticipations of consequences, loss of control feeling, state of shock, sacrifice, surprise, and the threat of danger. Furthermore, there were also external psychological stressors such as: death of family members and workers, worries about family, loss of home properties, and working at home at night.

This paper addresses the experienced stressors that affected human performance during the Fukushima accident. In addition, it discusses the root cause of the stressors and the possibility of avoidance during the accident. Furthermore, some factors mentioned in the workers' narratives are supposed to be stressors that increased stress levels.

The paper discusses the multiple stressors experienced under real extreme conditions during the Fukushima accident. Furthermore, it discusses the relation between stress and ineffective communication during the Fukushima accident based on previous studies on extreme situations [5], [20]. Furthermore, the possible effects due to high level of stress, during and after the accident, are summarized. In addition, the paper points out some important differences of stress levels between Daiichi and Daini workers; which should be investigated.

The paper summarizes the lessons learned from Fukushima that will be useful in perspective of stress. In addition, possible measures of stress remediation are provided to avoid reoccurrence of same problems.

3. Conclusions

This paper addresses the stressors faced during Fukushima for further consideration in NPP design, to avoid the same problems again and contributing to more optimal human performance. However, the paper finds many root causes of some stressors, and concludes that they could have been avoided easily during Fukushima by providing official reports, clear information to workers, dose checks, sufficient means of communication, and clear roles and responsibilities. In addition, it is found that the workload was a stressor in Fukushima due to a shortage of staff, and time pressure was also a stressor due to the rising levels of radioactivity. Furthermore, ineffective communication can be as a result of stress. Therefore, stress issues should be considered in investigating ineffective communications during Fukushima accidents.

The paper finds that stress was extremely high during Fukushima accident due to a combination of most possible stressors. However, no measures for coping with stress were applied during the accident; better decision making could have been achieved if stress had been managed during the accident. Hence, worker stress is one of the contributing factors during the Fukushima accident.

Some stress coping measures should be emphasized and other measures from aviation should be adopted by the nuclear industry including stress management plans along with the plant lifecycle to cover individual differences, psychological preparation, and stress management techniques. In addition, severe accident management plans should also consider external stressors as they could take place simultaneously with accidents that are due to natural disasters. Although some stressors can not be avoided, stress management techniques and personnel selection for important actions could be useful.

More information and investigations should be available about the successful human actions and the operators' comments on their stress level during the accident in both Daiichi and Daini; more available data from such real extreme conditions would contribute for stress studies which could be used to achieve safer risky industries by improving human performance.

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