IDENTIFICATION AND EVALUATION OF ZUGZWANG AND ZEITNOT HUMAN FAILURE EVENTS BASED ON FUKUSHIMA DAIICHI ACCIDENT CONTEXT QUANTIFICATION

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Abstract

The issued IAEA report on Fukushima Daiichi accident describes its context details thoroughly. It gives better opportunity for retrospective analysis of unit contexts before and during the accident, search for appropriate, but missed, or delayed accident management measures and actions, and can help a lot to prevent future accidents by looking for appropriate and timely alternatives.

This paper presents the capacities of Performance Evaluation of Teamwork (PET) method for retrospective human failure event (HFE) monitoring and analysis in order to reveal the accident symptoms of time-dependent compulsory and time shortage HFE producing conditions or Zugzwang and Zeitnot HFEs. The dynamic PET context quantification procedure is used together with Zugzwang and Zeitnot actions to identify, exemplify, evaluate and interpret the causes of HFEs in dynamics for all teams which participated in Fukushima Daiichi disaster: Main Control Room crew of Unit 1, Emergency Response Center team of Fukushima Daiichi Power Station, TEPCO Headquarters Emergency Response Center team, Fukushima Prefectural Government team, team of the Ministry of Economy, Trade and Industry, team of Nuclear and Industrial Safety Agency and team of the Japanese Government.

The intermediate use of symptoms for dynamic context qualification and quantification, as opposed to direct description and revealing the causes, gives better opportunities for the systematic identification, qualitative and quantitative interpretation of time-dependent (Zugzwang and Zeitnot) HFEs during the Fukushima Daiichi accident.

I. INTRODUCTION

Accident prevention requires study and understanding of the context of socio-techical system performance at every stage of the life cycle. This implies the description, identification, interpretation and evaluation of all occasions and root causes for each stage, which can lead to an accident. As a rule, the first step is a comprehensive retrospective analysis of the accident and its context. Data collection for description, qualitative and quantitative analysis of the accident context is often vague and incomplete. So when an accident is described thoroughly in details, it gives the best opportunity for retrospective analysis of context before and during the accident and search for appropriate, but missed or delayed accident management measures and actions. The issued IAEA report on Fukushima Daiichi accident[1] is an example of such a detailed description, which can help a lot to prevent future accidents by looking for an appropriate and timely alternative.

Human actions can fail to achieve their goal in *two different ways* [2,3]: the actions can go as planned, but the plan can be inadequate or the plan can be satisfactory, but the performance can be deficient. Both ways of producing erroneous actions are dynamic and intentional in character, i.e. an intention is considered to be always present. A mere failure is not an error or HFE, if there had been no intention or a plan to accomplish something in particular. However, sometimes intentional and planned actions are prevented by some compulsory conditions. These compulsions could be acceptable for normal and trivial incidental situation, but for accident conditions, e.g. a nuclear disaster such as Fukushima Daiichi, they register as delays of the implementation of relevant regulations and the express delivery of resources or untimely error-producing oversight and therefore have massive consequences (errors of commissions).

Opportunities for some actions of Fukushima Daiichi Power Station (PS) personnel at certain time intervals were reduced due to lack of time or under compulsion as a result of organizational interactions (communication, regulation and subordination in the decision-making) between the different teams involved in the disaster. Such adverse context could be alleviated by detecting and avoiding time-dependent compulsory HFEs in similar intervals.

Similar to chess, we will identify and interpret the erroneous actions during the Fukushima Daiichi accident related to actions under time pressure or compulsion (*Zeitnot* and *Zugzwang*).

II. COMPULSORY HUMAN FAILURE EVENTS IN DYNAMIC CONTEXT

II.A. Time-Context Curves or Contextures

In (Ref. 4) a statistical description of context was presented with a consistent procedure for macroscopic context quantification and assessment of cognitive error probability of the individual and group performance[5]. The context changes “on a second-by-second basis” and includes the interaction of the processes of a complex socio-technical system that consists of environment, human, organization, technology (HOT subsystem) and society. The basic idea of the distinction between macro- and microscopic levels is to change the set of microscopic accessible states with equivalent subsets of macroscopic states. This idea follows the Shannon theorem[5] that motivated the entropy as the measure of information, and was the basis for the used, in the PET method, analogy of energy and information. The process of cognition is described at each moment by its *microstates* (*states*). This is a specific *quantum state* that represents the most detailed possible description. By the PET approach, the problem is solved in at least two steps (levels). In the 1st one, only a rough measure is obtained for context on the basis of macroscopic accessible states (macroscopic level describes a holography-like mental process). In the 2nd one (and further) it is necessary to assess thoroughly the added potential of each bit of knowledge for each macroscopic level of information (microscopic level describes deep processing and/or other process mechanisms). Since it is impossible to describe the whole process in detail and all HOT system accessible states, it is evident that these steps add immeasurably to knowledge of actual context.

Fujita and Hollnagel (Ref. 6) also accepted the idea of context quantification in the HRA based on more realistic presentation: "According to the contemporary view of the human contribution to the accidents and incidents, human performance failures are due to the context (i.e. working conditions), rather than to inherent human error probabilities." They also considered the development of methods "by which the failure probability can be estimated from a characterization of the performance conditions alone" and models representing "how working conditions may influence the way in which people adjust their actions to make ends meet". Fujita and Hollnagel concluded that by "taking the performance of a joint human-machine system as unit of analysis, discussions about the influence of organizational factors are also given a new meaning…"

Let CP (t) is the probability of an adverse context for performing action [0,1] where CP = 0 is absolutely favorable context for performing human action, and CP = 1 is absolutely unfavorable context for implementing the action. The PET procedure could be used to determine the CP(t), or contexture. The PET is the only human reliability assessment (HRA) method that makes straightforward and explicit context quantification, based on *system symptoms* (*context factors and conditions* - CFCs). Favorable context for carrying out emergency measures is changed over in time. Accident time-context curves modeling for a complex HOT system, such as nuclear power plants (NPP) with pressurized or boiling water reactors (PWR/WWER or BWR) was demonstrated in previous studies[7, 8]. It gives better prospects for identification and interpretation of the HFEs over time.

II.B. Human Failure Events Definitions and Taxonomy

HFE or human error is *"a deviation from intention, expectation or desirability"*[9]. It is result of something that a human does or intends to do, that leads to outcomes different from what he/she had expected. These deviations are manifested by various symptoms and due to various causes. In order to be understood, we should see the difference between the characteristic symptoms of the object in a given situation. And to determine and prevent a HFE, we should identify and remove the causes of the disparity of objectively expected symptoms (φ_{on}) and subjectively recognized symptoms (φ_{sn}) that are determined in the scenario where: s - subjective; o - objective and n=1…N is a number of symptoms.

HFE can be relatively insignificant, with local influence on operator’s work, but they also can be crucial in case of serious accidents and emergency situations. It is a matter of concern of the safety analyses of organization, technology and performance, whether the team communication causes errors, or makes the operator’s work secure and reliable.

The operator’s errors strongly depend on operator’s knowledge and performance manner. The most of current HRA methods distinguish between two basic operator error modes – errors of cognition and errors of execution. Such concepts of HFE were used by PET method to propound the HFE taxonomy shown on Figure 1.

The PET criteria for different erroneous actions follow the Reason’s qualitative definitions:

- The PET HFE of cognition or execution is probable, when the $\varphi_{sn}(t) \neq \varphi_{on}(t)$, i.e. the differences between objective and subjective images of human action context symptom is not zero and zero-context is $|\varphi_{on}(t)-\varphi_{sn}(t)| \to 0$/min.
- The PET violation occurs when the objective image of symptom n is changed from $\varphi_{on}(t)$ to $\varphi^{v}_{on}(t)$ for of any reason, n=1…N is number of CFC (symptom).

The probability of communication error could be calculated as a difference between individual error probability of decision-maker and the crew error probability. The taxonomy also presents another popular version of HEA distinction – between errors of omission (EOO) and errors of commission (EOC).

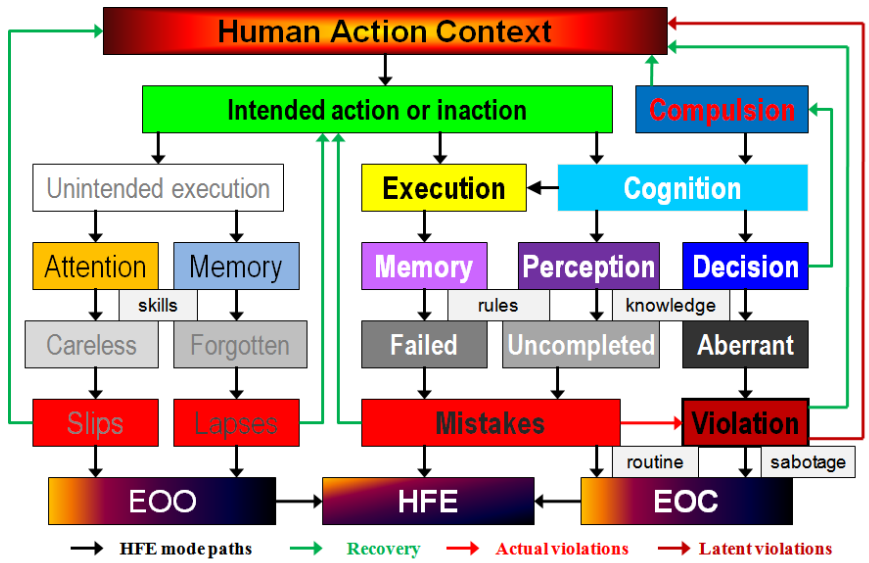


Figure 1. Human action context and human failure event taxonomy

As seen on Figure 1, the subject of analysis could be all feedbacks in realization of human actions – latent and actual failures or violations and recoveries. They appear in crew communication form and iterative individual cognition form. These forms could be identified and distinguished experimentally by running different accident and normal scenario on the full-scope, multifunctional or computer-based simulators of NPP. But in this article we will focus on only one particular case of time-dependent failures and violations that are related to the need for compulsory action or inaction.

II.C. Compulsion and Dynamics in Human Performance

The time-dependent compulsory actions or inactions may occur in emergency or exceptional situations, where sharp change of the context leads to necessity of change the rules or violations of customary norms and practices to be able to deal with the situation. The change of rule or policy must be seen in the dynamic context of given situation due to its possible temporary nature. The chess mistakes made due to shortage of time - *Zeitnot*, and due to unfavorable features of the context - *Zugzwang* situations, are examples of them. Three types of compulsory actions or inactions are addressed and illustrated in our study:

- ***Zeitnot* compulsory action**

In accident performed with a time control, time trouble, time pressure (German translation *Zeitnot*) is the situation where a operator has little time to complete the required actions. When forced to act quickly, the probability of making blunders is increased, so handling the clock is an important aspect of accident management.

- ***Zugzwang* compulsory action**

Zugzwang (German for "compulsion to move") is a situation found in an accident wherein one operator/crew or more operators/teams are put at a disadvantage, because they must make an action, when they would prefer to pass and not act, e.g. evacuation. The fact that the operators are compelled to act means that their position will become significantly weaker. An operator/team is said to be "in Zugzwang" when any possible action will worsen their position[10].

- ***O-Zugzwang* compulsory action**

Variety of *Zugzwang* situations are *Opposite* or *O-Zugzwang* HFEs ("compulsion not to act"). It is a situation found in an accident wherein one operator/crew or more operators/teams ares put at a disadvantage because they mustn't make an action when they would prefer to do (in case of high radiation rate or aftershocks).

These actions and inactions lead to delays and as a consequence to the HFEs - unrealized of critical tasks, omission of important moves or commission of inappropriate acts. Comprehensive study of all cases requires a lot of efforts and time. So in our study are shown only time-dependent actions and inactions that lead or are caused by optimistic but erroneous strategies or organizational misconceptions in emergency management and preparedness.

III. DYNAMIC CONTEXT ANALYSIS OF FUKUSHIMA DAI-ICHI#1 ACCIDENT

III.A. Previous Results and Conclusions

In our previous studies of the Fukushima Daiichi accident context we have already shown its severity, difficulty and low probability of successful performance in the first hours and days of the accident (for Unit 1).

I.A.1. Risk Resonance Context of Fukushima Daiichi#1 Accident

In (Ref. 11) following results were obtained for the probabilities of context and human error, shown on Figure 2.

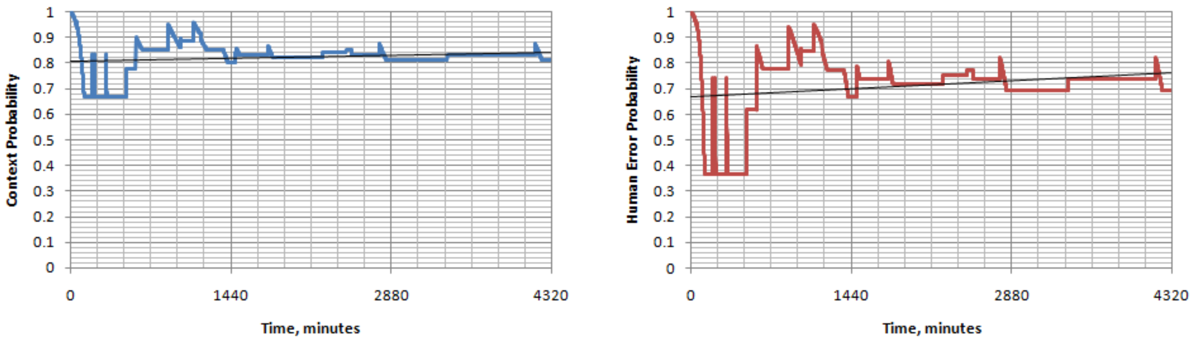


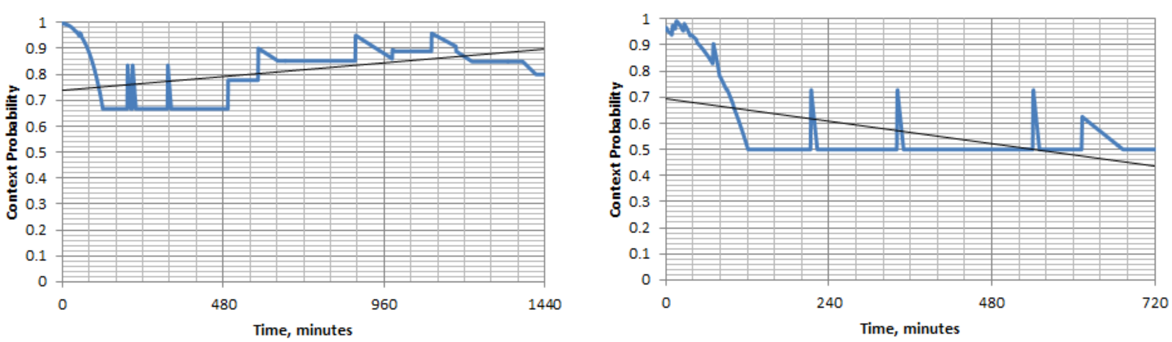
Figure 2. Context and Human Error Probabilities for the 'Fukushima Dai-ichi#1 Accident'

There, the following conclusions were also made:

- The unfortunate juxtapositions of external events reveal some poor design features (DB - design basis) and deficiency of safety barriers and investigations to ensure very severe accident context for a prolonged period.
- Besides, it is obvious, that in such adverse resonant context the successful performance of the plant personnel and teams of the emergency response centers was not probable at all.

I.A.2. Context Comparison for the Fukushima Daiichi#1 and Onagawa#1 NPPs after the Earthquake

The comparison of the context profiles during the first day after the Great East Japan Earthquake for the Fukushima Daiichi NPP, Unit 1 and the Onagawa NPP, Unit 1 was made in (Ref. 12). The contextures (CP) for both cases are shown on Figure 3.



a. Fukushima Daiichi#1 NPP Context   b. Onagawa#1 NPP Context

Figure 3. Contexts for the Fukushima Daiichi#1 and Onagawa#1 NPPs 12 Hours after the Earthquake on March 11th 2011

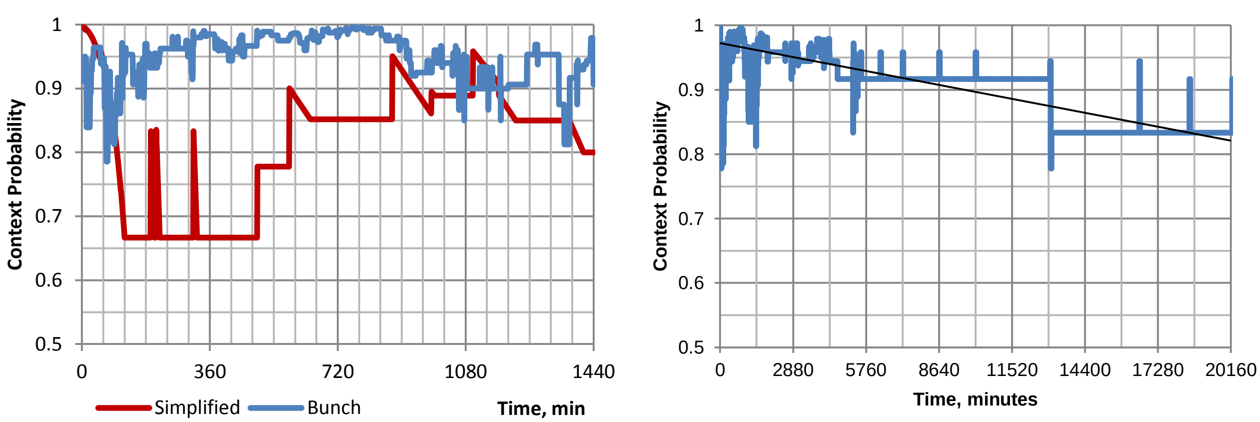
As seen from the CP calculations, the results for the Fukushima Daiichi#1 case are very high and the tendency is, for it to increase. In this situation the context is quite difficult and a successful decision-making is improbable. In the Onagawa#1 case, the CP is not so high and the situation is manageable. The basic reasons for the context disadvantages of the Fukushima Daiichi#1 NPP are the violations. The main violations are related to the following causes, as they are underlined in Table 1.

Table 1: Main Context Violations of the Fukushima Daiichi#1 NPS Accident and Their Causes

Violations	Causes
V1: The circuit breakers and disconnectors in switchyard were damaged by the earthquake.	Fukushima Daiichi#1 NPP site had been designed for the earthquake magnitude 8.2 (DB), when it was with 8.9.
V2: Diesel generators, distribution, instrumentation & control systems were submerged on basement by Tsunami.	Tsunami wave height was about 13m but Fukushima Daiichi#1 NPS had been designed for 6.51m (DB<10m).
V3: Long-term total station black-out (loss of offsite, on-site AC and DC power supply) was for all units.	Both causes (DBs) above together destroyed the Fukushima Daiichi#1 NPP site and battery depletion.
V4: Loss of shutdown heat removal after ≈10h due to tank depletion.	The passive isolated condenser DB for decay heat removal was shorter range than necessary in this long-term accident.
V5: Radiation rates and doses increased in units' premises and on the NPP site.	Potential lines leaks & external leakages due to high pressures in vessels, especially after core melts, spent fuel pool heating & hydrogen explosions.
V6-1: High pressure in dry well - max 8.4 bar; **V6-2:** Pressure in reactor pressure vessel (RPV) >7.9 bar; **V6-3:** max 7.8 bar in primary containment vessel (PCV).	Loss of decay heat removal, failure or postponement of pressure control and venting for long intervals of PCV (DB pressure of the PCV is 5.28 bar).
V7: Hydrogen explosions	Wrong moment for inappropriate combination of sufficient hydrogen accumulation, PCV pressure decreasing, ignition and steam-oxygen proportion

I.A.3. Comparison between 'Simplified' and 'Bunch' Contexts of the Fukushima Daiichi #1 Accident

In (Ref. 11) and (Ref.12) was presented 'simplified' chronological description of the context factors and conditions (symptoms) and context quantification of the Fukushima Daiichi#1 NPP accident based on the web information. The detailed context description of the same accident context was prepared in (Ref. 8) study, where accident context symptoms were collected in a 'bunch' as they are presented in (Ref.1). The distribution of the events/actions as PET symptoms (goals, transfers, functions, events, actions, parameters and violations) is not presented because of lack of space (Annex I is 17 pages, A3 format). The comparison of contextures for 'simplified' and 'bunch' context evaluations for 1 day (1440min) and 14 days (20160 min) are shown on Figure 4.



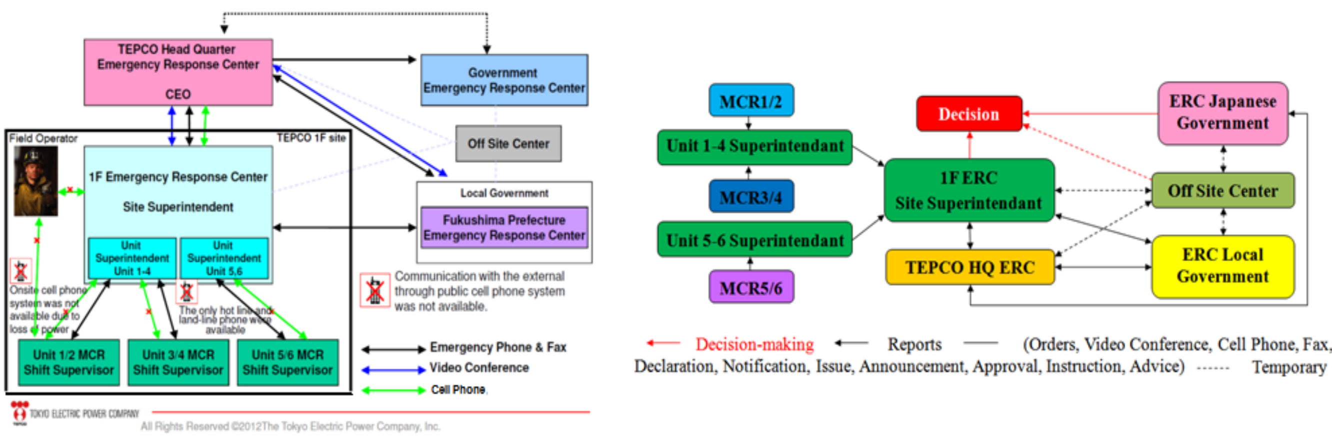
a. Fukushima Daiichi#1 NPP 'Simplified' & 'Bunch' Contexts b. 14-days Fukushima Daiichi#1 NPP 'Bunch' Context

Figure 4. 1-day and 14 days Contexts for the Fukushima Daiichi#1 NPP after the Earthquake on March 11th 2011

III.B. Context Analysis of *Zugzwang* & *Zeitnot* Human Failure Events in Fukushima Daiichi#1 Accident

III.B.1. Analysis of Fukushima Daiichi Disaster Teamwork

The PET method allows analyzing the teamwork communication and decision-making for group of operators (crew) or group of teams. The last was the case of the Fukushima Daiichi disaster management where the Local Countermeasures Office or Onsite ERC (emergency response center), whom NPP Disaster Countermeasures Office of the Japanese Cabinet Office delegated rights to manage and coordinate nuclear accident countermeasures between all internal (main control rooms - MCR, field operators) and external organizations. The distribution of parts of the "bunch" context to different teams participating in the Fukushima Daiichi disaster (e.g. MCRs, ERCs, TEPCO, Japanese and Local Governments, etc.) and context evaluation of each team and decision-making error probability for the group of teams was planned. Based on Kawano's presentation[13] and TEPCO Onsite Communication Scheme under Severe Accident Management, (the original and integrated, shown on Figure 5a), the PET digraph model of communication between group of teams during Fukushima Daiichi Accident was prepared. It is shown on Figure 5b.



a. The TEPCO Onsite Communication Scheme[13] b. The PET Digraph Model

Figure 5. The TEPCO Onsite Communication Scheme under Severe Accident Management (a), Integrated on 15/03/2011, and the PET Digraph Model of the Accident Communication and Management (b) of the Fukushima Daiichi Disaster.

III.B.2. Qualitative Context Analysis of Zugzwang & Zeitnot HFEs in Fukushima Daiichi#1 Accident

During the qualitative analysis of accident progression and symptom determination was found that information of the IAEA report is sufficient only for context distinguishing of MCR teams, but not for context distinguishing of ERC teams. It means that detailed context description for the Fukushima Daiichi#1 is possible only for Onsite ERC and MCR1, but both are not so different from the 'bunch' context description. More interesting is the identification of possible *Zugzwang*, *O-Zugzwang* and *Zeitnot* HFEs as result of delays and compulsory actions and inactions. A qualitative context analysis based on symptoms during the different time intervals of the accident progression is following:

a. First time interval (0÷51min) is between Earthquake (initiating event - IE) and Tsunami, where *Zeitnot* HFEs would be possible. All actions in this interval are in unexpected Zeitnot. And there are no blunders or differences between intentions and expectations of operators, no compulsions and consequently - no time-dependent HFEs.

b. Second time interval (149÷209min) is the ≈1h between calculation of the core uncovering of Unit 1, made by the site ERC technical support, up to the calculated time. All actions in and after this interval are in permanent *Zeitnot* (station blackout and no ultimate heat sink). Operators initiated plans to establish alternative water injection line from the fire protection system to the core spray. The radiation slightly increased, ongoing tsunami warnings were issued, but the numerous aftershocks caused the most trouble. Additionally, there were no lights – only emergency lights and darkness, no important instrumentations and almost no communication tools worked. The operators left and had to come back many times. *The shift supervisor decided not to dispatch more teams due to the danger from aftershocks. This inaction for period of time <18min could be determined as a negligible short O-Zugzwang HFE, but no blunders happen - no Zeitnot HFE.*

c. Third time interval (364÷397, 397÷584) is from the start of evacuation (2 km zone) up to the completion of evacuation (extended 3 km zone) accordingly. This was a precaution, *Zeitnot* and *Zugzwang* event, because the Unit 1 core uncovered, hydrogen was generated, the radiation rates increased everywhere and pressures in the dry well, RPV and PCV (>5.28 bar) increased up to DB pressures. The extension of the evacuation zone to 3 km by Japanese government was related to the core uncovering of Unit 2. It was completed successfully and the site superintendent directed preparations to vent the PCV. *No essential delays, Zeitnot and Zugzwang HFEs were made by site ERC and Local government.*

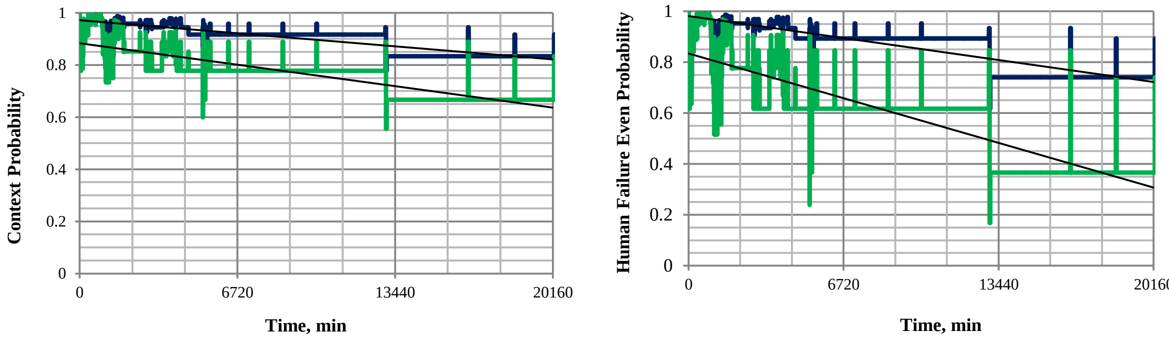
d. Forth time interval (544÷1490min) is from the excess of the PCV pressure (>5.28 bar) up to the successful PCV venting. In this interval all participating teams were in *Zeitnot* and *Zugzwang* not only because the uncovered core, hydrogen generation, increase of the radiation rates and very high vessels pressures, but also because the probability of an explosion in the Unit 1 PSV increased in time. As it was already mentioned in the previous interval, that site's superintendent and Local government did: preparation for PCV venting started (560min), 3km zone evacuation was completed (584min) and additionally the Prime Minister (PM), Minister of METI Ministry of Economy, Trade and Industry), and NISA (Nuclear and Industrial Safety Agency) were informed on containment venting plans for permission (644min, again at 795min - *151min delay*) and high dose rate readings (494min, again at 698min, 849min). However, in these conditions, the Japanese government reconfirmed the completion of 3 km zone evacuation at 659min (*75min delay*), notified about containment pressure increase (721min, *77min delay*), the METI (Minister announced the venting after 3:00 (734min, *90min delay*) and plans to vent Unit 1 PCV announced to the public (740min). The government ordered evacuation of 10 km zone (898min, *314min delay if they considered 3km zone insufficient for Unit 1 PCV venting*). METI issued the order for containment venting (964min, *delay 3h 50min,* ***totally 320min delay***). The Prime Minister arrived at the site (985min) and left the site (1038min, *additional 53min delay for the PCV venting*). Evacuation of 10km reported completed (1096min) and 2min later venting started (delay 6h 4min or ***364min delay***). Perhaps the total delay due to the government and METI inaction (*Zeitnot* & O-*Zugzwang HFEs)* is not > 6h, and about 4h (time between METI minister announcement and his order for PCV venting) but ***this delay may have been crucial for the explosion in the Unit 1***. The reason was probably the intention of the Prime Minister to reorganize the communication, decision-making and management at the Offsite ERC, which was not working properly (the government's opinion), but following the context description most of delays were Onsite and Offsite responsibility. The venting was commenced at 1424min (946min, >15h after the need of venting) and at 1490min the hydrogen explosion happened - the wrong moment for inappropriate combination of sufficient hydrogen accumulation, PCV pressure decreasing, ignition as a result of reenergizing and steam-oxygen proportion. This was *Zugzwang HFE* as result of delays (previous *Zeitnot* & O-*Zugzwang HFEs*) and violated process of cognition (lack of knowledge - limited understanding of venting as a pressure decreasing and high risk of hydrogen explosion).

e. Fifth time interval (425÷1126÷4278min) is from the excess of the 1 mSv dose limit in normal operation, through the excess of 100mSv dose limit for emergency workers and up to the NISA approval increasing the dose limit for emergency workers (250 mSv). This regulation was crucial during the Fukushima Daiichi accident for all units because of delays in tasks implementation. Based on these delayed change of regulation limits by NISA the field workers were evacuated twice at 817 and 1508min and MCR operators were also evacuated at 1508min. It seems that after ordering evacuation of 10km zone (898min) the exposure dose limit should have been increased to avoid task delays, but even after ordering 20km zone (1659min) the NISA delayed more than 43h (2619min) to increase the dose limit. It is difficult to evaluate the contribution of these regulations to the delayed tasks, but anyway postponement of the NISA decision could be treated as O-*Zugzwang HFE*. It is related also to the problem of stuffing: *some operators remained in the MCR for 3 days without sleep and some of ERC were awake as long as 36 hours, before they began to lose consciousness in their chairs*[13] - *Zugzwang HFE*.

f. Sixth time interval (1738÷3504min). Some delays were also available during the discussion about *the sea water injection without PM's approval* (re-criticality concerns). It was halted and site radiation readings increased. The 1F superintendent Yoshida judged, that it was of utmost importance to continue the sea water injection in order to avoid further event progress, so the sea water injection was in fact not stopped [13].

III.B.3. Fukushima Daiichi#1 Accident Quantitative Context Evaluation of Zugzwang & Zeitnot HFEs Likeihood

Based on qualitative analysis of Fukushima Daiichi#1 accident progression and symptom determination it is possible to quantify contexture (CP) and to compare HFE probabilities of real and hypothetical 'bunch' cases. This comparison gives an opportunity to evaluate the contribution of the Zugzwang and Zeitnot HFEs to the error likelihood during the accident. The comparison of contextures (CP) and HFE probabilities of real and hypothetical 'bunch' cases for 14 days (20160 min) are shown on Figure 6. Three relatively steady state intervals could be identified: 0÷1868, 1869÷2811, 2812÷13051 and 13052÷20160 min. If no *Zeitnot* and *Zugzwang/O-Zugzwang HFEs* happen, then the average HFE probabilities in these intervals could be improved as follows: 0.938613→0.875978, 0.952885→0.778319, 0.903315→0.634875, and 0.741488→0.368877. Especially significant could be the improvement for the last interval – more than 2 times.



a. Fukushima Daiichi#1 PS Context Probabilities b. Fukushima Daiichi#1 PS HFE Probabilites

Figure 6. Comparison of context & HFE probabilities of real & hypothetical 'bunch' cases for 14 days (20160')

CONCLUSIONS

Command & control and the division of roles and responsibilities in the operational decision making among TEPCO (Utility), the Government, and the Cabinet (PM) office were not clear. This invited intervention by the PM office and the Government in TEPCO management, which became burdensome during the recovery process[13].

The regulators did not have the necessary expertise and commitment to ensure the safety of nuclear power, which led to significant delay in the implementation of the latest regulations. According to Ref. 14 and Kondo lecture “their independence from the ministries promoting nuclear energy and the operators was a mockery”.

The lack of simple and reliable correlation (a numeric expression) between indicators of protective barriers and regulatory norms is not conducive to proper formulation and pursuit of strategies for coping with severe accidents.

Qualitative context analysis of the Fukushima Daiichi disaster could be supplemented with quantitative context analysis for evaluation of the relative importance of time-dependent HFEs - Zeitnot, Zugzwang and O-Zugzwang. However, additional information about the contexts of all offsite participating teams and 'best-estimate' thermal-hydraulic simulations are necessary to identify opportunities for avoidance of critical events (e.g. the hydrogen explosions). This would prevent the possibility for speculative use of these analyses.

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