OPERATORS' AUTONOMOUS DECISIONS DURING EMERGENCIES: DO THEY PROMOTE OR REDUCE SAFETY?

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When a disturbance occurs at nuclear power plants, operating crews strictly implement operating procedures designed to bring the plant back to a safe state in a variety of pre-analyzed events. However, operating events at nuclear power plants have shown that situations occur that are not completely covered by the emergency operating procedures and in which the operators took autonomous initiatives. By reviewing three studies performed at the Halden Human-Machine Laboratory (HAMMLAB) on a full-scope pressurized water reactor simulator, this paper investigates the extent and effect of the operators' autonomous decisions during emergencies. The results confirm that the operating crews make autonomous initiatives when implementing the emergency operating procedures. The degree of autonomous decision-making relates to the plants' procedural adherence practices, but significant individual crew differences are also observed. The majority of the operators' autonomous decisions have positive consequences for the plant's safety, but some have negative impacts. Crews that practice stricter procedural compliance have lower operator performance and more negative impacts to plant safety, compared to crews that follow the procedures more flexibly. Current procedural following regimes and training programs do not specifically address the operators' decision-making quality in events not completely covered by the procedures.

I. INTRODUCTION

Some years ago an international study compared human reliability analysts' predictions with observations made in the Halden Human Machine Laboratory (HAMMLAB).[1] In addition to the usual hurdles of predicting main control room crew behavior in emergency scenarios defined on paper, the analysts had the extra challenge of not being familiar with the participating crews' conduct of operations, and especially of not knowing, from previous knowledge or direct observation, how these would use and adhere to the emergency operating procedures (EOPs). Many analysts assumed strict procedural compliance and rule-based following as these are common practice in the industry and the design philosophy of the procedures, respectively.

To some extent the assumptions held true when "base-case" scenarios were analyzed. These are regularly trained emergencies with no other plant malfunctions than the initiating event (the plant malfunction that initiates the emergency). In the "complex-case" scenarios (scenarios with extra malfunctions in addition to the initiating event) on the other hand, the operators did not always maintain strict compliance and knowledge-based diagnosis and decisions were frequently made. The result was that the analysts' predictions departed from the observed behavior. This sparkled a discussion on whether this was a peculiarity of the participating crews and their plant's (or national) procedure adherence culture or if the study had raised issues of general concern.

This paper draws on this and two other studies in HAMMLAB to investigate EOP adherence and operators' autonomous decision-making in emergency (see TABLE I). Based on the observations in the studies the paper also discusses the impact of such decisions on plant safety.

TABLE I. The studies performed in the Halden Human-Machine Laboratory that are considered in this paper.

Study	# of scenarios	# of crews	Country of origin	Plants of origin
International HRA (Ref. 1)	4	14	Sweden	1
U.S. crews (Ref. 9)	3	5	U.S.	3
Swedish crews (Ref. 11)	4	6	Sweden	1 (same as above)

II. EMERGENCY PROCEDURES AND OPERATORS' AUTONOMOUS DECISIONS

When an emergency arises in a nuclear power plant the control room operators have to follow the emergency operating procedures, which they have been extensively trained on. As the operators control the plant largely, if not entirely, through the procedures it is important to understand how they do it, and specifically: (1) the degree of adherence and (2) the degree of active diagnosis and decision-making (diagnosis can be seen as an element of the decision-making process. In the rest of the paper the expressions 'decision-making' and 'autonomous decisions' will be used in this inclusive sense). Procedural adherence is about whether the operators have to follow the procedures "to the letter" or whether and to what extent they can deviate by taking autonomous decisions and initiatives. Autonomous decisions might be anticipating actions, performing "innovative" actions, re-diagnosing events, and re-directing the procedures, in ways that following by rote would not allow. According to Roth and colleagues[2] there are three views about the level of adherence required by "symptom-based" EOPs. Elaborating on their classification we can describe the three views as follows (see also TABLE IV).

The first view maintains that the EOPs provide detailed guidance for every contingency. This view requires following "to the letter", and operators' autonomy is allowed only when explicitly requested (as for instance when it is unfeasible or impractical to write detailed guidance). If situations are identified where the operators had to take autonomous actions that were not requested by the procedures, then the procedures should be rewritten to address those situations.

According to the second view, the EOPs provide detailed guidance to minimize the possibility of core damage but not for addressing all contingencies. Although strict procedure following will not always result in an optimal response in all situations (e.g. by allowing some delays) it will prevent core damage. Operators autonomous decisions and actions are not required, and even not desirable, to minimize the risk of core damage. If situations are identified where the operators took autonomous actions that were not requested by the procedures, then the operators should be retrained as how to follow the procedures more closely in those situations.

The third view is that the EOPs provide a systematic approach to minimize the risk of core damage, but operators' knowledge and abilities are necessary to realize the procedures' intent in the specific evolution of the accident. Autonomous initiatives might be necessary in situations not fully covered by the procedures. In such cases the operators should not follow the procedure literally, but have to use their knowledge of the procedures intents to e.g., anticipate actions, redirect procedures and address emerging contingencies. If situations are identified where the operators took autonomous actions that were not requested by the procedures, then the operators should be trained for ensuring they have the competence to make the right decisions in those classes of situations.

The different views on EOPs adherence entail different views on the role of the operators and the degree of active diagnosis and decision-making. The first two views advocate for strict procedural adherence, although from different standing points: the first aims at all-comprehensive procedures that prevent the operators finding themselves in unforeseen "lack of detailed guidance" situations; the second view admits that not all contingencies can be addressed in detail by the EOPs, but nonetheless strict following (which might even cause sub-optimal response, like delay) is preferred to autonomous initiatives, because the latter could result in errors of commission and thus increase the risk of core damage. These views envisage control-room operators as procedure implementers and the procedures as a tool that, at the same time, direct and control operators' behavior, thus reducing undesired response variability. The diagnoses and decisions to be made in response to a plant disturbance are preloaded into the guidance system: procedure following requires understanding the text, determining the value of plant parameters, and, when certain values are achieved or exceeded, executing as directed. The operator role is mainly one of stimulus-response cue manager.

Symptom-based emergency procedures are written with this view of the operator in mind. The Westinghouse Owner Group (which develops and maintains the EOPs for the majority of Pressurized Water Reactors worldwide) defines "diagnosis" as "the process used to direct the operator to the appropriate guideline(s) and guidance step(s) to address the current plant state (symptoms) and does not require identification of the cause (event) of the symptoms".[3] Thus, rather than understanding the situation and the objectives of the procedures, during an emergency "the operator responds to the changing states rather than controlling the plant" (id.). The operators may or may not engage in independent monitoring and diagnosing, since "the procedure system distributes diagnostic elements across the main body of the EOPs, foldout pages, and status trees, for systematic monitoring of critical safety functions, evaluation of parameters, and prioritization of responses" (id.). The idea is that operators following symptom-based procedures can restore and maintain safety functions without having to diagnose the events or the specific causes of the disturbance.

III. THE EXTENT OF AUTONOMOUS DECISIONS

The principle behind symptom based-procedures (also called rule-based) is that the operator is directed to the appropriate response without the need to interpret information, think of possible causes and consequences, and decide what to do. The precondition is that the accident evolutions addressed by the procedures can be predicted with sufficient precision and the responses pre-planned accordingly.

However, situations that are not completely pre-analyzed may arise. In fact, they did arise also after the TMI accident had led to the introduction of rule-based EOPs. Studies of significant operating events in nuclear power plants show that the majority involved non-typical conditions, i.e. deviations from operators' expectations, multiple equipment unavailability beyond those assumed in safety analyses, instrumentation errors that caused misunderstandings, and plant conditions not addressed by the procedures.[4, 5] For instance, on March 14, 1993 a steam generator tube rupture (SGTR) event occurred at Palo Verde nuclear generating station, unit 2. Differently from trained instances of SGTR, twice during the event the radiation monitor were not in alarm status when the applicable step in the procedure logic tree were reached.[6] "The training that the operators received for implementing the EOPs promoted strict procedural compliance and reinforced their decision not to repeat steps in the procedure that evaluated for a tube rupture" (id., p. 3). However, the crew, having realized that the event was a SGTR, took an innovative action and decided to enter a functional restoration guideline to mitigate "the loss-of-coolant accident aspect of the SGTR in a standard and proceduralized manner, actively inducing the opportunity for rediagnosis (the radiation monitors had mysteriously returned indicating the SGTR)".[7] So, although a situation that was not considered by the procedures arose, and although the crew initially followed the EOPs strictly, as they had been trained to, eventually the crew took an autonomous decision and brought the plant to a safe state.

This event inspired the SGTR complex-case scenario that was run in HAMMLAB as part of the International HRA Empirical Study mentioned above.[8] As in the reference event, 9 out of 14 crews took innovative actions (described in the report as knowledge-based actions, id. pp. 2-20) to enter the optimal recovery procedure for the SGTR, that is, did not follow a specific transition condition in the procedural progression. This behavior surprised many, but was partly dismissed as the result of a liberal procedure adherence regime of the participating crews, a peculiar combination of plant and national (Swedish) culture, with little relevance for the nuclear industry at large.

A new HAMMLAB study enrolled five operating crews from three different U.S. plants for studying diagnosis and decision-making in non-typical conditions.[9] The study run three accidental conditions in which at times the procedural guidance was not detailed, as a result of plant evolutions unanticipated by the procedures. The scenarios thus involved pant conditions similar in many ways to the "complex-case" scenarios faced by the Swedish crews. However, while the EOPs used by Swedish and U.S. plant are basically the same, the staffing and work practices of Swedish and U.S. crews are different. Particularly, U.S. crews are known for practicing strict procedural adherence.

Previous empirical studies of simulated challenging emergencies showed that control room operators had "to form accurate situation assessments and to generate response plans to cover aspects of the situations that are not fully addressed by the procedures" (Ref. 2, pp. 75-6). A study of emergency operation at French full scope simulator of a reactor with computerized procedures also saw the operators making "interpretations and initiatives"[10] to the point that even when implementing a procedure step which "appears simple at first glance, the operator can introduce interpretations and retain a certain degree of independence" (id.). These studies, however, did not concentrate specifically on the topics of procedures adherence and autonomous decisions and it remained unclear whether the behaviors observed with the Swedish crews and the observations from the earlier studies were fully comparable.

The U.S. crews in HAMMLAB displayed the high-level cognitive activities described in Roth's study, like situational understanding, response planning and initiatives. As the HAMMLAB scenarios were run longer than it is usually done in training/examination sessions, it was observed that procedural use and adherence became more and more challenging later in the events, and was not the result of introducing additional malfunctions. Rather, the crews spent more time and effort in interpreting the less familiar situations as well as in finding out how to implement the procedures in those situations. Procedural adherence and use varied substantially between crews from different plants (see TABLE II). For instance, a crew from one plant was very concerned of not performing actions not explicitly directed by the EOPs, and often browsed the procedures back and forth in order to find justification for contingency actions they wanted to perform (like switching off the pressurizer heaters that had automatically started during a depressurization, countering its effect). Crews from other plants took the same actions without hesitation. There were also differences in EOP use: one crew followed several EOPs in parallel (but not at the same time), assigned procedures parts or addenda to board operators, anticipated actions, re-diagnosed, and obtained extra information of the plant status from personnel outside the control room, while other crews did not, or did to a lesser extent. This crew's procedures use and adherence was very comparable to the Swedish crews' use and adherence. Procedure use and adherence differences were also observed among crews from the same plant. A clear example comes from an Interfacing System Loss of Coolant Accident (ISLOCA) scenario that had a leak of primary coolant in a location such that it could not be isolated by actions contained in the EOPs. Two of five crews did not attempt extra-procedural leak identification and isolation attempts (TABLE II). One of these was the already mentioned one that avoided actions not contained in the EOPs. The other crew that did not try extra leak isolations was from the same plant of two crews that spent considerable time and efforts at it. This indicates that intra-plant differences in making autonomous decisions among operating crews may be wide, but also indicate that procedure adherence is not only determined by the organization but also relates to individual crew factors. For instance, it is often observed that less proficient crews tend to follow the procedures mechanically, without taking into considerations the procedures' and steps' intents, if overwhelmed by situational complexity[9].

TABLE II. Extra-procedural diagnoses and decisions made by U.S. crews in a loss of coolant outside containment scenario. Large variations in the extent of autonomous decisions were observed both between and within plants.

Autonomous activity	**Crews**				
	Plant A			**Plant B**	**Plant C**
	1	**2**	**3**	**4**	**5**
Dispatch personnel for local inspection	Yes	Yes	-	-	Yes
Dispatch personnel for radiation monitoring	Yes	Yes	-	-	Yes
Detect different discharge pressure in the RHR loops	Yes	Yes	Yes	-	Yes
Discuss CCW tank not increasing as expected	Yes	Yes	Yes	Yes	Yes
Discuss lack of indications from the auxiliary building	Yes	-	-	-	Yes
Use plant information diagrams	Yes	Yes	-	-	Yes
Close PORVs after PRT symptoms	Yes	Yes	-	-	-
Retry closing and opening the check valves between RHR and RCS cold leg	Yes	Yes	Yes	-	Yes
Retry closing the isolation valves (source of the leak)	Yes	Yes	-	-	Yes
Close valves between RHR trains	Yes	Yes	-	-	Yes
Isolate the CCW form the RCPs thermal barrier	Yes	Yes	-	-	-
Try to isolate the CCW from RHR train A heat exchanger	Yes	Yes	-	-	Yes
Isolate the RHR system from the RWST	-	-	-	-	Yes

The extent of operators' autonomous decisions and actions depends on the formal requirements for procedures use and adherence, on unwritten plant practices, and on individual crews differences. Strict procedures implementation policies can limit the extent of autonomous decision-making in accidents with non-typical conditions and late in the evolution of the events, but do not remove them entirely.

IV. THE EFFECT OF AUTONOMOUS DECISIONS

Operators' autonomous decisions are a reality of accident response in nuclear power plants. Even when following the emergency procedures strictly the operators do not merely act as directed by the procedures but control the plant by building an understanding of the accident, of the plant conditions and of the procedures' intents. This understanding is the result of the "procedures' view" of the situation, their independent view, and, at times, the result of resolving the conflict between the two.[9] As we have seen, the extent by which operators make autonomous decisions varies and is dependent on the accident evolution, the plants' procedure use and adherence policies, and individual crew differences.

So the question of this paper is, are operators' autonomous decisions beneficial to plant safety? Answering to this question has important implications for the safety of nuclear power plants operations, from writing procedures to determining conduct of operations and training programs. The central question is whether stricter procedure adherence regimes should be imposed, also by automating the EOPs, or whether the control room crews should be given a more active decision role. There are two kinds of risks at stake here: the risk of implementing pre-planned plans that do not work and the risk of making adaptations that do not work. There is probably enough research and knowledge to evaluate the first risk, including a significant body of analyzed events at nuclear power plants that can tell us if the plans embedded in the EOPs have worked in the past and to what extent non-typical conditions have disrupted the planned responses. There is less empirical research on the operating crews' ability to successfully make adaptations when pre-planned plans do not work.

The HAMMLAB studies mentioned in this paper provides us some indications about the operator's ability at adapting, innovating, and improvising in emergencies with significant more unusual elements or novelties than contemplated in the procedures. The HAMMLAB simulations for the International HRA Empirical Study[1] did not explicitly study operators' autonomous decisions but focused on pre-defined tasks (human failure events), the majority of which could be solved by correctly following the procedures. Despite this, the challenges that made the two emergencies into complex-case versions (i.e., isolating a ruptured steam generator *without* radiation indications and starting feed & bleed *despite* misleading indications of steam generators levels) required operators' adaptation, else the tasks would have not been accomplished in time. In most cases the crews that took autonomous decisions succeeded while the crews that followed the procedures to the letter failed the tasks success criteria (typically by exceeding pre-defined time limits). There were also instances of operators taking autonomous decisions in executing the other pre-defined tasks but these have not been analyzed systematically.

The study with U.S. operators[9] designed the scenarios in such a way that literal procedure adherence would be problematic in critical phases of the accident such that safety-relevant tasks would not be performed without making autonomous decisions. Not surprisingly, crews that followed the procedures more strictly struggled with these designed challenges. For instance, in a multiple SGTR scenario literal following led to a deficient diagnosis and isolation (of only one of two leaking steam generators), while in an ISLOCA event the procedures were not able to isolate a reactor coolant leak thus leading to inventory depletion and erosion of safety margins. But there were also subtle ways in which strict following hindered crew performance, beyond the designed challenges. One example is in the communication with the plant operators in the SGTR scenario. The crews were instructed by the procedures to dispatch personnel to measure radiations on the SG sampling lines. The plant personnel would call back the control room to ask the crews to open the sampling valves in order to allow flow through the sampling lines. One crew did not open the valves but waited for meeting the explicit condition in the procedures, forgot to follow up the issue and never opened the valves, thus missing an opportunity for rediagnosis.

Overall, the crews that applied the procedures more strictly were not only less efficient with regard to the designed challenges requiring extra-procedural decisions, but were also less efficient in managing the emergencies as a whole, as indicated by avoidable releases outside the plant, delays, and lower margins to plant safety. Strict procedure following did not conduct to faster response: the completion times for the main operator actions in the simulated emergencies were not consistently different for crews with different procedural adherence levels. A further difficulty for strict procedures followers was that as the events unfolded the procedures required more and more operators' interpretations and autonomous decisions, as the guidance became less detailed and more situation-dependent. As a result, application of strict procedure-following strategies further down into the events resulted in higher rates of operational problems, decreased operators control over the plant, and caused more undesirable consequences to the plant (see, for instance, Table III).

TABLE III. Late in the events the crews that practiced strict procedures adherence had more problems than crews that had more autonomous decisions, as crews #3 and #4 had in a total loss of heat sink scenario.

Operational issue	**Crew 1**	**Crew 2**	**Crew 3**	**Crew 4**	**Crew 5**
Time cooling with the high-head safety injection	57 min.	96 min.	137 min.	118 min.	73 min.
Problems caused by accumulators injection	No	Yes	Yes	Yes	No
Excessive RCS cooldown and vessel integrity problems	No	No	Yes	Yes	No

The third HAMMLAB study we consider in this paper utilized emergency scenarios similar to the previous one, but this time with 6 Swedish crews.[11] Here all operators' autonomous decisions, defined as intentional actions not directed by the procedure and step in effect, were counted. This definition includes intentional deviations from prescribed actions like additional actions, anticipated actions, and new actions, but not the same deviations occurring unintentionally (by mistake). The study also evaluated the effect of these actions in terms of their impact on plant safety. The result showed that autonomous decisions and actions not directed by the procedure's step in effect were more often successful than not, that is, autonomous decisions had positive consequences to the plant in about 60% of the cases. The number of adaptation per se did not correlate with other crew performance measures, meaning that differences in crews' proficiency did not determine the extent of taking or avoiding decisions beyond the procedures guidance. On the other hand, the rate of adaptations that succeeded showed a medium correlation with the crew performance measure, meaning that crews with higher-rated overall performance in the scenarios had higher rates of autonomous decisions with positive outcomes than crews with lower performance ratings. The qualitative analysis concluded that inappropriate decisions were determined by insufficient engineering expertise and unfamiliarity with the plant responses in a variety of accidental conditions, including the underlying thermodynamics and heat transfer phenomena. One contributor to this lack of familiarity could be the result of focusing simulator training on correctly implementing the procedures for about an hour after an initiating event, when the procedure guidance is typically detailed enough. Yet, autonomous decisions and difficult interpretations are more likely later in the events, in addition to situations that departure from expectations, like with multiple overlapping malfunctions and unavailable or unreliable indicators, which also are not often trained.

V. CONCLUSIONS

Following the Three Miles Islands accident, the nuclear industry has invested heavily on proceduralizing emergency operation. One of the operators at TMI-2 during the crucial stages of the accident was Edwards Frederick who later said that "no operator should ever be placed on a situation that has not been pre-analyzed by an engineer". Comprehensive emergency operating procedures were written with the aim of directing the operators' step by step, without the need to identify the causes of the disturbances and finding out what to do. Operators' autonomous decisions would not longer be required, and even not desirable, as the procedures would be detailed enough for avoiding core damage. EOPs have thus been conceived according to views 1 or 2 discussed in section I and summarized in TABLE IV below. The problem is that these views have serious weaknesses: 1) the EOPs do not always provide detailed guidance, and 2) the operators do not merely assess plant parameters values and execute as directed, but interpret the procedures in light of their understanding of the events. These views natural corollary is strict procedural compliance. Strict compliance depowers the operator decision-making skills, and thereby weakens the third view on EOPs that assumes some degrees of operators' autonomy as necessary for adapting the procedures to the situations. The problem is that this view is the one that more realistically describes the operator role in implementing emergency procedures during emergencies.

TABLE IV. Three views on the emergency operating procedures (EOPs).

EOP view	**EOP principle**	**Assumed operator role**	**Autonomous decisions**	**View's weaknesses**
1. All-comprehensive guidance for responding to emergencies.	To provide detailed guidance for all contingencies.	Assess plant parameters values and execute as directed.	Should not occur, detailed guidance is always available (for all beyond skills-of-the-trade actions).	Detailed guidance is not always available. Assessing plant parameters, especially later in the events, requires interpretation and insights into the events.
2. EOPs provide detailed guidance for avoiding core damage.	To provide the optimal response path for avoiding core damage. Do not address all (minor) contingencies.	Assess plant parameters values and execute as directed.	Are undesirable as they might aggravate the risk of damaging the core.	Correct procedure implementation demands more than following by rote. The majority of autonomous decisions have positive consequences for the plant.
3. EOPs support the operators in minimizing the risk of damaging the core.	A systematic approach to minimize the risk of core damage that requires operators' knowledge for correctly realizing the procedures' intents.	The operators "right the procedures to the world" by understanding both the procedures' intents and the situation.	Might be necessary in situations not fully covered by the procedures. Operators might need to re-diagnose, anticipate actions, redirect procedures and address contingencies.	Not all operating crews have the variety and specificity of engineering expertise needed for correctly implementing the EOPs in events with significant elements of novelty.

The nuclear industry's reliance on pre-analyzing the accidents and preparing response plans is now extending to the realm of severe accidents. In severe accidents core integrity is lost, the EOPs are not longer relevant and the goal is to limit fission product release and provide ultimate heat sink for the decay heat. Current plants have not being designed and licensed for such conditions, conditions in which instruments may either be not available or not reliable, plant communication means may have failed, and important equipment may become unavailable. Event evolutions under severe accidents cannot be easily anticipated and certainly not to the same degree as accidents addressed by the EOPs. Despite this, the industry is moving into severe accidents management guidelines (SAMGs) with the same EOP thought process, that is, by writing "detailed guidance which only and totally depends on plant parameters and not on insights in the plant damage conditions".[13]

We have seen that, already in EOP space, accident evolutions may be different than what has been analyzed. Furthermore, strict procedure implementation is not effective in such conditions and the operators need to make autonomous assessments and decisions. There is limited empirical knowledge about the operators' success rates in making autonomous decisions during accidents that do not fit preplanned responses. Studies of simulated emergencies in the Halden Human-Machine Laboratory confirm that the operators do make autonomous decisions and find that most often these are correct. However, incorrect autonomous decisions are still observed.

If we return to the question raised by this paper's title, it is not possible to provide a definitive answer. But some conclusions can be made: 1) Unanticipated evolutions of the accidents addressed by the EOPs cannot be ruled out; 2) In these conditions, but also in late stages of the accidents, the EOPs cannot be implemented in rule-based mode, without insight in the event and in the procedures 'intents; 3) Operators' autonomous decisions are most often successful, but not always.

Innovative decision and adaptation are not new concepts for the nuclear industry. As a matter of fact, another important lesson from the TMI accident was that emergency response needed not only comprehensive procedures but also the ability to adjust to changes and disturbances in expected and unexpected conditions. Accordingly, the position of the Shift Technical Advisor (STA) was established for improving the technical expertise on accident mitigation, as well as to provide an independent view to rest of the operating crew. Early investigations[12] and recent empirical studies[9, 11] indicate that the STA implementation has come short the objectives and is often observed that during emergencies STAs work more as support for complying to the EOPs than as independent analysts.

Increasing the quality of the operating crews' autonomous decisions is not easy[11] and existing approaches that favor strict procedural compliance counter a more active role of the operators, a precondition for successful innovative decisions. Progress hinges on finding a better balance between anticipation and adaptation in emergency and accident response, which in turns depends on better understanding the operators' role and decision-making processes when implementing emergency procedures.

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