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Combining conventional and innovative risk modelling techniques to identify safety culture issues during the Three Mile Island nuclear accident

Md Shafqat Amin Inan

Department of Mechanical and Industrial Engineering, University of Norwegian Science and Technology, Norway. E-mail: md.s.a.inan@ntnu.no

Jørn Vatn

RAMS Group, Department of Mechanical and Industrial Engineering, University of Norwegian Science and Technology, Norway. E-mail: jorn.vatn@ntnu.no

Mary Ann Lundteigen

Department of Engineering Cybernetics, University of Norwegian Science and Technology, Norway
E-mail: mary.a.lundteigen@ntnu.no

Shenae Lee

Department of Software Engineering, Safety and Security, SINTEF Digital, Norway.
E-mail: shenae.lee@sintef.no

The partial nuclear core meltdown at the Three Mile Island (TMI)-2 reactor in 1979 was the first big nuclear accident of significant public interest. A combination of mechanical component failures, a lack of operator understanding of the developing accident progression, and major operator errors led to the first core meltdown in the history of commercial nuclear reactor operations. Many studies have analyzed severe accident progression and physical barrier failures, using conventional risk assessment techniques such as ETA and FTA, which are typically applied in risk modelling prior to the operation of, e.g., a nuclear power plant. To address human and organizational factors, a wide range of methods exists, and these methods are also applied prior to plant operation. In this paper, we adopt an alternative approach. First, we use the STEP method to analyze the sequence of events in the TMI-2 accident, based on existing investigation reports. Then we investigate how to apply two different methods for human and organizational factor assessment, namely the SPAR-H and Risk-OMT approach, to address more explicitly those human and organizational factor challenges pointed out in the TMI accident literature. The objective of this investigation is to determine the extent to which analytical techniques can identify key risk factors that can be mitigated prior to plant operation. For example, is it possible to address challenges related to, for example, safety culture, complexity, and so-called tight couplings in a more analytical manner.

Keywords: Nuclear accidents, Nuclear safety, Accident investigation, Human and organizational factors, Risk modeling, Human reliability analysis.

1. Introduction

1.1. *The Three-mile island nuclear meltdown accident in 1979*

The Three Mile Island power generation plant is situated in Londonderry Township, a small island on the Susquehanna River in Pennsylvania, USA. On 28 March 1979, as the night rolls into the graveyard shift at the Three Mile Island Nuclear Power Generation Plant, the world experiences an accident like nothing before. The accident occurred at the 2nd reactor present on-site, which was owned by EnergySolutions (Rogovin, 1980a). The reactor was a 906 MWe Babcock & Wilcox pressurized-water reactor that had been commissioned just three months before the accident. Fig. 1 shows a general schematic of the TMI-2 reactor, while reactor specifications are given in Table 1. What started with a small valve failure soon became a partial meltdown of the TMI-2 nuclear reactor core, an event the power plant's operating personnel member had never imagined, even in their worst nightmares. This became the first severe nuclear accident in the world. As the worst nuclear incident at that time, the accident was later categorized as a level 5 event on the IAEA International Nuclear and Radiological Event Scale (INES). (IAEA, 2013). The TMI-2 reactor core sustained heavy damage due to the partial meltdown, but there was no major release of radioactive material into the environment.

Case studies show that natural fear of radiation and other long-term hazards, lack of trust in the government and safety authorities,

Table 1. Three Mile Island Nuclear Power Generation Plant (Rogovin, 1980a)

Three Mile Island Nuclear Power Plant		
Location	Pennsylvania, USA	
Reactor Supplier	Babcock & Wilcox	
Reactor type	Pressurized water reactor	
Cooling source	Susquehanna river	
	TMI-1	TMI-2
Reactor Owner	Constellation Energy	Energy Solutions
Generation capacity	819 MWe	906 MWe
Construction start	18/05/1968	1/11/1969
Commissioning	Sep 2, 1974	Dec30,1978
Decommissioning	Sep20,2019	Mar28,1979

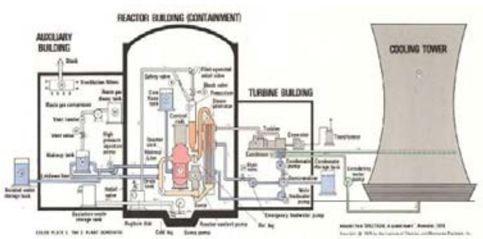

Fig. 1. Schematics of the TMI-2 nuclear reactor (Rogovin, 1980b)

and, most importantly, an aura of mystery surround nuclear accidents. Being the first core meltdown accident in a commercial nuclear reactor, the TMI-2 incident still plays a significant role in the public perception of risk in the nuclear industry. Given the importance of this event, several independent investigations have been conducted, and key risk factors have been identified. Methods like event tree analysis (ETA) and fault tree analysis (FTA) are generally used to model risks associated with nuclear systems (Clement, 2014, Amirsoltani et al., 2022). This study reassesses these well-established conclusions by complementing conventional methods such as ETA and FTA with additional approaches, including STEP analysis, the SPAR-H method, and the Risk OMT model.

1.2. *Objectives and subobjectives*

The main objective of this paper is to determine the extent to which a combination of methods can capture essential risk factors, enabling their mitigation before the start of a new plant operation. The corresponding subobjectives are to develop a detailed understanding of the accident causations and how these impacted the probability of experiencing the TIM-2 accident:

(i) To create a detailed timeline of the TMI-2 accident and use it to conduct a STEP analysis, based on analyses of nuclear safety investigation reports.

(ii) To model a simplified fault tree covering both technical and human system failures.

(iii) To determine human error probabilities during the TMI-2 accident using the SPAR-H method.

(iv) To use Risk-OMT model to identify technical, organizational and human aspects as Risk influence factors (RIFs) that contributed to the risk during the accident.

(v) To compare the results with conclusions found in TMI-2 investigation literature.

2. Methods

2.1. *Accident investigation methods*

While minor accidents can occur due to single-component failure, major accidents at the system level are usually the result of multiple active or latent failures within a complex system. (Rosness et al., 2010). Accident investigations are conducted to identify causal factors that contribute to the failure of system components and to reconstruct the accident sequence. This demonstrates the industry's commitment to health and safety and better risk management. (Sklet et al., 2004). Accident investigation models that are widely used may be broadly categorized as follows:

(i) Sequential models that generate a continuous timeline of events that set up a chain reaction of failures (domino effect). E.g., STEP method (Hendrick and Benner, 1986).
(ii) Logic tree models that focus on the logical relationship between different causal events, e.g., FTA and MORT (De Oliviera et al., 2022).
(iii) Systemic models that focus on processes and relevant systems of organizational culture. E.g., SCAT model (Rizky et al., 2022).
(iv) Epidemiological models that treat accidents as effects emerging because of hidden organizational components, e.g., EHS

management model and ICAM (Wahyu Cahyadi et al., 2024).

(v) Energy models that focus on the transfer of energy causing material loss or damage to people E.g., Barrier analysis method (Aggelen, 2016).

(vi) Human info-processing models that analyze the accident from the point of view of the human operator. E.g., HPEP modules (Barnes et al., 2002).

All these models have their own strengths and weaknesses in handling different organizational and accidental behaviors. These frameworks facilitate the identification of discrete risk factors and their cumulative impact, enabling a systemic understanding of a more holistic picture of events that occurred during accidents.

2.2. *Risk assessment models used in this study*

The use of a single risk analysis method often limits the investigation to a narrow view of the accident progression. Combining a set of qualitative risk assessment techniques may allow us to piece together the whole risk picture – capturing both events that transpired and events that were prevented. For example, the FTA demonstrates system or component failures relevant to the failure of only *one* top event, whereas a STEP diagram can identify multiple safety critical conditions at once. In this study we selected a set of complementary qualitative risk assessment methods to structure and model the risk picture associated with the TMI-2 accident. To address the operational and environmental conditions that can affect risk, we also selected models that are well suited to capturing changes in risk levels. Such an approach to risk analysis is referred to as dynamic risk analysis in the process industry (Lee, 2020). The primary goal was to apply results from accident investigation methods to risk modeling techniques that incorporate all risk-influencing factors, beyond what is possible when relying on a single risk analysis method. The risk analysis methods used in this study are described below.

2.2.1. *Sequentially timed events plotting (STEP)*

STEP analysis is a sequential accident investigation method (Hendrick and Benner, 1986) that is used to address the multi-linearity of actions and events. A graphical representation of the accident is generated using this tool. We examine the entire chain of events, from precursors to immediate aftermaths, identify key actors (humans, systems, components, etc.), and depict these events as 'event building blocks' on a STEP worksheet. (Rosness et al. 2016). The list of actors is placed on the vertical axis, while the horizontal axis depicts a timeline of events. Interdependence between actors and events, as well as non-linear temporal relationships, are evaluated to create a clear & consistent diagram for better communication about the accident.

2.3.2. *Fault tree analysis*

A fault tree is a logical representation of systems and their components, in which we identify pathways that could lead to system failure. It is a deductive method commonly used to model scenarios leading to the failure of a top event.

2.2.3. *Human factors SPAR-H model*

The SPAR-H method was developed at the Idaho National Laboratory in USA to analyze human performance and reliability issues in a nuclear power plant. The basic framework of the method decomposes human error probability (HEP) into diagnosis failures, situational responses, and action failures. The model addresses eight performance-shaping factors (PSFs) that affect operators' decisions. These factors are – available time, stress, complexity, experience/training, procedures, ergonomics/HMI, fitness for duty, and work process. (Gertman et al., 2005). These factors have a nominal value of 1. These PSFs function as sharp-end RIFs with a direct impact on human performance; thus, their values vary with different operating conditions. The SPAR-H model uses Eq. (1) to calculate human error probability (HEP) where f_i are the individual factors and NHEP is the nominal HEP value:

$$\mathrm{HEP} = \frac{\left(\prod_{n=1}^{8} f_i\right)\cdot \mathrm{NHEP}}{\left(\prod_{n=1}^{8} f_i\right)\cdot \mathrm{NHEP}+1} \tag{1}$$

2.2.4. *Risk-OMT approach*

The Risk-OMT approach was a further development of methods from the two projects - Barrier and Operational Risk Analysis (BORA) and Operational Condition Safety (OTS). The Risk-OMT models improved the way risk influence factors (RIFs) were incorporated, by distinguishing soft and hard RIFs into separate levels. (Vinnem et al., 2012). RIF structure diagrams show Bayesian relation among different events of the fault and event trees. This process is better suited than SPAR-H method to identify

Table 2. Three Mile Island nuclear meltdown accident progression timeline (Rogovin 1980b)

Incident marker	Approximate timestamp	Incident
1	4:00 AM	A valve in the feedwater system fails. As air is pushed into the pipes, the feedwater pump also fails.
2	4:00:01 AM	The turbine and generator fail just a second after the feedwater pump fails.
3	4:00:03 AM	As the temperature in the secondary circuit keeps rising, PORV opens at 2255 psig to depressurize the primary circuit.
4	4:00:08 AM	When the RCS pressure reaches 2355 psig, reactor scram occurs by confirmed insertion of 67 control rods into the nuclear reactor core.
5	4:00:X AM	The emergency feedwater system takes over the secondary circuit. As a valve had been mistakenly left closed during maintenance, the three emergency feedwater pumps fail to inject cooling water into the secondary circuit.
6	4:00:12 AM	The PORV is stuck open. Approximately 250 000 gallons of radioactive water is leaked to the floor of the containment building. In about two minutes, the RCS pressure drops from 2150 psig to 1640 psig.
7	4:00:30 AM	Although an alarm was received due to the high PORV outlet temperature, the printer overloaded because it had been receiving over 100 alarms per minute. The reactor operators do not know that the PORV is stuck open, releasing steam, and draining some water to the Reactor coolant drain tank.
8	4:00:X AM	The released water pools at the containment building floor. The water is soon pumped off to waste tanks in the auxiliary building. Radioactive steam finds its way into the atmosphere through a venting system.
9	4:02 AM	The emergency core cooling system (ECCS) is activated at 1600 psig pressure, pushing much needed cooling water into the reactor pressure vessel. The operators notice the water level inside the RPV rising back to normal limits and manually shuts down the ECCS.
10	4:08 AM	Eight minutes into the accident, Ken Bryan, an expert operator from TMI-1 first noticed the indicator light that meant the emergency feedwater valve to be closed and then opened it manually.
11	4:XX AM	As more primary coolant leaks out of the RPV, the primary circuit becomes depressurized. Primary coolant water starts to evaporate.
12	5:13 AM	As cavitation starts to cause serious vibrations in the main coolant pumps, the operators shut MCP B loop down - which causes the heat inside the RPV to rise even higher.
13	5:XX AM	Steam in the steam generator U-tubes locked the primary cooling circuit, stopping the circulation of cooling water.
14	5:20 AM	The top of the reactor core becomes exposed due to the lack of coolant. The temperature is now dangerously close to the melting conditions of the fuel-cladding matrix. Pellet-cladding interaction starts to occur.
	5:41 AM	The operators tried to save the other functional pumps from terrible vibrations. They shut MCP loop A pumps down.
15	6:18 AM	2 hours and 18 minutes into the accident, the new shift supervisor, Brian Mehler, identified steam bubbles in hot leg pipes and ordered thorough investigation to find its source. Then he made the first major ’correct’ move - he deduced the PORV to be stuck open and then closed the valve manually.
16	6:XX AM	The primary coolant water is locked by steam pressure. Circulation slows down inside the pressurizer, filling the pressurizer with water.
17	6:XX AM	Temperatures reach 2000°C, triggering the zirconium in the fuel cladding to oxidize and release Hydrogen gas inside the RPV.
18	6:50 AM	Fuel rods failed, initializing a partial meltdown of the nuclear core.
19		Later, the operators bring ECCS online. Although it ran for just ten seconds or so, it prevents a full-core meltdown.
20	7:24 AM	Plant operators realize the seriousness of the situation and declares ‘site emergency’.
21	7:XX AM	All non-essential power plant personnel are evacuated from the building.
22	7:XX AM	The emergency evacuation plans are triggered. General public from all over Harrisburg, Pennsylvania are evacuated to safer sites.

organizational factors as ‘soft influence’ behind failures of omission and failures of executions during an accident scenario.

3. Investigation of the TMI-2 accident

The proposed methodology was to combine all the methods mentioned in Chapter 2.2. The first task was to establish a timeline for accident progression, based on TMI-2 investigation reports. A STEP diagram was generated to identify actors and events that impacted the accident progression. A simplified fault tree of the event was also created based on the timeline developed in Chapter 3.1. While SPAR-H model was used to calculate human error probability in developing situations of the accident, Risk OMT was used to identify latent organizational factors that affected operators’ performances.

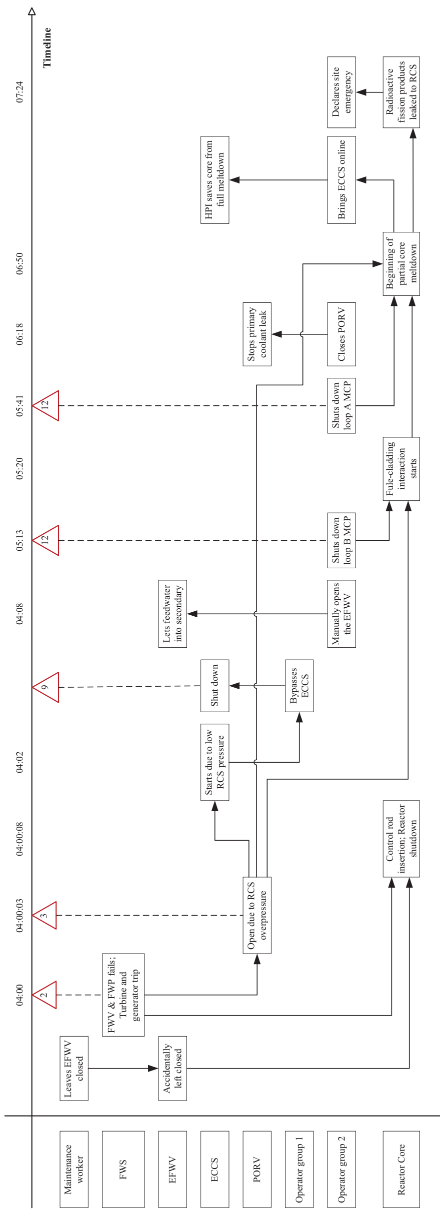

Fig. 2. STEP diagram of TMI-2 nuclear accident

3.1. *STEP analysis of the accident timeline*

The US nuclear regulatory commission’s special inquiry group’s report (Rogovin, 1980b) was consulted to create a timeline for the TMI-2 nuclear meltdown accident. Key events of the timeline are explained in Table 2. Unknown timestamps are marked with X. These events were then investigated to establish the STEP diagram for the TMI-2 accident. Actors and actions involved in these events were identified and then plotted on a timeline worksheet to create the diagram in Fig. 2. Important timestamps were also posted along the horizontal axis. The involvement of multiple actors along the vertical part of the diagram indicates that interactions between actors can be causal events for the accident. The top row line of triangles represents safety critical conditions. The numbers in these triangles correspond to incident markers on the timeline in Table 2.

Three types of analytical tests performed on the STEP diagram are used to illustrate the sequence of the TMI-2 accident. A *row test* of the generated diagram identifies all the actions of any ‘actor’. A *column test* is used to check the sequence of each event, and whether events occurring roughly at the same time are placed along a vertical line. The *necessary-and-sufficient test* is performed to justify the causal links between events. If any event is not sufficient to cause a later one, more events are linked to the second block until all causal relationships are established. This test was useful for identifying all the events that led to the partial core meltdown at the TMI-2 reactor.

The generated STEP diagram includes major operator decisions and component failures as *event blocks*. Based on the consequences of their actions, the TMI-2 operating personnel were categorized as two different actor groups in the diagram. Operator group 1 consists of people present in the control room for their regular night shift on March 28, 1979. Operator group 2 includes experts and additional personnel called upon to handle the accident situation. One finding from the US-NRC investigation was that the initial group of operators was overwhelmed by the speed and ferocity of the alarms at the beginning of the accident, and most of the correct calls were made by the second group of officers who joined after the accident had begun. Furthermore, the diagram demonstrates that PORV event block at 04:00:03 had the most severe impact on the events that followed. This matches role of the stuck-open PORV as the main component failure responsible for the TMI-2 accident, as is established in the literature.

3.2. *Generating TMI-2 core meltdown fault tree*

A simplified fault tree was generated (Fig. 3) based on the events listed in Table 2. This was inspired by the approach taken by Chima Clement (2014). To make the fault tree simple, only events most directly responsible for the meltdown accident were listed in it. Both mechanical system failures and human errors were incorporated. As operator decisions were part of the failure mechanism in multiple different safety systems, 'human error' (HE) appeared in the fault tree more than once. Numbered red-yellow markers were placed on key events on the fault tree – these numbers correspond to the incident markers on Table 2. According to the generated fault tree, the accident started with a combined failure of the feedwater valve and feedwater pump in the feedwater system (FWS). The FWS was designed to be backed up by the emergency feedwater system (EFWS), which consists of emergency feedwater valve (EFWV) and emergency feedwater pump (EFWP). Failure mechanisms for EFWV and EFWP were included in the tree. Failures in these two important systems (FWS and EFWS) led to the loss of secondary (LoSC) cooling of the reactor. Loss of primary cooling (LoPC) was addressed as a combination of failures in main coolant pumps (MCP), emergency core cooling system (ECCS), and LOCA - a loss of coolant accident at the reactor pressure vessel. A small break LOCA (SB-LOCA)triggered by the release event during the TMI-2 accident. Loss of cooling

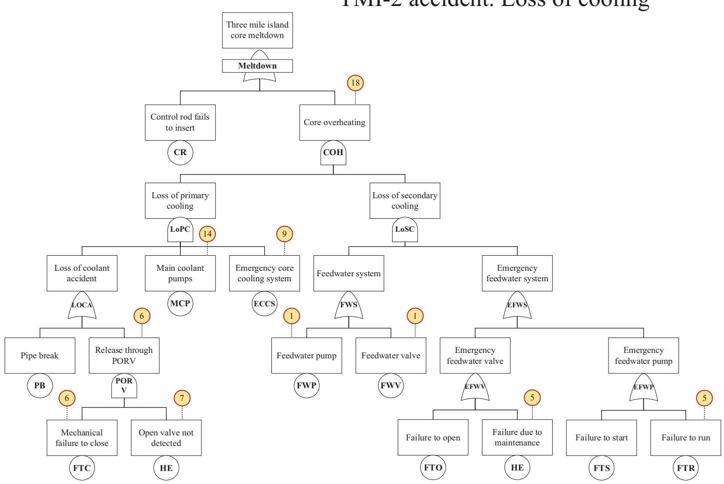

Fig. 3. A simplified fault tree of the TMI-2 meltdown accident

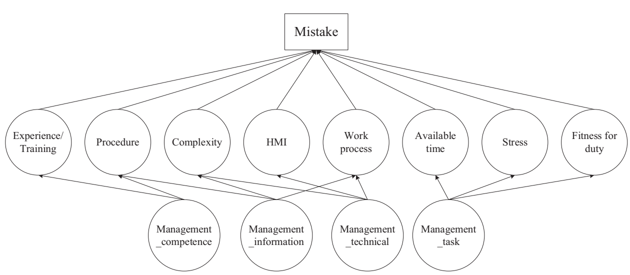

Fig. 4. RIF structure of the TMI-2 operator errors

on both primary and secondary side led to the core overheating (COH) event, which ultimately caused the partial meltdown of the reactor core.

3.3. *Organizational factors as RIFs*

Aven et al. (2006) identified the eight SPAR-H performance shaping factors as RIFs on a Bayesian belief network diagram and concluded that they have the same level of direct influence on personnel decisions. We used the Risk OMT approach to address these PSFs as ‘sharp-end RIFs’ that directly influence operator mistakes during the TMI-2 accident, while organizational factors were identified as ‘blunt-end RIFs’ that indirectly influence the mistakes. The risk structure in Fig. 4 illustrates the interconnection among the RIFs – an idea that helps us map organizational safety culture in a more comprehensible manner. The management factors that are placed one level lower than the sharp-end RIFs and have greater importance as cause of the accident.

3.4. *Human error probability calculation*

Errors in relation to generic tasks, decisions and actions taken by the operators during the TMI-2 accident were analyzed to assign scores to different performance shaping factors (PSFs) in accordance with the SPAR-H analysis method. These scores were used to calculate HEP. Nominal HEP was assumed 1/1000 because all activities were conducted indoors. Two stages of the accident - early and late, were considered for quantitative dynamic risk assessment. The resultant HEP values are shown in Table 3.

Table 3. Dynamic values of SPAR-H performance shaping factors

Dynamic PSFs	Early stage	Late stage
Available time	10 (barely adequate)	1(fail)
Stress	2 (high)	5 (extreme)
Complexity	1(nominal)	2 (moderate)
Experience/Training	10 (low)	10 (low)
Procedures	1(nominal)	5 (poor)
Ergonomics/HMI	10 (poor)	50 (missing/ misleading)
Fitness for duty	1(nominal)	1(nominal)
Work process	1(nominal)	1(nominal)
Total F	**2E3**	**2.5E4**
HEP value	**0.667**	**0.962**

The huge increase in the HEP value shows the crucial contribution of misleading human machine interface, where the PSF value jumped from 10 to 50. Another major contribution comes from ‘Procedures’. It means that the operators were not well-informed about the recovery procedures under the developing severe accident conditions.

5. Discussion

Three-mile island reactor meltdown accident investigation reports have historically concluded that the operator inexperience and misleading human machine interface were among the most important contributors to the severe consequences. It is expected that any attempt at risk assessment study on this accident would reflect these conclusions.

Our approach to combine several complementary qualitative and quantitative risk modeling techniques managed to develop the holistic risk picture of the accident. Strengths of a risk assessment method covered the weaknesses of another method. The fault tree managed to illustrate different pathways that could lead to a core meltdown. Generating a STEP diagram from the accident timeline illustrates a human error during maintenance as the initiating event. The incident markers on the fault tree and safety problems in the STEP diagram help us identify how a mechanical failure on the non-nuclear secondary side of the reactor, coupled with poor control panel design and errors in operator judgement snowballed into an accident of unforeseen significance. Applying SPAR-H method allowed us to identify which of the performance shaping factors directly affected the human error probability, whereas the RIF structure diagram illustrated how lack of proper organizational culture influenced errors during a high-stress situation. Herein lies the most important observation from this study. The complementary nature of SPAR-H and Risk OMT models facilitated the understanding of human and organizational factors that played crucial role in the operators’ errors. The operators in TMI-2 control room lacked proper training or prior experience to carry out their duties responsibly. Additionally, the human-machine interface at the control panel displayed misleading information that resulted in their poor judgement of water level inside the pressure vessel. The second group of operators managed to make adequate decisions later, using their experience with TMI-1 reactor as well as superior knowledge of thermal-hydraulic mechanisms of the B&W reactor. The use of detailed risk analysis techniques allows us to look beyond the direct causes like temporal or physical stress and conclude that organizational safety culture in the 1970s was not adequate for the operators to be able to prevent an unforeseen transient event ending in core meltdown.

Proper identification of risk influence factors is one of the main ways that nuclear safety culture can be improved. Studies about TMI-2 accident have led to decades of development of proper organizational safety culture practices. Now projects like the Halden HTO prepare the operators with knowledge and experience about a plethora of transient scenarios. Improved training methods, development of clear operational procedures as well as better control equipment have been the result of accident investigation studies that try to identify latent factors behind accidents.

6. Further work

Our approach successfully managed to replicate historically established conclusions. Important improvements will be made to extend the model to facilitate quantitative analysis and carry out investigations using other major nuclear accidents as case studies. The aim is to develop a model that can properly identify all risk-influence factors even before the start of powerplant operation. It can make the safety culture more robust with operators becoming more competent at handling unforeseen transient scenarios. This would be particularly beneficial for newcomer countries like Norway. With a new generation of nuclear reactors in R&D, detailed investigations with innovative risk modeling techniques can help us make the operation safer.

Copyright Transfer Agreement

The copyright transfer agreement document from the ESREL2026 website was submitted along with the submission of the final paper.

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