Learning how to Learn from Failures: The Case of Fukushima Nuclear Disaster

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Abstract: In this work, it is argued that learning from failures and safety competence should be an important part of the curriculum of Engineering and Management students. The case of Fukushima will be used to illustrate how to learn about learning from failures using multi-models inspired by reliability and risk analysis in order to investigate disasters. This type of analysis can offer richness to our understanding of the root causes and provide insight into policy making and support decisions for resource allocations for prevention of such disasters. The analysis is based on a workshop related to learning from failures where students and practitioners were first given a brief about the related theory of reliability analysis and decision science, followed by introduction of the analytical techniques that can be used (such as FTA, RBD and AHP). They were then given a brief in the form of a narrative of the accident from investigation reports, and they were then divided into small groups with the task to perform an analysis of the disaster followed by presentation of recommendations in the form of a written report and an oral presentation. Finally, a set of generic lessons and recommendations are provided in order to prevent future system failure.

Keywords: Fukushima Nuclear Disaster, PSA, FTA, RBD, AHP.

1. INTRODUCTION

In the wake of Fukushima nuclear disaster, few investigation reports have been published in an attempt to explain the accident and outline lessons learnt. Most notably it was noted that probabilistic safety assessment is underutilized in nuclear industry. For example in a report of the Japanese Government to the IAEA [1], it was noted that "*Effective use of probabilistic safety assessment (PSA) in risk management PSA has not always been effectively utilized in the overall reviewing processes or in risk reduction efforts at nuclear power plants*". Moreover, it was noted in a comment by the British Office of Nuclear Regulator's (ONR) final report on Fukushima [2] that "*This* [under utilization of PSA in nuclear industry] *is an important lesson, acknowledging that effective use of PSA could have helped help to prevent accidents like that at Fukushima escalating, and to help deal with them should they occur*". In the same report the ONR's final recommendations include "*The circumstances of the Fukushima accident have heightened the importance of Probabilistic Safety Analysis for all nuclear facilities that could have accidents with significant off-site consequences*". In this paper we analyze Fukushima disaster and develop a hybrid modelling approach using PSA related techniques.

2. BRIEF INTRODUCTION ABOUT THE ACCIDENT

In this section a narrative is provided in order to summarize abundant information in the literature reporting the incident. It is suggested that as the disaster happened a while ago, a primary data collection would be of lower quality as memories have faded and key persons may have disappeared. Therefore, it has been decided to use a secondary data analysis (which is a proven and widely used research method) for the problem structuring. A secondary data analysis of the disaster gives also the possibility to triangulate sources. Moreover, the case can be easily checked by others researchers. The same narrative was provided in the workshop conducted by the author. The delegates were then divided into two groups and each group was required to consult literature with respect to finding more evident about the disaster and utilize reliability engineering and decision science techniques in order to analyse the failure and make recommendations based on the analytic tools that have been used.

2.1 Logic sequence of the failure

On 11 March 2011 Japan suffered its worst recorded earthquake, known as the Tohuku event. It was classified as a seismic event magnitude 9.0, with maximum measured ground acceleration of 0.52g ($5.07 m/s^2$). The epicentre was 110 miles E.N.E. from the Fukushima-1 site. Reactor Units 1, 2 and 3 on this site were operating at power before the event, and on detection of the earthquake they shut down safely. Initially, on-site power was used to provide essential post-trip cooling. About an hour after shutdown a massive tsunami, generated by the earthquake, swamped the site and took out the AC electrical power capability. Sometime later, alternative back-up cooling was also lost. With the loss of these cooling systems Reactor Units 1 to 3 overheated, as did a spent-fuel pond in the building containing Reactor Unit 4. This resulted in several disruptive explosions, because overheated zirconium fuel-cladding reacted with water and steam and generated a hydrogen cloud which, was then ignited. Major releases of radioactivity occurred, initially to air but later via leakage to the sea. The operators struggled to restore full control. This was a serious nuclear accident, provisionally estimated to be of Level 5 on the Nuclear Event Scale (INES), a figure which was later amended to a provisional Level 7 (the highest category). The Japanese authorities imposed a 20km radius evacuation zone, a 30km sheltering zone and other countermeasures. Governments across the world watched with concern and considered how best to protect those of their citizens who were residents in Japan from any major radioactive release that might occur [3].

Some have commented on reports of plant damage caused by the earthquake, concluding that the loss of effective cooling for the reactors stemmed directly from the earthquake rather than the subsequent tsunami. However, the information available on the emergency cooling systems and analysis of the circumstances does not support such a hypothesis [2].

This case study is a good example of a double-jeopardy, where the combination of earthquake and tsunami caused destruction on a scale that was not anticipated in the initial design specifications. For example, the plant was protected by a sea-wall - designed to withstand a tsunami of 5.7 meters (19 ft), but the wave that struck the plant on March 11 was estimated to have been more than twice that height, at 14 meters (46 ft). This, coupled with the now reported land movement of 2.4m experienced by much of Japan, ensured that the Tsunami caused enormous damage along the coast [4].

2.2 Consequences of the failure

The earthquake occurred under the sea near the north east coast of Japan. It lasted over 90 seconds, and caused widespread damage to property, although, due to the civil building design standards most properties did not collapse. As a result of the earthquake Japan has moved 2.4m laterally, and dropped 1m vertically. Also, the earth's axis has moved 0.17m and the length of the earth's day is now shorter by 1.8 microseconds [4]. This was by any measure a major global event.

The earthquake produced a tsunami 14m high that struck the coast of Japan, and travelled up to 10km inland, devastating infrastructure already weakened by the earthquake.

There were approximately 15,000 confirmed deaths and 10,000 people remain missing. It has been reported that the accident eventually cost Japan between 5-7% of its GDP, or US$300-600 billion [5].

The infrastructure affected included many different types of facility, such as houses, hospitals, electricity and water supplies, petrochemical and oil installations. However, it can be argued that the most significant damage in a global context, was to the Fukushima Nuclear Power Station at the town of Okuma. Fukushima is a city in the Tohoku Region of Japan. It lies 250km north of Tokyo, covering an area of 746.43km^2. As of May 2011, it had a population of 290,064.

The damaged caused by the earthquake and subsequent tsunami, which arrived at 15.41 JST [3], resulted in mandatory evacuation of the population within a 20Km radius around the site, loss of containment of radiological material to air, contamination in the sea (since detected in the Irish Sea) and of drinking water in Japan.

2.3 The Japanese Nuclear Industry

Japan is heavily dependent on its nuclear industry, with 54 nuclear reactors currently in operation consisting, of 30 Boiling Water (BWR) and 24 Pressurised Water (PWR) reactors. The industry is regulated by the Nuclear Safety Commission (NSC) through the Nuclear and Industrial Safety Agency (NISA), which are accountable to the government through the Ministry of Economy, Trade and Industry (METI) [3]. It was the stated goal of the Japanese government, prior to this event that, 50% of their electrical power should be nuclear power (although this, of course, may not continue to be the case). In the short to medium term the Japanese government has suspended operations at Tohoku until the sea defences are improved, which is estimated could take years to complete.

In an article in the Guardian Newspaper [6], Mr. Naomi Hirose, president of the Tokyo Electric Power Company (Tepco), which runs the stricken Fukushima plant, said "*nuclear managers should be prepared for the worst" in order to avoid repeating Japan's traumatic experience*", and then he continues to say "*…we have to keep thinking: what if..*" Hirose said that "*although the situation facing Fukushima Daiichi on 11 March was exceptional, measures could have been adopted in advance that might have mitigated the impact of the disaster. Tepco was at fault for failing to take these steps*". According to him, "*preventative measures included fitting waterproof seals on all the doors in the reactor building, or placing an electricity-generating turbine on the facility's roof, where the water might not have reached it. In addition, wrong assumptions were made*", he said. Finally he concluded with the following lesson: "*What happened at Fukushima was, yes, a warning to the world,"* he said. The resulting lesson was clear: *"Try to examine all the possibilities, no matter how small they are, and don't think any single counter-measure is foolproof. Think about all different kinds of small counter-measures, not just one big solution. There's not one single answer. We made a lot of excuses to ourselves … Looking back, seals on the doors, one little thing, could have saved everything*".

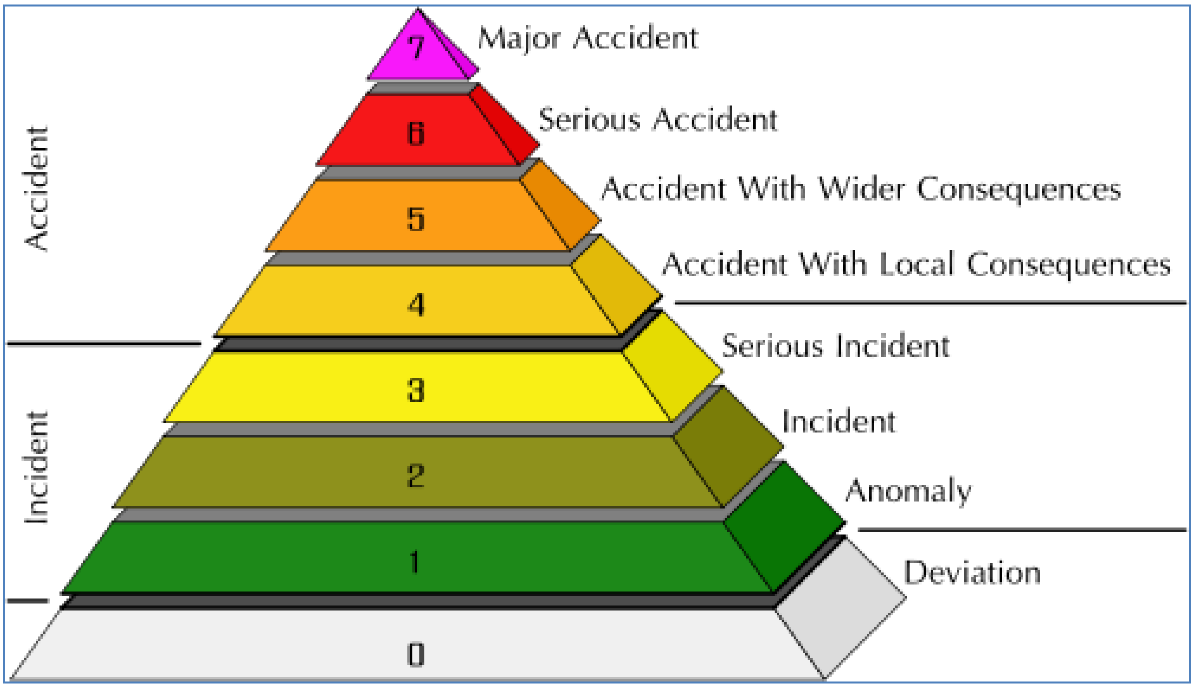
2.4 Some basic information about risk assessment in nuclear industry

The International Nuclear and Radiological Event Scale (INES) was introduced in 1990 by the International Atomic Energy Agency (IAEA) in order to enable prompt communication of safety significant information in the event of nuclear accidents. The selection of a level, on the INES (Figure 1), for a given event is based on three parameters: whether people or the environment have been affected; whether any of the barriers to the release of radiation have been lost; whether any of the layers of safety systems are lost. Broadly speaking, events with consequences only within the affected facility itself are usually categorised as 'deviations' or 'incidents' and set below-scale or at levels 1, 2 or 3. Events with consequences outside the plant boundary are classified at levels 4, 5, 6 and 7 and are termed 'accidents'.

The scale is intended to be logarithmic, similar to the movement magnitude scale that is used to describe the comparative magnitude of earthquakes. Each increasing level represents an accident approximately ten times more severe than one on the previous level. Compared to earthquakes, where the event intensity can be quantitatively evaluated, the level of severity of a man-made disaster such as a nuclear accident, is more subject to interpretation. Because of this the INES level is assigned well after the incident of interest occurs. Therefore, the scale has a very limited ability to assist in disaster-aid deployment.

Nuclear reactor incidents/accidents are classified using the following scale (In descending order of criticality):
7 - Major Accident (Chernobyl, 1986 – USSR and Fukushima, 2011 - Japan)
6 - Serious Accident
5 - Accident With Wider Consequences (Three Mile Island, 1979 - USA)
4 - Accident with Local Consequences (Windscale, 1957 – UK)
3 - Serious Incident (2013; In a further incident of the Fukushima Daiichi nuclear disaster, 300 tonnes of heavily contaminated water had leaked from a storage tank.)
2 - Incident
1 - Anomaly
0 - Below Scale/No Safety Significance.

Figure 1: The INES scale of nuclear accidents



Note that up to level 3 on this scale the event is classified as an incident, whereas from level 4 onwards the event is classified as an accident.

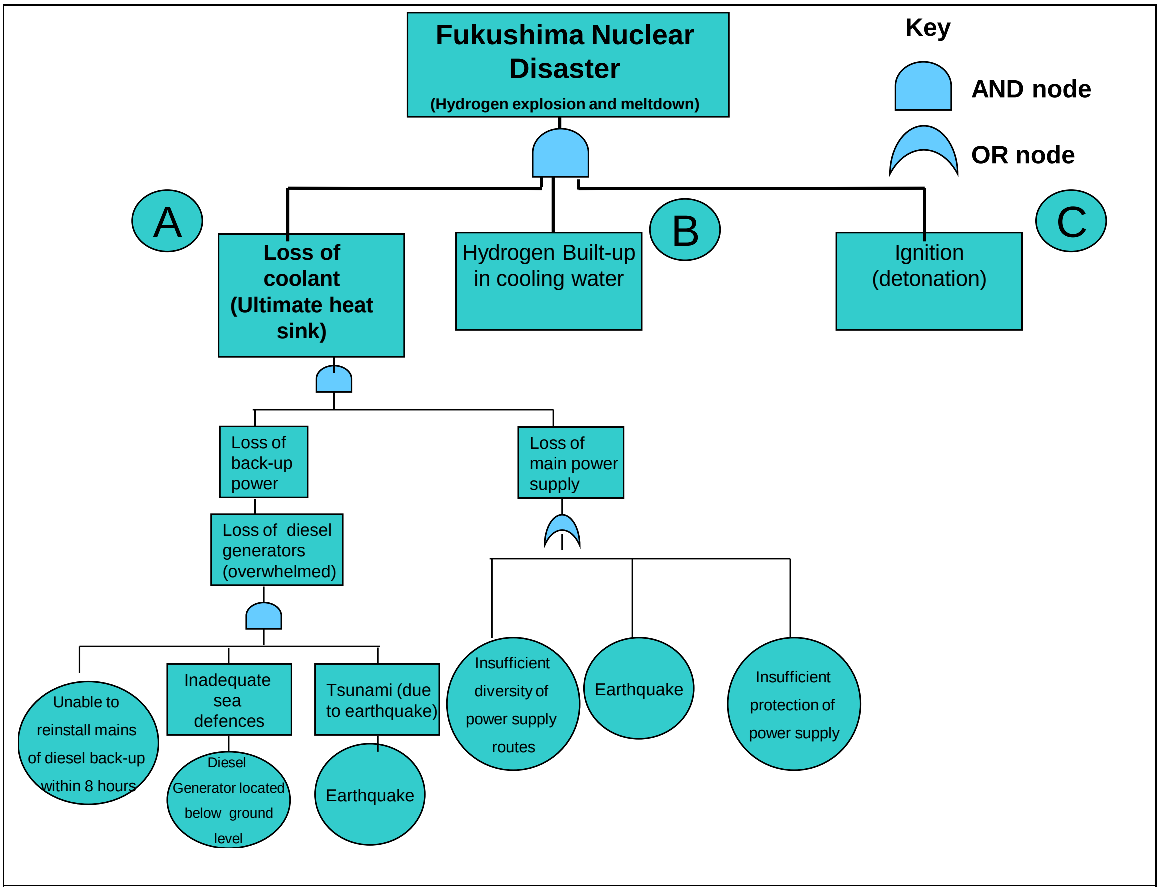
3. ANALYSIS OF 1ST GROUP OF DELEGATES

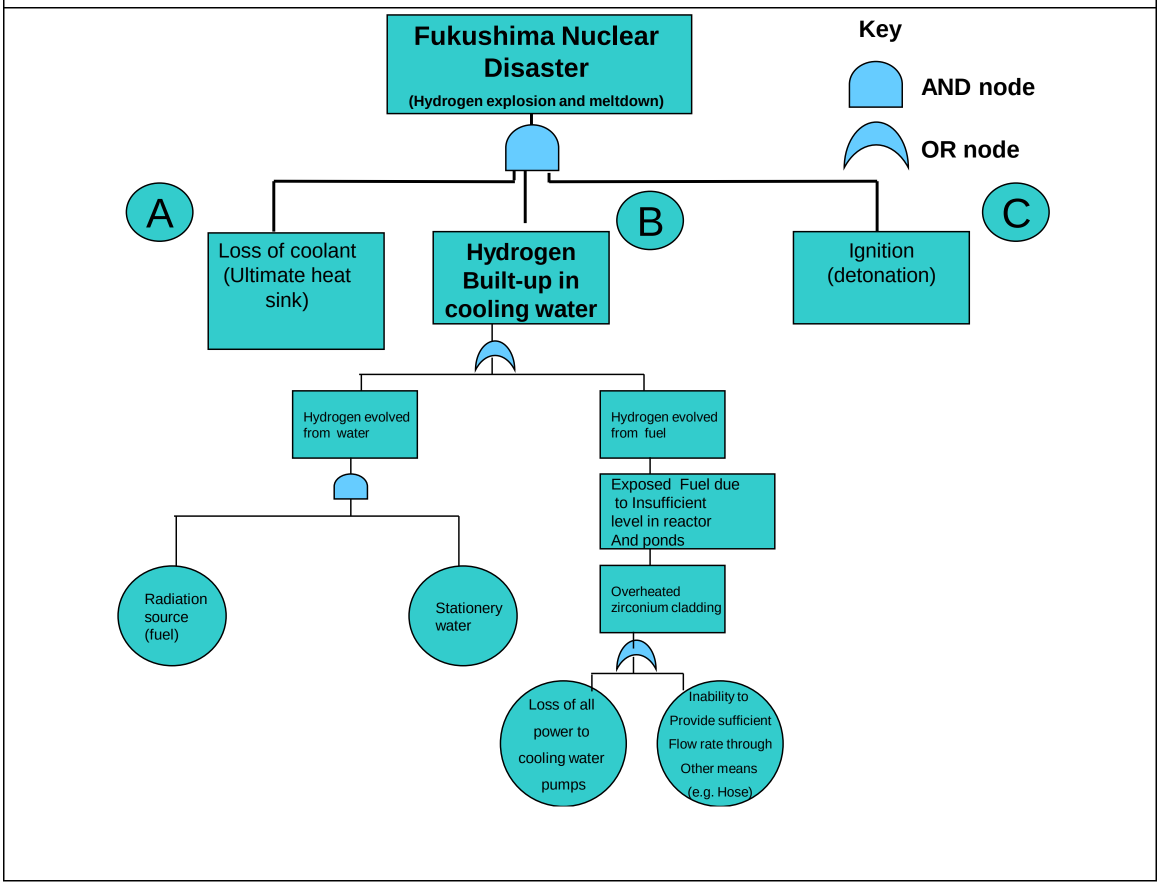
3.1 Summary of the analysis of the causal factors of the disaster

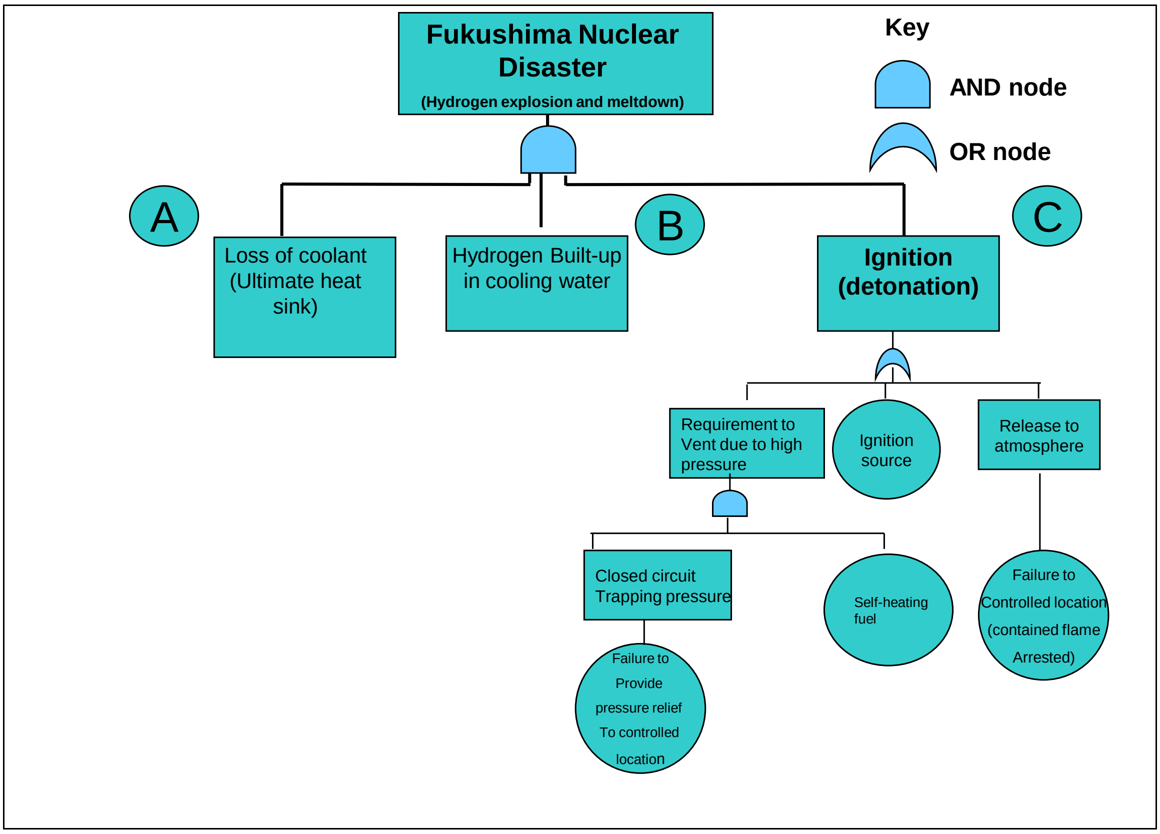
The Fukushima Daiichi incident was fundamentally down to poor design, in that the normal mains and both backup power supplies were allowed to fail due to a single common mode failure, albeit from an extreme natural event. The mains supply integrity was such that the earthquake damaged it beyond repair and no diverse supply remained intact. The diesel generator system was located in a plant room likely to be swamped, and again no diverse connection point remained. And finally, neither could be repaired before the backup power supply was exhausted. The potential for an earthquake-generated tsunami in excess of the existing sea defences, and therefore capable of these effects, was not only realistic, it was actually foreseen in 2007 and calculated as likely in the lifetime of the plant [7]. But the plant continued to be operated and the sea defences were not improved, and the resilience of the cooling water system was not increased. Furthermore, the ability to provide cooling by other means was insufficient both with respect to the training and readiness to do so, and also as regards to the physical hardware to do so. Quite simply, without the installed pumps they could not provide enough water to prevent the pressure rising to unacceptable levels by any other installed emergency system [3]. The ability of the installed design to control, contain and direct excessive pressure was insufficient. Even if cooling could not be re-established there should be a means of safely directing the vented material to a suitable location. This was absent. In addition, the vent was not controlled from the point of view of fire suppression. In both cases, the venting to a suitably large installed system containing, for example, nitrogen blanketing would have limited the potential for the vented material exploding.

Fault Tree It is proposed that the process of evolution of the hydrogen explosion above Fukushima can be represented by a Fault Tree, as in Figure 2. The hydrogen explosion and the meltdown were due to three simultaneous factors; loss of coolant (ultimate heat sink), hydrogen built-up in cooling water and ignition (or detonation). The term ‘ultimate heat sink’ refers to the function of dissipation of residual heat after a shutdown or an accident.

Figure 2 (a,b,c): The Fault Tree Analysis of Fukushima Nuclear Disaster


Fukushima Nuclear Disaster
(Hydrogen explosion and meltdown)
Key
AND node
OR node
A
Loss of coolant (Ultimate heat sink)
Hydrogen Built-up in cooling water
B
Ignition (detonation)
C
Loss of back-up power
Loss of main power supply
Loss of diesel generators (overwhelmed)
Unable to reinstall mains of diesel back-up within 8 hours
Inadequate sea defences
Tsunami (due to earthquake)
Insufficient diversity of power supply routes
Earthquake
Insufficient protection of power supply
Diesel Generator located below ground level
Earthquake


Fukushima Nuclear Disaster
(Hydrogen explosion and meltdown)
Key
AND node
OR node
A
Loss of coolant (Ultimate heat sink)
Hydrogen Built-up in cooling water
B
Ignition (detonation)
C
Hydrogen evolved from water
Hydrogen evolved from fuel
Exposed Fuel due to Insufficient level in reactor And ponds
Radiation source (fuel)
Stationery water
Overheated zirconium cladding
Loss of all power to cooling water pumps
Inability to Provide sufficient Flow rate through Other means (e.g. Hose)



Given that the possibility of such a large tsunami was foreseen [7], it follows that through that the consequences were also foreseeable via a suitable FMEA. Therefore, the failure to carryout suitable hazard analysis, and implement the actions thus identified, was also a design failure. In short, the event was foreseen and design shortcomings were not investigated nor addressed. This aspect of the disaster, the hydrogen explosions, was fundamentally due to the lack of resilience of the cooling water circuit.

4. ANALYSIS OF 2nd GROUP OF DELEGATES

The second group part has applied the Analytical Hierarchical Process (AHP) to decide on the future of nuclear power usage in Japan following the Fukushima devastation by earthquake and tsunami effects. This part of the paper demonstrates the applicability of AHP in multiple criteria decision making processes.

4.1 Summary of the analysis of alternative nuclear power decisions for Japan

Exploration of the Fukushima incident leads back to the question; "*What went wrong*?" Could the station blackout have been avoided? Was it an engineering design and operations problem or a management and regulatory system failure? A Greenpeace International report [8] on the incident claimed that the accident marked the end of what it called the *'nuclear safety' paradigm*. The report drew the unusual conclusion that the notion of *nuclear safety* does not exist after what happened at Fukushima, but all that can be talked about concerning nuclear reactors are risks, unknown risks in the worst case. The report went on to say that, at any time, an unforeseen combination of technological failures, human errors or natural disasters at any one of the world's reactors could lead to a reactor quickly getting out of control. The report questioned the defence in depth of the engineering design barriers for nuclear power plants and disputed the PRA based postulation of only one core meltdown likely to occur in every 250 years. Being a humanitarian focussed organisation, Greenpeace did not consider the technicalities leading to the Fukushima accident, but rather focussed on the response both by the licensed operator, in this case TEPCO, and the Japanese regulatory authorities. It did not spare the IAEA in laying the blame and flaws on the agency's stance on the incidence. What becomes clear, one of the contributors to the report claimed, is that the weaknesses in the regulation and management of Japan´s nuclear power industry have not been 'hidden' faults in the system. On the contrary, people had been aware of, written and warned about them for decades [8]. So, from the humanitarian viewpoint of the report, the Fukushima accident was a regulatory system failure. Risks were known but no action was taken to address them. From a neutral perspective this does not justify the claim that safety in nuclear stations is non-existent. Rather, it points to the need to address some system deficiencies and suggests improvements that can make nuclear power even safer.

The IAEA report, on the other hand, conceded that Fukushima was an extremely unprecedented case and claimed that the response was the best that could be achieved considering the circumstances. However, it accepted that there were insufficient *defence-in-depth* provisions for tsunami hazards, in the sense that although these were considered both in the site evaluation and in the design of the Fukushima Daiichi NPP, and the expected tsunami height was increased to 5.7m after 2002, the tsunami hazard was actually underestimated. However, the view is that this was just a *black swan event* and does not invalidate the applicability of PRA postulates in nuclear power applications. In the Fukushima case the additional protective measures taken as result of the evaluation conducted after 2002 were not sufficient to cope with the high tsunami run up values and all associated hazardous phenomena. What comes out clearly from the IAEA report is that the design review underestimated the tsunami effect and this could therefore be classified as a design and reengineering failure. The nuclear authorities generally differ regarding the humanitarian view, in the sense that they see the incident as offering an opportunity for improvement in nuclear power probabilistic risk assessment, rather than a trumpet for propagating the message that nuclear power should be scrapped or be perceived as a public hazard. The general consensus at the *World Nuclear Fuel Cycle 2011 Conference* was in support of this view, the prevailing view at the conference seeming to be that nuclear energy will be providing utility power around the world for a long time, despite the accident at Fukushima Daiichi. This assertion was based on expert knowledge with minimal application of the decision making tools available at the time.

Faced with the foregoing two opposite views regarding the place for Japan's (and ultimately the world's) nuclear power usage, we shall now explore the available options for human safety driven improvement (or change) applicable to the Japan circumstances with respect to utility power after the Fukushima incident.

Option 1: Replace all nuclear power with alternative sources

This is a popular view among the environmental protection and humanitarian organisations. The Greenpeace report [8] suggested that a significant nuclear accident is bound to occur every decade, based on known incidences, and that puts a question mark over the applicability of nuclear power from the environmental safety perspective. The option to replace all NPPs in Japan is, however, based on the assumed existence of renewable energy sources, or other safer alternatives that could make up for the nuclear phase-out.

Option 2: Continue using NPP with improved barriers to external influences and better legislation

This is a popular view among the nuclear industry professionals. It is based on the belief that nuclear is one of the safest forms of energy and that PRA postulates on the probability of occurrence of catastrophic nuclear accidents are generally correct, i.e. the probability is remote. Failure in this case is an opportunity for learning, albeit that it comes at a great cost. Others have gone as far as proposing a review of how sites for nuclear power plants are selected by considering the historically based probability of natural occurrences.

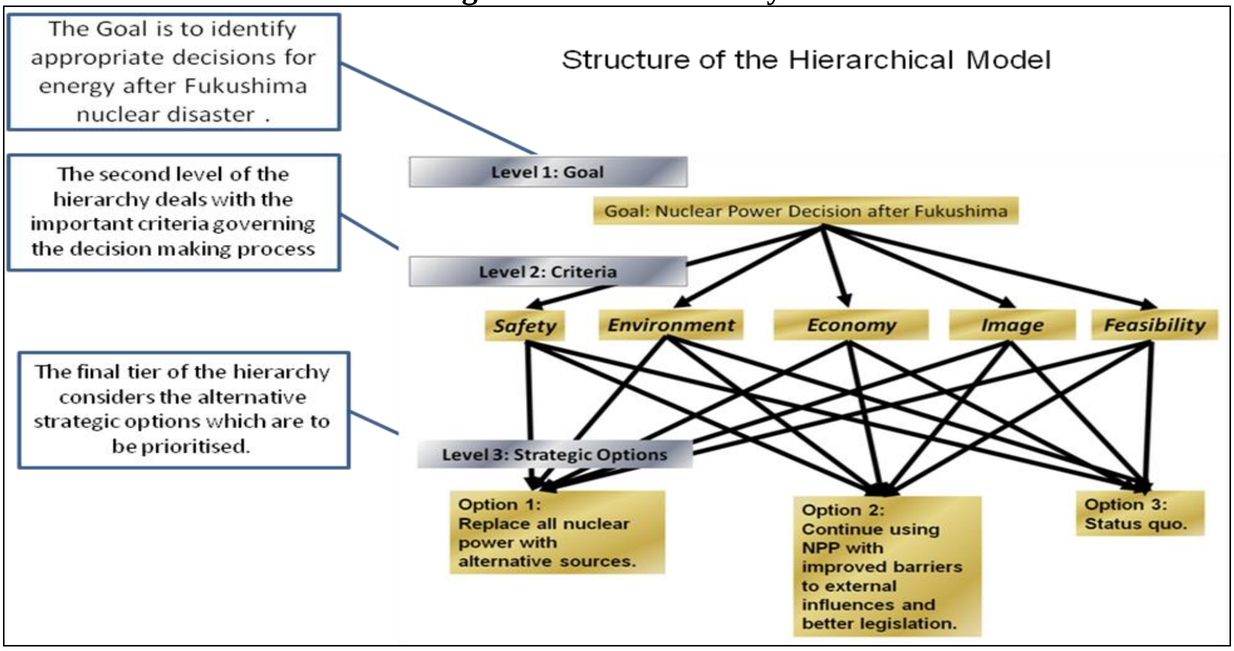
Option 3: Continue with status quo

This option is based on the view that nuclear accidents of large magnitude are *black swan* incidents, one in every 250 years according to present probabilistic risk assessment theory. This *black swan* claim however, would appear to the environmental pressure group to be undermined by the much shorter time lapse between the Chernobyl and Fukushima disasters.

4.2 Application of MCDM

The three available options here are subjected to an MCDM process, viz. AHP based on the attributes of Safety, Environment, Economy, Image and Feasibility. The image criterion is considered from the legislature's point of view, i.e. that of the Japanese government and its nuclear regulatory agency, the Nuclear Industrial Safety Agency (NISA) and, on the extreme end, the IAEA and its affiliates. The AHP hierarchy thus developed is shown in Figure 3.

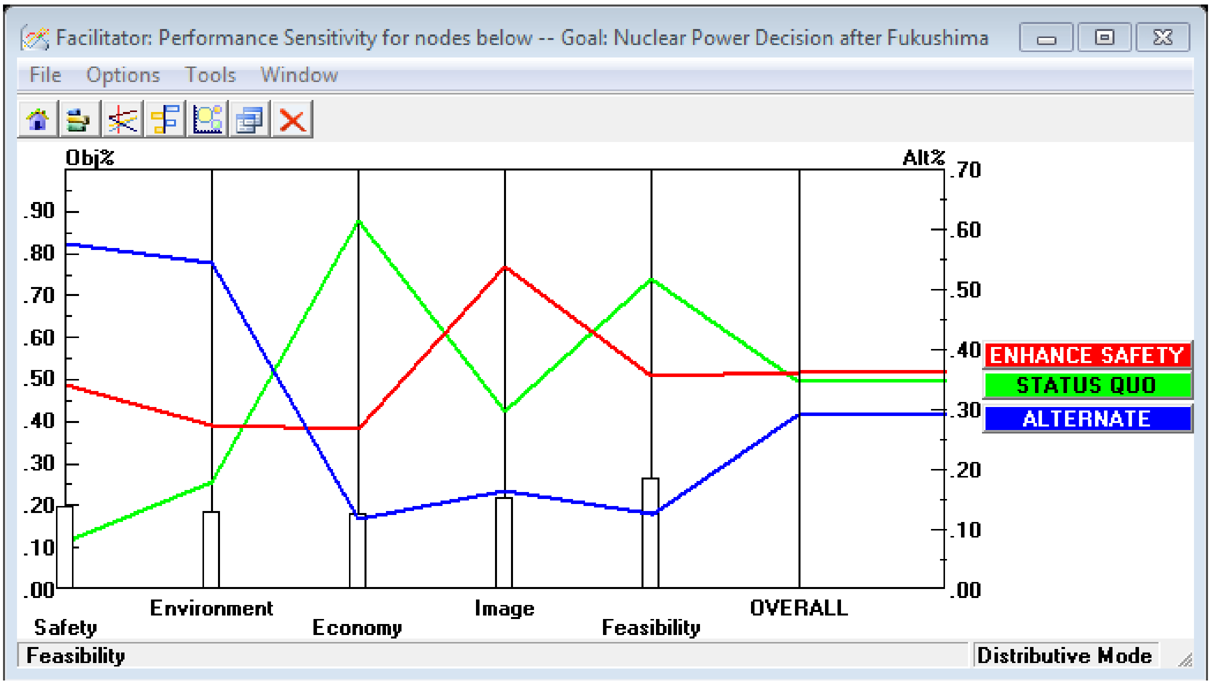
Figure 3: AHP Hierarchy



The AHP Results

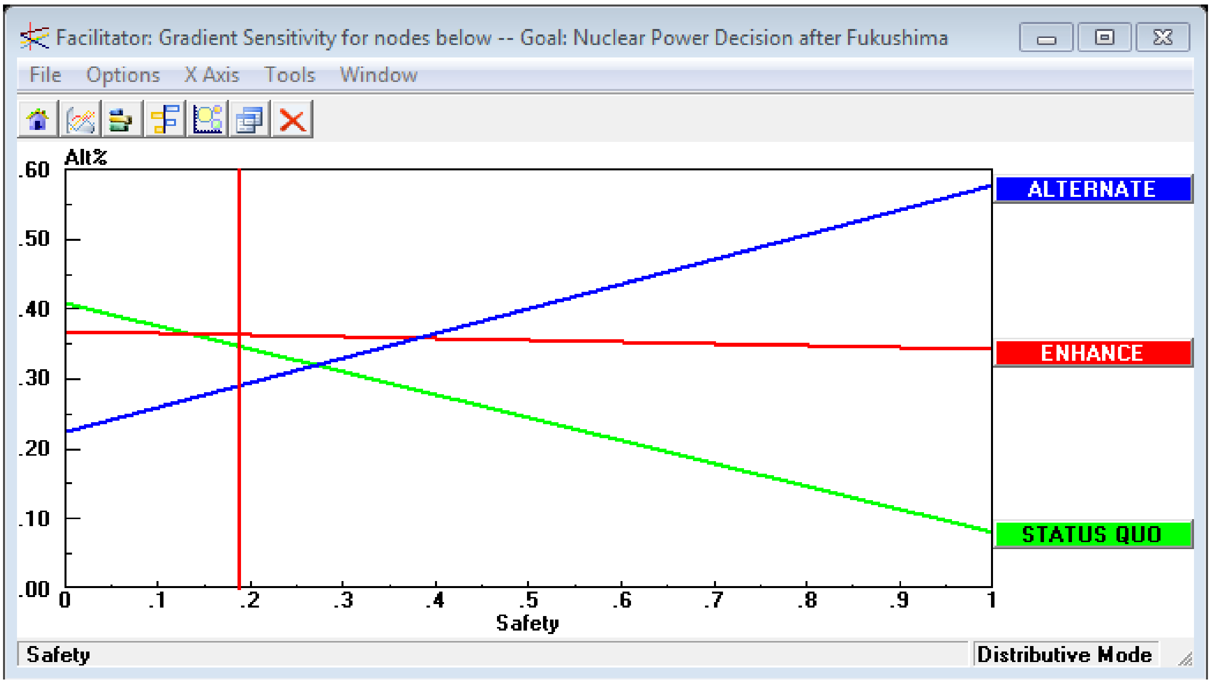
Following traditional AHP guidelines the five attributes in the hierarchy were weighted, between 0 and 1. The attribute "*feasibility"* has the highest score, whatever alternative is to be chosen; first and foremost the alternative has to be feasible, then the rest can be considered, otherwise the analysis would be of no practical use and a waste of resources. Subsequent pairwise comparisons were done, more importantly the one with alternatives for the opposing sides i.e. environmentalists and IAEA.

Figure 4: AHP Synthesis and Sensitivity Analysis



The performance sensitivity nodes representation in Figure 4 shows how the different alternatives rate with respect to the objective. It depicts the option *enhance nuclear safety* as the preferred option.

Figure 5: AHP Safety Sensitivity Graph



The gradient sensitivity with respect to the attribute "*safety"*, shown in Figure 5, indicates that, as far as safety is concerned, the use of alternative energy sources is the preferred option, while disregarding safety would result in the *status quo* option being preferred. This can be illustrated by moving the vertical line that indicates the importance of "safety" to the left, then the highest intersecting option (most preferred) becomes the one that belongs to the option *status quo.*

The favoured alternative is to continue using nuclear power in the foreseeable future, but with enhanced safety features, derived from revised PRA/PSA, to deal with the advent of extraordinary forces of nature such as the one that devastated Japan in March 2010. The concept of continuous improvement touted by proponents of *Probabilistic Risk Assessment* should be the guiding principle. One proposal is to possibly reconsider tectonic characteristics for nuclear power sites. Another is that the defence-in-depth structural design should also take account of the incidence of terrorist action such as the 7/11 attack on the World Trade Centre.

It must be mentioned, however, that normal AHP uses aggregate analyses from a number of people, presumably to reduce subjectivity, include all relevant stakeholders and promote consistency. But this has not been the case with this study as only one small group of participants was employed to carry out the analysis. Nevertheless, it does provide a framework which could be used by a number of participants to settle the nuclear power debate. The use of *expert knowledge* as prescribed by AHP could add more credibility to the findings of the analysis.

5. CONCLUSION

It is noticed that both teams of delegates have produced slightly different, yet complementary, mental models although they were exposed to the same narrative. The main differences were in the level of detail each group went into and techniques chosen where the fault tree analysis where used by the first group and it offered insight into the technical issues, whereas the second group used qualitative strategic analysis using the AHP approach. Nevertheless, on the whole, there were more agreements than otherwise in the findings of the two groups.

The paper demonstrates using the case of Fukushima nuclear disaster, that both qualitative and quantitative approaches are important techniques, which are useful to gain better insight into analysis of risk at different levels. This is in line with what Apostolakis has previously proposed [9].

It is clear from the fault tree analysis that the main causal factor was due to initial poor design specifications, especially related to the height of sea walls, and the installed backup systems, in that there was insufficient provision for alternate cooling water supply by other means or for controlled safe pressure relief.

Whereas on a more strategic level the nuclear power generation debate relates to the issue of regulation. According to [10 and 11], it is proposed that the time has come to introduce a Japanese and a global independent nuclear safety commission in order to separate national economic and political interests in promoting nuclear power from the regulatory function, which concerns all nations. Accordingly, it was recommended to elevate the mandate of the IAEA to include a licensing function for nuclear power plants, thereby changing its status from an advisory body to that of an international institution with authority to make legally binding decisions. This is in line with the findings of this paper, since it was noticed that the root causes for the disaster can be attributed to deficiencies in regulation and in setting design specifications based on risk assessment. In terms of setting design specifications based on risk assessment, it can be claimed that more research is needed in this field where the emphasis should shift from ‘probability’ assessment to ‘possibility’ identification. Mathematically, it is relatively easier to formalise the former than the latter.

To test for a cumulative probability of a one in ten million chance of a nuclear failure each year would require living for many years to prove its validity. But it could also mean to build 1,000 reactors and operate them for 10,000 years and expect a probability of one of them to fail during that period, which is a better proposition than the original one but still quite a long time.

Now, let us compare these ambitious estimates with the current state. Across the world there are about 435 nuclear power reactors operating, with over 140 in Europe, and 54 in Japan (Weightman, 2011), and around 100 in the USA. Fukushima is the third major nuclear accident (i.e. it was preceded by Three Mile Island and Chernobyl) and all three happened within less than half a century, which makes us question our models and original assumptions. So the current state suggests that the Mean Time Between Failures (MTBF) for the three major accidents (in 1979, 1986, and 2011) currently stands at just 10 years, which is very far from the ambitious 1 in a 10 million chance. This view is supported by [12] which also suggests a catastrophic accident to be expected every 12-15 years. Clearly, Three Mile Island, Chernobyl, and Fukushima each arose from very different circumstances, invalidating various modeling and risk assessment assumptions, and resisting assimilation into a single data set. It is difficult, with such a small sample size, to make generalizations about where current risk models fail, though we agree with the argument put forward by [10] which suggests that the original ambitious annual failure risk estimates were serious underestimations.

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