The Impact of Severe Nuclear Accidents on National Decision for Nuclear Decommissioning

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1. Introduction

After the Fukushima accident, some countries have been concerned about their nuclear power programs. Germany decided to close their Nuclear Power Plants (NPPs) entirely [1]. In fact countries new to nuclear power generation now feel there is a real necessity for early preparation for decommissioning, as unexpected premature shutdown of NPPs has intensified after the Fukushima accident. Locally, the Korean government decided to shutdown Kori-1 permanently in 2015. This decision was an indirect consequence of the Fukushima accident as well as design obsolescence.

Until now, many researchers have tried to identify the impact of severe nuclear accidents on a country's or international nuclear energy policy [2-3]. However, there is little research on the influence of nuclear accidents and historical events on a country's decision to permanently shutdown an NPP versus international nuclear decommissioning trends. To demonstrate the correlation between a nuclear severe accident and the impact on world nuclear decommissioning, this research reviewed case studies of individual historical events, such as the St. Lucens, TMI, Chernobyl, Fukushima accidents and the series of events leading up to the collapse of the Soviet Union. For validation of the results of these case studies, a statistical analysis was conducted using the R code. This will be useful in explaining how international and national decommissioning strategies are affected by shutdown reasons, i.e. world historical events.

2. Method and Hypothesis

In this section, the methodology used for statistically analyzing the data was the Pearson correlation test. This paper investigates the relationship between severe nuclear accidents and the number of international NPPs designated to be shutdown for decommissioning, which forms the hypothesis of this study.

2.1 Pearson product-moment correlation coefficient (r)

The Pearson's correlation coefficient (r) is a technique for investigating the relationship between two quantitative variables [4]. The correlation may be any value from –1 to +1. If the value is 0, there is no 'linear' correlation. A negative sign means the dependent variable will decrease when one independent variable increases [5]. This paper analyzed two variables; time period and the number of NPPs. The R code (version R-3.2.3), at a 95 percent confidence level was used for the statistical analysis. Using this program, the Pearson's correlation coefficient (r), p-value (two-side) and df (degree of freedom) were measured. The p-value is the probability that a statically significant event has occurred. When the p-value (one-side) is less than $\alpha=0.05$, the hypothesis is supported. As the p-value decreases, the result is more statistically significant.

2.2 Hypothesis

Historically, the reasons for plant shutdown were significantly influenced by the international nuclear decommissioning strategy, during that period [6]. Reasons of shutdown can be divided into 3 categories: accidents, economics and political issues. Focusing on accidents and political issues, this study evaluated the impact of nuclear events on the international status (operating, shutdown, etc.) of NPPs. To confirm this correlation (events and history influencing NPP shutdown) the following hypothesis was statistically analyzed:

> *The number of NPPs relegated to permanent shutdown will increase in response to historical incidents such as nuclear severe accidents and major historic events (i.e., end of cold war).*

3. Results

3.1 Data collection and assumption

For these case studies and the correlation analysis, data were collected from the IAEA annual report in 2015. In addition, an empirical equation was developed to reflect the impact of nuclear severe accidents and historical events. This equation was developed based on the literature [2-3]. However, it was very difficult to evaluate the impact of several historical events. There are only a few studies [2-3] that attempt to develop an empirical relationship For example, to consider the impact of several accidents on the public, many social scientists focused on the importance of risk perception by each country's citizens, levels of public knowledge and mass media influence. Usually, the public and the government quickly forget the accident as time goes by. This can be seen in a recently survey on Japanese perception from 2011 to 2015. According to a human cognitive paper, the memory time of the public is

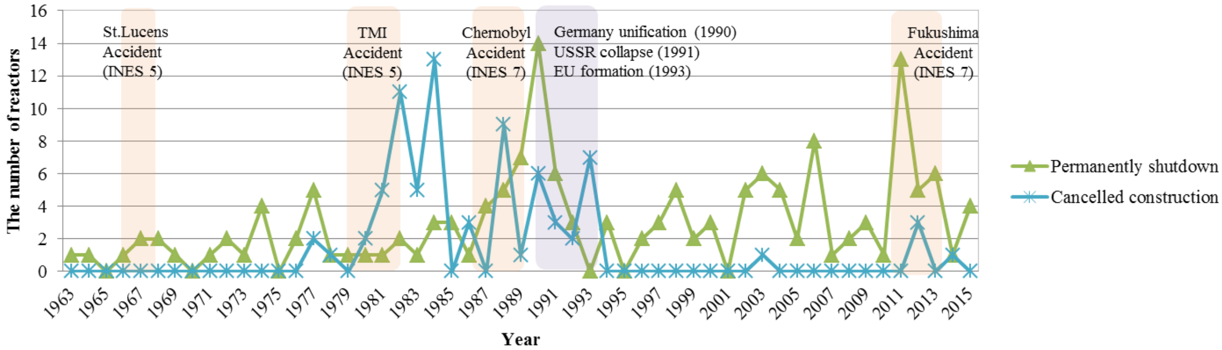

Figure 1.Permanently Shutdown and Cancelled Construction of Nuclear Power Reactors by Year

generally 5-7 years. In addition, when a nuclear event (high on the IAEA incident scale, 5-7) occurs in a country, it can have a significant effect on the surrounding countries. This is particularly true when the distance between the area where the accident occurred and a neighboring country's capital is short. However, this study focused on the international nuclear event scale (INES) and the effect of time, by year, on the number of permanent shutdowns that occurred. To capture and confirm this information, this study developed an empirical equation for evaluating the impact of a severe nuclear accident, by year from assuming that the accident occurred in year 1. The empirical equation below was employed from the end of the year the accident/historic event occurred until the present:

$$\text{Impact on Severe Accident} = e^{(-(the\ year - 1\ year\ after\ the\ accident\ occured))} \times e^{(-\frac{1}{INES})}$$
(1)

As an example, the results from employing the empirical equation, in the case of 'The end of the cold war' and associated historical events are given below.

3.2 Case studies and supporting statistical results

For nuclear power plants, permanent shutdown of a reactor is regarded as the first stage of decommissioning. Some countries try to establish their nuclear decommissioning policy as part of their nuclear energy policy, before reaching the reactors' lifetime. However, sometimes countries have to prematurely shutdown their reactors because of political reasons affected by historical events, anti-nuclear activities or the occurrence of a severe accident. Thus, it is significant to investigate the reasons for reactor shutdowns and understand the factors that result in a country's final strategy decisions. Figure 1 shows the fluctuations in the status of shutdown and cancelled construction of reactors by year. When a historical event related to nuclear incidents occurs, a pronounced tendency to prematurely shutdown reactors (green line), and cancel construction (blue line) is observed as shown in the figure. These events include severe nuclear accidents. Accidents with an INES ranking of over 5, such as St. Lucens in 1966, TMI in 1979, Chernobyl in 1986 and Fukushima in 2011 are highlighted in Figure 1. In addition, this paper includes one of the most significant modern world historical incidents (1990 – 1993 highlighted in purple), which included the end of cold war, German unification in 1990, USSR collapse in 1991 and EU formation in 1993.

St. Lucens accident

As shown in Figure 1, historical events tend to have influence over the issue of when reactors are permanently shutdown or construction is cancelled. An exception is the St. Lucens accidents in Switzerland. In the St. Lucens case, the reactor's core was melted but radioactive material was not released. Also, in 1966 information exchange was limited in the number of venues for media and communication, and there was no regulator requirement for early notification of a nuclear accident. The 'Convention on Early Notification of a Nuclear Accident', an international convention included nuclear operating countries' duty on severe accident notification to surrounding countries, was established only after the Chernobyl accident. As a result the influence this 1966 event had, was localized.

To support this "localized phenomenon" theory, the following analyses were conducted. First, it was determined whether there was a correlation between the "event" and the shutdowns and canceled constructions that occurred. This was evaluated by conducting a Pearson's product-moment correlation using the R code. The results supported the localized explanation with r=-0.1006381, t = -0.80287, df = 63, p-value = 0.4251 (two-side). In case of the number of cancelled construction, there is no correlation because there was no new plan of NPPs construction in the world at that time (r=-0.1168796, t = -0.93411, df = 63, p-value = 0.3538). However, according to the literature review, after this accident, Switzerland decided to give up nuclear power plant construction for a period of time. In nearby Austria, although construction of an NPP was almost completed in 1978, the plant was ultimately shut down because of a public referendum. Though the statistical analysis does not support a direct correlation for shutdowns and canceled construction with the St. Lucens accident, we still could not say 'zero correlation with St. Lucens.

TMI accident

In 1979, the Three Miles Island (TMI) accident occurred in the US. It had the same ranking as the St.

Lucens accident. However, despite the fact that there was no release of radioactive material to the environment, a local resident exodus phenomenon occurred. This led to this accident's large social impact, i.e., increase in serious anti-nuclear activities. In addition along with former president Jimmy Carter's Anti-nuclear bomb policy, the United States cancelled their construction of nuclear power plants. At some point after the TMI accident, the number of reactors cancelled increased but the energy policy fostered the continued operation of the remaining nuclear reactors until they complete their lifetime. From 1979 to 1984, many international nuclear power plants' construction plans were cancelled. This accident frustrated some countries' nuclear energy plans, especially the US and Sweden. This paper found a positive correlation between the accident and cancelled construction of nuclear power plants as shown in Table 1. However, there was no significant correlation between the number of permanently shutdown NPPs and the TMI accident based on Table 1,supporting our interpretation of the historical data.

Chernobyl accident

In late 1980s, the number of permanently shut down reactors and cancelled construction was high, and this tendency was still ongoing in early 1990s. The Chernobyl accident was caused by human error during a low-power engineering test of the Unit 4 reactor on April 26, 1986. This accident was the most devastating nuclear accident along with the Fukushima accident in 2011. Both accidents received an INES ranking of 7. As a result of the Chernobyl accident, former Soviet Union republics and large parts of Europe were contaminated. After the accident, several European countries, i.e., Italy, Finland, Switzerland and Sweden, decided to restrict the use of nuclear energy by halting construction and shutting down nuclear reactors. Statistical analysis' results also support this phenomenon with the observation of a positive correlations between the accident occurrence and the number of world NPP shutdown (or the number halting construction).

Historical events relating to the end of the cold war

With the anti-nuclear movement in Europe during 1990-1993, negative awareness of nuclear power plants was expanded. Moreover, Soviet Republics' and East European's almost broke down because of economic difficulties in communism and the Gorbachev reformation. This historical event had an impact on European government's decision making regarding nuclear energy. German unification occurred in 1990 which led to the permanent shut down of East German reactors. The result of the R code analysis showed correlations between timeline events in 1990-1993 and the number of permanently shutdown (r= 0.3306818, t = 2.7812, df = 63, p-value = 0.007135). In addition, there was also a correlation between the cancellation of NPPs' construction projects during this period (r=0.3446725 t = 2.9143, df = 63, p-value = 0.004929). Thus it could said that these events had a significant impact on nuclear energy use and policy.

There are, however, other factors involved in the development. At that time, several prototype reactors were approaching their lifetime limits. During 1990-1993, 13 units were closed for fulfilling their purpose and operating full-term through their design lifetime. There were also political factors. With EU formation, the European Commission (EC) requested an agreement between EU and the government which hopes to enter the EU club. These agreements contained a clause for premature shutdown of Russian types of reactors like VVER and RBMK which were evaluated as 'not safe reactor'. This event also affected many countries' decision on nuclear power, such as Bulgaria, Lithuania and Ukraine, until 1999.

During the 10 years before Fukushima accident occurred, there was no cancellation of NPP construction plans except one which is SINPO-1 at North Korea in 2004. This case is unique as the case of political influence on the decision under pressure of international politics. This action was to prevent the country from expanding their nuclear weapon capability. In the 2000s, there were several shutdowns of NPPs because of political reasons and/or of economical reasons. However, there was no clear correlation between the number of shutdowns and historical events in 2000s. At that time, with the purpose of sustainable economy development and CO2 reduction, the era of nuclear renaissance ensued. Many countries adopting phase-out nuclear energy policy, such as Italy, Belgium and Switzerland, changed their nuclear energy policy to re-start NPPs, but this trend did not last long because of the Fukushima accident. For example, Belgium had a high level of dependence on nuclear energy at 54% before the Fukushima accident. But, they were pressured from the EU's nuclear phase-out policy while struggling with the energy security issue. Even though they selected the phase-out policy after the Chernobyl accident, they still relied on nuclear energy by extending the lifetime of their NPPs for 10 more years in 2009. However, they eventually returned to their past nuclear phase-out policy, and this situation was similar as Italy and Switzerland.

Fukushima accident

On March 2011, a major catastrophe, on the scale of Chernobyl ranking at INES 7, occurred. In the Fukushima accident, the core melted on Units 1, 2 and 3, resulting in cooling loss, and a hydrogen explosion in Unit 4. As a result of this event, many nuclear reactors around the world were shutdown, especially in nuclear phase-out countries like Switzerland, Italy, Germany, Belgium and Japan. Right after the Fukushima accident, Japan decided to shutdown all of their NPPs. First the government announced to the public that Japan would be 'the zero nuclear energy country'. But by May 2012, it seemed impossible to replace existing nuclear power generation with renewable or alternative energy sources. Recently, the Japanese government restarted the operation of their Sendai 1 nuclear power plant. It is mentioned here because this study only covered the number of 'permanently shutdown' NPPs. According to the Pearson correlation, the result of shutdown NPPs was r= 0.4161523, t = 3.6326, df = 63, p-value = 0.0002825 (two-side). Because the p-value was less than α=0.05 and r=0.416, we know there was a positive correlation between Fukushima and permanent shutdown. However, there was no significant correlation between the number of cancelled NPP construction projects and the Fukushima accident based on these results (r=-0.01558395, t = -0.12371, df = 63, p-value = 0.9019 (two-side)). Only in Bulgaria, was cancellation of the construction of NPP after the Fukushima accident, by the Russia government was observed. However, for evaluating the impact of this accident, it seems premature to make judgment on this result as the time period is still too short to correlate the world trends with this event. The shutdown status of Germany's NPPs after 2011, for example, is related to more or less the reactor aging issue that drives their permanent shutdown in 2016~2017. Table 1 shows the summary of the results from the Pearson correlation test.

Table 1. Summary of Results of Pearson Coefficient Test

	Cancelled Construction			
	P-value (two side)	t value	R(Pearson coefficient)	Df
St. Lucens	0.354	-0.934	-0.117	63
TMI	0.049	2.005	0.245	63
Chernobyl	0.093	1.706	0.210	63
The end of cold war	0.005	2.914	0.345	63
Fukushima	0.902	-0.124	-0.015	63
	The number of world NPPs (Shutdown)			
	P-value (two side)	t value	R(Pearson coefficient)	Df
St. Lucens	0.425	-0.803	-0.100	63
TMI	0.342	-0.957	-0.119	63
Chernobyl	0.058	1.933	0.237	63
The end of cold war	0.007	2.781	0.331	63
Fukushima	2.83e-4	3.633	0.416	63

4. Conclusions

In conclusion, nuclear severe accidents and historical events have an impact on the number of international NPPs that shutdown permanently and cancelled NPP construction. This directly impacts international nuclear decommissioning policy and nuclear energy policy trends. The number of permanently shutdown NPPs was selected as an indicator because any relationship between the number of permanently shutdown NPPs and historical events can be immediately identified. As pointed out in Figure 1, there is a direct relationship between NPP permanent shutdown and historical events. This relationship indirectly reveals a potential correlation between historical events and international decommissioning trends.

To determine the extent of the impact an accident can have on the nuclear energy policies of a country,, like phase-out policy, this paper evaluated the number of NPP construction projects cancelled after a severe accident. Interestingly, a positive correlation with historical events and NPP construction cancellations was revealed. It means historical accidents can influence nuclear phase-out policy. Still, there are exceptions, such as the the accident which occurred in the1960s (St. Lucens) and period after the Fukushima accident. Thus, the historical decommissioning trend can be driven by historical events. This means several historical accidents and changes in the international political situation can result in the shutdown of NPPs for decommissioning. This conclusion is quite similar to previous studies from Z. Csereklyei in 2013 [3].

However, it is not the only significant factor in determining shutdowns. Another important consideration is the large number of reactors that have been closed after running approximately full-term of their lifetime. In addition to the reasons for shutdown, there are several general factors influencing the selection of decommissioning policy. For example, decommissioning also depends on a country's nuclear energy policy, reactor type and operation periods. Therefore, it is suggested that future studies address the general factors for determining nuclear decommissioning policy and strategies.

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