MSc Program
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Analysing Decision Making Process towards Life Extension Application of a Nuclear Power Plant

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
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Vienna, 26.04.2016

Affidavit

I, **BAVESH MOORTHY**, hereby declare

1. that I am the sole author of the present Master's Thesis, "ANALYSING DECISION MAKING PROCESS TOWARDS LIFE EXTENSION APPLICATION OF A NUCLEAR POWER PLANT", 92 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

Vienna, 26.04.2016

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Signature

कथं विद्यामहं योगिंस्त्वां सदा परिचिन्तयन् ।
केषु केषु च भावेषु चिन्त्योऽसि भगवन्मया ॥१०-१७॥

The Holy Bhagavad Gita: Chapter 10, Verse 17

ABSTRACT

On the paths and ideologies to alleviate dependence on carbon derivative fuels in light of climate change, improve energy security in the uncertain world of today coupled with reliability of energy supply, policy makers face some arduous choices and decisions. Prolonging the existing life of certain nuclear power plants helps alleviate some of the concern on a stable, reliable and dependable energy source in the near future while avoiding the hassles of new constructions involving studies, feasibility and assessment tests, etc. Nuclear power generators have a host of issues to consider when undertaking license renewals ranging from technical through regulatory to economics. This paper delves on the decision making process that all inherent parties- plant engineers, managers and operators would face when working together to ensure, when feasible, extension of the existing life of the power generating plant. Understanding the flow of ideas requires a thorough comprehension of the factors that are central to the process. Considering the composition of the atomic power plant in the form of a group cluster simplifies understanding the logical reasoning behind various issues that pertain to the individual constituent components and the group as a whole. Regulatory overview, with frequent checks and proper documentation of the decisions shall help in furthering the learning curve towards a better decision in the future. Logical reasoning aside, an informed decision would involve a plethora of influential factors including operating and maintenance history, technical compatibility, interference patterns, to name a few.

Keywords: nuclear power plant, plant life extension, decision making process, regulatory, license renewal

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LIST OF ABBREVIATIONS

ASN	Autorité de sûreté nucléaire *(Nuclear Safety Authority)*
BOP	Balance of Plant
BWR	Boiling Water Reactor
CANDU	Canada Deuterium Uranium
CO_2	Carbon- dioxide
$CO_{2eq.}$	Carbon- dioxide equivalent
COP	Conference of Parties
DG	Diesel Generator
EC	European Commission
EIA	Environmental Impact Assessment
ENSREG	European Nuclear Safety Regulators Group
ES	Electrical Systems
GHG	Greenhouse gas
HE	Heat Exchanger
HP	High Pressure
HVAC	Heating, Ventilation and Air- Conditioning
IAEA	International Atomic Energy Agency
IC	Integrated Circuit
ICS	Instrumentation and Control Systems
IEA	International Energy Agency
INES	International Nuclear and Radiological Event Scale
IPCC	Intergovernmental Panel on Climate Change
kWh	kilowatt-hour
LP	Low Pressure
LOCA	Loss of Coolant Accident
LWR	Light Water Reactor

NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply Systems
IAEA	International Atomic Energy Agency
OECD	Organisation for Economic Cooperation and Development
PLEX	Plant Life/ License Extension
PLIM	Plant Life Management
PSA	Probabilistic Safety Assessment
PWR	Pressurised Water Reactor
RPV	Reactor Pressure Vessel
SG	Steam Generator
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

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Any momentous work shall be incomplete without heralding the people who have been instrumental along the way.

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1. INTRODUCTION AND LITERATURE REVIEW

Six decades have passed since the commercial harnessing of nuclear energy brought about the Soviet Union to launch the first successful nuclear power plant as we know of it in the present day (Knief, 1992). The Soviets, Americans and others started the race towards building and safely harnessing the energy of the nucleus. This thesis work concerns Nuclear Power Plants operating on fission technology.

The nuclear industry from its beginnings has always had the oversight of not only regulatory bodies at home, but even with the founding of the International Atomic Energy Agency (IAEA) a global oversight on its activities.

With the development of nuclear power plants over the years came about the issue of ageing plants and whether to renew their licences, build new plants or rather to look towards alternative sustainable green carbon neutral energy sources.

Atomic power generation has been only around for the better part of half a century; nevertheless it has garnered a sizeable share of the energy production in the world market. While the development and learning curve of the nuclear power generation industry has matured really quickly, there are still numerous fields open to improve and learn from mistakes.

Over the years various notable incidents have shaped the public sentiment towards atomic energy starting with the Three Mile Island incident in 1979 in the United States, the Chernobyl incident in the erstwhile USSR in 1986 that was important from the European perspective and the latest being the Fukushima accident in 2011 in Japan.

Nevertheless, atomic power generation has its learning curve wherein technicians, operators and regulators improve their standing over time by self- assessment, testing, observing, correcting and further applying the garnered knowledge to the everyday operation of the industry. Even today, the amount of knowledge exchange is tremendous in the field with newer countries wishing to generate power from fission reactions to those already in the field wishing to use reprocessed and spent fuel in the next generation of nuclear reactors with greater operating efficiency.

1.1 Relevance of Nuclear Power in today's Energy Mix

Among the myriad of energy sources available in the present day, the energy produced by splitting of the atom still ranks as one of the reliable, low- cost and climate- change conscious sources. Other major energy generating sources, as seen from Figure 1, include Coal, Natural Gas, Hydroelectric and Oil dominating the global market. There are other upcoming energy sources including tidal energy, geothermal energy, wind energy and solar energy to name a few. Furthermore, non- renewable wastes, chemical heat, shale oil and peat are also significant sources of energy on a globally.

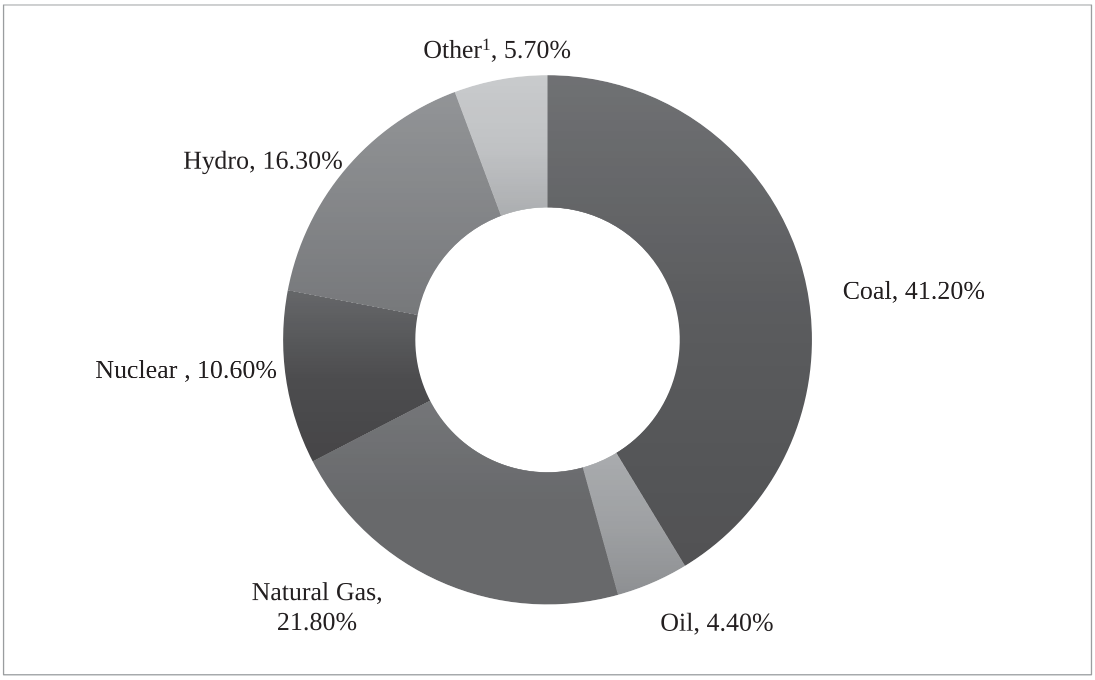

Fig. 1: Electricity Generation by Fuel (IEA, 2015a)

1. Includes energy tidal energy, geothermal energy, wind energy, solar energy, non- renewable wastes, chemical heat, shale oil and peat

NOTE: Totals in the above graph may not add up due to rounding

The share of nuclear power in the global electricity generation market accounts approximately for a tenth of all power generation in the present day (Figure 1). The lion's share of the pie belongs to coal while over half of the energy produced in the present day accounts some way or the other to fossil fuels. In the years ahead, this would have to be downsized for reasons pertaining to climate change and emissions reduction.

While each of the above mentioned energy sources have their advantages and due disadvantages, this thesis shall concentrate on nuclear power as a viable alternative to some of the currently viable energy generating sources, under the context of extending the life of the existing plants.

The following section highlights the factors and aspects that have become important to consider the retention of nuclear energy in the world energy producing basket. The sections reviews climate change, the reliability of Uranium as a fuel, the non-interrupted supply with a mention of the economics at play.

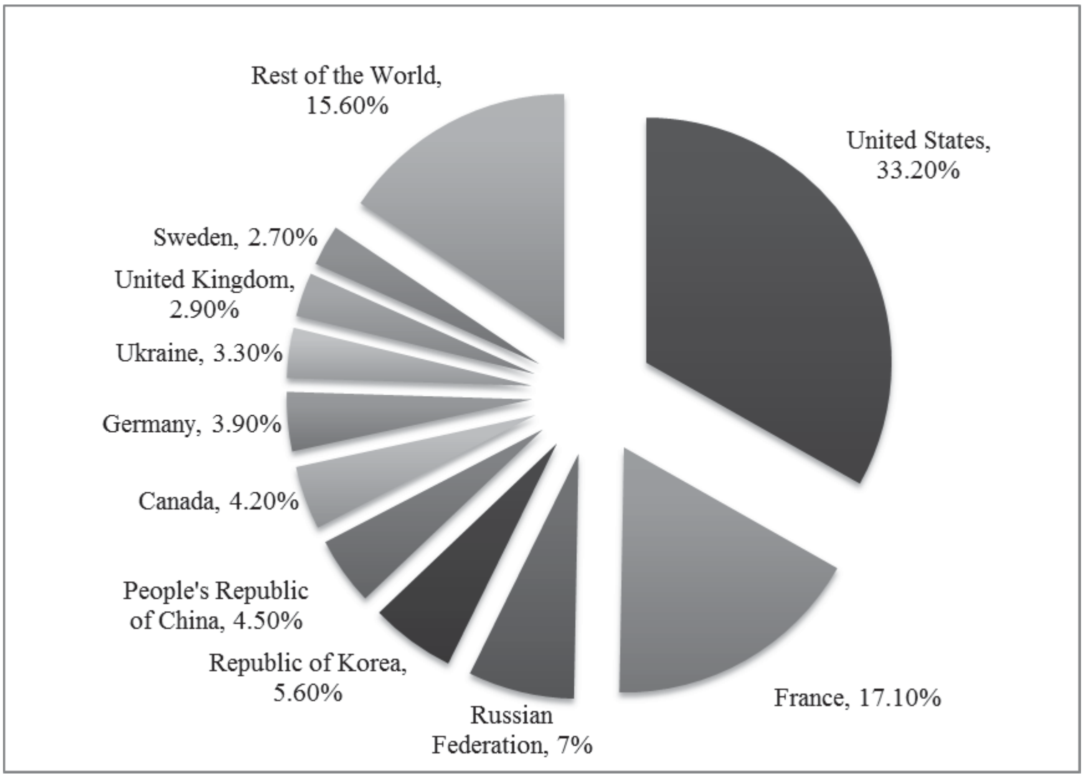

Fig. 2: Producers of Nuclear Energy (% of world total) (IEA, 2015c)
NOTE: Totals in the above graph may not add up due to rounding

Figure 2 above shows the largest current producers of atomic energy with their global share in production. The United States of America with almost a hundred nuclear power generating reactors produces a third of the global commercial atomic power generation output.

1.1.1. Lower Greenhouse gas Emissions

Climate Change is *sui generis* nowadays; beginning with anomalistic weather patterns bringing into question if the actions we take nowadays are worth, if anything, the chance to save the planet from an increase in warmer thermodynamic effects.

The COP 21 held under the auspices of the United Nations Framework Convention on Climate Change in Paris in 2015 helped only to strengthen the cause and bring to light challenges that face the modern world (UNFCCC, 2016). Numerous think tanks, NGOs, international organisations, governments and activists put out their voice in support of reaching a consensus towards doing a bit to save prevent excess temperature increase.

The current state of the world with excessive energy demands while increased constraints on emissions of greenhouse gases emphasises the need today to look ahead and appreciate the importance of power generating sources with less amounts of greenhouse gases per unit of energy generated.

A report published leading up to the COP 21 in Paris with "*The power sector is leading the change to decarbonize*" as one of the subtopics discussed in it, clearly indicates moving towards non greenhouse gas emitting power plants as the sole option notwithstanding the fact of an increased power generation wherein emissions from gases that cause global warming set to rise by only a fifth at the current estimates of projection (IEA, 2015b).

Lowering emissions in view of impending catastrophic consequences due to unprecedented anthropogenic emissions were highlighted in the fifth and latest series of Assessment Reports published by the IPCC (IPCC, 2015). While highlighting, keeping in view of the unprecedented industrialisation, that each of the last three decades has been the warmest on record, the change has been unequivocal in light of the millennia gone by (IPCC, 2014).

In Europe, a position paper stressed the drawbacks on removing nuclear power from the energy mix towards emissions of CO_{2eq}. The paper predicted an increase of 35% of emissions of CO_{2eq} in a future without contribution from nuclear power (FORATOM, 2015). This would mean the commitments that the EU proposed leading up to COP 21 of reducing 40% of its greenhouse gas emissions below 1990 by 2030 would be thrown into jeopardy. The EU has more than accomplished its share under the Kyoto Protocol adopted to the UNFCCC by reducing 23% against its initially proposed 20% (European Parliament, 2015).

The IAEA itself released a report specifically catering to the aim of abating climate change which emphasized on '*decarbonisation of the electricity sector*' depending on a due increase in the global energy demand. The report predicts that should the status quo continue, the world shall move towards decarbonisation and nuclear energy will increase the share of supply into the world's energy basket (IAEA, 2014a).

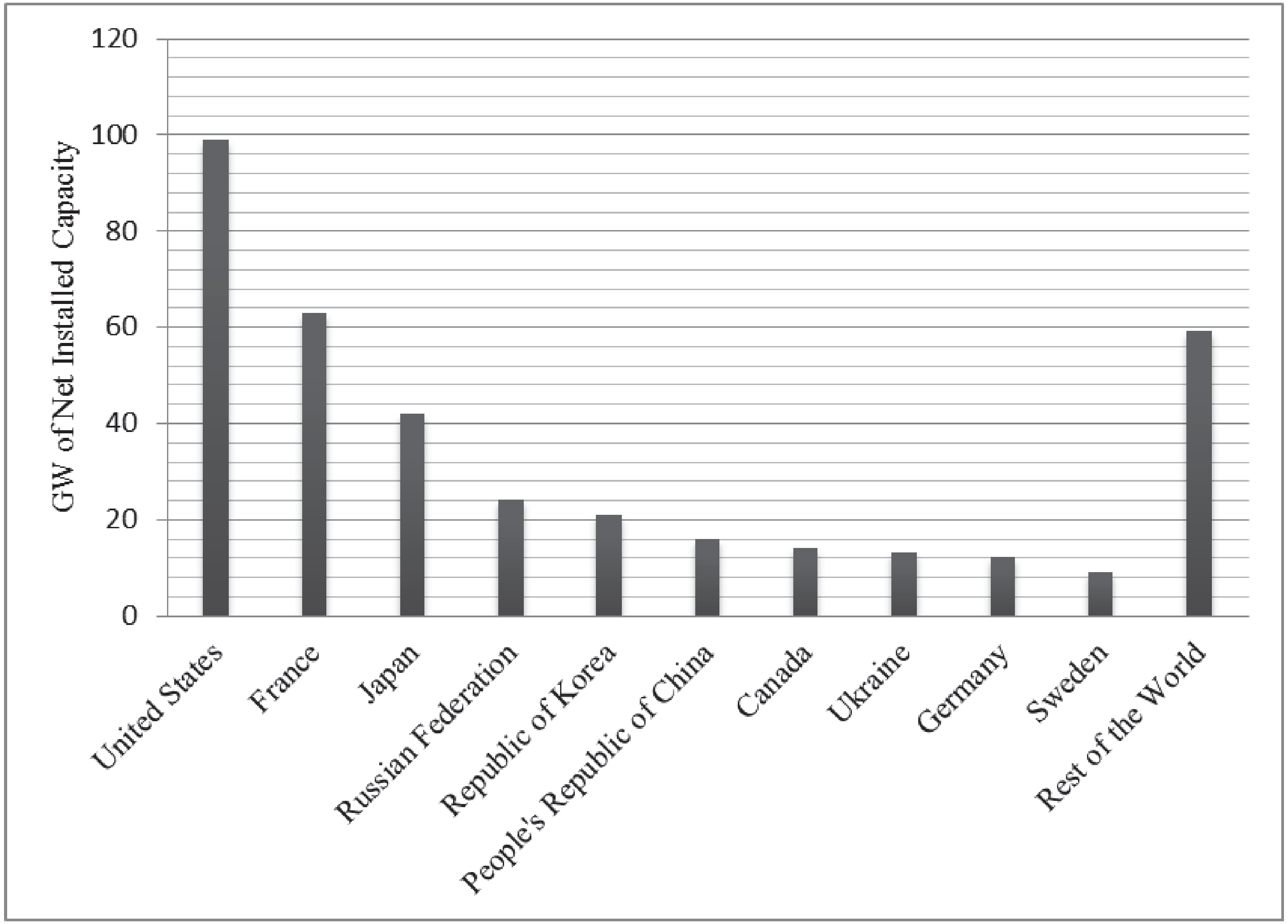

Fig. 3: Net Installed Nuclear Capacity (in GW) (IEA, 2015c)

Some countries are trying to increase their energy generated from nuclear power plants, while nuclear energy is a political and public sentiment issue for others wishing to opt out of it in the near future. Figure 3 in the preceding page shows the current net installed capacity of nuclear power plants in the countries with the largest power generation. As the data is from 2015, conspicuous of its net installed capacity is Japan, in the aftermath of the events of March 2011, though it has re- entered the nuclear energy generating circuit late in 2015 and as seen from figure 4 the share of nuclear energy is not yet an appreciable one in the total energy production in Japan.

1.1.2. Energy Supply Reliability

Reliability is an important criterion when mentioning it in the field of energy demand. With exploding populations across the developing world, the human race has come to have a growing thirst for energy and power generation.

The largest currently installed source of renewable energy worldwide, wind is inherently dependant on air currents that may fluctuate erratically between the doldrums and gale force winds (during which the turbines would have to stop generation of power after a certain designed wind speed is reached in the ambient atmosphere). Comparing the fastest growing renewable source of energy in the past two and a half decades, solar energy, as a standalone energy source, is even more undependable for its midday peak curves and long downtimes during inclement weather and seasonal fluctuations (IEA, 2015a). Nowadays, with the advent of wide climatic anomalies, even hydroelectric power plants that supplied until late 35% of Tanzania's power had to be shut down due to shallow rivers (BBC, 2015).

It may be true that renewable energy sources are gaining a strong foothold in the world energy share but they truly lack the base- load reliability aspect. Though fossil fuels (coal in particular) have been the one of choice for load- following power plants, nuclear load- following power plants do contribute to the energy mix in France (NEA, 2011).

1.1.3. Security of Energy Supply

The oil shocks of the mid- 1970s have helped propel nuclear energy as an alternative energy source in contrast to hydrocarbons, a so- called hedging instrument. The Organisation of Petroleum Exporting Countries, based in Vienna, which gained prominence through the 1973 Oil Shock and the Oil Crisis precipitated in 1979 could not help do much about the situation as the economies of OECD countries were affected. The latest available annual report from OPEC showcases that shocks are still present today (OPEC, 2015). While oil prices today are a minuscule of what they were once just a few years ago, oil futures speculate movement northward, thereby making it more expensive (OPEC, 2016).

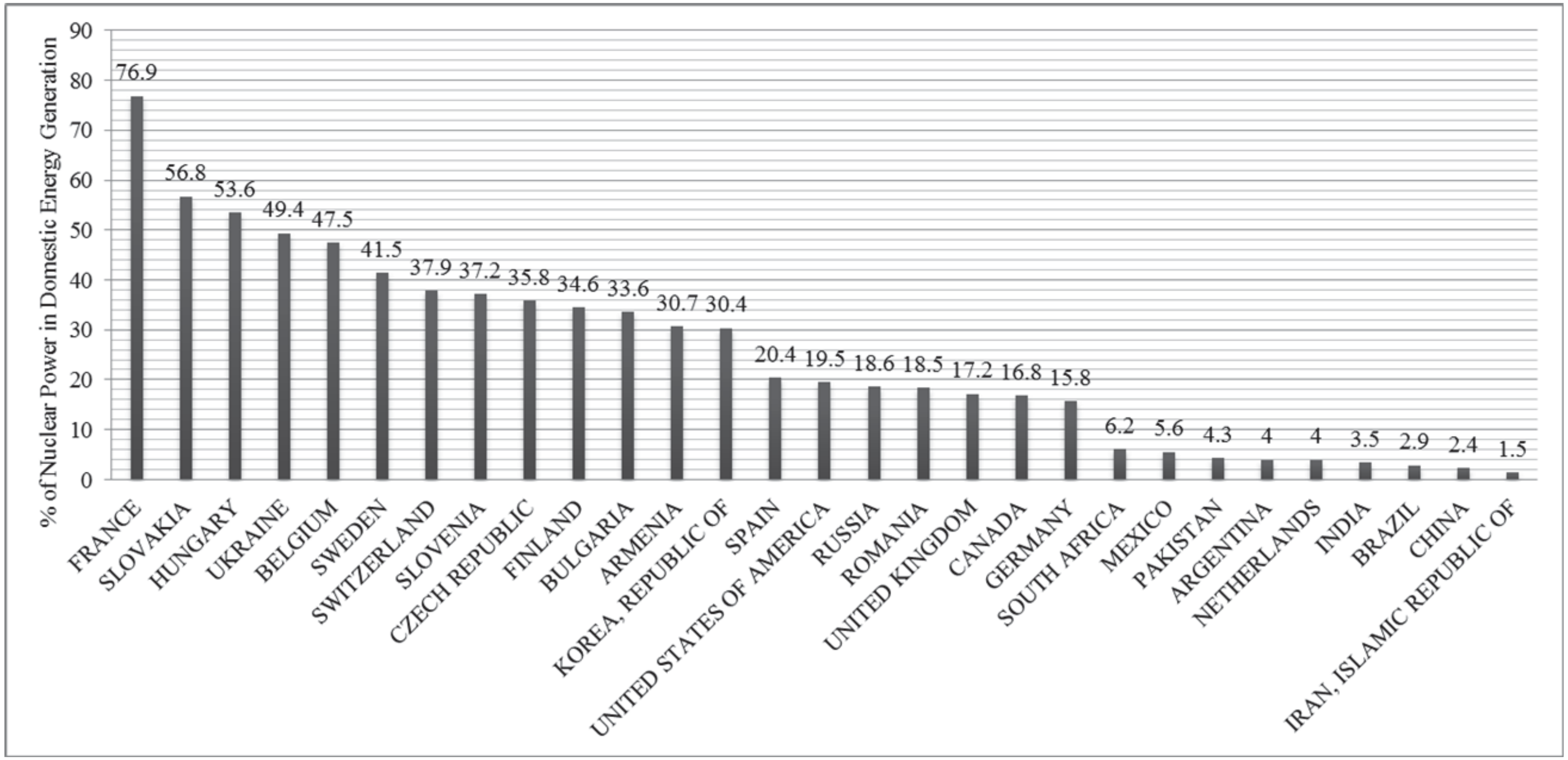

Fig. 4: Domestic Market Share of Nuclear Power Generation in selected Countries (IAEA, 2016)

The above (figure 4) shows an important aspect of each country's nuclear power generating capability- interesting to note is that while France generates over three-quarters of its energy needs from nuclear power, energy hungry giants to the tune of China and India generate under 4% of their needs from nuclear power. The latter trend is set to dramatically change as their demand grows in the upcoming years. While nine of the top eleven countries below belong to the European Union, while Switzerland belongs to the European Free Trade Association and Ukraine along with the other ten countries belongs to the Council of Europe.

The following table highlights the current identified estimated reserves of Uranium available across the world.

Table 1: Distribution of Identified Uranium Resources (<US$130/kgU) (NEA, 2014a)

COUNTRY	ESTIMATED RESERVES
Australia	29%
Kazakhstan	12%
Russian Federation	9%
Canada	8%
Niger	7%
Namibia	6%
South Africa	6%
Brazil	5%
United States	4%
People's Republic of China	3%
Mongolia	2%
Ukraine	2%
Uzbekistan	2%
Botswana	1%
Tanzania	1%

Keeping this is mind, oil has always been a fuel of political ways; wars have been fought for its control, out in the open or proxy wars, but wars nevertheless. Comparing sources of nuclear fuel, the socio-political stability of these regions has to be mentioned. While OPEC is a cartel, there is literally little to no odds of a particular region or nation state that mines and produces uranium to gain a monopoly. OECD countries account to about 35% of supply source. The top countries include Australia, the CIS state of Kazakhstan, Russia, Canada, the United States, to name the top five which all have stable governments in place (NEA, 2014a).

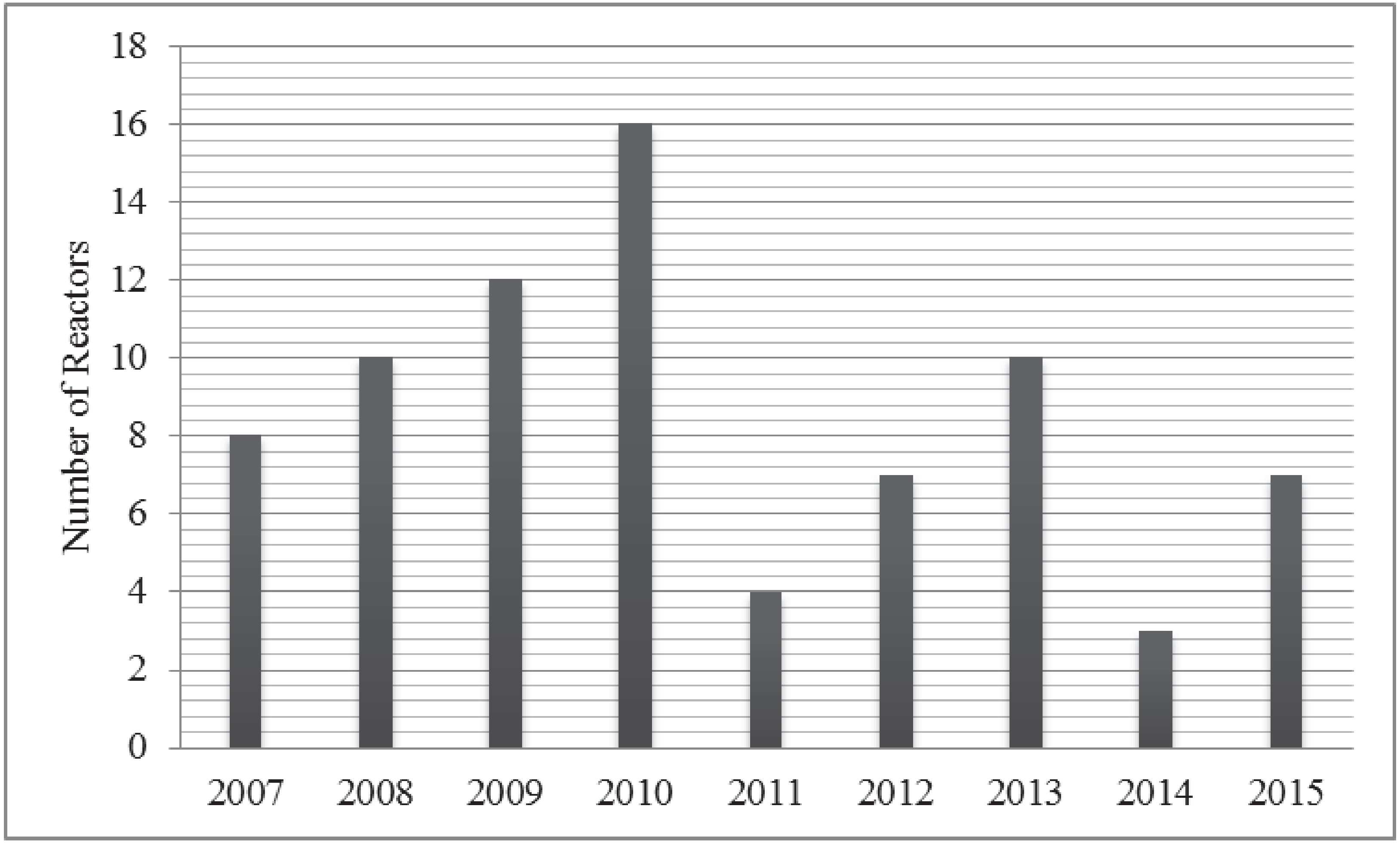

Fig. 5: Trend of Construction Starts until year- end 2015 (IAEA, 2016)

The Nuclear Suppliers Group, created in the aftermath of India's 1974 nuclear test stands to ensure that all uranium mined and transported across international borders is accounted for. The member countries have guidelines that incorporate into them the treaties of Nuclear Non- Proliferation of Nuclear Weapons, the Treaty of Rarotonga, the Treaty of Semipalatinsk, the Treaty of Pelindaba, the Treaty of Bangkok and the Treaty of Tlatelolco (NSG, 2013). The guidelines are a way of ensuring that a mutual watch is kept on one another towards procuring uranium as a fuel to power generating units.

Security of energy supply is an important aspect when it comes to planning for the future needs of a country. One way to gauge the amount of thought and planning to have an energy- secure future is to look at the plant constructions that have begun in the last few years. The above (Figure 5) shows that towards the start of the last year cycle there was a boom in power plant construction in the nuclear sector, with almost 16 plants starting their construction in 2010, which abated in the aftermath of the events of March 2011. Nevertheless, at least seven plants started construction in 2015, the last full year on record as this thesis is written.

1.1.4. Cheap source of Electricity

Inflation is an important area of concern for many an economist. Going ahead, volatilities in power generation share thereby affect the national economies in more ways than one. Capital costs aside, fuel costs and running costs to generate the same amount of electrical power have nuclear energy costs among the lowest in the industry (IPCC, 2007). Only hydroelectric power was cheaper to run.

An information paper released by the World Nuclear Association detailed on a scenario of increase in nuclear fuel prices (primarily Uranium). The paper argued that the contribution of the fuel is relatively small when contextually considering the total overall cost for production of electricity. Furthermore, it stressed that even a large increase in fuel prices would have little effect on the total cost of electricity produced. A n example considered was a hypothetical doubling of the market price of Uranium would lead to an increase in the fuel cost by 26% for an LWR and the resultant increase in the cost of electricity generated from the said plant would be about 7% (World Nuclear Association, 2008).

The same paper highlights that including processing, enriching and fabrication into fuel elements wherein half of the fuel cost is accrued to the latter two processes, the total fuel costs for a NPP are about one third of the cost for plants powered by coal- firing technology and between a quarter and a fifth for plants running on gas combined- cycle technology.

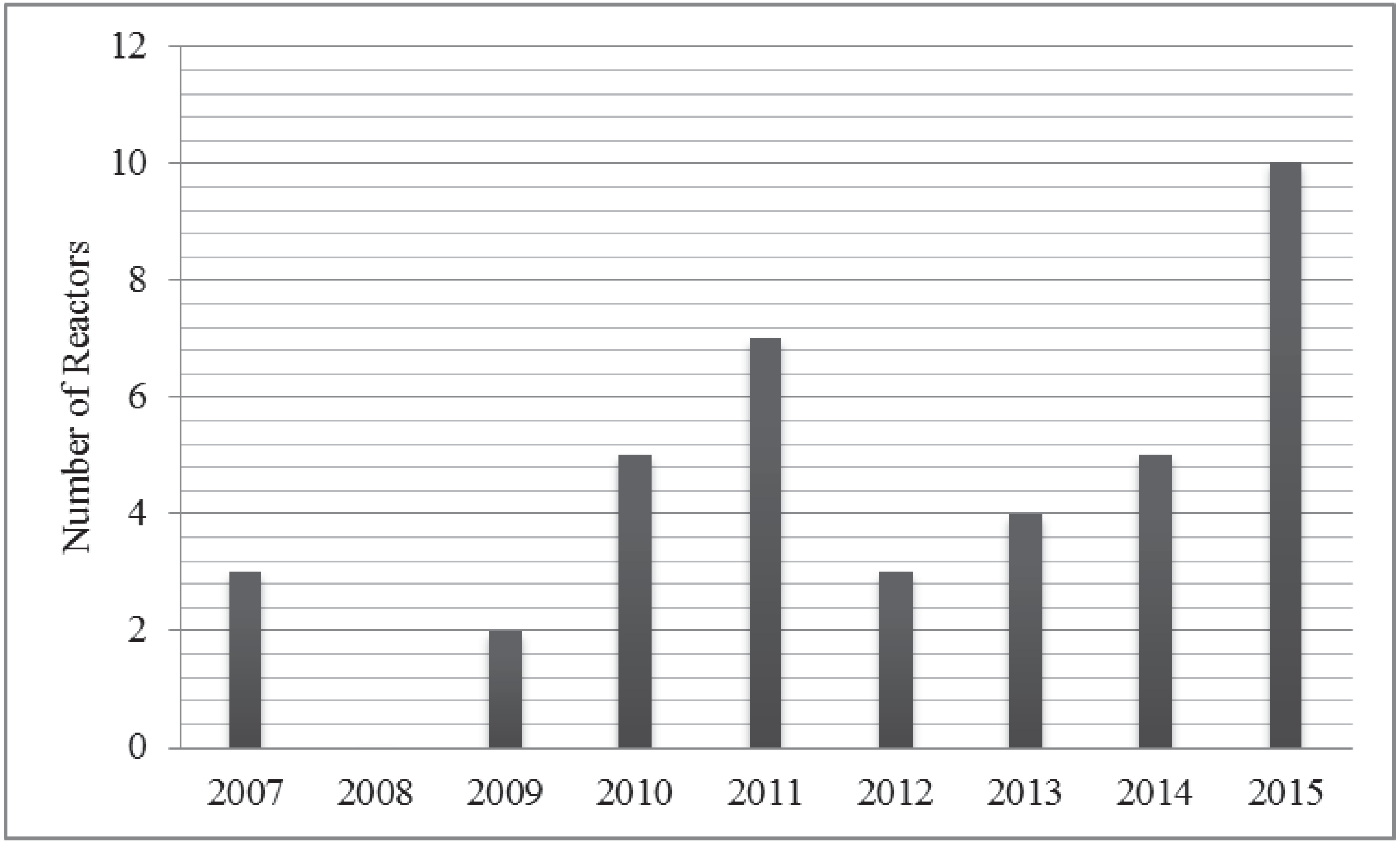

Fig. 6: First Grid Connections until year- end 2015 (IAEA, 2016)

The preceding page showcases reactors that have been connected to the grid, internationally in the recent past (Figure 6). It is interesting to note that after the events of March 2011, the following year saw a decline in the number of reactors connected to the grid but since then there has been a steady increase in the number of first grid connections. Though the drop may not be attributed to one particular event alone, there may be a multitude of factors that would be at play including construction starts as seen earlier (Figure 5) wherein some plants were delayed due to extra safety tests that were undertaken prior to commissioning and finally connecting to the grid.

1.1.5. Abstention from Nuclear Power

The one Japanese word in everyone’s mouth, if not *tsunami*, is *Fukushima*. While understanding the issue of the basic design being overwhelmed under never hitherto predicted scenarios, many countries are deciding to call it quits with atomic power. Even France, a country that heavily depends on nuclear for its share of energy production was projected to cut back the share from the current three- quarters to just a half by 2025 (Le Monde Diplomatique, 2012a). Japan, five years on after the fateful day in 2011, due to its geography and economy had to ultimately restart its nuclear power plants (NEI, 2016) after various theories were proposed in the aftermath of the earthquake and resulting tsunami in March 2011 (Le Monde Diplomatique, 2012b).

While nuclear energy is spoken of as a carbon free source of electricity, whether there would be a common future for nuclear energy coupled with other energy sources is a good question. A paper deliberating on the issue laid bare some claims towards the history of operation and voiced in the negative (Verbruggen, 2008).

Policy issues drive moving away from nuclear power as in the case of Germany (Bruninx et al, 2013). The paper argues that the impact of the policy- driven phase out will be profound in the German energy market. The proposed replacement would be from carbon emitting fossil fuel sources and the energy exporter that Germany currently is may become an unfeasible scenario in the future.

On whether nuclear energy is a solution for climate protection and sustainability, policy issues again crop up into the view with papers arguing that in wake of the events of March 2011, the mood has dampened and that countries are looking for an alternative way ahead (Mez, 2012).

That being said, the same policy issues towards attainting a carbon free power generating system shall drive countries to keep their nuclear plants in place and even go for new ones in the future.

1.2. Operational Groups of a Nuclear Power Plant (Chitumbo, 2013) (IAEA, 2007a) (IAEA, 2013)

Theoretically breaking up a complex system can aid in understanding its innate working characteristics. Similarly, the idea of operational groups of the nuclear power plant shall help in comprehending with ease these 'islands of operation'. The latter part of this thesis, while delving into the decision making process, shall be better understood with the information conveyed by the following backgrounder.

The author wishes to convey that instead of the traditional idea of analysing individual components by their state and nature of operation and location on the system flow, the idea of operational groups is being introduced to simplify the logic behind the decision making process. With this grouping, the author wishes to achieve a broader view towards groups that are major and minor contributors by sheer size and importance in the end process. With these islands of operation, the topic of component interference and interaction which shall be dealt later, the reader shall be better suited to comprehend the same.

The entire operational system can be divided into four broad categories for the sake of clarity.

- Nuclear Steam Supply Systems (NSSS)
- Balance of Plant (BOP)
- Instrumentation and Control System (ICS)
- Electrical System (ES)

The above four categories, broadly seen, comprise the entire working system of the nuclear power plant, from the miniscule valves of the drain systems in the BOP through the various pumps integral to the NSSS and BOP to the Reactor Pressure Vessel (RPV), Steam Generator (SG) and Heat Exchanger (HE) in the NSSS. With the various parts that constitute each sub- part of operation of the above four categories, there are theoretically a large number of components that would be involved in the discussion, but for the sake of simplicity, this thesis shall highlight some deemed crucial to the discussion by the author, under the purview of life extension application of the atomic power plant.

1.2.1. Nuclear Steam Supply System

The NSSS comprises of, among others the following:

- Reactor Design
- Reactor Containment Building
- Reactor Pressure Vessel
- Steam Generator (Heat Exchanger)
- Fuel Rod & Control Rod

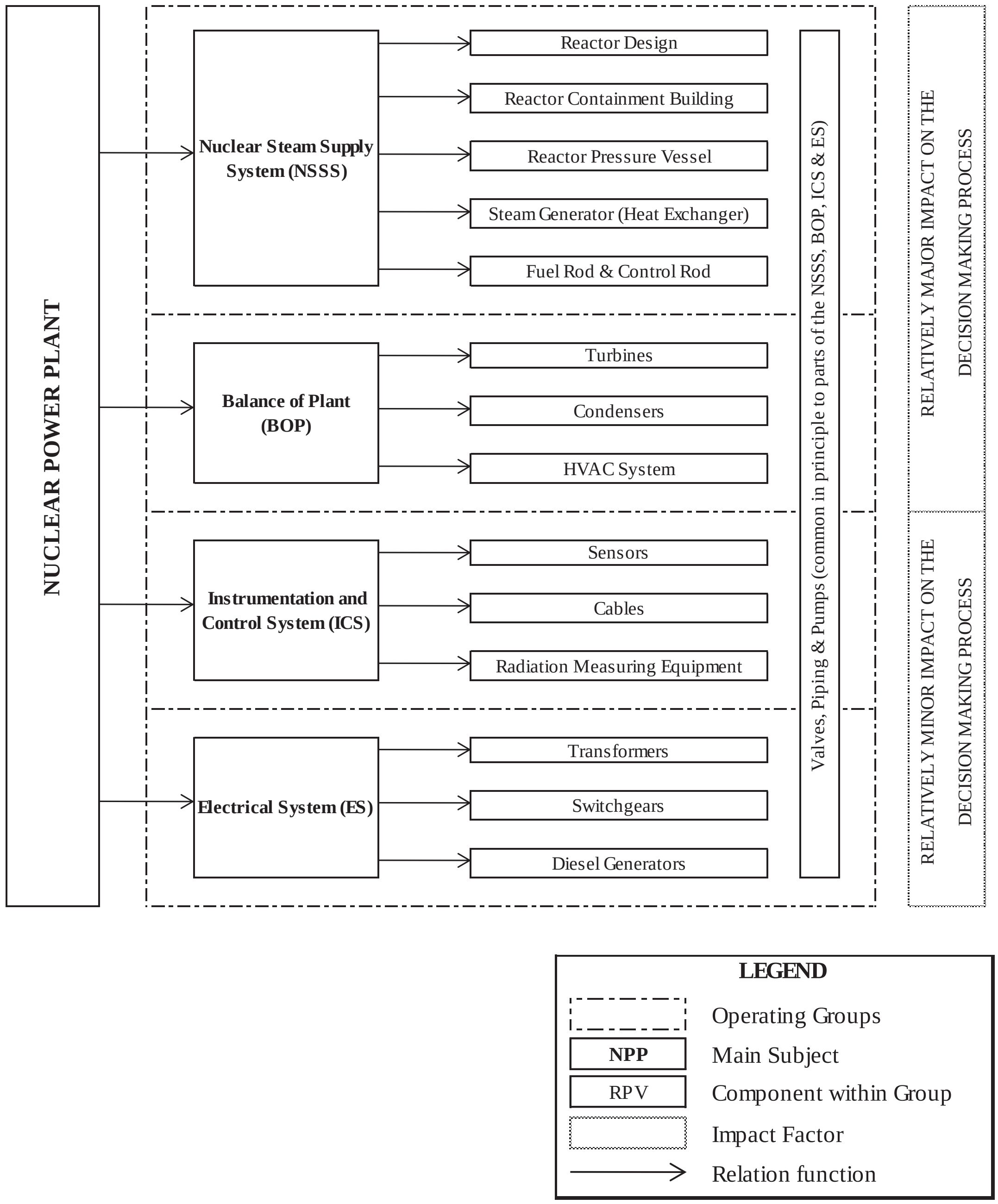

Figure 7: Operational Groups of a Nuclear Power Plant with select components (Chitumbo, 2013)

1.2.1.1. Reactor Design

The adopted and agreed upon design of operation and working of a nuclear power plant is a very important part of the NSSS. Over the years, scientists, physicists and engineers have learnt various feasible and non- feasible design options towards nuclear reactor types. The design part of the reactor, decided when finalising on what type of reactor would be used to generate power, is a decision that is taken years in advance, and during the life extension phase of the atomic power plant, cannot be modified per se, except that refurbishments to the existing regime be effected through costly programmes for reasons of safety.

The design of the nuclear power plant comprises of a primary system and a secondary system of operation. The former consists of the reactor pressure vessel, steam generator, coolant pumps and interconnecting piping while the latter comprises of the HP and LP turbines, re- heater, main electrical stages and interconnecting piping.

Thirty years ago, the events of April 1986 that transpired in the town of Pripyat in the then Ukrainian SSR were caused due to the design of the nuclear power plant. The Chernobyl incident as it came be known as changed public opinion and galvanised the mood against opting for nuclear power in many a country. The RBMK type of reactors were highly unstable due to their graphite tipped moderating elements that would speed up the reaction before slowing it down (World Nuclear Association, 2016a). Ignalina 1 and 2 in present day Lithuania comprised of two reactors which were shut down by the European Union before guaranteeing Lithuania's accession to the European Union. The decision thus taken was purely on the initial design of the power plant. Similar closures were also effected in Bulgaria and Slovakia. Meanwhile, Cernavoda 1 in Romania, a Canadian CANDU type reactor, was unaffected by the accession process (World Nuclear News, 2007).

1.2.1.2. Reactor Containment Building

The structure that houses the reactor core and cooling and circulation system and pumps is the containment building. The containment building may be of reinforced concrete, steel or lead. Their main function is to withstand high operating temperatures and pressures and providing a leak- free operating ambience.

As the design would have it, not all of the older designed power generating plants have a containment building. While issues concerning safe operation of the power plant were brought to the fore, all modern plants encompass a containment building while the older plants have been retrofit with them.

As would be seen later from this thesis work, the containment building, over the years it is in operation is affected by not just factors from an internal perspective, but even from external factors of the environment. A technical feasibility towards safe operation of the power plant is vital as would be discussed when assessing the residual lifetime of the reactor containment building structure.

1.2.1.3. Reactor Pressure Vessel (RPV)

The heart of the operation of any nuclear power plant lies here, within its RPV. A site of complex, calculated reactions, the RPV is one that is being continuously monitored, with a wide variety of instruments to check for anomalous behaviour. RPV can be of various types, depending on the type of the power plant decided upon in the design aspects.

This is the part wherein the fission reactions occur, with radioactive bombardment an integral part of the routine of activities that occur inside the RPV. The RPV houses the moderator, the coolant and the fuel rod which help maintain a state of control over the reactions that occur within its boundaries. Effecting control over the operation of the nuclear plant requires understanding the state of the RPV at any and all points of time during the course of the operating life of the power plant.

The RPV is one of the parts wherein a replacement of the existing system shall be a cost concern for the decision makers, especially noting that changing the operating core of the working of the system shall entail a series of other changes which in turn would balloon the cost estimate required to maintain an economically feasible option towards running of the nuclear power plant. Numerous issues that are essential to the decision making process concern the RPV. While regulatory issues concern the operational capabilities of the RPV, the technicalities are the first to be scrutinised under the operating history and feasibility studies to ascertain the RPV use can be further prolonged in a safe manner without expecting adverse reactions.

Continuous monitoring of the RPV is commonplace in most nuclear power plants. Furthering the idea to understand the state of the inherent material during the operation, modelling and simulation are vital besides having in place systems to ensure that reporting of anomalies is done at the earliest.

1.2.1.4. Steam Generator (SG) [Heat Exchanger (HE)]

The main function of the SG is transmission of thermal power from the reactor core comprising of the RPV to the secondary circuit where the flowing coolant takes away the heat generated. Removing the heat from the core, it helps maintain the desired design operating conditions and making certain a safe transfer of thermal energy to the secondary circuit prevents radioactive contamination.

The SG comprises of a vital capital significant investment when considering the economics of the nuclear power plant. Depending on the technical considerations, the SG is tailor- made to suit the RPV design. The steam generator is an integral part of all plant designs to date excluding the Boiling Water Reactor (BWR) type wherein a pressure vessel is used to produce the steam to run the turbines.

Studies have shown that operating conditions influence the degradation of the SG and controlling these parameters would help keep in check the degradation due to natural ageing (IAEA, 1997).

The heat exchanger working as part of the power generation system is quintessential to removing the heat efficiently from the primary part of the nuclear power generation system into the secondary loop with the secondary coolant, ensuring that only the thermal properties are transferred without a loss of coolant or transfer of radioactive material. The principle involves use of materials with high thermal conductivity to ensure maximum thermal efficiency. The primary coolant flows in metallic tubes around which the secondary coolant runs in close proximity with adequate safety measures.

Constituting the very border between the hazardous operating environment of the radioactive world and the relatively safer side of business with interaction to the surrounding environment, HEs are the site of leakages resulting in Loss of Coolant Accidents (LOCA). Main issues that concern include thermal stress and pressure stress due to the thermal gradient of operation, perforations due to pH variations in the operating fluid over time, etc. (IAEA, 2009). Radiotracers are used as an option to find leaks in heat exchanger operation. In operating CANDU reactors in Canada, problems with SGs were the second largest cause of outages (Pembina Institute, 2004). The issue is further delved upon considering the environmental impacts in the decision making process further in this thesis.

1.2.1.5. Fuel Rod and Control Rod

A typical fuel rod comprises of fuel and its cladding. Depending on the type of the nuclear power plant, the loading of the fuel varies. An example of fuel channels in use in CANDU reactors show that from operating experience through the years problems with these fuel channels have historically been the cause for the single largest cause of power outages (Pembina Institute, 2004). The control rod and the moderator form part of the nuclear core to maintain the nuclear reactions in a commercial state of operation by controlling the said reactions and should the case need be, even shut down the operation of the system. Fuel rod assembly along with the control rod are stacked up in the structure that form the heart of the power generation within the core. Mathematical calculations can reveal fuel burn- out and use. Probability calculations can also reveal probable modes of rupture, should it be an important criteria due to the reactor design.

As is seen from the above components of the NSSS, each of the constituents comprise an elemental part of the nuclear reactor and their safe operation in turn ensures prolonged commercial power generation. Comprising of highly critical components, the NSSS is thereby a major factor in the decision making process that shall be discussed in depth during the course of this thesis.

1.2.2. Balance of Plant (BOP)

The BOP involves among others the following:

- Turbine
- Condenser
- HVAC system

1.2.2.1. Turbine

They are the hydraulic machines converting hydraulic energy into mechanical energy. The thus generated mechanical energy is further used to run an electrical generator which is coupled to the turbine shaft which ultimately converts the mechanical energy into electrical energy (Bansal, R.K., 2012a).

The turbine system comprises of the high and low pressure turbine along with the associated machinery including control valves, lubrication oil and bearings. The turbines are a capital intensive investment towards safe plant operation. The turbines constitute the linkage between the NSSS discussed earlier and the ES which shall be discussed later.

The turbine receives the steam generated from the heat exchanger part of the steam generation system on its high side and with the mechanical moving parts including vanes transfers the energy from steam into rotational motion of the shaft which moves the magnets on the generator.

Turbine failures concern the type of impact the steam has on the runner, and depending on the velocity of impact may cause chipping of the vanes causing a drop in hydraulic efficiency of operation. Over time, embrittlement occurs especially in the moving parts due to the temperature variations within the normal operating conditions. Furthermore, the casing, guide tubes other equipment that are subject to similar ambient would also experience the effects of ageing, thermal and pressure stresses.

1.2.2.2. Condenser

Conversion of steam into liquid water such that it can be further used in the system to produce power requires the use of the condenser. The steam outlet from the lowest pressure extraction point of the above steam turbine leads into the condenser forming the condensate (Rajput, 2011a). The condensate thus generated would be used as feed to further the cycle of operation.

In the condenser, the steam at high operating conditions is cooled with cooling water from the outside ambient. This is where the proximity to an open water body is elemental when setting up a nuclear power plant. The condenser thus forms the part of the plant that is in direct contact with the outside and it is vital to protect it from not just leakage from the inside but also foreign agents from the outside. The salinity and acidity of the cooling water within the circuit become important. A highly acidic operating environment in the intake and due circulation in the secondary circuit shall lead to corrosion of the heat exchanger piping.

Cooling towers or spray ponds also form part of the condensing circuit when cooling water is recirculated over and over again. With the aspect of safety, cooling towers, though large are safe against most external influences due to their defence system.

1.2.2.3. Heating, Ventilation and Air- Conditioning (HVAC) system

Ensuring a safe and clean operating environment is of utmost priority in any plant. Thereby, the HVAC systems have an important role in maintenance of this ambience. The system involves fans, ducts and filters among others. Forcing the air through the ducts requires fans and removing the unwanted impurities requires the filtering system- which functions as a unit in ensuring a proper ventilation regime for the entire plant. Conditioning the air is important to have safe conditions of operation in place, including optimal conditions of work for the plant personnel.

The fans, ducts and filters are usually maintained in the existing regime. With proper maintenance of the three components, a dust free operating environment is achieved. With rotating parts in the fans, they would need to be replaced as per the usual end of life regime, while filters, due to their inherent composite materials would not be usable after a certain design lifetime. The ducting, with its necessary insulation would also face a similar ageing. Thus the HVAC system would be, barring any severe anomalous incident, renewed every few years during the operation of the plant.

The HVAC system, during a radioactive leakage, would be a prime conduit for transfer of radiation making a localised incident a global accident. While the filters and ducting in place in the plant, especially in parts involving the secondary circuiting may not be fitted with the defence required to thwart the spread, usual conditions of ensuring a lockdown during the case of an anomalous behaviour would be sufficient to achieve safe operation of the plant with a viewpoint from the HVAC system.

As is seen from the three components and systems considered under the BOP, they are quite crucial towards maintaining a safe operating environment in the plant. An untoward failure in operation of the turbine or the condenser would lead to initiation of consequences that would bring the plant into shut- down thereby causing unplanned downtime. The HVAC system, even when maintained properly, may not have the required defence to prevent spread of contamination due to its design parameters. Hence, it is considered a semi- critical part of the system as it performs usually within the required conditions, but in case of a radioactive leak, its withstanding capability may be severely tested.

1.2.3. Instrumentation and Control System (ICS)

The ICS involves among others the following:

- Sensors
- Cables
- Radiation Detecting Equipment

1.2.3.1. Sensors

Operation of equipment needs to be monitored and anomalous behaviour reported immediately to the concerned authorities at the control centre. Sensors carry this job of continuous monitoring of the plant. As they are either analogue or digital in nature with their inherent characteristics, sensors have a limited design lifetime.

Analogue sensing equipment were commonplace in the older nuclear reactors. Today, with the advancement of technology, conversions into digital sensing equipment have been undertaken as part of the retrofitting efforts in some plants while others still maintain the old regime system. Digital sensors meanwhile with integrated circuit (IC) chips aid in more accurate and faster data monitoring. Due to their composition the ICs would have to be replaced at regular time intervals to prevent faulty reading from being reported.

Technological attacks are an important concern to digital sensors, a topic discussed in the digitisation aspect towards decision making process later in this thesis.

1.2.3.2. Cables

Relaying the gathered data to the appropriate control centres is done with the help of cabling. The volume of cables that are in place and would require regular maintenance would be voluminous for a nuclear power plant. Cables, depending on the use can be of various degrees of magnitude and importance.

Though stationary, through the course of their operating lifetime, they would be subject to abrasions due to unclean operating environment, loss of insulation due to pests in the plant, electromagnetic effects of operation leading to a gradual decrease of the operating parameters and efficiency of transmission.

Cables are again subject to routine replacement maintenance that ensures a loss of transmission does not occur.

1.2.3.3. Radiation Detecting Equipment

Any leakage from the operating primary circuit is brought to notice by detectors that are able to measure the radiation that is present in the ambient environment. Radiation is one of the agents that affect the operation from the outside ambient, as shall be seen in the environmental factors that affect the decision making process later in this thesis work.

The equipment to detect radiation can be of various types depending on their use. Wherein needed, they could be permanently mounted in spaces that would be susceptible to radioactivity, in which case due care should be taken to ensure the device operates and functions properly at all points of time. Further, there are other devices that would be locally mounted due to maintenance work being carried out in a particular area during downtime. The third type of equipment are mountable and portable that may be hand- held which aids in ensuring that a person does not receive more than the legally permissible dosage of radiation.

Considering the above parts of the ICS, it can be clearly seen as they are regularly maintained and if the said maintenance regime is ensured, they parts would be regularly replaced as they approach their set design lifetimes and they would only be an issue of minor concern contributing to decision making.

1.2.4. Electrical System (ES)

The ICS involves among others the following:

- Transformers
- Switchgears
- Diesel Generators (DG)

1.2.4.1. Transformers

Transformers, working on Faraday's Law of Electromagnetic Induction, is an integral part of the electrical system that converts low alternating voltage to high and vice versa.

They can be classified differently based on different parameters. Depending on whether they require to increase or decrease the voltage, they would be classified as step- up and step- down transformers respectively. With respect to the geometric configuration, they would be classified as core and shell type.

The transformer has two windings- a primary and a secondary, the current flowing in one induces a proportional current and voltage on the secondary winding- when the windings are more dense on the secondary circuit, it is a step up transformer and vice versa when it is a step- down transformer. In the science of power generation and transmission, the transformer is a capital intensive, bulky component, though highly reliable being stationary and having hardly any moving parts. To prevent eddy currents, the core is laminated and transformer oil is present to maintain relatively smooth operation.

1.2.4.2. Switchgears

In industrial level applications, the switchgear is primarily used to control, protect and isolate equipment. It comprises of circuit breakers, fuses and switches. This is an electrical equipment that also helps to ensure safe maintenance of downtime by disconnecting the plant from the grid should the need be so.

Parts that would require change including switches, fuses and circuit breakers are replaced at periodic intervals ensuring they would not be a major factor towards unplanned downtime.

1.2.4.3. Diesel Generators (DG)

By the design standards and characteristics, they are in place to provide backup power during instances of loss of power. The incident of March 2011, the Great East Japan Earthquake of magnitude 9.0 did cause a normal shutting down of power generation of the Fukushima Daiichi Nuclear Power Plant. It was what happened an hour later, overwhelming the initial design conditions that wreaked havoc upon the plant (World Nuclear Association, 2016b). 12 of the 13 DG sets were inundated by the 15m high *tsunami* waves that came crashing on the coast which had sunk by half a metre after the earthquake. Without a proper cooling system to provide for heat removal from the core, which though out of power generating schedule had residual heat due to the fission by-products on the increase. This generated heat would then lead to a core meltdown leading to only the second time an INES level 7 event was recorded in history, with the first being of course Chernobyl.

Over the years, stress tests, peer reviews, newer recommendations and guidelines have been put in place to avoid the events that transpired on that fateful March morning in Japan in other parts of the world. Nevertheless, DG sets, through operating experience have been fairly reliable to step in when needed to supply the required power in running the redundancy systems.

The group of components within the electrical system that have been discussed here show that they, though large, are fairly stable in their operation and can be reliable within the designed operating parameters. They are a relatively minor criteria when it comes to the decision making process.

1.2.5. Similar common components

- Valves
- Pumps
- Piping

1.2.5.1. Valves

They are constituent of components from the NSSS through the BOP and ICS to the ES. The DGs do have valves in their component setup in the ES. Depending on which part of the operating system they find themselves in, valves are subject to varying conditions of operation.

1.2.5.2. Pumps

Pumps are hydraulic machines converting mechanical energy into hydraulic energy (Bansal, R.K., 2012b). Pumps are critical components in the NSSS, wherein they may be part of the reactor coolant and water circulating systems, they are of a decreasing role of importance when in the secondary circuit supplying water into the condenser to cool the steam into the condensate, and they have a set design lifetime due to the rotating parts they encompass. Thereby, they have to be replaced at regular intervals to aid in safe operating conditions for the nuclear power plant.

1.2.5.3. Piping

Piping per se is ubiquitous in a nuclear power plant. Pipes are of different materials, being able to withstand the different operating extremes, and with the wear and tear that is brought upon them by continuous use, they undergo stress corrosion cracking, brittleness due to irradiation among others as would be seen from the technical literature review of structural materials from later on in this thesis. The system of pipes involves the critical job of preventing leakage of the fluids that flow through it, which may or may not be hazardous when an incident or an accident occurs. In the NSSS, the piping is of course a very critical component of transmission as it has the radioactive fluid that moves through it through the pipes within the steam generating/ heat exchanging system.

There are also the small valves, wires and cables in the allied components that are replaced within the specified timeframe set by the component manufacturer. In effect, at the end of a thirty- year life cycle, most if not all of the components and equipment having a minor impact on the decision making process would have been replaced once or more, depending on their set design lifetime characteristics.

Considering the issues dealt with above, it can be clearly seen that NSSS and BOP have a greater impact on the decision making process than ICS and ES. NSSS, by the sheer importance of its constituent parts is vital to the decision making process. Component constituents of the BOP are a serious factor considering their interaction with components of the NSSS, but maintaining the ICS and ES regularly is important to reduce their unpredictability quotient. NSSS and BOP can be considered as major impacting criteria towards decision making, while ICS and ES are minor impacting criteria.

1.3. What is Plant Life Extension? Analysis and review of literature

Plant life extension of nuclear power plants is a rather modern technological concept that aims to achieve prolonged efficient operation of nuclear power plants (encompassing the myriad of components including the reactor vessel and the associated important parts) at an established safety level of operation irrespective of service life set for the power plant initially. Looking forward, this technology realistically provides a pathway to expand the share nuclear energy has in today's energy market.

1.3.1. Probabilistic Failure Rate in Reliability Engineering

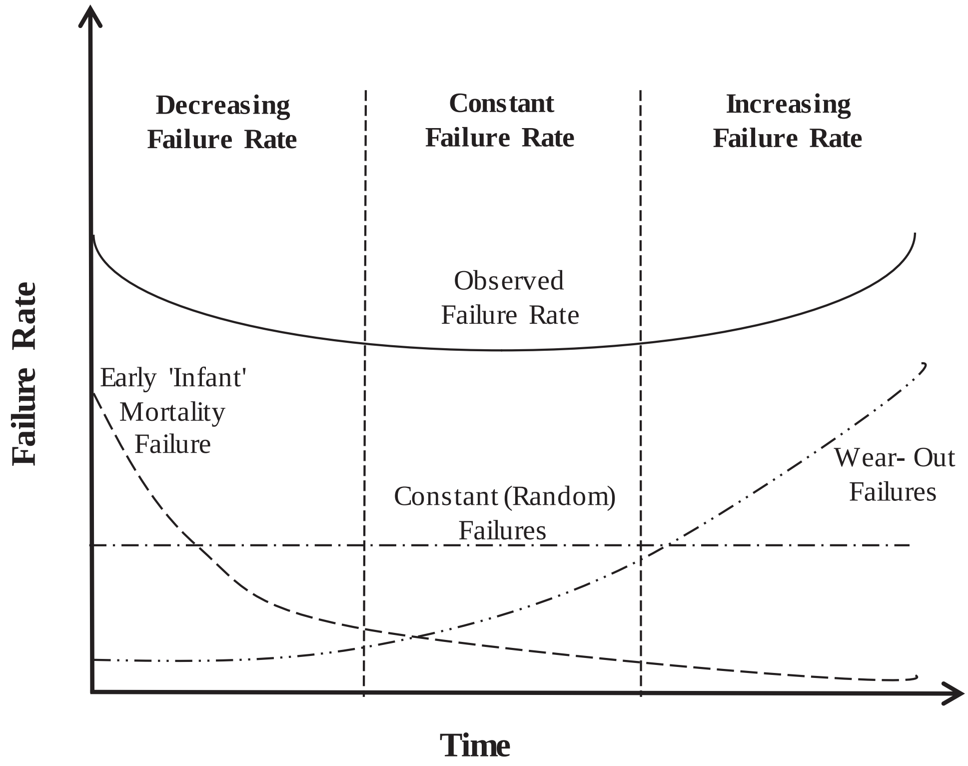

Fig. 8: The Bathtub Curve (Klutke et al, 2003)

With the progressive operation over time the inherent properties of objects industrially deteriorate owing to degradation and ageing of materials. The object evolves into a characteristically different state after years of use and service. This leads thereby to a decrease in the performance, which may or may not affect the profitability and most important of all- safety.

The bathtub curve above shows the conceptual idea of service life management, i.e. I- the initial phase of operation, II- the basic design service life, and III- long- term operation (Bugaenko et al., 2002). Component study should be aided by the bathtub curve among other probabilistic safety studies which shall help to understand how the components and their constituent part interact and react under various operating conditions and what effect ageing has on them.

The curve is known as such due to the steep curve contributions towards the start and end of designed component life from the early mortality and wear- out curves respectively with a relatively flat section during the constant random failures part. Reliability studies, engineered from component history can use the bathtub curve but it may not be suitable when applying to a component at an advanced level of use in its life.

During the initial phase of operation, any defects that may have either crept in during the manufacture of the component or during the installation of the concerned part at the site and so on are revealed. During the basic design service life part of the curve, the part is probabilistically expected to function reliably. As the part enters it's the last phase of long- term operation, the effects of degradation and ageing become appreciable.

Studying the curve further, operational lifetime of a component can be easily understood by studying its position on the curve. The curve needs to be understood along as a part of the technicalities of the component's operation. The design characteristics of the plant components, when acting under normal design conditions would naturally follow the operating parameters. Analysing them shall help understand when to expect component failure, albeit in a probabilistic manner.

The decreasing failure rate part of the curve concerns mainly the initial life of the components. Defects that creep up during the component manufacture and installation that would be amplified during initial testing and use concern the infant mortality failures. The curve suggests that probabilistically, this would be a significant number that would factor in our decisions. Even while considering component life extension, new components may be affected by early failure due to faulty manufacture, while these should not be falsely considered as operational interference from the components. Operational interference is an important aspect of the decision making process as shall be seen later in this thesis.

The middle section of the curve with constant random failure justifies the probabilistic aspect of safety issues wherein a certain set of components, however minuscule shall fail which should call for a replacement of the said component. Components that fail during this phase of the plant life require routine replacement and care should be ensured to replace them without excessive downtime. Considering the wear- out curve, probability shows that it gradually increases with time becoming more appreciable as ageing progresses.

Ageing accentuates the failures due to component wear and tear. This is seen from the wear- out curve probabilistically being more pronounced that the constant curve of random failures. Component refurbishment is highly recommended for parts that are determined by their set design lifetime characteristics in this stage of operation. This third section of the curve has been historically the most important due to the sheer number of failures that are proposed by the probabilistic studies. This section of the curve shall be crucial to understand the logic behind the decision making process towards life extension.

1.3.2. Technical overview

Life extension procedure of nuclear power plants has been discussed over the years at various symposiums that were organised in individual countries and also in Vienna under the auspices of the IAEA.

In the early days of plant operation, researchers were presenting equipment failure data and analysing them; especially wherein the case could be studied in multiple reactors in operation of the same type (Ovchinnikov, F. Ya. et al., 1981). With residual life assessment, exchange of technical know- how among participating member states and proposing possible regulation the knowledge has only increased over the years towards an informed nuclear community (Novak and Podest, 1987).

In the United States, the Nuclear Plant Aging Research Programme Plan (NPAR) published by the regulatory authority – U. S. Nuclear Regulatory Commission, mentioned progress in analysing the effects of ageing on components, systems and structures. The report released highlights of safety evaluation and measures to standardise life extension (NRC, 1991).

The qualitative aspect of life extension became of concern with due reference to management of the service life of the power plant- the entire life cycle included, and due concern to the safety aspect of operation with a process flow on the decision making for renewal of plant license as safety of operation was a priority (Bugaenko et al, 2002).

Combining the aspects of technological, economic, safety and regulatory issues, the plant life management programme was brought about to address the above issues at once (Contri, 2008). Plant life management also is an integration of economic planning coupled with ageing management with safety and operational optimization playing an important role in the working of the power plant (IAEA, 2006).

Materials pose an important concern when reviewing the technical aspects of running of a nuclear power plant. The three main issues that concern materials include corrosion, neutron induced embrittlement and stress corrosion cracking of structural materials (Zinkle and Was, 2013).

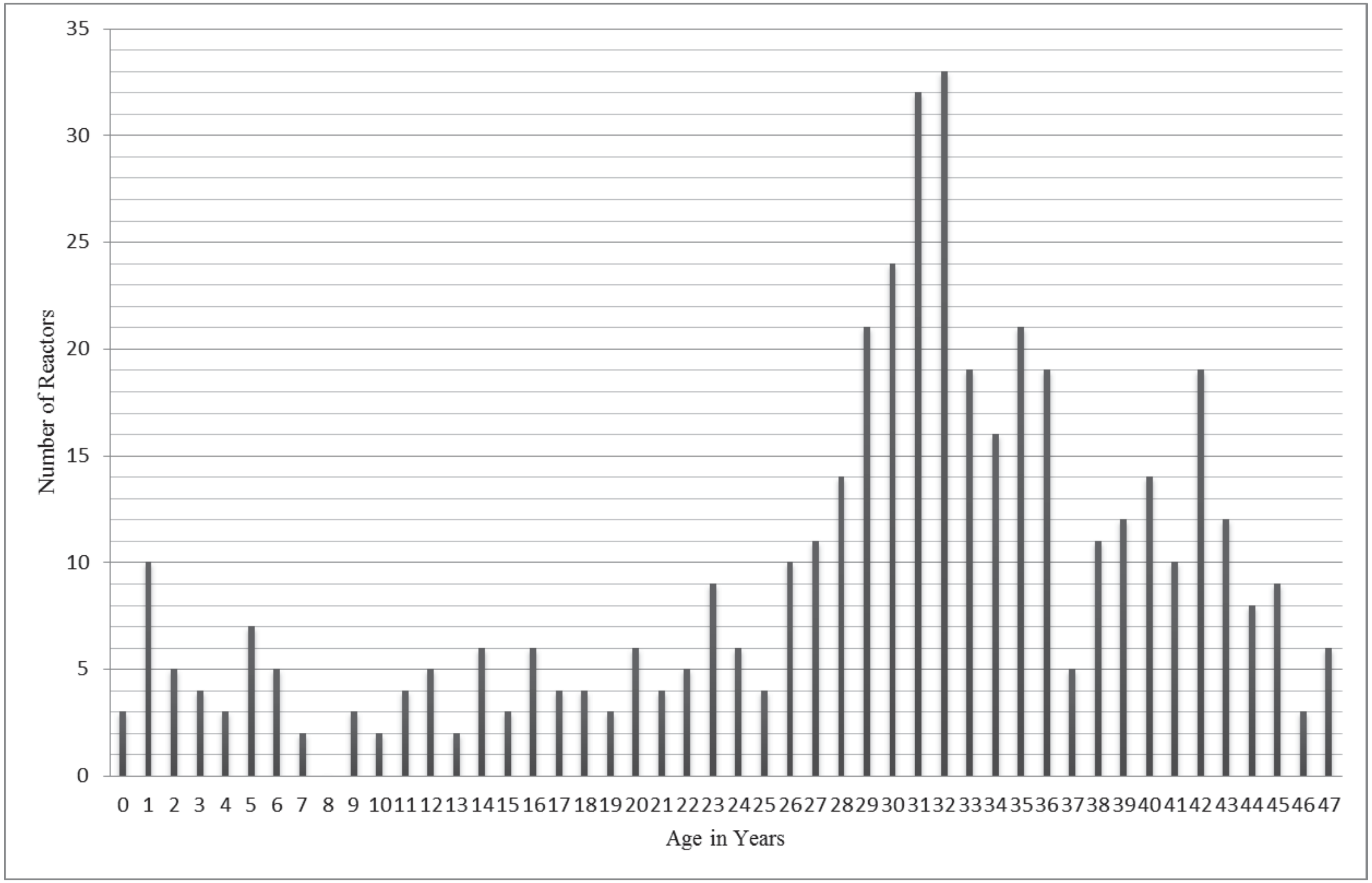

Fig. 9: Operational Reactors by Age

NOTE: Age of a reactor is determined by its first grid connection.
Reactors connected in 2016 to the grid are assigned 0 years.

While fatigue due to ageing can affect both metals and the structural components of nuclear plants, it is paramount that specific components and locations that would be prone to fatigue are accounted for and managed in such a way they would be prevented from causing unplanned downtime (Rosinki, 1998).

In service degradation due to ageing and other effects on the reactor pressure vessel cannot be studied in situ due to the operating conditions. Hence, modelling and experimentation through irradiation, annealing and other conditions that simulate the operating conditions can help to understand the effects over time and the material behaviour that would be necessary to evaluate ageing and life extension of critical components (Nanstad et al, 2001).

When considering the issue of concrete structures towards plant ageing, the performance was found to be ‘very good’ with most issues, as understood from the Bathtub curve of the ‘Early- Infant Mortality Rate’ type which were observed during the construction and thereby rectified (Naus, 2009). The paper stresses ageing can result in degradation over time when the effects are not kept in control.

A report by the American Physics Society Panel on Public Affairs on the study conducted on American nuclear plants on license renewal for operation proposed three recommendations for the path moving forward when tasked with the question of licensing beyond the agreed set life of 60 years for most power plants on the continental United States. The paper spoke of stressing on the safety of the plant to ensure renewal was a feasible option (APS, 2013).

With great advancements in technology nowadays, there are materials that can be used to make reactor vessels lasting for over a century (Rosatom, 2015). The extreme temperature, pressure and radiation resilience that would be required towards safe operation for the proposed 120 years of the RPV would be a breakthrough should the unit go into pilot testing and would revolutionise nuclear power plant operation as we know of it in the present day.

1.3.3. Licensing overview

Different countries pursue different licensing processes with two international bodies, the International Atomic Energy Agency and Nuclear Energy Agency under the auspices of the Organisation for Economic Cooperation and Development Agency are the two main agencies generating nuclear regulations at the supranational level. International initiatives for regulation harmonization across borders were spearheaded in the past by regulators and the industry too.

A comparison of licensing regimes across a selected group of countries revealed that there needed to be in place a coherent set of laws in the better interest of clarity, transparency and consistency (Bredimas, A. and Nuttall, W. J., 2007). There are binding and non- binding legislative measures; in the case of the former these account for treaties, conventions and protocols while the latter includes simple safety standards and guides issued by the supranational bodies from time to time.

Safety has always been an important aspect concerning the running of nuclear power plants. Licensing procedure aids to the idea of upholding the safety during plant operation. The INSAG reports of the IAEA deal with the safety aspect of NPPs from multiple points of view (IAEA, 1992) and updating reports as the technology progresses (IAEA, 1999).

Moreover regulatory overview is an important part of safe operation, with proper licensing to start with. Various countries' nuclear regulators have operated at different levels of interference towards the safe working environment that shall be beneficial to the effective and efficient running of the plant. While challenges have been made public for the independence of the regulatory bodies (IAEA, 2003), the licensing and regulations also stems from the ruling governments and their view towards nuclear power. The issue of regulatory independence and the effect it has on decision making will be discussed a bit later in this section.

A regulatory pyramid with the legislative Nuclear Energy Act for each nation state is the authorisation, by law to enforce the power generation by nuclear methods; followed by decrees that may be issued; guidelines and other regulations put in place followed at the base by the framework of technical standards of specification and codes is mentioned in literature (Brennecke, 2013) as one way of looking at the devolution of power from the law makers in the legislative section to those adhering to the standards and specifications at the plant engineer's level.

Licensing concerns in Sweden stem from nuclear power in Sweden being a highly political issue and is not yet in a complex level. Swedish public have been supportive of nuclear power, more than most European neighbours, with support even increasing after the Chernobyl incident. The licensing of a new plant in Sweden is based on the Precautionary Principle, wherein when prohibitions and measures of precaution are considered the risk for damage is sufficient enough (Michanek G. and Söderholm P., 2013).

While there are issues concerning technical aspects of ageing plants, when the first generation plants are brought into purview, it is common knowledge that their safety would not match those that of the more modern plants. Then, the sole option would be to retrofit the existing equipment with compensating measures. These involve licensing issues that would have to be taken care of when agreeing and approving the said life extension of the components (Kovalevich and Verezemskii, 2001).

While the existing regulatory regimes across the world may be quite similar, studies analysing the existing regime codes have found flaws in the present set up. Reanalysing the existing licensing basis being absent is one important issue (Newberry and Kuo, 1998). When there are mechanisms to introspect the existing regulatory framework, deficiencies can be found and rectified at the earliest. Instead, the paper argues the license regime in the USA focusses on systems and components that are already within the scope of the existing for regulatory issues pertaining to life extension and renewal.

While sceptics argue about the possible dimming of prospects for the nuclear industry after the events of March 2011, there are counter- arguments on how there would be more stringent laws and regulations (Kessides, 2012) that if not already in place five years after the event, would eventually come into place.

Trying to understand the flow methodology of the decision process may not be crystal clear due to various influencing factors that are at usually at play. A real case of application of the license renewal towards a particular component revealed the possible options and the methods of procuring the data but the thought and flow of ideas was tough to gauge (Chandiwala, F. and Evans, W. P., 1999). Most plant operators try to satisfy the basic requirements that are needed towards the license renewal in the application document that is available at the nuclear regulator's office. The French regulatory authority *Autorité de sûreté nucléaire* (ASN) for instance asks for particular certificates, control procedures and financial guarantee among others for a similar life extension of a component (Autorité de sûreté nucléaire, 2013).

1.3.3.1.Regulatory Independence

Licensing is authorised by the national regulatory authorities. Some selected nuclear regulators are listed below:

Table 2: Nuclear Regulatory Authorities in Selected Countries

COUNTRY	**REGULATORY AGENCY**	
	ABBREVIATION	EXPANSION
Canada	CNSC	Canadian Nuclear Safety Commission
Finland	STUK	*Säteilyturvakeskus* (Radiation and Nuclear Safety Authority)
France	ASN	*Autorité de sûreté nucléaire* (Nuclear Safety Authority)
India	AERB	Atomic Energy Regulatory Board
Japan	NRA	*Genshiryoku Kisei Iinkai* (Nuclear Regulation Authority)
Sweden	SSM	*Strålsäkerhetsmyndigheten* (Swedish Radiation Safety Authority)
UK	ONR	Office for Nuclear Regulation
USA	NRC	Nuclear Regulatory Commission

Having considered some issues pertaining to the licensing regime, it is important to understand that the national nuclear regulators' independence in decision making should not be influenced by political motives.

Reactor operators should be overseen by a body that is answerable not to the whims and fancies of politics but rather work towards ensuring the highest level of safe operation for the nuclear power plant, in such a way that the general public come to trust the decisions thereby made by the said regulatory body. National regulatory bodies shall therefore be at the forefront of mitigation issues, especially when concerning safe operation of the power plant.

A regulatory body can be said to have three broad function that justify its existence (IAEA, 2003):

- Working towards developing and enacting appropriate regulations
- Verifying compliance with the above
- Enforcing corrective measures in light of deviation

The nuclear industry is one that is highly policy driven at a national level. Hence, the challenges to regulatory independence is an important aspect that should be considered when discussing regulatory independence. Working towards minimal interference would be the most suitable option for today's nuclear regulators.

Regulatory quality management is important when adhering to safety regimes that shall not compromise the safe operation of the nuclear power plant. With external influences that may be due to the above political factors, due to policy issues and public sentiment, industrial factors of profitability or internal issues due to a slack safety criterion of operation, non- participation in peer reviews, poor international co-operation, etc. contribute to the reducing quality of decisions made by the regulatory body.

It is paramount understanding that regulatory agencies are an integral part of the decision making process though plant operators are the ones who make the decisions to go for a license extension or renewal. With an independent regulator at the top of the functional pyramid, a safe playing environment is created. Transparent decision making is further promoted by a neutral independent regulatory body.

Obviating the need for public accountability for actions is not what regulatory independence stands for. The regulator should be accountable to the public, the parliament (wherein present) and the government. It should not be dictated to terms especially on decisions concerning safety.

There should be regular auditing and reviews done of the decisions made by the regulatory authority. The licences renewed, the regulations passed and other issues including financial should be audited by an independent third- party to promote a culture of transparency towards the safety in operation of the nuclear regime in each country.

It would only be logical that decisions requiring regulatory change due to modern technological achievement be made assuring the general public of a safer tomorrow rather than bowing to pressures from lobbyists and politicians who wish to further their ends. This aspect of licensing shall be spoken further in the decision making process when analysing specific components during individual stages.

1.3.4. Peer Reviews and Stress Tests

Under the issue of nuclear safety and security, peer reviews constitute the global playing field of nuclear operators by critically comparing one another and ensuring they are maintaining the highest standards of excellence.

One elemental aspect of peer reviews to ensuring that the nuclear regulator is an independent body and there is no unwanted influence in its operation, which further highlights the importance of the previous section of this thesis. Peer reviews, in light of regulatory independence, can even be conducted on reviewing the national regulatory framework (IAEA, 2015) towards safety in operating of nuclear power plants. Literature review suggests peer review guidelines towards a variety of issues including towards decommissioning of nuclear power plants (NEA, 2014b).

Peer reviews are commonplace in the industry today as it works to ensure incidents that may be of concern to one operator are looked into in other plants and thereby ensuring should any untoward incident occur, the plant operators are prepared to face it.

When peer reviews are conducted, every participant member raises issues of concern, and they are individually replied to by the concerned operator (Canadian Nuclear Safety Commission, 2014). Such peer reviews only play a constructive role when they are critical of the plant, and this shall further the ability to advance on the learning curve for the concerned operator. Furthermore, in depth review of the plant with its various operating parameters only helps the participants to understand and identify issues before they become of serious concern to the authorities leading to mitigation.

Monitoring, as would be discussed later in this thesis is an important aspect towards proper data accruement. Cross- checking and counter- analysing component operational history is beneficial towards understanding component operation. Modelling and simulation of various scenarios are important as would be seen from the stress tests described here forth.

Stress tests to measure defence towards various external operating conditions were carried out in light of the meltdown event in Fukushima. The European Union, with its constituent member states decided to carry out the tests with peer review of the various operating plants within its geographic region. The tests were carried out on 132 nuclear reactors at 58 different sites (European Commission, 2012). The European Nuclear Safety Regulators Group (ENSREG) was invited by the European Commission to develop the tests to prevent a grave accident from occurring within their geographical boundaries. By carrying out the stress tests and later subjecting to peer review the EC set the standards early towards a safe operating environment. The peer review showed that all regulatory authorities had taken special measures towards increasing the robustness of the plants under their purview. The review, analysing and studying the available data from different plants was able to propose areas for further improvement (ENSREG, 2012).

Understanding the effective methods of working of stress tests, as a preventive measure and thereafter scrutinising by peer reviews only helps the industry to address the flaws in it. By responding to the queries posed in the peer review, individual regulators can assure their general public about putting safety before all else.

1.3.5. Economic overview

There are economic tools available to help designers and plant operators decide what measures are required to remain competitive in the power generation market. With data available from initial investment cost through capital, recurring maintenance costs, running costs, the analysis is made on the refurbishment costs that shall determine the rate of return for the proposal after which evaluations and reports are made selecting the best possible criteria including how nuclear energy production compares with other alternatives available (IAEA, 2007b).

While there are indeed risks and uncertainties involved with economic planning towards the setting up, running and life extension of a power plant (Kessides, 2010), the progression to an economic outlook emanates from a strong technical and regulatory mind set to make a project successful. The economics, though highly important in the decision making process, are not being researched on in this thesis.

1.4.Outline of Study Methodology and Research Question

The study pertains to try to analyse the decision making flow process for the replacement of a particular component of the working system of the operational power plant, with a view on the technical and regulatory issues that affect these decisions. Economics, though too is involved in the entire decision making, its role is limited more to choosing one of the available options towards the end of the process with satisfying the needs of the investors in case of a private operator or optimising use of taxpayer money in the case of government run plants.

The overarching question is safety as the first priority towards future plant operation. A safe operating plant is one that adheres to the safe operating code of conduct. For the research, the process flow beginning from the first instant of conceptualising the idea to moot for plant life extension to the final stage of decision making was considered.

Prioritising safe operation requires forming criteria to ensure decisions made adhere to the overarching goal. The decision makers should know what to look for when they are involved in the decision making process. Having considered the various aspects thus far in the introductory section of the thesis, outlining some aspects that would aid in a more logical decision making would be in order.

Concerning Policy and Public Perception

Addressing the larger issue from the outset of policy making, politics and public perception, if the three are against renewal of license, the plant operator has no option but to do away with the plan.

Concerning Operating Groups

When there are plans for increase in the share of nuclear power generation forecast, understanding which components are crucial towards furthering the safe operating life would bring the islands of operation into purview. The NSSS and BOP being the groups with a major influencing factor the decision making process, concentrating on if the constituent parts need to be replaced, analysing their operating history, their possible interaction, their economics among others would aid in clarifying the stance on whether to go forth with license renewal.

Concerning Plant Life Extension

An understanding of the state of the component, i.e. what stage in the operational curve does it find itself and whether it would be able to withstand the operating conditions for the remainder of the lifetime of operation of the plant. Adding on, technology and licensing for the individual component should be ascertained as to whether an upgrade through retrofitting and refurbishment is required and on whether the license needs to be amended for the same. Conducting stress tests and peer reviews would aid in a logical decision making process with user data and experience being shared and compared, thereby knowing if it is a viable option.

These criteria, among others, are the formative base when understanding the possible decision making processes that each plant operator and regulator would have to look for when undertaking a life extension application. As shall be discussed in the next section, the 5Ms of gathering the required data towards responding to the questions posed above shall aid in a transparent and safe operating environment.

There were assumptions of rationale involved during some of the processes involved in the decision making process that follow, some which included a simple positive or negative outcome to a particular question pertaining to the situation at hand, while some others involved a more elaborate sequence and loops that would bear upon different outcomes. While there would have been multiple outcomes possible, in cases not all may have been considered for the sake of logic.

The study begins with a flowchart that delineates the various processes that are most likely to be in the same grouping to simplify the various large processes into a linear flow to comprehend them. Then the processes are dealt with individually, analysing their individual input parameters and possible outcomes. This is analysed as the thesis progresses.

The decision making process study that commences in the forthcoming chapter of this thesis delves on the methodology of working with various issues that have to be considered going into the process including importance of some aspects that are overarching to the entire process such that they are important in the everyday running of the plant. Starting with the nuclear power plant at the helm with the approved license agreement to start with, the flow progresses through the component lists from which the particular component under consideration may be selected, the analysis of the operation of the particular component, technical feasibility of it to continue further operation for the estimated request life of renewal application, the possible interference and interaction among other components it receives input from and delivers its output to, i.e. those in the same working sub- section, other environmental factors that may affect its operation, the licensing regime to suit the adoption of the component finally arriving at the decision.

2. DECISION MAKING PROCESS

2.1. Method of Research

The theme dealt with in this thesis comprises concentrating on and highlighting the decision influencing factor flow in leading up to the process of renewal of licensing towards eventual extension of the life cycle of a nuclear power plant. The lead up in decision flow to assessing if a certain power plant will be able to withstand future operating loads and conditions, surrounding circumstances with the effect of improving some existing parts due to modernization, but keeping in view not adversely affect the stability of the operating of the system as a whole will be looked into.

The flowchart of decision making has been chart with keeping in view the natural evolution of ideas that would eventually lead up; finally culminating in concerned authorities of the nuclear plant taking the decision to go ahead by submitting the application to extend the commercial life of the plant.

The work shall give inputs into decision making, the flow methodology with emphasis on some aspects that may be currently being overlooked in the decision making process. The issues that may arise during routine checks which may or may not have the possibility to influence future decisions, including but not only life extension would be looked into.

The five important aspects that shall be overarching to the entire study and recurring throughout the decision making process shall be the following five 'M's.

- Measurements
- Mechanisms
- Modelling (Simulation)
- Mitigation
- Monitoring

As shall be observed when explaining the sequential flow of thoughts and ideas later in this thesis, these five aspects are omnipresent in every minuscule step and decision that an engineer, a plant operator or a regulator would have to take to ensure safe operation of the plant in ensuring the safe operation of the plant by safety in use of atomic power and protecting public health with due attention paid to the key areas reactor safety, radiation safety and safeguards emanating from security aspects that concern the plant operation.

2.1.1. Measurement (of data)

Ascertaining that a particular component functions properly without showcasing any erratic behaviour during its normal operating cycle is an important aspect in the life cycle analysis of any component. Within the boundaries of its normal operation curves, the dependability towards reliable operation of the component is significantly high than that if it were to be tested somewhere beyond the set design life of the component on the curve. Routine measurements to detect anomalies are important to keep unexpected event proliferations in check. These checks should be carried out frequently and diligently- a time frame of no more than three months, once every quarter would be an appropriate routine to follow for data measurement.

The foremost important aspect would be to ensure the documentation is proper for the components and parts. With effective documentation, measurements later on during the operating cycle can be tested and verified to stand true to the certificates issued by the manufacturer. It would be important to ascertain the availability of lifetime characteristics documentation for the concerned part in the construction and installation design documentation. This document would be the base reference towards reassessment of the part. Should this particular document be non- available, a method would have to be devised to get the proper documentation. The easiest one would be to ask the supplier to provide the required documents, should that fail one way would be to extrapolate the data under the expected operating conditions from a similar component supplied by a different manufacturer or supplier. Though nuclear power plants are rigorous with their documentation efforts, there would be a small blip that would show up, something that would be commonplace in the older reactors that were set up before the era of digitisation.

Digitisation would be another way to ensure that measurements are readily reported and recorded. Though it may seem easy, one important aspect to consider is the durability of analogue equipment to external influence; something pertinent in this age of modernisation and easy data and information flow across borders. An example of this would be the Stuxnet virus that infiltrated into Iranian nuclear systems wreaking havoc (Symantec, 2011).

2.1.2. Mechanism (of testing)

A rigorous approach to examine each component during its reassessment measurement process should be put in place. The process, documented in writing, should encompass all the steps that would be important towards putting in place an effective testing mechanism of operation of the concerned part.

During the course of operation, with time, there would be some changes to the testing mechanism that would have to be incorporated to ensure successful tests are carried out and documented. Though some may be small in magnitude, others may be appreciable in nature. An example would be when digitisation of the plant was undertaken, analogue measurement methods would have been rendered obsolete. Though this is a great change in the mechanism of carrying out the measurement, the results tabulated would not differ before and after the change would have been carried out.

Ensuring a standard test is carried out shall help to find deviations from the normal as all input parameters corresponding to the mechanism of carrying out the test remain a constant.

2.1.3. Modelling (current software, or data from experience)

An important tool for any engineer today is one that predicts future occurrences and simulation; be it on a computer software or mathematical go a long way towards understanding the characteristics of operation of a particular component.

Mathematical models are conjured using equations that specify, albeit mathematically, the operating conditions and the ambience the part is in and would have to be expected charting the future course of events (Tkachev, 2008). With mathematical modelling, physicists and scientists are able to propose and predict methods to estimate the failure probability of a particular component which would take into account the operational experience in different ambient environments. Using various quantities as inputs the thermal, strength and mechanical properties of a metal for different applied loads and defects that would occur would be profoundly visible at the end of the experimental model.

With the advent of software and computer aided designing, with just the touch of a button many an information is revealed. Computer aided modelling software help to understand how various parts would act under the given operating conditions. By using a computer modelling software, design and modelling times would be drastically reduced. The simulation of the actual working environment would help the user to learn about the progression of the life of the component quickly and help discover when there would be a greater chance of failure and under which specific combination of the random input parameters (which would be ambience the component finds itself in during normal working). Assisting the engineer during routine maintenance, the modelling software would be able to recall information and record data and giving the option to reuse the data offering upgrades to the incumbent part.

When stress tests are conducted, as discussed earlier in this thesis work, modelling and simulation help in identifying the flaws that are present not just in the individual component, but also in the system as a whole. The operational group ideology propagated earlier would help further clarify the interactions during the testing phase of carrying out these tests.

2.1.4. Mitigation *(of anomalies)*
With the power of discovering a possible non- conformance, arises the question of mitigation of the said and bring it to the standard operating conditions. While palliation procedures may differ variedly depending on the operating environment, it is important to bring it to the notice of the concerned authority.

Mitigation can be classified into various types:

2.1.4.1. Minor anomalies that do not require any change
An error that falls within the expected confidence intervals would be due to an advanced life of the concerned component. This should only validate that the equipment would safely operate at least until the specified design life that is mentioned in its lifetime characteristics.

2.1.4.2. Minor anomalies requiring change of equipment (a routine change necessitated by expiration of set design life)
When a part is approaching the end of its useful design life, a well organised plant operator would know that a replacement of the part is imminent. When measurements match modelling, with the detection of this aberration, the operator should be ready to replace the component keeping downtime to a maximum.

2.1.4.3. Major anomalies with equipment change and licensing approval
When a major defect is detected on routine conformity to the norm measurement check of a particular component, the issue should be brought to the notice of the hierarchical higher- ups involved in making the decision. Reporting of the anomaly is an important step to ensure unforeseen downtime is avoided.

An anomaly of this nature would involve triggering a chain of events that would proceed through verifying the obtained data from one or many alternate sources. Thence, on the engineer in charge would have to create the required documentation and send it for due consultations among the higher ranked engineers to decide on how to proceed and which replacement equipment would be able to fit in place with the minimum distortion to surrounding operating environment, furthermore future interferences and interactions would have to be duly studied beforehand. When analysing the operational experience of the component, this issue is further elaborated upon with the specific issue of a major level accident on the INES scale.

2.1.4.4. Major anomalies leading to system failure
With a similar progression sequence as the previously discussed type, these have the added urgency of a greater catastrophic effect precipitating should no action be taken.

While such anomalies are rare in occurrence, due to routine checks, designs, modelling and monitoring that nuclear power are rigorously subject to they may nevertheless show up during examination.

An erratic component would only bring its directly interacting local constituents into uncharted territory, which may be avoided for all safety reasons.

An important aspect is prevention before setting out on mitigation. When monitoring and measurements conform to the modelling, the operator should be ready to replace the part before its starts exhibiting erroneous behaviour. This would be pertinent in the case of minor anomalies that would be rectified by a simple change of equipment due to expected wear and tear.

2.1.5. ***Monitoring*** *(towards maintaining a safe working environment)*

Live data relay and transmission are commonplace in most modern day reactor control rooms. While measurement concerns only data received, monitoring activates the full loop of giving the required necessary input to manage and control the component. The feedback completes the circle of operation, wherein the data is measured by various means, the plant operator receives the above said and triggers a correction mechanism. This is a very important aspect of control room dynamics.

Monitoring and accruing of data is indispensable towards understanding the working of the system. As discussed earlier, proper data monitoring towards the cause of peer reviews shall help understand anomalous operating conditions. With such reviews, the monitored data can be presented and cross- verified among other such operators in other conditions to study and analyse the history of operation and compare if there are deviations from the normal operating curves.

Monitoring can also be divided broadly on two categories:

- Monitoring existing components
- Monitoring replaced components

2.1.5.1. Monitoring existing components

Monitoring normal components and activating the feedback brings them to the desired state of operation. This is routine work for the operator. A case for load- following procedure of nuclear power plants would involve the plant operator to monitor the required parameters to ensure that the reactor in question has an output as demanded by the load, which would have to be produced by the power generating units. Reactors in France, which produces three- quarters of its energy from nuclear fission of the type PWR- 900, PWR- 1300 and N4 and Russian VVER- 1000 reactors in Germany operate on a load- following mode (NEA, 2011).

2.1.5.2. Monitoring replaced components

Another important aspect of monitoring concerns those parts that have been replaced without or without after having obtained licensing approvals authorising the new part. The operator would have to specially keep in view not just the part that has recently been replaced but also monitor the components it interacts with to observe and monitor if they show interference patterns due to the presence of the new part. The new component as it is fitted into the working cycle of the existing power plant may or may not precipitate a response from the other components.

This would have to be noted in the log books and used to enhance the learning curve of operational aspects towards interference of the new component when in the specific environment of operation.

As seen from the operational groups of the operation of the nuclear power plant, there are major and minor criteria that affect the decision making process. The criteria of ascertaining whether a part component discussed above is of grave concern towards the life extension application is clearer with respect to certain components while not so for some others. Components that are replaced every few years at the end of their lifespan, due to normal wear and tear are considered only a minor impacting factor in the decision making process. While other components that include the RPV, SG, etc. carry a greater risk to the safe operation of the NPP should they fail unexpectedly.

The above ideology of the 5Ms needs to be viewed keeping in purview of the minor and major impacting criteria. While a rigorous maintenance regime shall ensure the components and parts are replaced over time, care should also be paid to erratic operating history that would be a cause for concern for the decision makers. The five Ms are listed here under the method of research because effective implementation and utilisation of the above shall foster a safer operating environment, one in which the data is available for all to see and the decision making process is logical.

When there are discrepancies or an absence in the linear flow of the five Ms above, a regime should be introduced to collect the required data, corroborate the testing mechanism towards the above data collection, leading to a pedantic modelling with meticulous mitigation and fastidious monitoring. This regime that would be created would thereby guarantee a stable starting point of knowing all the starting parameters towards effective decision making process is achieved.

2.2. Block Diagram of the Decision Making Process for a component for life extension

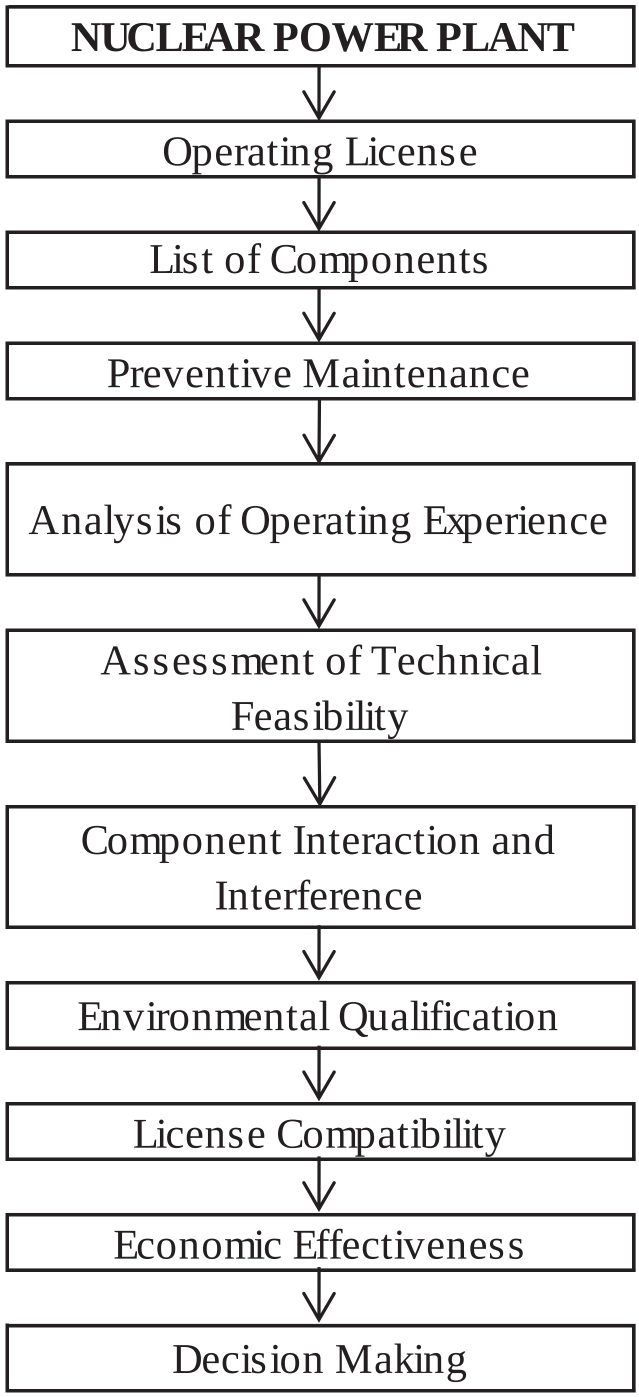

Fig. 10: Simplified Block Diagram of the Decision Making Process

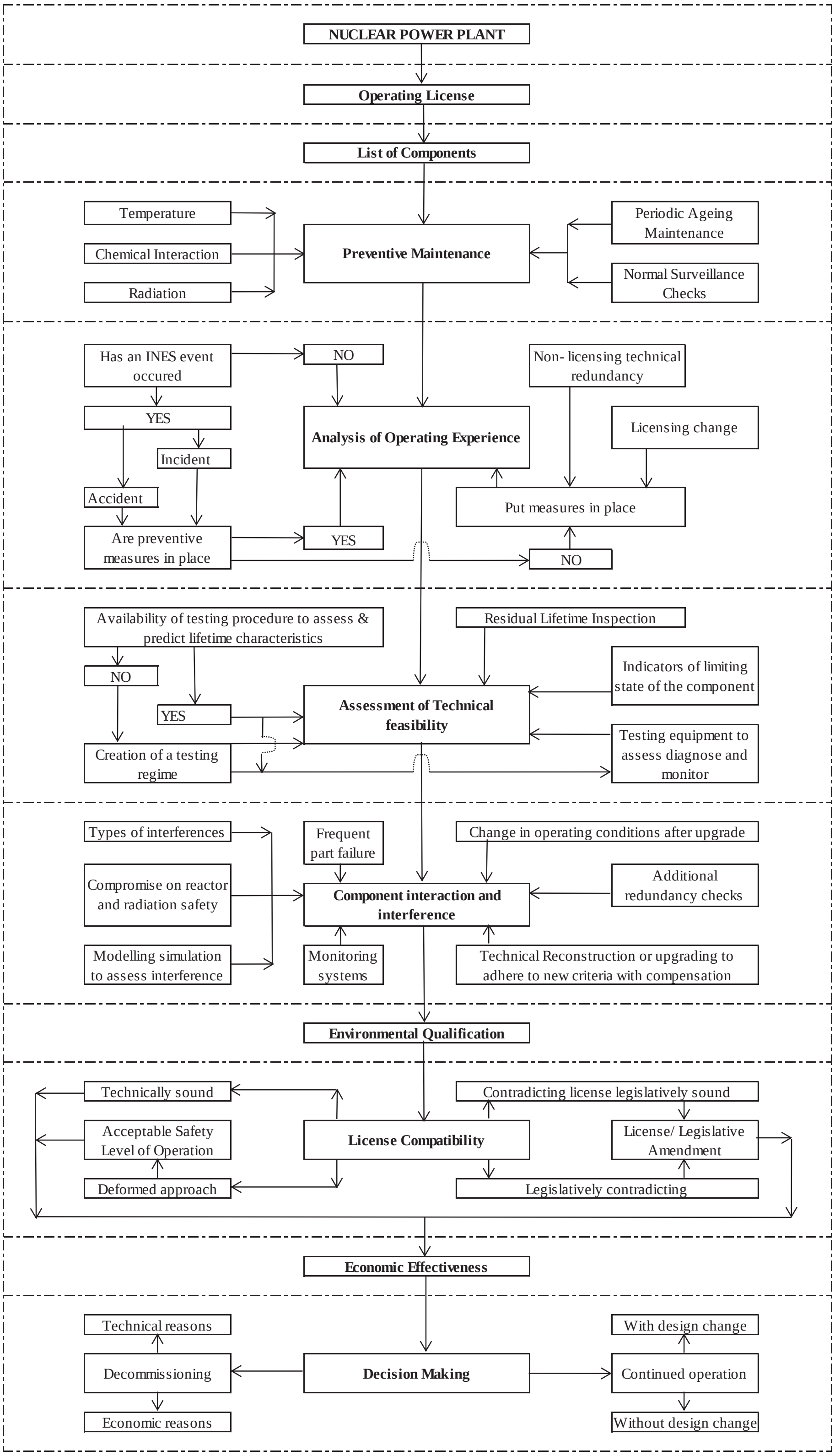

Fig. 11: Detailed Block Diagram of the Decision Making Process

2.3. Decision Making Process with Reactor Oversight

The following explanation of the above block diagram shall elaborate on factors affecting decision making with the intension of applying for renewal of licensing for the operation of the nuclear power plant. Though literature review suggests two to three years should suffice for the development of documentation towards application to renew the license (Alonso et al, 2012) while in the United States, the Nuclear Regulatory Commission proposes 30 months for completing the same (NRC, 2012), some of the processes shown above and discussed in detail henceforth would require longer periods of attention to detail, especially those involving regular maintenance over particular time intervals.

2.3.1. The Nuclear Power Plant (Figure 12)

The Power Generating Unit lies at the heart of any nuclear power plant. Like all other components, reactor vessels, steam generators and turbines are prone to failure too. Decision making process with a bird's eye view of the whole process can be summed up into three main aspects that concern plant life extension.

- Legislative Standardisation
- Technical Aspect
- Economic Consideration

With the above idea of standardising legislation and thereby effecting regulatory changes to the running of the nuclear power plant, the main idea would be the overview of the technical aspects that would be overseen by the new regulatory guidelines for the safe operation of the plant.

Every plant is sanctioned to run in accordance with its approved license, this shall be the next step in the logical decision making process to conform adherence to the existing license.

2.3.2. Operating License (Figure 13)

Licensing lies at the crux of the operation of any atomic power plant. Licenses are issued, nationally, based on criteria set by the national nuclear regulating body. They may or may not differ in the particular content across international borders, but in principle, they authorise by law to permit the working of the respective power plants under the designed and accepted boundary conditions. It encompasses the idea of legislative standardisation with prior approval from the concerned nuclear regulatory authority in the operating country.

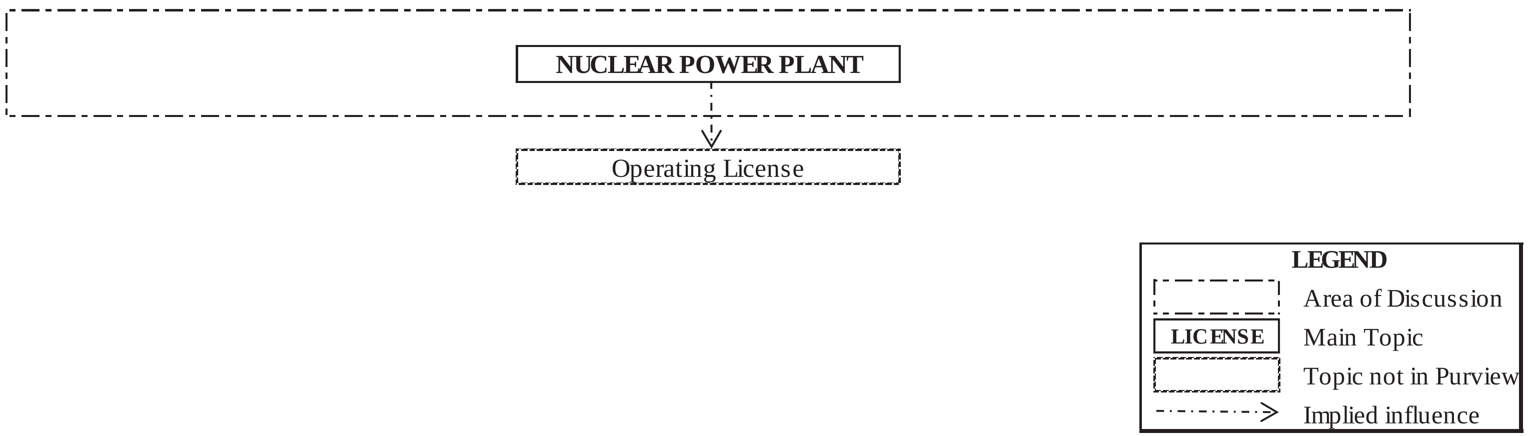

Fig. 12: Part Diagram of the Decision Making Process- Nuclear Power Plant

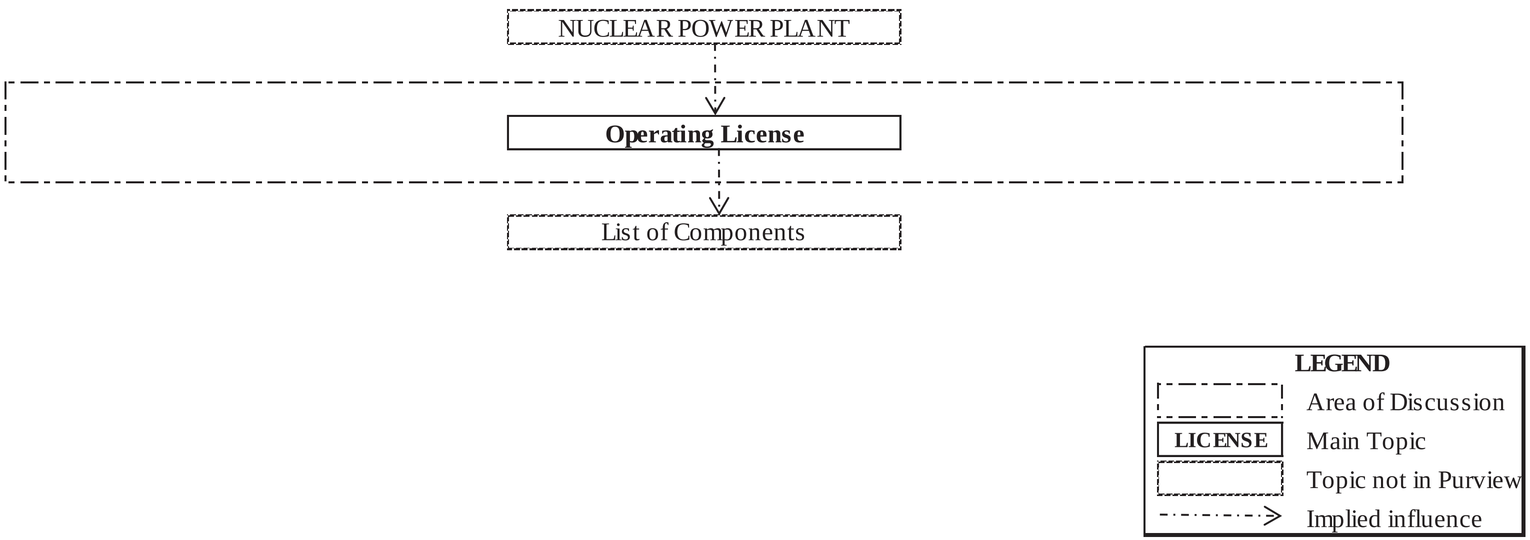

Fig. 13: Part Diagram of the Decision Making Process- Operating License

Adherence to the licensing regime is quintessential to the plant operation, hence when looking ahead to modify particular parts that are essential to the plant's operation, due care should be enforced to see that proposals do not deviate from the approved licenses. On the other hand, if they do and that is the best available alternative, then due care should be enforced for alteration, which shall be dealt with as the decision flow progresses and matures.

2.3.3. List of Components (Figure 14)

Every reactor has a multitude of components, in varying sizes, shapes and relative importance that are its forming blocks. Every operator would have a list of components which give information not only about the lifetime performance characteristics, but also manufacturer data, permissible operating range, contact address for routine maintenance and also in case of failure.

There would be certain exceptions wherein a whole ranging list of components would not be available. In such cases, classification lists would have to be drawn based on the general classification of components for the particular type of reactor, for all BWRs, PWRs, etc. whether old or new would have a similar general classification list. Once this list has been drawn, the list of components that would be influential towards monitoring, assessing and predicting operating conditions would have to be created by means of a special list.

The creation of the said new list shall help future planners to have at hand all the required data thereby needed to understand the working and operation of the component. With the design characteristics, the records of normal operation and the maintenance records, the anomalies that have been occurring would be easily identifiable.

This would lead the decision making process into the next plausible step of preventive maintenance.

2.3.4. Preventive Maintenance (Figure 15)

It refers to the idea of stalling natural degradation of the equipment by the ageing process. This does not stand true for extraordinary conditions of plant operation or in case of an accident. Preventive maintenance measures should be rigorously and frequently carried out on each and every component that would be of concern when applying for the renewal of license. Some parts may be too minuscule to make an impact but they could interfere with other more important parts in operation which may affect the overall decision making. Mitigation, as mentioned earlier can be kept in check by preventive maintenance which is a very important reason to avoid unforeseen interruptions.

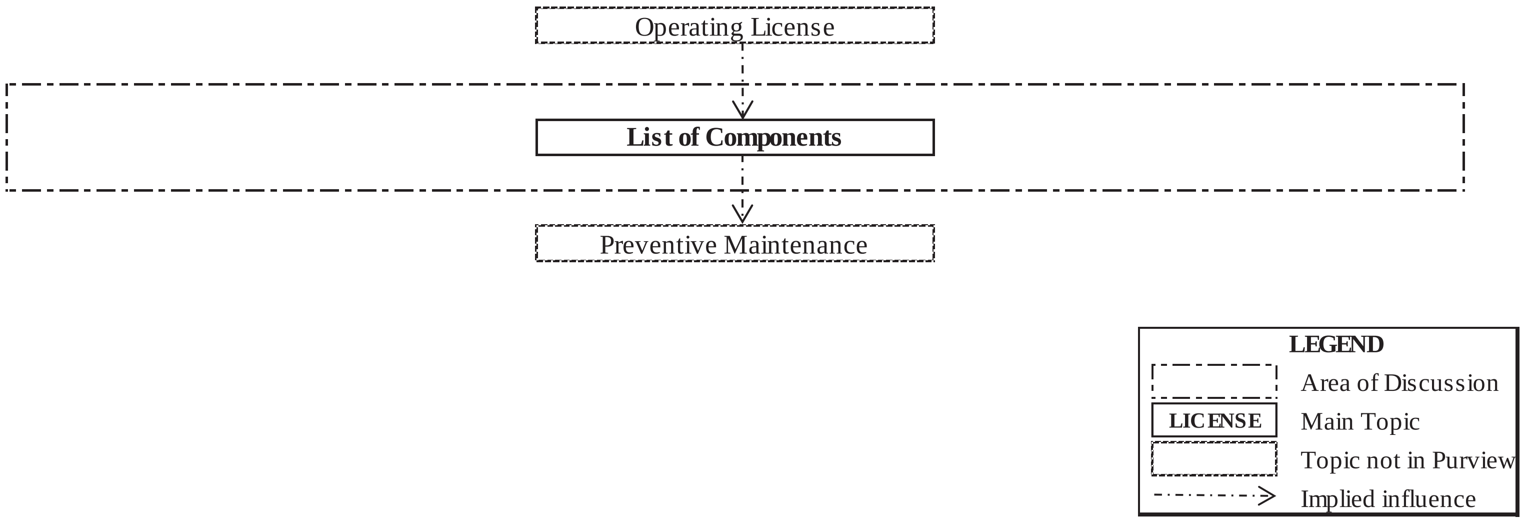

Fig. 14: Part Diagram of the Decision Making Process- List of Components

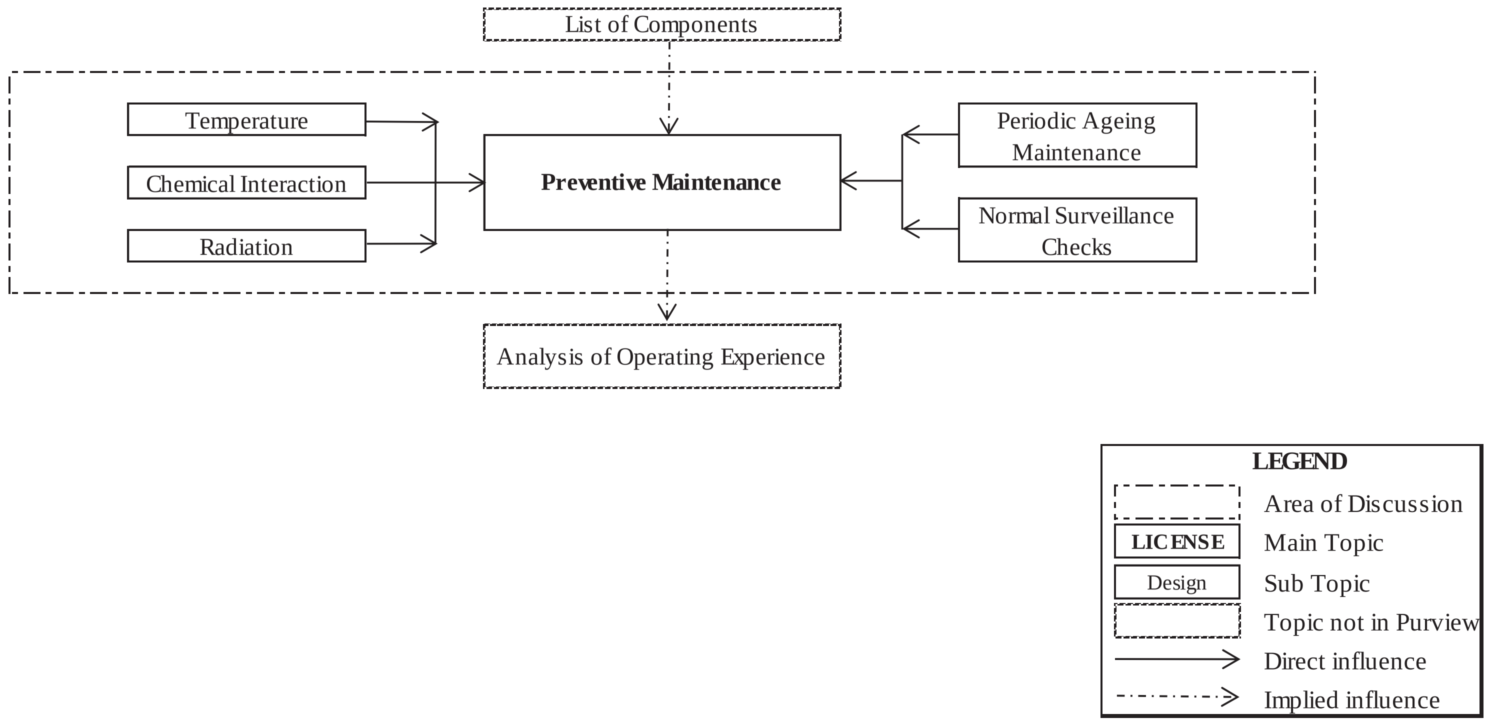

Fig. 15: Part Diagram of the Decision Making Process- Preventive Maintenance

- *Is there periodic (ageing) maintenance?*

  Ageing is an inherent characteristic of every component. Ensuring preventive maintenance gives an added level of confidence in the safe working of the power plant. Hence, each component, however insignificant the progression is, it should be checked at regular intervals.

- *Are there normal surveillance checks?*

  Besides of course measuring, recording and analysing each constituent component thoroughly, overall general checks of a surveillance nature are recommended to observe the whole picture and ensure the whole machinery is running smoothly. The surveillance programme also schedules routine inspections towards maintenance.

- *Temperature Observation*

  The ambience of operation of each part is to be observed and compared to ensure there is no deviation from the recommended operating conditions.

- *Chemical Interaction*

  This particular measure involves parts that are exposed to continuously changing ambient and therefore would be susceptible to effects of wear and tear, albeit chemically. Examples of these would be corrosion of pipes supplying coolant water, pumps, valves that would be the site of scale deposition, etc.

- *Irradiation*

This is of specific concern to parts that are liable to be bombarded by neutrons, or other atomic particles that may, among others, cause them to become brittle. The reactor vessel and primary containment walls are some examples of places where this effect should be highly noticed.

Once the required maintenance for prevention of any untoward occurrence has been ensured to be in place, the records should be checked which is the history of component operation.

2.3.5. Analysis of Operating Experience (Figure 16)

Every component has a history. When heading into licensing renewal, the concerned engineer and operators need to pay special attention to the operational dossier of the components that would be central to the regulatory authority approving the application to continue operation beyond the initial set design lifetime of the plant.

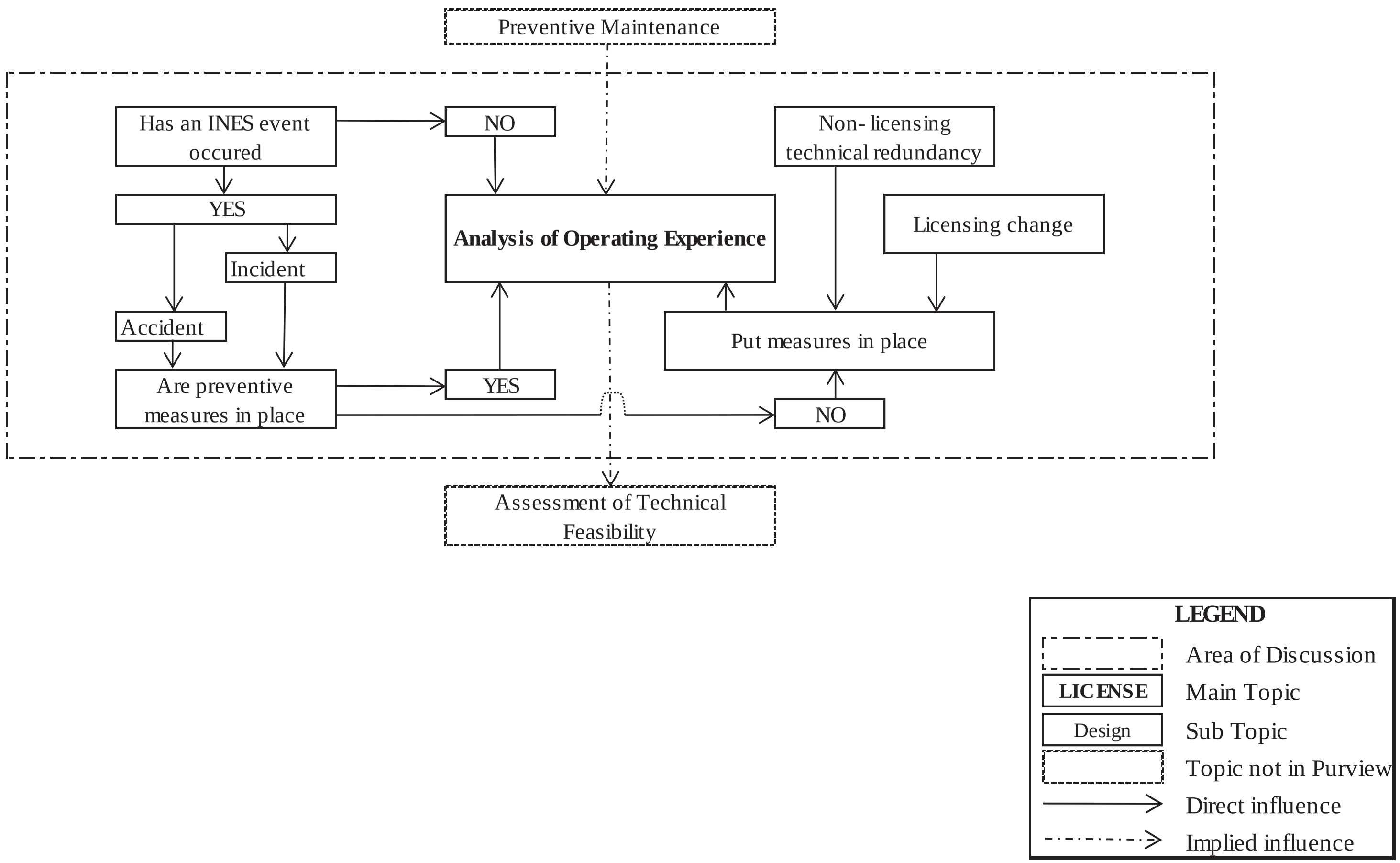

Fig. 16: Part Diagram of the Decision Making Process- Analysis of Operating Experience

2.3.5.1. Has an incident[1] or accident[2] occurred that resulted in an INES[3] event?

The International Nuclear and Radiological Event Scale (INES) of the IAEA is a tool developed in the 1990s to aid and "*facilitate the communication of safety significance of events at nuclear installations with sources of radiation"* (IAEA, 2014b).

When an event has been generated in the, the issue is to be scrutinised carefully to see no lingering effects of the first occurrence shall in any way affect the future operation of the performance of the component.

When no such event has occurred, it is safe to assume the concerned part has had a clean history.

Instead, when there have been events generated,

- *if it were an incident …*

  the issue would be of relatively lower significance as there would not be a serious breach of the defence of the plant, furthermore it would not usually be a major issue concerning future operation when the source of the accident is rectified to prevent a similar occurrence.

- *if it were an accident …*

  ascertaining that there are redundancies put in place to preventing a similar occurrence, notwithstanding the fact that an accident level event in the INES occurred on site and that the plant is in operation. If on the contrary, then efforts to add redundancy measures should be ensured. This would increase the operational safety to start with and confirm that other checking procedures, examinations and decisions can be carried on according to plan.

  Furthermore, special scrutinizing of the concerned component and its interactions and interferences with those it is directly affecting should be carried out. The data collected should bring to light what may go wrong in the future.

  Stressing on the mitigation idea propagated earlier with specific reference to the licences that are infringed upon due to major anomalies in operation, the issue of licensing of the particular concerned part is vital before proceeding in the decision making process. If a component has been replaced, without affecting the immediate interacting components, by another one of the same kind, with assuredness that within the operating design parameters of the component it shall display stable

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[1] Incident: 'An event that is less severe than an accident when used in the context of reporting and analysis of events.' When communicating the event significance to the general public, on the INES scale of one to seven, all events up to and including Level 3 are classified as *Incidents*. (IAEA, 2008)

[2] Accident: 'An event that has led to significant consequences to the people, the environment or the facility, with examples including lethal effects to individuals, large radioactivity release to the environment, reactor core melt, etc.' When communicating the event significance to the general public, on the INES scale of one to seven, all events of Level 4 or above are classified as *Accidents*. (IAEA, 2008)

[3] INES: Refer appendix (5) for INES classification

characteristics, the license agreement need not be revisited to update it with regard to this equipment. Instead, if the concerned component has been altered in design, performance or another factor, with or without affecting the immediate interacting components, an update of the license to continue operating with the concerned component should be put into force. This part under question may act adversely, perhaps contrary to the initial license issued by the concerned regulatory authority and thereby render it illegal to continue operating when should any untoward event occur and a legal case thereby ensues the plant operator would be running an unauthorised plant, pertinent to the changes brought about by the design modifications emanating from the replaced part.

An important factor to take into consideration in the aftermath of an event registered on INES is ensure proper mitigation sequences have been put into effect. Extenuating would bring about with it increased overview of the concerned part and thereby increased effective documentation.

Moreover, ascertaining barrier integrity has not been compromised and rather should it have been compromised, efforts put in place in the aftermath have restored the integrity are essential to ensuring smooth operation.

In light of the events transpired, care should be enforced in the way of emergency prepared to deal with other such future events. Emergency preparedness is a term that encompasses a plurality of issues, which is discussed at various stages of the thesis including interferences between components and implementing redundancies to be prepared during the worst- case scenarios.

Therefore, engineers working towards analysing the history of operation of a component with the aim of applying for license renewal can study the various documents, expert reviews from regulatory boards and internal quality control audit among others to make an informed decision concerning the component under question. The operational history can be used as a tool of extrapolation, learning and instruction for similar component-case- scenarios in other power plants where such rigorous documentation was not in place and to study the effectual interplay between various components under the operating circumstances.

2.3.6. Technical Feasibility Assessment: Extension of Component Service Life (Figure 17)

Nuclear power generation is a field that brings together physics, mathematics and engineering branches. These three explain why the technicalities of running and operating a nuclear power plant are of utmost importance. Beginning with the decision flow process, technical feasibility is an important aspect to life extension. It is fundamental to ascertain a specific undertaking is feasible technically before venturing to procure finances and pushing for legislative changes that would have to be incorporated to support the advancements in technology.

2.3.6.1. Assessment and thorough inspection of the residual lifetimes

- *Component*
  Assuming the component has faithfully served its purpose of being reliable and useful thus far would not amount to it being reliable beyond its set design lifetime. With the passage of time, the effects of ageing become more pronounced as wear and tear become more appreciable in the daily working interaction of the said component.

  Measurements to ensure that a component is performing with conformity to the rules of operation are first carried out. Then these measurements are compared with the inherent data present in the lifetime characteristics that shall help ascertain the residual lifetime of the component.

- *System*
  The system of operation would be licensed by the licensing regulatory authority which, under the then present circumstances would have approved of the plant as state of the art. As decades pass, advancements in technology would shift the argument in favour of safe life extension of existing systems without adversely affecting their ability to operate.

  As the set design lifetime is taken in consideration for a system of operation of a nuclear power plant, care should be taken to ensure that changes that would have been carried out over the years due to normal and preventive maintenance would not, in theory and practice, have altered the core of the system, i.e. when a significant change, that would amount to design change in operation of the system, would have been carried out, the regulatory overview of the concerned authority and thereby special addendum to initially drawn license application is brought about.

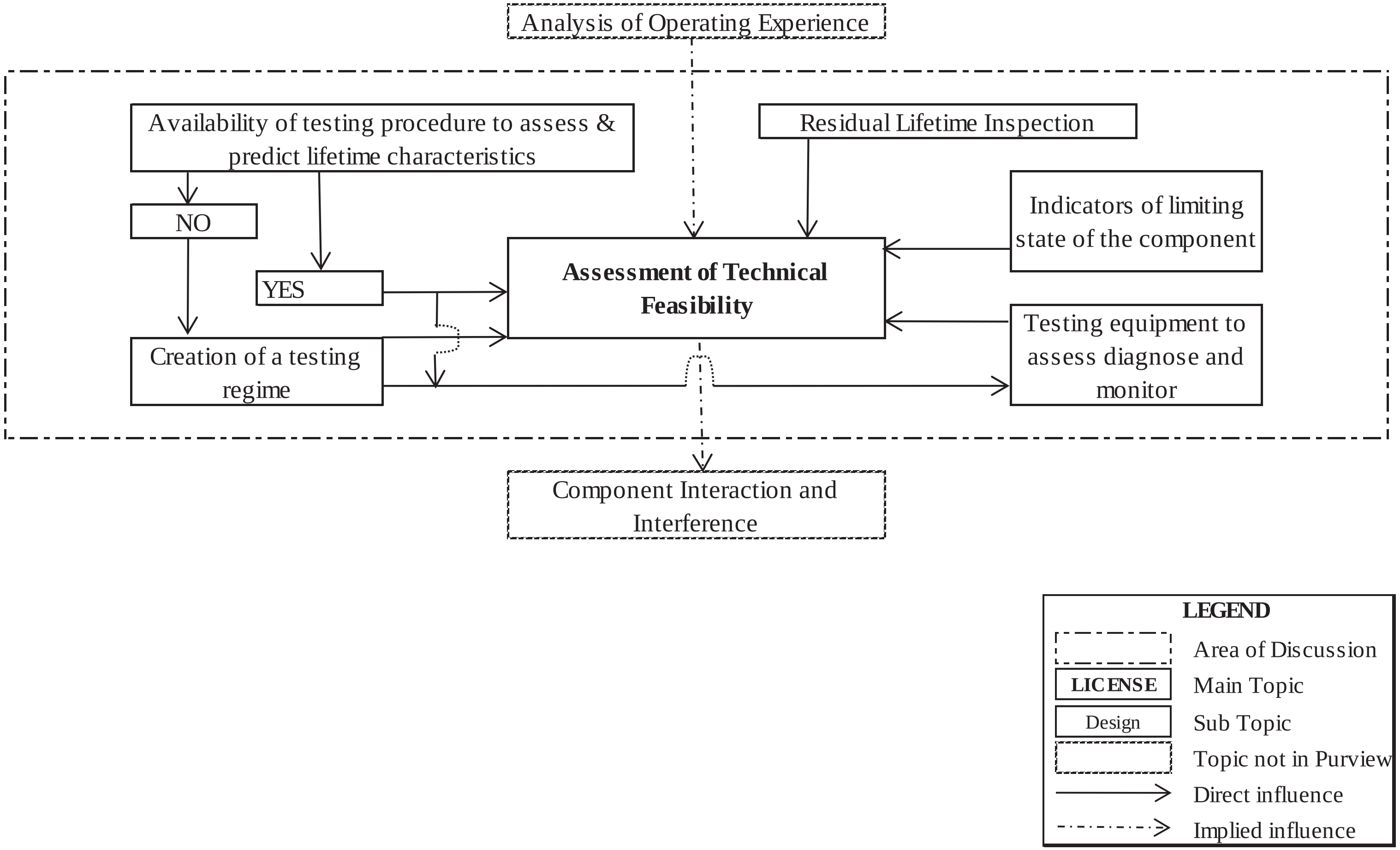

Fig. 17: Part Diagram of the Decision Making Process- Assessment of Technical Feasibility

- *Structure*

  As seen in the technical literature review structural components tend to be long lasting in most cases. There would be indeed some changes effected to the mechanical structure and integrity but nonetheless these would not be appreciable in the usual operating conditions.

  There would also be instances when the same does not hold true, which would be the case in light of a highly corrosive ambient environment or when materials of a lower quality that the proposed state of the art were adopted towards building the structure. In this case, with experience of testing in laboratories and/ or simulation data can help gauge if the concerned structure is suitable to continue operation. Residual lifetimes of structures are usually twice or longer than the usual initial licensed set design lifetime and the margin of error in not appreciable to be a cause of concern.

  As tests, examinations, operating experience and modelling would support the continued use of the structure towards an extended lifetime of operation; complacency should not creep into the measurement and monitoring of the structure. A stress or a crack that would have been below the minimum level of observation could take roots and develop rapidly before the next routine maintenance operation (as an example, three months). In such cases the residual lifetime would be starkly shortened pending repair work which when carried out accordingly shall restore the integrity to the compromised structure.

2.3.6.2. Available criteria and expected indicators of limiting state of the component

During the assessment of the technical feasibleness of a component, system or the structure, the operational curves as such described in the lifetime characteristics of the design and construction documentation should be referred to analyse and ensure observed effects during routine and out of the ordinary maintenance checks are within the boundaries of operation.

Limiting state refers to the conditions of operation wherein by probabilistic safety assessment tests have shown a greater prospect towards breakdown. The criteria and indicators that are obtained directly or by extrapolative means would have to be compared to the existing database of information available from the manufacturer or the supplier to assure operation within expected intervals and that it does not tend towards approaching its limiting state of operation.

Indicators of limiting state, when observed should be immediately fast tracked to verify if it were just an anomalous observation, equipment behaving expectedly due to ageing or rather erratic behaviour- the last of which would generate a series of progressive sequences towards potential maintenance measures with or without involving replacement.

2.3.6.3. Testing procedure to assess and predict lifetime characteristics

Carrying out tests on all equipment shall give the engineer an idea on the state of the plant. In today's scenario, documented tests should be enforced by regulatory means to ensure that every part undergo thorough, frequent and rigorous testing.

- *Creation of a testing regime with expert technical advice and recommendation under a regulatory overview*

  When deciding to apply for the license renewal of a concerned power generating unit and an effective thorough testing procedure is found to be absent, efforts must be ensured to put into place a regime that would enable the plant operator to carry out the required procedure to check the safety of operation of its equipment. Creation of a testing regime should be carried out under the auspices of a high level expert review committee and the regulatory commission. The expert review board shall aid in creation of the procedure within the framework of the license authorising use of the power plant issued by the regulatory commission.

Modelling simulation and mathematical analyses with due input from the observed data and variations shall help to further the knowledge of the working of the component and aid in estimating the residual lifetime. Residual life is an important observation on affairs of health of the power plant following modelling and simulation work complementing existing set life design curves, helping decipher compromising the further safe and reliable operation of the concerned component, system or structure. Furthermore if a replacement would be required, the lifetime characteristics on the said operation would help to find a suitable framework wherein minimal downtime shall ensure uninterrupted reliable operation of the power plant.

2.3.6.4. Testing equipment to assess, diagnose and monitor

With a proper testing procedure in place, the right equipment to conduct the examination is required, that shall aid in the relatively easy comprehension of the observed results.

The equipment to conduct the tests would have to be agreed upon in the afore-mentioned testing procedure by the high level expert review committee and approved by the license regulatory authority. The testing apparatus should have the following three characteristics for it to be effective:

- *Assessment*

  Assessment of the observed data from the component or system or structure would indicate if the observed data has been properly recorded. Failing the same, input parameters for the following two processes shall be erroneous leading to false decisions being agreed upon.

- *Diagnosis*
  The analysis of the test data should reveal discrepancies in operation of the said component, system or structure. The mechanism of diagnosing the information to understand the working of the said under the influencing parameters should also be documented as a part of the learning curve to enhance the knowledge. Critical diagnoses can be carried out by a suitable engineer who would further report it further up the hierarchical order. A proper diagnosis of the situation shall aid speeding up the time involved to make an informed decision.

- *Monitoring*
  Equipment monitoring and maintenance to the highest levels of accuracy permissible under the given circumstances help assure the decision makers from faulty equipment which may jeopardise their effective decision making capability. A monitoring regime should be in effect to counter maintenance of the equipment and their safe storage in permissible environments during times of non- use.

When the technical feasibility of a particular component has been thoroughly analysed, assessed and tested, the next step would be to study the possible effects it has on the other components during use.

2.3.7. Component interaction and interference during use (Figure 18)

Well- oiled machinery in basic mechanical engineering avoids interference in the working of other parts. Such a system is desired towards effective efficient running of the system. As various components complement each other, they work together in a symbiotic relationship without distortion of the ambient working environment by unintended vibrations, temperature variations, etc.

As seen from the operational group overview from the introductory part of this thesis work, the interaction and interference study requires grouping of components based on their operation to aid in understanding their working parameters and those that may be influential to other components in the vicinity. When intending to study the interaction individually the basic idea of working as a unified system is missing. Hence, the author in this thesis speaks of the ‘islands of operation’ wherein each part is known to have some influence on its neighbouring directly interacting components. The level of interference and interaction do vary from one component to the other but ensuring that each component is viewed towards its interference capabilities in the larger context of the operating groups helps in easier mitigation of issues that crop up during routine testing and use.

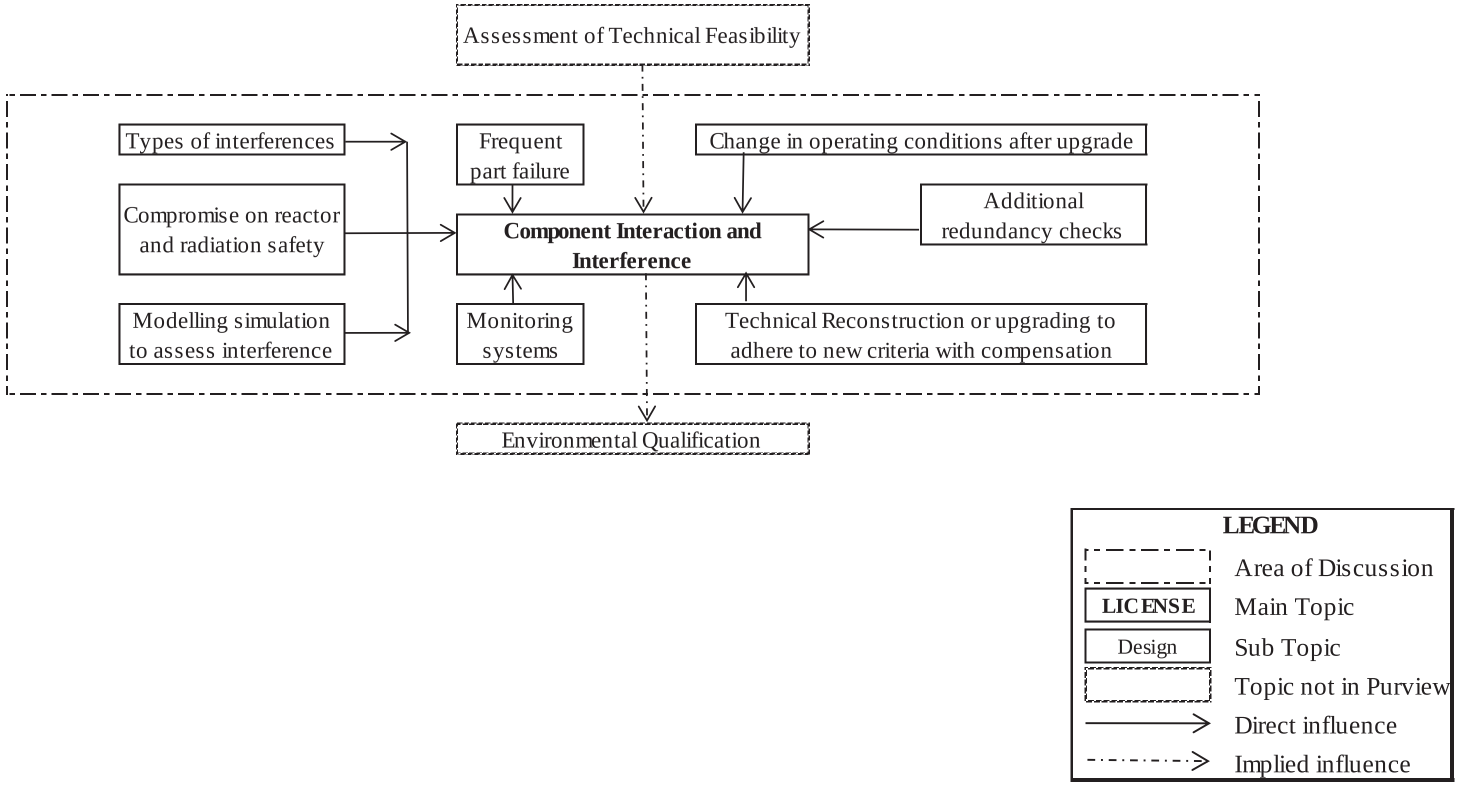

Fig. 18: Part Diagram of the Decision Making Process- Component Interaction and Interference

A scenario of interaction must be studied on a case by case basis to better under the working of the system at hand. The interactions brought about may be eventually detrimental towards the overall goal of efficient working of the system as a single unified entity. Perturbations can occur as the system ages- for each component has its own rate of ageing as do various species present on Earth. Each of them age at a different rate, wherein their interactions over time with the others that co- exist do significantly change and alter the dynamics. Differential ageing is built- in into any operating system that we find today across the myriad of system in all fields; being able to use it to our advantage is wherein we are able to get the maximum out of the system under the given operating circumstances.

Components that work well in their place in the system help towards maintaining the entropy of the system low and this is a very important thermodynamic aspect. This implies minimum entropy of the system shall effectively ensure the availability of maximum conversion of heat into work. A universe with increasing entropy is in an increasing state of disorder, which should be avoided for a multitude of reasons- besides the obvious fact of decreasing profitability, the residual life of the components are also affected by untoward entropy changes. Entropy is unavoidable for all operating conditions and therein is an inherent property of any real working system. A corollary of the second law of thermodynamics suggests a closed system "*entropy of an isolated system either increases or remains constant*" (Rajput, 2011b). This explanation of the principle of increase in entropy of the system cannot be avoided only because creating a perfect closed system is impossible with losses in transmission, thereby leading to suggest increase in entropy. Entropy always increases is the best way to define the second law. Disorder always increases as lifetime of a component progresses.

Every component therefore interferes in a certain small part in the working of the next- in- line component which shall further affect the next one in the sequence and so on. This interaction is understood usually in the design and modelling phase. Counteractions to negate this are futile as understood from the entropy aspect of the second law of thermodynamics; they can instead be minimised. Vibrations can be minimised by shock absorbers, heat loss prevented by insulation jackets and so on and so forth. This is the initial design aspect towards interaction of the components. With progress in life and deterioration in the inherent state of the equipment it shall be up for replacement, or an upgrade, depending on how the plant operator wishes to go about. Either of the two would call for inspection on further component interaction as life of the system progress. Seeing the bigger picture of the entire system working well, the engineer would not wish to increase the system's disorder and thereby entropy due to the influence of the said new part. Controlling and abating this proposed increase shall help sustain or prolong the residual life as proposed in the lifetime characteristics as proposed in the set design life documentation. This effectively renders the idea of checks a very important part of replacement during operation of the plant.

This is a very important concept that will be crucial towards making an informed responsible decision leading to plan life extension by license renewal. The operator of the plant shall have to decide on which equipment to go with during the design stage of decision making towards eventual replacement or upgrade of the equipment. There are various factors that affect the eventual decision which are pertinent to the issue at hand. Decision making should be thoroughly researched and informed. Among others, themes that would have to be looked into include operational history of the component thus far, the ambient surrounding environment and location, history of interactions or interferences not only on other equipment and components but also affecting at the location in the cycle, redundancies in place to counter the effects, should so be the need, modelling and simulation, when and wherever possible to aid the engineer in informed technical decision making, presence of monitoring systems to gauge live-time interaction and interference, should so need be the case leading to technical reconstruction or upgrade being suggested of the said component to adhere to the new criteria with correction measures to correct the induced change in the system.

2.3.7.1. Analysing operating experience (does the part fail unexpectedly quite often)

Operational history is the first step towards making technically informed knowledgeable decisions. With proper documentation that would be available in most plants under proper regulatory efforts, this analysis of operating history would help the plant operator comprehend how the component has fared thus far during the course of its lifecycle and if it conforms to the set design characteristics as laid down in the design documentation supplied from the manufacturer. Assuming the component were reliable thus far during the course of its life, replacing it with an exact copy would be the perfect solution with the operator not having to worry about changes to the design of the system, undue further interferences from or to the next- in- line components, etc. On the other hand, if the said component were to be were to be causing interference and the same has been brought to the notice of the operator, the issue at hand is correction of the system operating parameters with respect to the localised series of equipment that constitute the region of interference.

2.3.7.2. Change in operating conditions during upgrade

The engineer and the plant operator then decide on how the change in conditions would be kept to a minimum. Avoiding change is of utmost important to keep the costs of refurbishment low, to avoid long downtimes and furthermore to hold the licensing agreement valid for the agreed conditions of operation. There a multitude of scenarios that could come into play as the decision to go for an upgrade is made. Upgrading existing systems with the aim to extend the life of operation of the plant is of utmost importance to the plant operator who wishes to operate the plant with minimal downtime but maximum return of investment. A change in the said operating conditions would mean reworking, reanalysing and remodelling the said section of the system. A multitude of options would be available to decide upon, but with the recommendations of experts and the section engineer among others knowledgeable to the subject, an informed and knowledgeable decision has to be made. Stressing on the ‘informed and knowledgeable’ is important for the safe and secure operation of the place without compromises affecting reactor safety and radiation safety.

2.3.7.3. Types of interferences

The plethora of the options signifies various levels of interference that would eventually find place in the system. The basic instinct of usual thought flow towards decision making in light of eventual license renewal is to go for the least interfering pattern found from the various analyses and options. The same may or may not be beneficial in the long run. Two scenarios are considered in the following paragraph- the first being the said minimum option, the second a variant with increased interference. Any option of increased interference and component interaction without economic feasibility is not being discussed.

Assuming the plant operator decides to minimum risks opting for the option of least interference. This option could now come with the following baggage- old equipment with outdated technology which may or may not still have suppliers today but years down the line would be exorbitantly difficult to procure should a second upgrade be needed; or perhaps the equipment would find the option economically untenable going ahead due to procurement costs in the present scenario; the option has higher operating and maintenance costs, etc. to name a few.

On the other hand, an interference may be higher in absolute terms for just the particular part alone being introduced into the working of the system, but instead if the operator were to be far- sighted and decided to replace a section of the system with a set of new equipment wherein the overall interference is drastically below even the incumbent level- this option though tough on the financing aspect would be one of the better suited scenarios when planning to work towards plant life extension. This possible interference scenario wherein the individual component is unsuitable for replacement but looking at the greater picture a better option is found may be an important aspect that decides on how some plants maintain their costs to a minimum in the long run without being bogged down over shorter periods of time.

2.3.7.4. Compromise of reactor and radiation safety

Any good agreement reached always has compromises. Equipment selection towards life cycle extension down the line shall, of all factors, not compromise on the safe running of the reactor equipment and radiation emanation. The mission that allow for the very existence of atomic power in the present day is towards protecting the health of the general public and safety in the use of nuclear power. Two of the key areas in understanding this mission statement are reactor safety which comprises among others of integrity of barriers and emergency preparedness and of radiation safety comprising of public radiation and occupational radiation (NRC, 2015). These cornerstones of the nuclear power industry shall not be compromised.

2.3.7.5. Additional redundancy checks

When a new system is being in view of safe reliable operation leading up to the eventual license extension to operate the plant for a longer duration of time, there must additional redundancy measures that would have to be put in place to ensure the above discussed compromises do not affect the integrity of the working of the system components. Usually redundancy measures are couple with increase financial spending and upkeep but these measures are the exact ones that would be the selling points towards a safer nuclear industry powering tomorrow's energy grid. Redundancy is again a techno-economic issue that is required a certain minimal level of authorisation by the regulatory authority as they decide on what equipment are more likely to fail and with varying degrees of relative importance to the overall smooth functioning of the system as a whole. The issue of how redundancies have to be put in place also concerns the prior operating history of the component and on how many there should be to prevent a reoccurrence of a particular past event.

2.3.7.6. Modelling simulation to test and assess interference

Assuming the plant operator has agreed to go ahead and adopt a new component or a new set of equipment as replacement, now with the available modelling software or mathematical models the tests have to be carried out to ascertain the decision being made is technically sound. There are various ways to support a decision- some would be simply the better of two available alternatives at hand, some others would be sound arguments- these are very ones that strengthen and reinforce the belief that the nuclear industry is safe for operation in spite of the recent events trying to portray it in a negative light. Modelling should be cross verified by two or more methods of analysing the same base information available. This shall ensure that the result thereby obtained was meticulously worked upon and the best option is the one that shall be decided upon. Modelling involves assuming some parameters of operation that may perhaps be known only during live- site running and testing for the manufacturer may have not provided all test data to the plant operator towards engineering him towards the right decision. Such data assumption for unavailable data should be treated with care and varying the operating conditions may be detrimental towards future plant operation. The existing operating conditions of the plant are documented with the plant operator, but if these are to change, the modelling results would inform the operator of the same and the operator would have the option to redress the issue. As the operator looks to modelling and simulation to help him engineer a decision, assessing the level of interference and interaction is crucial in deciding whether to opt for the particular equipment or choosing another option would be the best alternative. Assessing and analysis the resulting data is of utmost importance for the safe and effective running of the nuclear power plant. The plant operator should thereby have reliable models to help him decide. The data analysis should be carried out by a high level expert review committee that is already knowledgeable on the subject and wish to give their knowledge towards the safe running of the plant. The technical analysis and scrutiny shall help ensure any discrepancies, should such be found be immediately brought to the notice of the concerned and rectification procedures to correct the anomaly can be adopted effectively working together to submit a review that is sound, technically and safe for the general plant operation.

2.3.7.7. Monitoring systems to determine live time interaction and interference

To assess the live-time operation of the equipment, options should be at the disposal of the section engineer and plant operator to aid in live time data relay. With modernisation, data is abundantly available at the fingertips of everyone. When a flag was raised during the modelling and simulation phase of decision making but the decision makers decided to go for the relatively safest option, notwithstanding the inherent flaws for the lack of a better alternative, assessing live time data to correct some local parameters would be one of the options available to engineer the learning curve of understanding the new equipment at hand. This learning curve should be developed to aid in further understanding the consequences of the decision making process by choosing the alternative agreed upon. This study should be further used as a learning tool to aid in future decision making by closing the gaps found during the previous decision making process.

2.3.7.8. The aftereffects: Technical reconstruction/ upgrading of the interfering component to adhere to the new criteria + compensation measures to correct the new change thereby created

When a modification or an upgrade to the existing settings is agreed upon, a cornucopia of assignments open up to work at the particular section of the system to accommodate the new decision.

A simple upgrade with no change in the connections including the pipes and valves at the site is rare in the industry. Some minor fittings and pipe length would have to be altered depending on the complexity of the replacement and the level of importance of the component on the working of the system.

When reconstruction work is called for due to a more complex job, time management is a priority. Avoiding excessive plant downtime is the first operator requirement usually. Considering and accounting for the changes that have to be incorporated to accommodate the new equipment, the estimation of the working time is tough to append a number to. Theoretically, reconstruction work should ensure air flow as a means of ventilation and temperature regulation is not obstructed wherever possible. New obstructions in movement of personnel in the plant site should not be erected unless avoidable but only if there is an alternative option to accommodate the needs of the assessor or engineer. While reconstruction could result in a change of the ambience, it should in no way allow change in operating conditions at the site due to change in intake air temperature by a high degree that affects the normal running of the equipment.

Compensating the change effected is an important part of upgrading and reconstruction. An example would be when the upgraded equipment is remarkably smaller than its predecessor, the pedestal and other components would have to be modified to accommodate this in the plant. Notwithstanding the location, such options to achieve compensation would help a long way to make the plant more accessible towards operation and testing of the equipment. Compensation may concern not only the equipment measured but the measuring equipment too. Conversions from analogue to digital that have been effected through the years in event of modernising the data collection technique have brought about notable compensating equipment that would have to be retrofitted on the existing component for it to be tested and analysed. Such examples would be when torque measurement devices used to be hand- held analogue but have been upgraded to hand- held digital or in- place digital methods. The latter of the two options would call for retrofitting equipment to accommodate the new live testing method.

Interference and interactions may occur not just in the scenarios and situations as mentioned above, but also due to some external factors that may affect the due operation of the equipment.

2.3.8. Environmental Qualification (Figure 19)

In the broadest sense, the evaluation of the combined and overlapping influences and effects of radiation, temperature, pressure and relative humidity, vibration, chemicals, wear, etc. Making sure the operation of components of the system are not affected by the conditions of the environment and process, especially if the same would result in lowering of the safety level of equipment operation.

Factors of the ambient environment are instrumental in the decision making process from the point of conceptualisation of the need to set up a nuclear power plant in the first place with scouting for site, construction work and during operation for the cooling calculations. Similarly during life extension, though it may concern a specific part per se or the plant in its entirety, the ambient working conditions have to be studied and prognostic changes to the ambient have to be studied. Mechanical equipment include engines, valves and pumps. They have a variety of constituent parts- metallic and non-metallic that encompass an active function (revolution and rotation) or a passive function (leakage prevention).

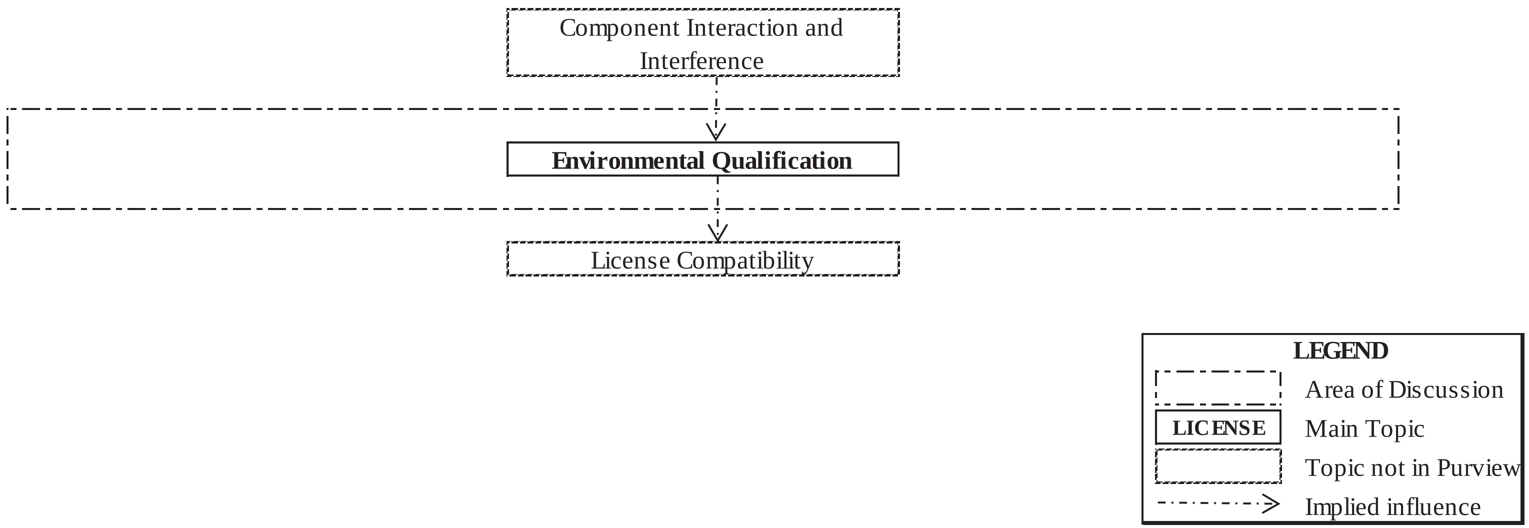

Fig. 19: Part Diagram of the Decision Making Process- Environmental Qualification

A usual working example would be due to presence of a plant along the coastline, the salt- laden ambient moist air corroding the pipes exposed to the atmosphere. Countering this effect would aid in long life and reduced maintenance costs. A more serious environmental factor would be similar to that seen in the Fukushima Daiichi incident in March 2011. Such events of a catastrophic nature would, though be attributed to environmental factors, would also account to the underlying design flaw towards boundary design estimation of worst- case scenarios. This thesis shall not delve into the details of the causative agents and aftermath of the same for which there are enough literary sources arguing various points of view on the issue.

2.3.8.1. Wear

Wear and tear is very important in the everyday working of the mechanical equipment on site. Ageing is the one important topic that affects the quality of the day to day functioning of nuclear power plants. When materials age, they tend to lose some of their innate design properties as listed in the lifetime characteristics set- design document. This erosion of working quality over extended periods of time, though below the minimum level of detection initially, becomes more pronounced as time progresses. With ageing due to ambient environment, rotating parts, moving components, the structure that makes up the concert equipment may show signs of unreliability. Probabilistic safety assessment tests and modelling show that loss of the working characteristics happen, for a reliable component towards the end of its useable useful lifetime that is determined in part by adhering to the manufacturer's conditions of use and surrounding plant conditions.

2.3.8.2. Chemicals

Chemicals, not only chemical solutions comprise a part of the system that need to be in a safe environment of operation. When looking at the conditions of operation, when not involving usual replacement due to ageing, but instead due to unintended corrosion of a particular component, due care should be adhered to the affected part to observe and study any attacks and reactions among the constituent components are avoided. Some issues may be due to the ambient environment they operate in, including corrosion resistant pipes and valves, to start with.

2.3.8.3. Pressure and Relative Humidity

When dealing with these two factors, they have a varied influence depending on what operating conditions are being looked into. When concerning equipment that have their operability criteria based on conditions of internal operation pressure maintenance regime along with relative humidity should be checked to ascertain leakage prevention occurs. The cooling tubes and pipes, both leading into the power generating unit and on the secondary side are prone to pressure variations, due to their role in power generation.

2.3.8.4. Temperature

When concerning mechanical components, the internal operating temperature is more likely to have an effect on the running than the external intake temperature.

Diesel engines have a higher than ambient operating temperature. Clearances that were designed may have grown due to increased thermal activity at the localised site or they may be brittle due to temperature shocks during operation. Thermal analysis by modelling shall help to resolve predictability issues towards failure in operation.

Temperature is vital for operation of liquids such as lubricating oils which have a specified temperature range of operation. It is vital to maintain the temperature of operation within the recommended set design parameters, notwithstanding which shall lead to improper operation of the equipment and evaluation of replacement oil shall have to be considered and testing of the material to analyse its effects to withstand the conditions.

2.3.8.5. Vibration

The two important aspects of vibration can be classified according to source:

Operating equipment induces vibration transmitted due to moving mechanical parts; the reciprocating engine is such an example. This is vibration generated due to the parts interacting and depending upon the frequency of rotation and movement the vibration could be a major factor and oil dampeners, springs, or cushions would have to be provided to mitigate the vibratory effect.

From the NSSS operational group previously mentioned, an example from CANDU operation in Canada showed that excessive vibration led to the breakage of internal pipes in the steam generator (Pembina Institute, 2004). When the rupture is of a serious nature, it may cause a LOCA. This would lead to increase in downtime during operation.

For equipment on standby, transmission of vibration through connections and linkages are the primary sources of distortion. When there are sources that produce vibration in the ambience, sources that may be mounted on the equipment to facilitate testing measures, care should be effected to ensure the operation of the equipment is not adversely affected by the same for then corrective measures would have to be put in place.

2.3.8.6. Radiation

Any nuclear power plant has some equipment that are constantly subject to the bombardment of nuclei and others that are shielded from the same. The idea of radiation wear to equipment in the non-nuclear application is an important one. The component in the particular section has become radioactive due to a leak in the system which has been unintendedly resulted in the concerned equipment being rendered liable to disuse. With irradiation, metallic and non- metallic components of the sub- section of operation of the plant are affected variedly. When equipment replacement occurs for an irradiated part, due care should be enforced to ensure all traces of radioactivity have been removed and the leak has been plugged to prevent further contamination of the section. Radiation related environmental issues are unique in power plants with stringent quality control programmes.

Radiation detecting equipment, as discussed previously under the ICS of the operating groups of the nuclear power plant are vital to ascertain if there is any background radiation due to an exposed source. These may be permanently fixed detectors of radiation or portable depending on the required use.

2.3.9. Scope of existing license accommodating the proposed replacement (Figure 20)

Licensing regime has been mentioned earlier in the decision process flow. When plant operators decide to substitute, replace, or upgrade any of their existing equipment due to any reason, thinking ahead, they would have to ascertain the selected equipment shall not stand contrary to the existing approved license which authorised the plant operation in the first place.

Furthermore, when testing mechanisms and equipment to test the operational characteristics of components are introduced, they should be in accordance with the existing legislation or license and due care should be effected to ensure that any change when necessary would be in accordance with the licensing agreement.

2.3.8.1. When in line with the technicalities of the existing license

When parts of larger magnitude are up for upgrades, including the power generating unit, the issue of licensing approval comes into play. The initially approved of license was with respect to the initially designed and agreed upon operational design parameters. These parameters, after a thorough study by the technical advisory committee, the economic committee, the plant operator would be agreed upon and approved to be licensed to operate by the nuclear regulatory authority pertinent to country of operation. The issue with this drafted document arises when contradictions to the agreed upon state of operation is brought to the notice of the regulatory authority.

In the best transparent method of operation, the plant operator should have to inform the regulatory authority regarding a modification of the operating parameters pending approval from the authority. This way, with public interaction, shall aid in the unambiguity of the legal terms that shall authorise the further operation of the plant as a whole with a note on the changed parameters which were specifically approved of by the regulatory body. This best practice shall aid in not only the plant operator being a respected name in the industry but also indicate lucidity in the working of the industry. With the effort thereby made to start with asking for the licensing authority to approve of the change, the entire process flow to ensure that with the new license, the plant shall be more secure and safe in its operation.

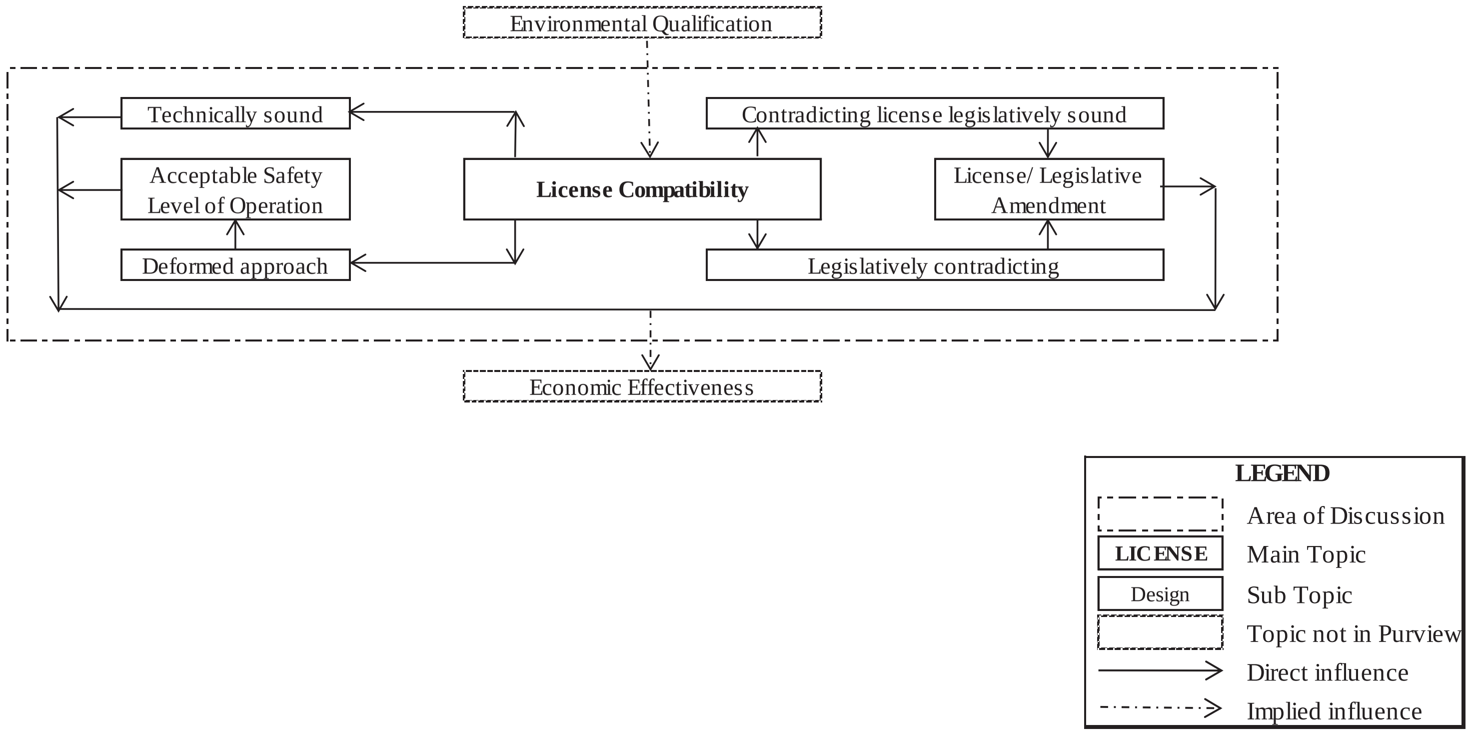

Fig. 20: Part Diagram of the Decision Making Process- License Compatibility

Ensuring that the licensing authority reissued the license is way to help diminish the view of the public about the industry having a free pass. The licensing authority could agree on a timed renewal of the license with checks every few years to ensure the system is running properly with the change approved.

2.3.9.2. When contradictory to the agreed license but within the legislation

The issue of a plant operator requiring a change in operating conditions for which the plant was not initially authorised to but nevertheless within the scope of the national legal framework pertaining to the issue of the said technology. When a plant operator wishes to extend the operating life of the plant, the change thus brought about towards having the current operating license amended in light of the changing circumstances shall aid in the smooth flow of processes towards getting the proposed life extension.

Furthermore, the high level technical expert review committee shall have to recommend the issues of how the change shall affect the operating parameters of the plant. When the plant operator finally decides after the modelling, technical evaluation, economic and compatibility issues, the licensing authority shall have to authorise not just the proposed change, but change towards the entire area of proposed interference.

The idea of equipment interaction and interference in the operational existence of other similar equipment in the vicinity has been discussed in a previous sub- section of this thesis. The interaction of the equipment should be thoroughly studied to ascertain that any untoward and unexpected interaction among the components would be avoided. As the interactions are identified, mitigation and correction efforts would have to be studied too. The follow- on domino effect from replacing just one part of a sub- system can be magnified as the flaw gets amplified. This scenario is where the regulatory authority should take due charge and study the possible interaction diagrams and models put forth by the plant operator's technical team to make a technically informed decision.

A technically informed approach analysing all variables of operation shall enforce the safest mode of operation within the boundaries of the plant operating procedure. Moreover, engineering the approach to study the various options shall also increase the operator's technical know- know thereby advancing on the learning curve of atomic power generation. It would be acceptable to understand the alternatives, to see if they would suit the system currently in place, to further the technical knowledge and choose the best option available.

When the nuclear regulatory authority decides on the submitted proposal for plant modification but within the national legislative framework, the licensing regime would have to be thoroughly updated to accommodate the new part, with possible specific clauses to ascertain and ensure the safe operation of the part in the future. With such a step that aids in the effective reassurance of the nuclear regulatory authority to the general public of changes being approved and being in line with national legislation and measures such as frequent plant inspections to assess the smooth running of the subsection of the plant wherein the particular part is located and the plant as a whole, the nuclear regulatory authority can ensure progressions in violations, if any, can be immediately taken action upon.

2.3.9.3. When contradictions arise due to the existing nuclear legislation

Another important view is when existing law pertaining to operation of nuclear power plants is not modern to accommodate the safer option being sought for by the plant operator. This issue is one of serious concern for all reasons from licensing to economic. Without an agreement, the plant can end up being shut down or choosing a non- viable alternative scenario wherein shareholders of the parent company shall be against the option. Though the scenario is a bit far- fetched, the idea is to get the required technical expert data towards engineering the proper change in legislation.

The nuclear legislation shall deal not just with the particular license alone, but instead towards all licenses in the future and getting them into line with the law. It shall also affect the operators in the industry. The route to get the government along with the regulatory body to accept the required proposed changes requires meticulous planning, countless studies, reviews, expert technical advice, public participation to get their backing, should that be the case, an environmental safety review, should it be mandated, among a plethora of others.

Assuming the reactor operator is advocated by the high level technical expert review committee towards a new way forward to ensure continued plant operation beyond the existing design life, the operator shall have to consider the options to work beforehand to present a suitable case. The background work on why the new proposal is a better alternative to the incumbent legislated license. As the plant operator, the foremost question would be if the licensing regulatory authority would eventually approve of the proposed change which shall affect, besides this one case all future cases. Extending the license which is at the forefront of the decision making process should not be compromised due to a lack of oversight on a modern technology.

As the supplier or manufacturer presents the new options, though they may be approved by regulatory authority to sell their goods in the market pending individual product authorisation, the new issue towards the particular scenario considered here shall ensure that a good debate ensues that all parties stand to profit from the discussion. Testing data and technical reports accompanying probable future use, modelling and simulation analyses of the equipment under test conditions and running conditions would further the case towards pushing forth with a legislative change which shall follow suit with the required license being approved of.

2.3.9.4. The deformed approach and the acceptable safety level of operation (Kovalevich, 2000)

This approach involves a not- so transparent flow of events and should therefore be avoided whenever possible. The deformed approach involves a '*formal violation*' of the operational aspects of the legislative overview. A safe and secure operating environment shall have to be agreed upon by all players in the industry, overseen by the nuclear regulatory authority. If the nuclear regulatory authority is incapable itself of ensuring a level playing field for whatever reason including turning a blind eye to violations of a grave nature, it should be brought to the notice of the IAEA to prevent such drastic violations in the working culture of the nuclear power plants. For considerations of economic and social reasons, it is unacceptable to agree on ageing first generation power plants of the 1960s to perform on the same level as those of the newer reactors. This shall be the first concern that should be addressed. Standardisation of legislation managed under the purview of the nuclear regulatory body shall only aid in the abetting of a safe nuclear operating ambience. Usual legislation requires direct and indirect approaches that satisfy the need for change. There are various aspects and terms to be considered therein.

2.3.10. Economic Effectiveness (Figure 21)

A project that involves inducing a change in the system should also carry a cost- benefit analysis. The idea to study the economics of a proposed project shall help the plant operator explain to investors the reason behind the new proposal. Keeping in view of the massive capital costs that usually involve projects in the industry, the return of investment should be studied to see that it will be a profitable venture for the company.

Economics play a very important role in the decision making process. While this thesis has delved deeply into the technical and rational decision making process, economics, though a separate entity in itself towards achieving the final aim, contributes in part towards this decision making process in view of the time and investment. Economic dependability on a company shall increase the shares of the company in the stock market (for private operators) bringing it much needed capital flow and helping further investment into projects of a similar nature.

Every component that is being decided upon for replacement or upgrade needs to undergo an economic feasibility test to ensure the component shall not fail before it, as part of the entire scheme of the system reaps profit for the investor. In the capitalistic view of things, any investment that grows over time, in quality or quantity is worth investing in. Similarly is the case for the upgrade or replacement wherein quality upgrades or running efficiency uplift are sought after.

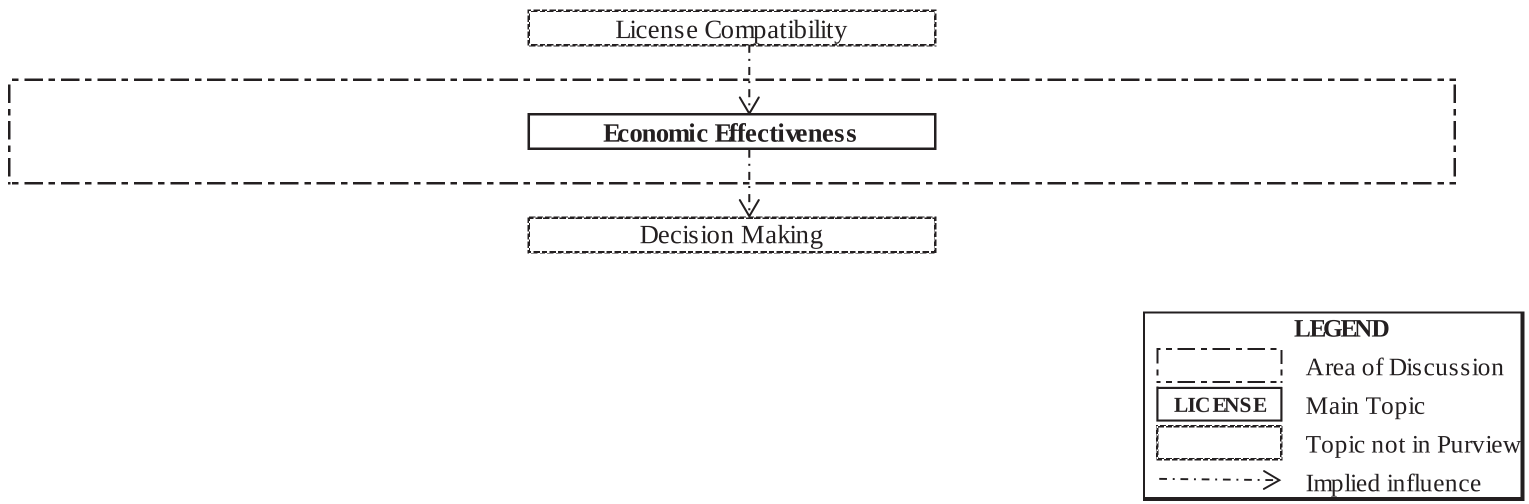

Fig. 21: Part Diagram of the Decision Making Process- Economic Effectiveness

With due course of time, the component, with its right place in the system shall engage in productive power generation more efficiently and lesser downtime shall only have a ripple effect in other such sound investments proposed by the plant operator. When the project is not sound, but has to be carried on anyway, as would be the case in some, the option to choose the best alternative of the available options shall have to be put in place. With such an option, the operator would be allowed to run the plant in conformance with the license agreement without having to incur losses otherwise on the highly invested capital. Low energy prices due to competition, low oil prices, and other external contributing factors also weigh into the decision making process mechanism towards agreeing on a suitable option that shall be the best compromise achieved to further the running of the place, without safety liabilities brought about by the decision.

Once the economics have been considered, with the other issues that have been deliberated upon, the time has come to finally make the call.

2.3.11. Decision making (Figure 22)

The final call towards agreeing on whether the project towards replacement, retrofitting or upgrade of the component shall go ahead with the information as obtained through various tests, reports, studies, expert opinion etc. shall be taken by the concerned board. The board shall proceed with its decision and request the nuclear regulatory authority, should the need be, to oversee the process within the framework of the licensing regime, or pending license renewal and authorisation for the new decision. Decisions to decommission or renew licences can be due to a variety of factors including safety concerns, public opinion and due to concerns of adherence to international legal commitments by adherence to treaties signed. A country could put in place a framework to withdraw all its nuclear power plants from the grid in a delineated timeframe, which though amounts to decommissioning and decision making, but on a policy stand point of at a political level.

Nevertheless, in this thesis, the idea of plant operators, private and government are considered with a national regulatory body. Their rationale of decisions can be broadly classified as two- fold:

2.3.11.1. Decommissioning

- *Technical*
  Withdrawal of the plant from operation due to defects, faults, ageing equipment, maintenance regime and like shall affect the technical reports that the expert committee would submitted towards the safe running of the plant. The decision thereby made to avoid refurbishment of the component and thereby allowing the plant to be decommissioned.

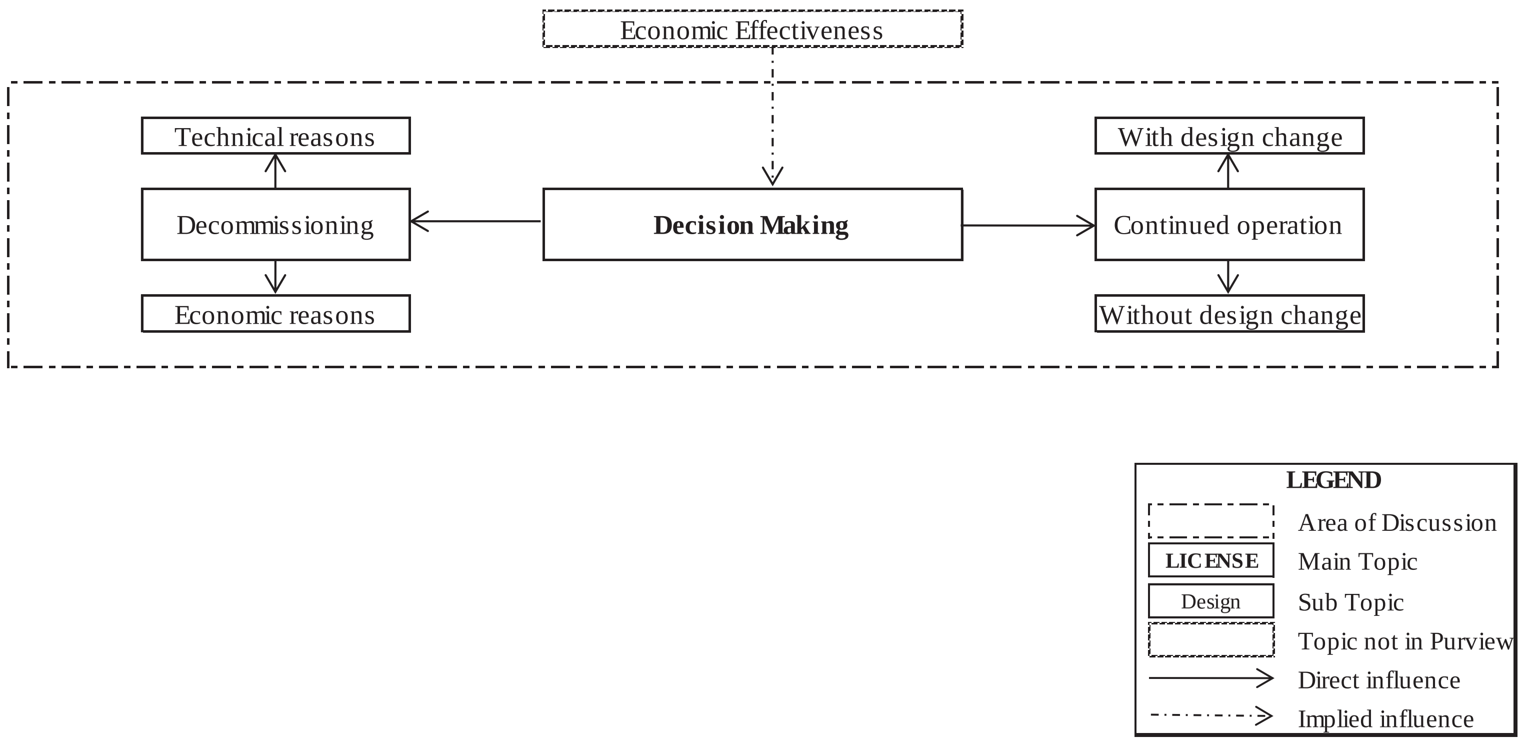

Fig. 22: Part Diagram of the Decision Making Process- Decision Making

- *Economic*
  A plant may be pulled out of the grid due to increasing running costs. These costs are variable over time and hence the decision which a year ago would have seemed untenable would have to be enforced.

  Economics may also have nothing to do with the particular plant in question, but rather about a company declaring it insolvent (for private operators) and unable to further the running of the plant. In such cases a sale may be effected to offload some of the plants to a willing buyer, but when that is not the case, in the private industry, the plant would have to be decommissioned.

  Economics are also important for the understanding the evolution of the energy market, wherein predictions about future evolutions would enhance debate on where the energy prices would be in a year or twos time and whether it would be a feasible option.

2.3.11.2. Continued Operation

- *With change in Design*
  A change in design obligations would be emanating from the technical tests and analysis opting for an alternative that would require the license being updated to accommodate the new component or a legislative change for modernisation reasons.

  The decision thence enforced would ensure the plant to continue its operation, in a safe manner after the required changes would have been carried out in accordance with the law.

- *Without design change*
  When a simple upgrade or replacement without affecting the pre- existing license regime is decided upon, care should be taken to ensure that the new part undergoes testing and monitoring to assess any out of the normal working and the notification should be documented to understand the working patterns of the new component. Interference and interactions that may arise due to new component in place should be seen to be within the acceptable levels of deviation from the normal as suggested in the licensing document. This would effectively ensure that though the component was changed with a lax of oversight from the nuclear energy operator due to non- modification of the existing licensing regime, nevertheless, they would be informed of the changes that have been carried out to the operating components in the system.

This information exchange and transparency helps build trust and confidence in the decisions that are carried out over time.

2.4. Discussion and Study Introspection

From the above analysis of the decision making process, the progression of ideas, thoughts and working of a common operator towards working towards the extension of the life, with license renewal of a nuclear power plant have been studied. The flow of ideas, albeit in a flow may not be exactly the same in the day- to- day working of a common plant due to the eccentricity in the workings of the human mind. As one analyses the simple flow chart with the basic points, one finds a natural progression that leads from one system of work to the next.

The natural progressive nature of the flow shall help when working with multiple components that require decisions to be made on their working on an everyday basis for the continuous and optimal operation of the nuclear power plant.

Creating the block diagram involved analysing possible paths that the decision flow would take, the interactions that would occur towards the decision making in each of these steps, how the decision thus made would further affect others made down the line and if a feedback loop would be in place for the entire procedure.

In understanding the parts that are to be replaced, there is much more than simple decision making through complex channels at play for sometimes it is pure logic, while other times the work culture and ethic of the plant and the location are called into question.

The method of research with the ideas of the five 'M's that include measurement, mechanism, modelling, mitigation and monitoring is a vital aspect to maintaining the plant in a good running condition. Under the assumption the above five aspects are thoroughly carried out during the course of operation of the plant, the various connections and interconnections in the block diagram would work to yield sound results.

A feedback loop was implied in the consideration but avoided in explicit mention because decisions made are part of the learning curve of understanding how the system works and hence decisions and mistakes made in the past would thereby influence the thought process of deciding what technology, techniques and methods would be best suited to prolong the life of a said component.

Discussing the entirety of the decision making process, the learning and understanding of previous decisions are carried on the shoulders of those involved in making the decisions. The decision making process flow should be an integral part of the learning curve towards plant operation as the data and knowledge garnered in going through the process shall aid and further the existing available plethora of information towards aiding and assisting in informed socially responsible decision making.

With the listing of the parameters and steps above, the author wishes to have shed light on the complex albeit important process wherein decisions are made towards extension of particular component parts and thereby the entire plant for a certain period of time.

3. CONCLUSION

Decision making process in this thesis work is mired in a quagmire of secrecy with some techno- economic issues while others may not be logically comprehensible. Creating a sense of logic in the working of the twists and turns that aid and abet the decision flow process would only highly encourage the learning curve development by understanding mistakes committed over time and appreciating the decisions reached upon thus far.

The nuclear industry per se has, over the years, been subject to much public scrutiny and negative sentiment. Time and again flaws in the working of the system and the industry as a whole are highlighted to much public dismay. Transparency setting initiatives are important to better the image of the industry to aid future policy makers ease in agreeing to approve and license the operation of a nuclear power plant.

In principle, the life span of any nuclear power plant can be extended indefinitely but due care should be addressed to the issues resulting in ageing by material wear and tear during normal operation circumstances.

3.1. Main Findings

The successful completion of any work is ascertained on measuring it against proposed satisfying the criteria it initially set out to achieve. In that regard, the faithful introspection of the section concerning the research question above in this thesis is warranted. While safe operation of a plant can only be guaranteed by adhering to prescribed rules and regulations of operating safely, the following criteria are discussed:

In the issue of public perception, the author acknowledges that decisions made may not have a particular logical reasoning in spite of certain nuclear power plants being deemed worth of safe operation. When concerning policy issues, life extensions (including refurbishment and retrofit upgrades) should only happen when the stages in the decision making process are satisfied and with a high degree of certainty, i.e. the meticulous process of identifying if the plant will be durable for the proposed lifetime extension.

Operating groups, with the estimated component interference and interaction and the varying degrees of importance each individual component and the entire group taken as a whole has on the decision making process shall be influential. With a proper preventive maintenance regime coupled with smooth operation over the years, there would be only confidence among the operators on safe operation for the remainder of the plant life. Understanding the operating groups as a system itself, with not just individual components but the entire set of components interacting as a single part to the outside shall help simplify the comprehension of whether it would be feasible to propose license extension, technically and economically. Sometimes, in special cases the decision to not renew the life of a nuclear power plant may simply be due to the initial design and may not have to do anything with issues of specific plant operation. The initial reactor design being a very important criterion towards life extension may not be technologically viable under the present system of safety restrictions (World Nuclear News, 2007).

Life extension, involving the above ideas requires a thorough understanding of how various parts and their constituent component work, albeit in a fashion that keep the plant running. With regular rigorous maintenance, operating history analysis, assessing technical feasibility, component interaction issues, external influencing factors, besides of course the issue of licensing and economics a life extension can be surely carried out. Technicalities addressing the decision making process can be managed by the five Ms discussed earlier. With such a method of researching involving a plethora of issues and personnel as advisors to aid in the decision making process, plant operators can make logically viable and informed decisions.

3.2. Future Follow-Up

With the scope vast for study, only a part of important decision making issue has been dealt with above. Economics of plant operation with specific concern to each individual part is a world of its own. Without a sound economic backing no plant shall be deemed successful in its working and operation. Similarly, efficient economic operation of the plant shall only happen with a sound technical team that is able to provide recommendations and solutions to the issues at hand. These two issues would have to legal in their working and operation- thereby regulatory issues come into purview.

While public participation is mandated by many a regulator in their guidebook and operation, this thesis concerns the issue of how the plant operator with the inherent team of technical advisors, engineers and other plant personnel operate. When under the purview of the existing license, the public would usually not require any notice to further operation of the plant. Instead, as licensing changes are required the public face comes into view, as to if the public would prefer the continual operation of the plant.

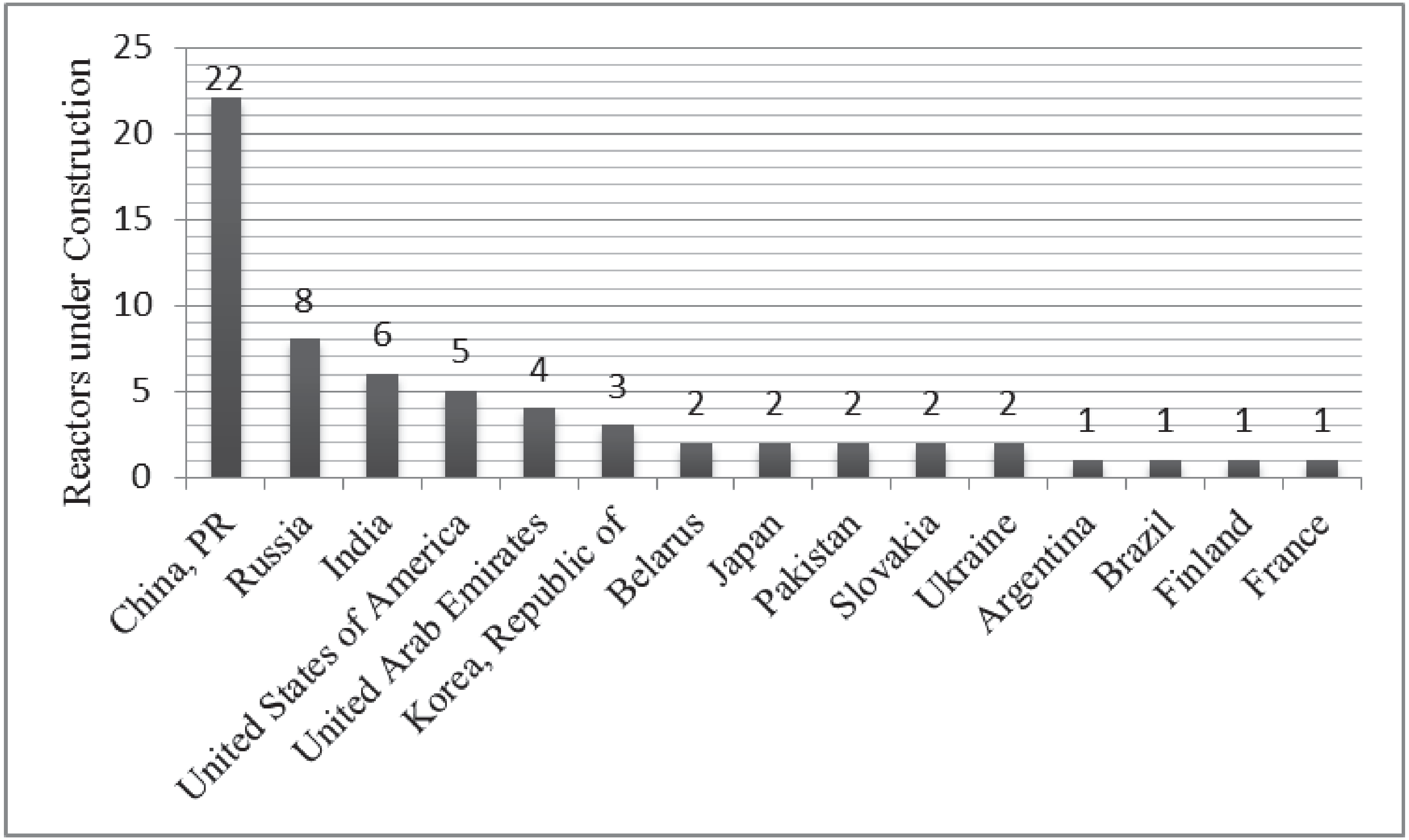

Figure 23: Reactors under Construction by Country: Total of 64 Reactors (IAEA, 2016)

The study of feasibility of continued operation affecting the environment, through Environmental Impact Assessment (EIA) is one that shall pertain more to the initial setting up of a plant and its further life extension more than individual component life extension. There would be interaction between the public and the operators planned during a certain routine time interval, which would help alleviate the concerns of the public- such interactions portray a face that the plant operators are also mindful of the surroundings they operate in. Environmental studies on effects to the local populace are crucial to make the system more transparent and improve public opinion of the operation.

Will the barriers that exist today in swift identification and rectification of anomalies be overcome? Mitigation of problems is central to safe operation. The working culture and ethic should be quintessential in moving forwards with a strong workforce that is trained and equipped to identify and effect the required modification. Will a unified vision set up for a long- term action towards sustainable energy production be able to convince policy makers to remove licensing and regulatory barriers for effective knowledge transfer? What other short- term issues would need to be altered to ensure nuclear energy stays in the energy mix for the long run?

Another important question is whether there would be a unified agreement to come up with a logical decision making pattern that shall aid the new countries joining the nuclear energy producing club to adhere to in absence of personnel however well trained they may be with a shortage of experience handling issues of such nature. With guidelines in place, the newer countries shall be able to, with the help of consultants and other experienced personnel from abroad, broaden their knowledge database and move ahead on their national commercial atomic generation learning curve.

One very important factor is decision viability. If the proposed sequences of events are carried out towards ensuring a safe operating environment, the author sees no reason as to why there would not be to allow for license renewal and extension of plant life of the NPP; the most important of which are safety in plant operation, adequate maintenance and a rigorous licensing procedure. Justifying the viability of a decision shall help policy makers educate the general public and alter their sentiment in the wake of the recent events.

There is a great interest in the number of countries that are opting to construct new nuclear power plants, as seen from above (Figure 23). Further, appendices I- IV highlight recent life extensions that have been agreed through license renewal, a list of power reactors under construction, planned and proposed reactors in various countries respectively.

Considering this work as part of roadmap towards having an energy secure future, current trends of working in the energy sector are unviable and unsustainable for the long- run. Decisive action needs to be taken and implemented furthermore to aid in the energy revolution that the future awaits from the present day. Besides energy efficiency, other methods including carbon capture and storage, nuclear power and newer transport solutions need to be brought to the marketplace to help us have any slim chance of attaining the goals signed up to in the Paris Agreement (UNFCCC, 2016).

By codifying and agreeing in writing a logical flow, however untenable human logic would be to adhere to it, to have checkpoints to ensure the steps are followed in principle to ascertain and identify errors in the decision making process and further using it as a learning tool to make informed decisions in the future when concerning situations of a similar nature, this thesis wishes to make the decision making process transparent.

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LIST OF FIGURES AND TABLES

APPENDICES

Appendix I: Select Recent Life Extensions Granted (2010- 2016)

TABLE OF RECENT LICENSE EXTENSIONS GRANTED			
Plant Name	**Country**	**License Renewed**	**Source**
Darlington 1	Canada	January 2016	1
Darlington 2	Canada	January 2016	1
Darlington 3	Canada	January 2016	1
Darlington 4	Canada	January 2016	1
Kozloduy 6	Bulgaria	January 2016	2
South Ukraine 2	Ukraine	December 2015	3
Doel 1	Belgium	October 2015	4
Doel 2	Belgium	October 2015	4
Krško	Slovenia	July 2015	5
Metsamor 2	Armenia	December 2014	6
Kola 4	Russia	October 2014	7
Kozloduy 5	Bulgaria	October 2014	2
Kalinin 1	Russia	July 2014	8
Pickering 1	Canada	September 2013	9
Pickering 2	Canada	September 2013	9
Bruce A 1	Canada	June 2015	10
Bruce A 2	Canada	June 2015	10
Ringhals 4	Sweden	February 2015	11
Wolsong 1	Korea, Republic of	February 2015	12
Dungeness B1	United Kingdom	January 2015	13
Dungeness B2	United Kingdom	January 2015	13
Columbia	United States of America	May 2012	14
Smolensk 1	Russia	December 2012	15
Point Lepreau	Canada	February 2012	16
Prairie Island 1	United States of America	June 2011	14
Prairie Island 2	United States of America	June 2011	14
Salem 1	United States of America	June 2011	14
Salem 2	United States of America	June 2011	14
Paolo Verde 1	United States of America	April 2011	14
Paolo Verde 2	United States of America	April 2011	14
Paolo Verde 3	United States of America	April 2011	14
Kewaunee	United States of America	February 2011	14
Kola 3	Russia	January 2011	15
Bilibino 3	Russia	December 2010	15

Duane Arnold	United States of America	December 2010	14
Leningrad 4	Russia	December 2010	15
Cooper	United States of America	November 2010	14
Beloyarsk 3	Russia	April 2010	15
Bilibino 4	Russia	March 2010	15
Kola 1	Russia	March 2010	15
Kola 2	Russia	March 2010	15
Kursk 1	Russia	March 2010	15
Kursk 2	Russia	March 2010	15
Novovoronezh 5	Russia	March 2010	15
Bilibino 1	Russia	February 2010	15
Leningrad 1	Russia	February 2010	15
Leningrad 2	Russia	February 2010	15
Novovoronezh 3	Russia	February 2010	15
Novovoronezh 4	Russia	February 2010	15

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Appendix II: Power Reactors under Construction

TABLE OF POWER REACTORS UNDER CONSTRUCTION				
Start *	**Country**	**Reactor**	**Type**	**Gross MWe**
2015	China, People's Republic of	Changjiang 1	PWR	650
	India	Kakrapar 3	PHWR	640
	India	Kalpakkam	FBR	470
	Russia	Beloyarsk 4	FNR	750
2016	India	Kudankulam 2	PWR	950
	Russia	Novovoronezh II-1	PWR	1070
	Korea, Republic of	Shin-Kori 3	PWR	1350
	Korea, Republic of	Shin-Kori 4	PWR	1350
	United States of America	Watts Bar 2	PWR	1180
	China, People's Republic of	Sanmen 1	PWR	1250
	China, People's Republic of	Haiyang 1	PWR	1250
	China, People's Republic of	Hongyanhe 4	PWR	1120
	China, People's Republic of	Ningde 4	PWR	1080
	China, People's Republic of	Changjiang 2	PWR	650
	China, People's Republic of	Fuqing 3	PWR	1080
	China, People's Republic of	Fangchenggang 2	PWR	1080
	China, People's Republic of	Taishan 1	PWR	1700
	India	Kakrapar 4	PHWR	640
	India	Rajasthan 7	PHWR	640
	Pakistan	Chashma 3	PWR	300
2017	Slovakia	Mochovce 3	PWR	440
	Russia	Pevek FNPP	PWR x 2	70
	Russia	Leningrad II-1	PWR	1070
	China, People's Republic of	Taishan 2	PWR	1700
	China, People's Republic of	Sanmen 2	PWR	1250
	China, People's Republic of	Haiyang 2	PWR	1250
	China, People's Republic of	Yangjiang 4	PWR	1080
	China, People's Republic of	Fuqing 4	PWR	1080
	China, People's Republic of	Shidaowan	HTR	200
	China, People's Republic of	Tianwan 3	PWR	1060
	Russia	Rostov 4	PWR	1200
	Russia	Novovoronezh II-2	PWR	1070
	Korea, Republic of	Shin-Hanul 1	PWR	1350
	India	Rajasthan 8	PHWR	640
	Pakistan	Chashma 4	PWR	300

2018	Slovakia	Mochovce 4	PWR	440
	France	Flamanville 3	PWR	1600
	Finland	Olkilouto 3	PWR	1720
	Korea, Republic of	Shin-Hanul 2	PWR	1350
	Brazil	Angra 3	PWR	1405
	Argentina	Carem25	PWR	27
	China, People's Republic of	Yangjiang 5	PWR	1080
	China, People's Republic of	Tianwan 4	PWR	1060
2019	United States of America	Vogtle 3	PWR	1200
	United States of America	Summer 2	PWR	1200
	China, People's Republic of	Hongyanhe 5	PWR	1120
	China, People's Republic of	Yangjiang 6	PWR	1080
	China, People's Republic of	Fuqing 5	PWR	1150
	Romania	Cernavoda 3	PHWR	655
2020	China, People's Republic of	Hongyanhe 6	PWR	1120
	Russia	Leningrad II-2	PWR	1070

*: Latest announced year of proposed commercial operation

Source: World Nuclear Association (2015): Plans For New Reactors Worldwide. http://world-nuclear.org/information-library/current-and-future-generation/plans-for-new-reactors-worldwide.aspx Accessed: 20 April 2016

Appendix III: Planned Reactors

TABLE OF PLANNED REACTORS		
Country	**Reactors Planned**	**MWe Gross**
Argentina	2	1950
Armenia	1	1060
Bangladesh	2	2400
Belarus	0	0
Belgium	0	0
Brazil	0	0
Bulgaria	1	950
Canada	2	1500
Chile	0	0
China, People's Republic of	42	48330
Czech Republic	2	2400
Egypt	2	2400
Finland	1	1200
France	0	0
Germany	0	0
Hungary	2	2400
India	24	23900
Indonesia	1	30
Iran	2	2000
Israel	0	0
Italy	0	0
Japan	9	12947
Jordan	2	2000
Kazakhstan	2	600
Korea, Democratic PR	0	0
Korea Republic of	8	11600
Lithuania	1	1350
Malaysia	0	0
Mexico	0	0
Netherlands	0	0
Pakistan	2	2300
Poland	6	6000
Romania	2	1440
Russia	25	27755
Saudi Arabia	0	0
Slovakia	0	0
Slovenia	0	0

South Africa	0	0
Spain	0	0
Sweden	0	0
Switzerland	0	0
Thailand	0	0
Turkey	4	4800
Ukraine	2	1900
United Arab Emirates	0	0
United Kingdom	4	6100
United States of America	18	8312
Vietnam	4	4800
WORLD	173	182,424

Source: World Nuclear Association (2016): World Nuclear Power Reactors & Uranium Requirements. http://www.world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx Accessed: 20 April 2016

Appendix IV: Proposed Reactors

TABLE OF PROPOSED REACTORS		
Country	**Reactors Planned**	**MWe Gross**
Argentina	2	1300
Armenia	0	0
Bangladesh	0	0
Belarus	2	2400
Belgium	0	0
Brazil	4	4000
Bulgaria	0	0
Canada	3	3800
Chile	4	4400
China, People's Republic of	136	156000
Czech Republic	1	1200
Egypt	2	2400
Finland	1	1500
France	1	1750
Germany	0	0
Hungary	0	0
India	36	41600
Indonesia	4	4000
Iran	7	6300
Israel	1	1200
Italy	0	0
Japan	3	4145
Jordan	0	0
Kazakhstan	2	600
Korea, Democratic PR	1	950
Korea Republic of	0	0
Lithuania	0	0
Malaysia	2	2000
Mexico	2	2000
Netherlands	1	1000
Pakistan	0	0
Poland	0	0
Romania	1	655
Russia	23	22800
Saudi Arabia	16	17000
Slovakia	1	1200
Slovenia	1	1000

South Africa	8	9600
Spain	0	0
Sweden	0	0
Switzerland	3	4000
Thailand	5	5000
Turkey	4	4500
Ukraine	11	12000
United Arab Emirates	10	14400
United Kingdom	9	11800
United States of America	24	26000
Vietnam	6	6700
WORLD	337	379,200

Source: World Nuclear Association (2016): World Nuclear Power Reactors & Uranium Requirements. http://www.world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx Accessed: 20 April 2016

Appendix V: INES Table (International Nuclear and Radiological Event Scale Table)

LEVEL 7	MAJOR ACCIDENT	ACCIDENT
LEVEL 6	SERIOUS ACCIDENT	
LEVEL 5	ACCIDENT WITH WIDER CONSEQEUENCES	
LEVEL 4	ACCIDENT WITH LOCAL CONSEQUENCES	
LEVEL 3	SERIOUS INCIDENT	INCIDENT
LEVEL 2	INCIDENT	
LEVEL 1	ANOMALY	

Source: IAEA (2008): INES- The International Nuclear and Radiological Event Scale: User's manual. International Atomic Energy Agency, Vienna.