NUCLEAR POWER PLANTS FOR SRI LANKA BY YEAR2020

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Degree of Master of Science

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Abstract

Ever increasing demand for electricity, due to increased consumption, industrial development and electrification, will have to be met by the Sri Lankan electricity industry. Ceylon Electricity Board has a long term generation plan, which mainly focuses on coal power. Despite the massive environmental pollution, it is not wise to depend only on coal power since coal resource is also a limited conventional resource. Therefore a country like Sri Lanka should have a good mixture of energy options for electricity generation rather than adhering to one conventional energy source as coal.

Aim of this study is to investigate the possibility of adopting Nuclear Power option to Sri Lanka. Due to the limited capacity of the current electricity network to absorb an economic scale nuclear power plant, the consideration was made for the year 2020, by which time the electricity network capacity will be large enough. An interesting fact is that some countries smaller in size than Sri Lanka successfully adopted nuclear power plants for their electricity generation. Hence this study could be considered as timely.

The study focuses on following facts;

1. Future demand and generation of Sri Lanka up to year 2020
2. World status of the Nuclear Power Plants and Technology
3. Pre-feasibility study - Technology
4. Pre-feasibility study - Economics
5. Pre-feasibility study - Site Survey
6. Pre-feasibility study - Environmental Impact Assessment

The technological pre-feasibility study addresses suitable type and size of a nuclear power plant for Sri Lanka. Thereby the CANDU technology is discussed which is adopted mainly in India and Canada.

In economic pre-feasibility study, the Leve1ized Unit Electricity Costs were calculated for the nuclear power plant as well as for the coal power option. As per the calculation unit electricity cost for the nuclear option seems to be slightly higher than from the oal option at current market conditions. Also a sensitivity analysis was done considering the changes in fuel cost and it shows that nuclear power unit cost dependency on fuel price is very much less than that of coal option. Under the economics, the possible initial financing methods for a country like Sri Lanka are also discussed.

For the site survey, author proposes 9 locations for initial consideration. Screening to select final sites, should be done by the authority that is responsible for feasibility study. The main criteria for selecting these sites were population density, cooling water availability, and land availability. The selected sites should also have minimum impact on the environment.

Existing local regulations and international obligations as well as required local regulations for setting up a nuclear power plant are also discussed in this document. Especially the adaptation of International Atomic Energy Agency (IAEA) safeguard system is elaborated.

The worst nuclear power plant accident in the world history is analyzed to have a clear picture on the possible maximum damage in case of a major accident, even though the probability of occurrence of such a disaster is extremely low. India, the closest neighbor country of Sri Lanka, is increasing nuclear power share drastically and some nuclear power plants are being built near to Sri Lanka. A complete information regarding the locations of Indian nuclear power plants are also discussed.

For the formidable question, "In case of a nuclear accident, can Sri Lanka bear it?", the most common answer will be "NO!". It is not possible to rule out accidents. On the other hand, as the conventional fuels deplete and their prices escalate, the only long term sustainable and dependable energy source is nuclear. Renewable sources such as solar, wind, hydro etc are either limited in availability or economically unviable as a standalone supply source. Unless there is an economically competitive supply of energy, any country will not be able to provide its services at an acceptable price and thereby will become economically bankrupt. Thus the recommendation conceived from this project is "Study the subject of nuclear power at national level and be cautiously ready to implement nuclear power projects at an appropriate stage in the future to come"

DECLARATION

The work submitted in this dissertation is the result of my own investigation, unless otherwise stated.

It has not already been accepted for any degree, and is also not being concurrently submitted for any other degree.

UOM Verified Signature

B.M.A.T. Priyadarshana
Date: 30-03-2010

I endorse the declaration by the candidate.

Eng. W.D.A.S. Wijayapala

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Acronyms

ABWR	Advanced Boiling Water Reactor
AEA	Atomic Energy Authority
AGR	Advanced Gas Cooled Reactor
BOO	Build Own and Operate
BOT	Build Own and Transfer
BWR	Boiling Water Reactor
CANDU	CANada Deuterium Uranium
CAESAR	Clean And Environmentally Safe Advanced Reactor
CEB	Ceylon Electricity Board
ECA	Export Credit Agencies
ECCS	Emergency Core Cooling System
EPZ	Emergency Planning Zone
ESBWR	Economic Simplified Boiling Water Reactor
GCR	Gas Cooled Reactor
HLW	High-Level Waste
HWR	Heavy Water Moderated Reactor
HTGCR	High Temperature Gas Cooled Reactor
IAEA	International Atomic Energy Authority
ILW	Intermediate-Level Waste
INES	International Nuclear Event Scale
JVC	Joint Venture Company
LLW	Low Level Waste
LMFBR	Liquid Metal Fast Breeder Reactor
LUEC	Levelized Unit Energy Cost
LWR	Light Water Moderated Reactor
MSR	Molten Salt Reactor
NPP	Nuclear Power Plant
OMR	Organically Moderated Reactor
PHWR	Pressurized Heavy Water Reactor
PWR	Pressurized Water Reactor
RBMK	Reaktor Bolshoy Moshchnosti Kanalniy (High Power Channel Reactor)

SSTAR	Small Sealed Transportable Autonomous Reactor
VLLW	Very Low Level Waste
4S	Super-Safe, Small, and Simple

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It is a pleasure to remember the co-operation offered by the colleagues in the post graduate programme, friends and specially my wife who encouraged me to continue the studies from start to end.

Chapter 1

Introduction

1.1. Background

Electricity is an essential requirement of the modern society. The high reliability of electricity supply at an affordable price is the key for developing a country like Sri Lanka. The electricity production has to encounter the increasing demand in the coming years. Therefore it is necessary to analyze the various options available for generating electricity in Sri Lanka.

1.2. Present Situation of Electricity Generation in Sri Lanka

1.2.1. Present Electricity Generation

The table 1.1 gives the statistical data on installed capacity, electricity generation, maximum demand and percentages of hydro thermal mix for last four years [1].

Item	Unit	2005	2006	2007	2008
Installed capacity (to national grid)	MW	2410	2433	2443	2645
Energy Generation (to national grid)	GWh	8769	9388	9814	9901
Maximum Demand	MW	1748	1892	1842	1922
Hydro: Thermal (100%) on Energy Gen.	%	40:60	50:50	40:60	42:58

Table 1.1 – Electricity Generation Statistics

The installed capacity of wind power plant is 3 MW and its contribution to energy generation is about 2.2 GWh annually.

From the above data, possible annual average hydro power generation capability is about 4000 GWh and the rest of the requirement has to be met by thermal power generation. The available thermal power generation consists of Oil and Gas turbines while the Coal powered power plants are being constructed.

1.2.2 Future Plans

Being the national electricity supplier, Ceylon Electricity Board (CEB) has forecasted the electricity demand up to year 2025 [2]. Table 1.2 indicates some of the details in this forecast.

Year	Demand (GWh)	Growth Rate (%)	Gross Losses (%)	Generation (GWh)	Peak (MW)
2010	10,327	8.2	15.2	12,172	2,517
2011	11,166	8.1	14.9	13,114	2,712
2012	12,070	8.1	14.6	14,127	2,921
2013	13,040	8.0	14.3	15,210	3,146
2014	14,079	8.0	14.1	16,390	3,389
2015	15,190	7.9	14.1	17,683	3,657
2016	16,378	7.8	14.1	19,066	3,943
2017	17,654	7.8	14.1	20,552	4,250
2018	19,019	7.7	14.1	22,141	4,579
2019	20,480	7.7	14.1	23,842	4,931
2020	22,040	7.6	14.1	25,658	5,306
2021	23,708	7.6	14.1	27,600	5,708
2022	25,497	7.5	14.1	29,682	6,138
2023	27,412	7.5	14.1	31,912	6,599
2024	29,459	7.5	14.1	34,295	7,092
2025	31,648	7.4	14.1	36,843	7,619

Table 1.2 – Load Forecast

Based on this forecast CEB proposed a generation expansion plan up to year 2020 which is the least cost generation expansion sequence as shown in table 1.3 [2].

From the plan it is obvious that the country will depend more on limited fossil fuel powered electricity generation in the near future which seems to be the best option at present.

Power Plant Capacity (MW)	Fuel	Year of Commissioning
2x300	Coal	2011
300	Coal	2012
300	Coal	2013
300	Coal	2014
300	Coal	2015
300	Coal	2016
300	Coal	2017
300	Coal	2018
300	Coal	2019
105	Gas Turbine	2020

Table 1.3 – Proposed Generation Expansion Plan

1.3. Motivation

Future expansion or the new construction of hydro power plants in Sri Lanka will add very little to total installed hydro power capacity, since hydro potential has been exploited to a maximum. Due to the world's increasing demand for oil and gas, their limited available quantity (probably enough for a few decades) and high prices, the country cannot rely on those two fossil fuels for electricity generation. Coal is used extensively all over the world for electricity generation and will continue for several hundred years. But upon extinction of fossil fuel oil and the increased use of coal will lead to high coal price as well as shorten the availability period. The other concern is that the coal burning causes high environmental pollution. The comparison data for pollutant emission is given in Table 1.4 and Table 1.5. Even though the coal power seems to be the immediate and only solution for Sri Lanka (as at the moment 3x300MW coal power plants are being constructed), it is not advisable to consider it as the only option for power generation on long term basis.

The construction of large scale renewable energy power plants should be further studied for economy, technological viability and the capacity since some of the technologies are not well developed yet.

There is an enthusiasm for re-considering nuclear power for electricity generation all over the world as new, safe and economical nuclear technologies are emerging. In Sri Lanka, CEB announced an invitation to the local experts to contribute their knowledge for a study to find out the possibility of using nuclear energy to generate electricity, in year 2008, April [3].

The author is an Engineer in CEB and selected this topic to investigate the possibility of using nuclear technology for electricity generation in Sri Lanka as a timely appropriate topic.

	NOx	SO2	CO	CO2	Hg	Methane	Thermal	Particulate Matter	"Fuel" Extraction	Fuel Residue
Coal	6.0 lb/ MWh	13.0 lb/ MWh	little	22.49 lb/ MWh	Yes	Mine fumes	Yes	Yes	Yes Deaths of miners	Ash, fly ash
Oil	4.0 lb/ MWh	12.0 lb/ MWh	Yes	16.72 lb/ MWh	0.02 ppm	no	Yes	Yes	Yes	Engine blow by, gases
Natural Gas	1.7 lb/ MWh	0.1 lb/ MWh	Yes	11.35 lb/ MWh	?	NG~80% methane & burned	Yes	Yes	Yes explosions	Very low if any
Wind	*	*	*	*	*	*	Insignifican t; no	no	No (birds)	no
Solar	*	*	*	*	*	*	radiation/ conduction from panels	no	no	no
Hydro	*	*	*	some	*	reserv-oir	no	no	Affects downstream	no
Geo-thermal	*	?	*	*	*	?	Yes	no	Brine spills	Saline spills
Nuclear	*	*	*	*	*	*	Yes	no	Yes	Spent fuel

Table 1.4 – Pollutants Emission

*Very little or no. (At the construction stage or at the operation)

Year	1000 Tons per Year			
	Particulate	SOx	NOx	CO2
2006	0.4	51.72	36.13	2,974.8
2011	1.9	66.29	41.85	6,122.7
2016	4.9	64.74	30.69	11,875.3
2020	7.3	92.88	43.1	17,475.4

Table 1.5 – Pollutants Emission Estimate: Sri Lanka

In the background study, the author investigated the world nuclear status comparing area of the country, population and nuclear electric energy capacity (Table 1.6). From these data it is obvious that some countries smaller than Sri Lanka have adopted nuclear technology for electricity generation.

Hence the basic study of nuclear energy for electricity generation in Sri Lanka in the near future is considered as a possible option.

	Country	Reactors in operation		Reactors under construct.		Max. single unit size (MW)	Total System Capacity (GW)	Area (1000 sqkm)	Population (Million)	Pers / sqkm
		Units	Total MW	Units	Total MW					
1	Argentina	2	935	1	692	600	24.00	2,737	39.7	15
2	Armenia	1	376			376	3.50	30	4	134
3	Belgium	7	5,801			1,015	10.40	31	10.7	350
4	Brazil	2	1,901			1,350	86.50	8,547	191	22
5	Bulgaria	4	2,722	1	953	1,000	9.40	111	7.6	68
6	Canada	18	12,599			881	111.00	9,976	33.6	3
7	China	9	6,572	3	3,000	1,060	622.00	9,597	1,336	139
8	Czech Republic	6	3,368			1,000		79	10.2	129
9	Finland	4	2,676	1	1,600	860	10.00	338	5.2	15
10	France	59	63,363			1,500	84.00	547	61	112
11	Germany	17	20,339			1,345		357	82	230
12	Hungary	4	1,755			473		93	11	118
13	India	15	3,040	8	3,602	540	147.00	3,288	1,095	333
14	Iran, Islamic Republic			1	915		33.00	1,648	69	42
15	Japan	56	47,839	1	866	1,315	226.00	378	127	336
16	South Korea	20	16,810			1,000	81.40	98	49	498
17	Lithuania	1	1,185			1,185		65	3.5	54
18	Mexico	2	1,310			650	58.00	1,958	107	55
19	Nether - lands	1	482			482		42	16	382
20	Pakistan	2	425	1	300	300	19.50	804	166	206
21	Romania	1	655	1	655	655	17.40	238	22	93
22	Russian Federation	31	21,743	4	3,775	1,170		17,075	143	8
23	Slovakia	6	2,442			436	7.80	49	5.4	110
24	Slovenia	1	656			666		20	2	99
25	South Africa	2	1,800			900		1,220	44	36
26	Spain	9	7,588			1,045		505	40	79
27	Sweden	10	8,910			1,170		450	9	20
28	Switzerl- and	5	3,220			1,165		41	7.5	182
29	Ukraine	15	13,107	2	1,900	950	52.00	604	46.7	77
30	United Kingdom	23	11,852			1,200	82.00	245	61	249
31	USA	104	99,210			1,700	1,088.00	9,630	298	31
	Total	443	369,552	26	20,858				4,103.1	58
	Sri Lanka						2.60	65.6	20.2	308

Table 1.6 – World Nuclear Status: Statistical Data, 2006*

*Reference: Nuclear Power and Sustainable Development, Brochure-2006, International Atomic Energy Agency (IAEA)

Chapter 2

Problem Statement

2.1. Identification of the Problem

From the table 1.1 and 1.3, it is evident in the near future major portion of the electricity production of Sri Lanka will be from fossil fuels. The fossil fuels are limited resources and with the increased consumption, the cost will be increased leading to utmost competition and possibly a risk of extinction. To maintain continuous production of electricity to suite the present and future increased demand, the electricity production is needed to be diversified to possible several options which are more sustainable.

On the other hand burning of fossil fuel causes environmental pollution which has severe impacts on existence of life. Therefore it is appropriate to consider the cleaner technologies for electricity generation.

The problem is what options available for Sri Lanka to produce electricity and the extent of their suitability with the economical, social, environmental and technological compliances.

2.2. Objective of the Study

This project addresses the possibility of generating electricity using nuclear power in Sri Lanka in the near future, probably by the year 2020. The detailed background study, initial economic and social feasibility study, basic technological study, safety and environmental study will be covered in this project.

The outcome of this project will provide single source of required information for energy planners, policy makers and normal public for considering whether the nuclear energy is a viable option for Sri Lanka.

2.3. Importance of the Study

The study of the possibility of electricity production using nuclear technology is important due to following reasons.

- Due to the advancement of nuclear technology, the available fuels for nuclear energy production seems to be unlimited which will be further discussed in subsequent chapters.
- Technological advancement make this technology safer, hence this is widely adopted all over the world. New countries like Bangladesh, Indonesia, Thailand and Malaysia have taken steps to implement nuclear power plant projects. However possibility of major accidents and their consequences are still a concern.
- This is a clean technology. The pollutant emissions can be considered as negligible. However initial construction, nuclear material processing, nuclear fuel production have impacts on environment.
- Fuel cost contribution to electricity cost is very small and the initial construction cost is reducing due to new advance methods of constructions.
- At the moment Sri Lanka is having peaceful background which is necessary for this kind of activities.
- Problem of nuclear waste management will be a major factor.
- Past studies reveal that Sri Lanka is having Thorium resource which is a possible option as a nuclear fuel.

Chapter 3

Basics of Nuclear Power Technologies

3.1. Basics of Nuclear Power

Nuclear thermal power is generated from two types of nuclear reactions called Nuclear Fission and Nuclear Fusion.

3.1.1. Nuclear Fission

Nuclear fission is a nuclear reaction in which the nucleus of an atom splits into smaller parts, often producing free neutrons and lighter nuclei, which may eventually produce photons (in the form of gamma rays). Fission of heavy elements is an exothermic reaction which can release large amounts of energy both as electromagnetic radiation and as kinetic energy of the fragments (heating the bulk material where fission takes place). At present nuclear fission is the reaction used to generate electricity in all the nuclear power plants. Examples of nuclear fission are as follows.

$$^{235}_{92}U + ^{1}_{0}n \rightarrow 2\ fission\ \ fragments + 2.4\ neutons + 192.9MeV$$

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{144}_{56}Ba + ^{89}_{36}Kr + 3^{1}_{0}n + Energy$$

$$1MeV = 1.6 \times 10^{-13} J$$

3.1.2. Nuclear Fusion

Nuclear fusion is the process by which multiple like-charged atomic nuclei join together to form a heavier nucleus. It is accompanied by the release or absorption of energy. The fusion of two nuclei with lower mass than iron generally releases energy while the fusion of nuclei heavier than iron absorbs energy. At present this technology is not used for electricity generation but the eperiments are continuing to harness the nuclear fusion. An examples of nuclear fusion reaction is s follows.

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}_{0}n + 17.6MeV$$

Where D and T stand for deuterium and tritium. (I.e. isotopes of H)

3.1.3. Chain Reaction

Elemental isotopes which undergo induced fission when struck by a free neutron are called fissionable; isotopes that undergo fission when struck by a thermal, slow moving neutron are also called fissile. (Ex. U-238 is fissionable but not fissile. In U-238, fission can take place only nutrons having energy greater than 1MeV. But U-235 is a fissile material.)

The nutrons produced by the fission reaction can combine with other fissile fuel and can produce nore nutrons. If enough fissil fuel is present in the medium continuation of this process take place, occuring a sustanable chain reaction.

3.2. Basic Components of a Conventional Nuclear Power Plant

Figure 3.1 shows some of the basic components of a conventional nuclear power plant (NPP).

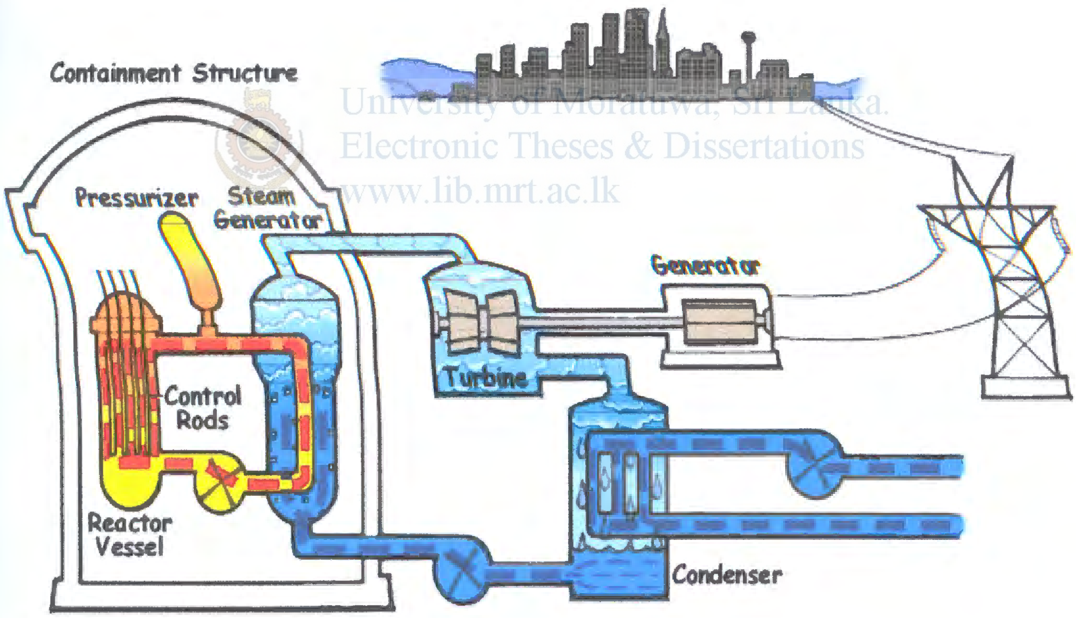

Figure 3.1 – Components of a NPP

3.2.1. Nuclear Reactor

The nuclear reactor is a device in which nuclear chain reactions are initiated, controlled, and sustained at a steady rate. Generated energy within the reactor is taken off by a circulating coolant.

Nuclear fuel and the moderator are contained inside the reactor. Moderator is a substance which slows down the fast neutrons produced in the fuel to thermal slow moving neutrons. The moderator material may be light water, heavy water, graphite or liquid metal.

Effective neutron multiplication factor of the reactor core is defined as below.

$$K = \frac{Nutron\ production\ from\ fission\ in\ one\ generation}{\begin{pmatrix} Nutron\ absorption\ in\ the \\ preceeding\ generation \end{pmatrix} + \begin{pmatrix} Nutron\ leakage\ in\ the \\ preceeding\ generation \end{pmatrix}}$$

When the chain reaction is self sustaining and the neutron population is neither increasing nor decreasing is referred to as the *critical* condition and can be expressed by the simple equation $K = 1$.

If the neutron production is greater than the absorption and leakage, the reactor is called *supercritical* and is represented by $K>1$.

If the neutron production is less than the absorption and leakage, the reactor is called *subcritical* and is represented by $K<1$.

3.2.2. Reactor Coolant System

The heat generated by the reactor core is removed by circulating coolant. The coolant may be the light water, heavy water, gas, liquid metal or the liquid salts.

3.2.3. Steam Generator

The coolant flowing through the steam generator, transfer thermal energy producing water steam inside the steam generator.

3.2.4. Steam Turbine and Electric Generator

Steam produced in the steam generator drives the steam turbine and electric generator coupled with turbine to produce electricity.

3.2.5. Reactor Control System and Safety Shutdown System

Nuclear reaction inside the reactor core should be controlled so as to achieve sustainable controlled chain reaction. This is done by inserting control rods in to the reactor core. These control rods consist of neutron absorbing material which controls the neutron density inside the core.

Safety shutdown system may be control rods which absorb neutrons or a liquid injected to the reactor core which again absorb the neutron.

3.2.6. Containment Building

The containment building, in its most common usage, is a steel or reinforced concrete structure enclosing a nuclear reactor. It is designed, in any emergency, to contain the escape of radiation to a maximum pressure. The containment is the final barrier to radioactive release, the first being the fuel ceramic itself, the second being the metal fuel cladding tubes, the third being the reactor vessel and coolant system.

3.2.7. Spent Fuel Storage

The storage which situated in the premises of nuclear power plant (NPP), temporarily store the spent fuels. Usually the volume of the spent fuel is smaller and this storage is sufficient for a long period of time. Disposal of spent fuel will be discussed in more details in relevant chapters.

Chapter 4

Nuclear Power Plant Pre-feasibility Study: Technology

Technological pre-feasibility study is based on several assumed conditions and available data from various sources which are mentioned at the relevant sub-sections.

Technical Feasibility

Under this section following important facts needs to be assessed.

- System capacity
- Technology

4.1. System Capacity

As discussed in the Chapter-1 Table 1.3 of this document, the total installed capacity of the Sri Lankan power system will be around 6000MW in year 2020. To absorb this much of energy the entire transmission system and distribution system should be developed. Time to time CEB planning section plans and executes projects which will enhance the absorbing capacity of the Sri Lankan power system. For example "Colombo City Electricity Distribution Development Project" could be shown. Therefore it is assumed that the entire electrical system will be developed to absorb projected energy supply in the year 2020.

Nuclear power plants are normally base load power plants owing to the fact that the power level of the plant can not be varied easily and these plants needed to be run at maximum capacity for economical usage. As per the CEB data, the present daily demand curve of the Sri Lankan power system is shown in figure-4.1 (below) and it indicates the present base load demand is around 800MW. Considering the average annual growth rate of 7.8% (Table 1.2) and the maximum demand forecast in year 2020, the possible base load will be around 2000MW (Assuming linear extrapolation).

As seen from the long term generation expansion plan, the major portion of the power will come from coal based plants. But these plants are much easier to start or stop and connect with the grid compared with nuclear power plants.

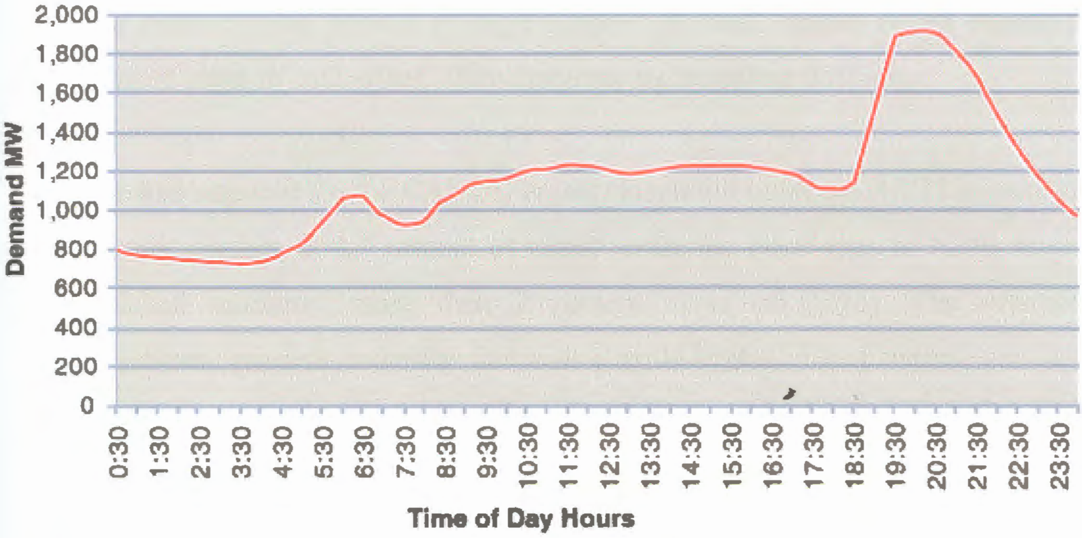

Figure 4.1 – Average Daily Demand Curve

4.2. Technology

For further study it is needed to select suitable type and size of a nuclear power plant.

There are various type of NPPs classified according to reaction type, moderator type, coolent type, reactor vessel possition, reactor temperature, type of the technolgy and type of the output. A complete classification is given in the Appendix-1.

4.2.1. CANDU (CANada Deuterium Uranium) Power Plant

In this document the CANDU type nuclear power plant is mainly considered because of the many advantages it possess. The other consideration is SSTAR (Small, Sealed, Transportable, Autonomous Reactor) and is also disscussed at the end of this Chapter.

The advantages of CANDU over other types are as follows.

- The CANDU technology is well developped over the past few decades. The new generation (Generation-4) NPPs are still under development. Adopting well developped technology eleminate the requirement of much modification during operation. CANDU type reactors are mainly operating at Canada, India and China. Table 4.1 gives the details of CANDU NPPs in the world.

- Most of the reactor types are single vessel type. This make the metalic vessal bulkier and weighs several tons making the handling exteamly difficult at the construtiion stage. In CANDU design the reactor vessal is not a single unit. The reactor vessal consist of large number of small vessals called channels, situated close to each other. This eleminate the handling difficulty.

- The fuel required for the CANDU reactor is natural Uranium (U235 content of natural uranium is 0.7 percent of mass) while the other type of NPPs reqire enriched uranium (more than 2 percent mass of U235). The uranium enrichment process make the fuel cost slightly higher. Using natural uranium eleminate the risk of proliferation of enriched nuclear material which is a requirement under IAEA (International Atomic Energy Authority) Nuclear Non Proliferation Treaty.

- Fabrication and handling of nuclear fuel bundle from the natural uranium is simpler in CANDU type reactors. The typical fuel bundle is shown in the Figure 4.1 below.

- The CANDU reactor can use various type of fuels including waste generation from other type of reactors, specially from Light Water Reactors because the waste from this tye of reactors normally contain Uranium more than 0.5 percent of mass. Natural Thorium can be used in the CANDU reactors. The thorium resources were found in Sri Lanka. This will be further discussed in coming chapters. The Figure 4.2 shows the fuel cycle options for CANDU reactors.

- The CANDU reactor posses the advantage of online refuelling facility. The other type of reactors need temporary shut down for refuelling. This feature of CANDU reactor improves the duty cycle or the capacity factor of the power plant. The online refuelling facility also improves the fuel burning and helps to reduce mined Uranium consuption 30 to 40 percent than other type of reactors.

- The CANDU Extends life expectancy of the reactor because major core components like fuel channels is accessible for repairs when needed. Typically about 60 years of life expectancy exist for this NPP while other type of NPPs last about 30 to 40 years.

Country	No. of CANDU Plants (operational)	Total Installed Capacity of CANDU (MW)	Max. CANDU Power Plant Capacity (MW)	Mini. CANDU Power Plant Capacity (MW)
Canada	16	11,303	881	516
India	15	3,800	540	187
South Korea	4	2,823	715	678
China	2	1,330	665	650
Romania	2	1,305	655	650
Argentina	1	600	-	-

Table 4.1 – World CANDU Plants as at Year 2003

Figure 4.2 – CANDU Fuel Bundle (37 element, 50 cm long & 10 cm diameter)

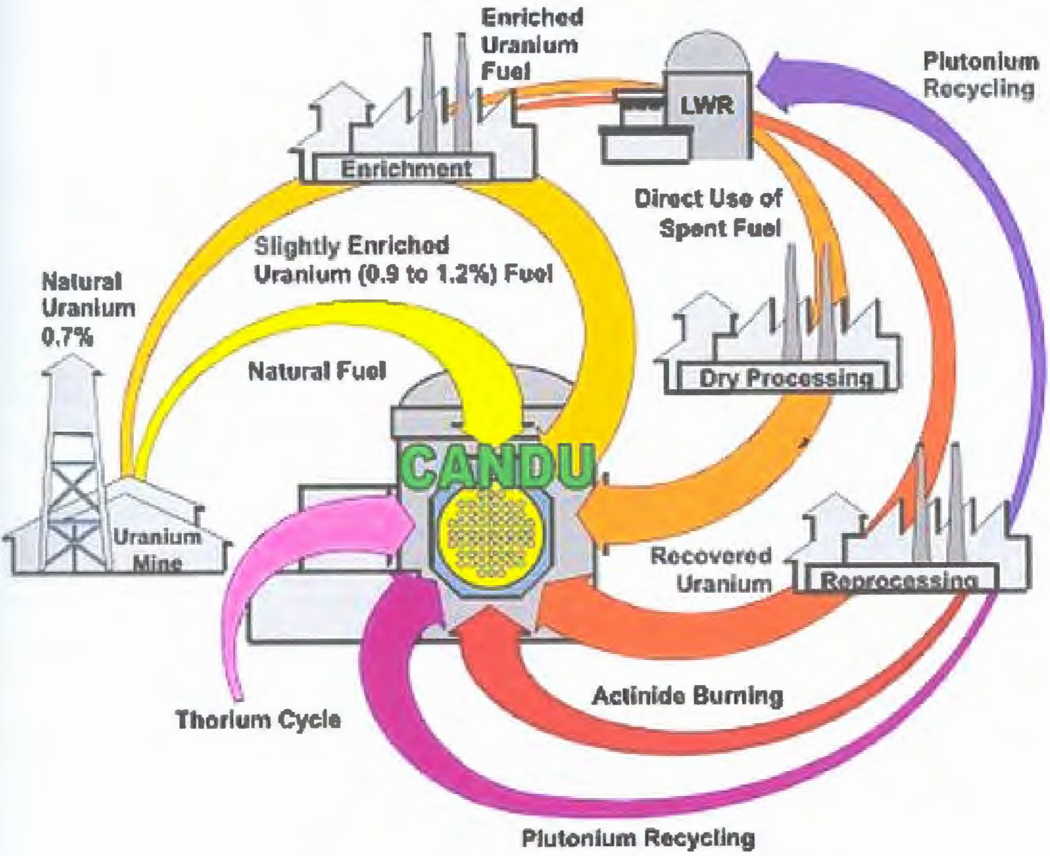

Figure 4.3 – CANDU Fuel cycle options

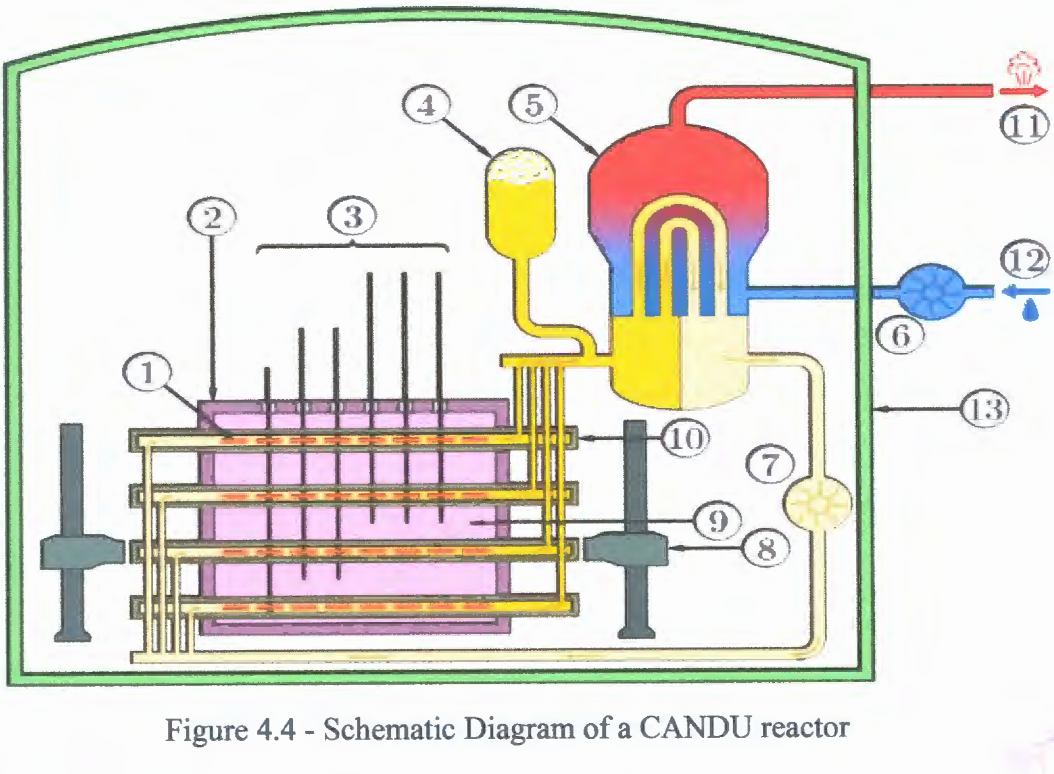

Figure 4.4 - Schematic Diagram of a CANDU reactor

Figure 4.4: The primary loop is in yellow and orange, the secondary in blue and red. The cool heavy water in the calandria (CANDU reactor core) can be seen in pink, along with partially-inserted shutoff rods.

Key			
1	Fuel bundle	8	Fueling machines
2	Calandria (reactor core)	9	Heavy water moderator
3	Adjuster rods	10	Pressure tube
4	Heavy water pressure reservoir	11	Steam going to steam turbine
5	Steam generator	12	Cold water returning from turbine
6	Light water pump	13	Containment building made of reinforced concrete
7	Heavy water pump		

4.2.2. Suitable Size of the Nuclear Power Plant

There is no fast and hard rule for selecting a size of a single unit power plant in relation to total installed capacity of an interconnected power system. The selection of size of the power plant depends on transmission network capability to absorb the new amount of energy without effecting stability criteria. For this, a comprehensive analisis needed consdering future improvements to transmission network, site location and demand growth. As a thumb rule the single unit power plant should be less than or equal to 15 percent of the total installed capacity of an interconnected power system [4]. As per the demand forecast the peak demand in the year 2020 will be around 5300 MW and total installed capacity will be around 6000 MW [2].

Therefore maximum possible single unit size will be around 900 MW based on the above said thumb rule. Readily available CANDU power plant designs are 220MW, 700MW and 900 MW. Thus 700 MW size can be conveniently selected to cover up a portion of the future base load.

The medium level CANDU reactor which is called Douglas Point type (Name derived from Douglas Point reactor in Canada) have the design capacity of 220MW. In India there are 11 units of this type operating successfuly (Operating capacity of each 202MW). Even if the 700MW size is not selected for Sri Lanka, the Douglas Point type can be adopted integrating with new advanced features.

The reference data for the unit selected is "Qinshan Phase-III 700 MWe class CANDU 6 NPP, China" which was in service from December 2002 [5] . The unit data are given in the Table 4.2.

Reactor	
Type	Horizontal pressure tube
Coolant	Pressurized heavy water
Moderator	Heavy water
Number of fuel channels	380
Fuel	
Fuel	Compacted and sintered natural UO2 pellets
Form	Fuel bundle assembly of 37 elements
Length of bundle	495 mm
Outside diameter	102.4 mm
Bundle weight	23.5 kg (includes 2.1 kg zirconium alloy)
Bundles per fuel channel	12
Heat Transport System	
Reactor outlet header pressure (gauge)	9.9 MPa
Reactor outlet temperature	310 degree C
Reactor coolant flow	8.6 Mg/s
Number of steam generators	4
Steam generator type	Vertical U-tube with integral steam drum and pre-heater
Steam temperature (nominal)	268 degree C
Steam quality (minimum)	99.75%
Steam pressure (gauge)	4.7 MPa
Number of heat transport pumps	4
Heat transport pump type	Vertical, centrifugal, single suction, double discharge
Net heat to turbine	2064 MW (th)
Electrical output (gross)	728 MWe

Table 4.2 - 700 MWe class CANDU 6 NPP Data

4.2.3. Fuel Requirement of CANDU 6 Unit

Initial charge

The fuel bundle shown in figure 4.2 is used in this type of reactors.

Initial charge of fuel (Nos. of bundles) = 4560 Nos.

Initial charge of fuel = 107,160 kg

Initial natural Uranium charge = 97,584 kg

Initial zirconium alloy = 9,576 kg

Transitional period

Transitional period starts from about 100 to 110 days and lasts until the equilibrium state which is normally attained in 400 to 500 days. In the transitional period refueling starts and the quantity of material to be refueled based on reactor core flux analysis and experience.

After equilibrium state

When the equilibrium state reached, approximately 10 channels per week and 8 bundle shifts per channel are required to be fuelled for full power operation. Therefore fuel requirement for a reactor in full operation year is as follows.

No. of uranium bundles required = 4,160 Nos.
Fuel required = 97,760 kg
Quantity of natural uranium required = 89,024 kg
Zirconium alloy required = 8,736 kg
Approximate Volume of required fuel for one year = 22 Cubic Meter

4.2.4. Cooling Water Requirement of Nuclear Power Station

There are two types of water cooled systems.

Closed cycle — the steam is cooled in towers or ponds and the water that is not lost to evaporation is recycled through the plant again.

Once-through— the steam is cooled by more water that is pumped from an outside source in pipes through a condenser.

Table 4.3 indicates the water usage of each type of NPPs.

Type of Cooling	Water Withdrawal (liters/MWh)	Typical Water Consumption (liters/MWh)
Ones Through Cooling	94,635 to 227,124	1,514
Closed Cycle (Cooling Towers)	3,028 to 4,164	2,725

Table 4.3 – Cooling Water Requirement

4.2.5. Waste Disposal

The nuclear waste can be classified into following four groups.

(I.) Exempt waste & very low level waste

Exempt waste and very low level waste (VLLW) contains radioactive materials at a level which is not considered harmful to people or the surrounding environment. It consists mainly of demolished material (such as concrete, plaster, bricks, metal, valves, piping **etc**) produced during rehabilitation or dismantling operations on nuclear industrial sites. Other industries, such as food processing, chemical, steel **etc** also produce VLLW as a result of the concentration of natural radioactivity present in certain minerals used in their manufacturing processes. The waste is therefore disposed of with domestic refuse.

(II.) Low-level waste

Low-level waste (LLW) is generated from hospitals and industry, as well as the nuclear fuel cycle. It comprises paper, rags, tools, clothing, and filters *etc*, which contain small amounts of mostly short-lived radioactivity. It does not require shielding during handling and transport and is suitable for shallow land burial. To reduce its volume, it is often compacted or incinerated before disposal. It comprises some 90% of the volume but only 1% of the radioactivity of all radioactive waste.

(III.) Intermediate-level waste

Intermediate-level waste (ILW) contains higher amounts of radioactivity and some requires shielding. It typically comprises resins, chemical sludge and metal fuel cladding, as well as contaminated materials from reactor decommissioning. Smaller items and any non-solids may be solidified in concrete or bitumen for disposal. It makes up some 7% of the volume and has 4% of the radioactivity of all radioactive waste. Generally, short-lived intermediate-level wastes (mainly from decommissioning reactors) are buried, while long-lived intermediate-level wastes (from fuel reprocessing) will be disposed of deep underground.

(IV.) High-level waste

High-level waste (HLW) arises from the 'burning' of uranium fuel in a nuclear reactor. HLW contains the fission products and transuranic elements generated in the reactor core. It is highly radioactive and hot, so requires cooling and shielding. It can be considered as the 'ash' from 'burning' uranium. HLW accounts for over 95% of the total radioactivity produced in the process of electricity generation. There are two distinct kinds of HLW:

- Used fuel itself.
- Separated waste from reprocessing the used fuel

4.2.5.1. Managing HLW from used fuel

Storage is mostly in ponds at reactor sites, or occasionally at a central site. Some 90% of the world's used fuel is stored thus and some of it has been there for decades. The ponds are usually several metres deep, to allow three metres of water over the used fuel to fully shield it. The water also cools it. Some storage is in dry casks or vaults with air circulation and the fuel is surrounded by concrete.

Either way, after 40-50 years the heat and radioactivity have fallen to one thousandth of the level at removal. This provides a technical incentive to delay further action with HLW until the radioactivity has reduced to about 0.1% of its original level.

After storage for about 40 years the used fuel assemblies are ready for encapsulation or loading into casks ready for indefinite storage or permanent disposal underground (deep permanent repository).

4.2.6. Spent Fuel Reprocessing

Any used fuel will still contain some of the original U-235 as well as various Plutonium isotopes which have been formed inside the reactor core, and the U-238. In total these account for some 96% of the original uranium and over half of the original energy content (ignoring U-238). If the fast breeder technology is considered then U-238 becomes a usable resource and the energy content is hundreds of times larger. At the moment fast breeder technology is not popular due to some international political reasons.

Used nuclear fuel reprocessing is done in several countries like France, UK, and Russia with a capacity of some 5000 tons per year. But in Canada the spent CANDU fuel bundles are preferred to be directly disposed.

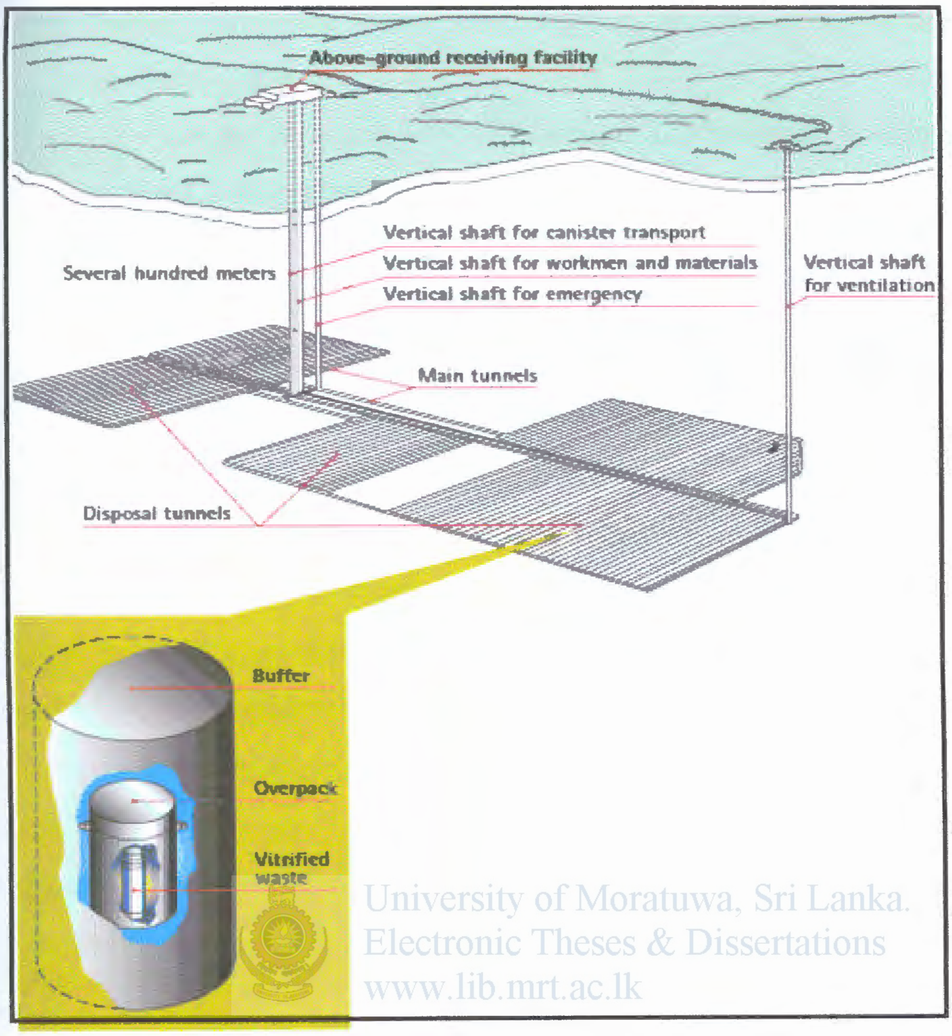

Figure 4.5 - Graphical Conception of Underground Disposal of HLW

4.2.7. SSTAR (Small, Sealed, Transportable, Autonomous Reactor)

This type of reactors are still under developing stage. Several well known international companies are involved in making this type of reactor successful. Some of them are Hyperion Energy – USA and Toshiba – Japan.

Hyperion Mini Reactor has the following important features [7].

- Nuclear power plants smaller than a garden shed and able to power 20,000 homes.
- Totally sealed and self-operating, has no moving parts and, beyond refueling, requires no maintenance of any sort.
- It just quietly delivers safe, reliable power – 70 MW thermal or 25 MW electric via steam turbine – for a period of seven to 10 years.

- Natural heat-producing process that occurs with the oscillation of hydrogen in uranium hydride.
- It cannot go "supercritical," melt down, or get "too hot." It maintains its safe, operating temperature without the introduction and removal of "controlling rods" – an operation that has the potential for mechanical failure.
- Small enough to be transported on a ship, truck or train — approximately 1.5 meters wide.
- Hyperion power modules are buried far underground and guarded by a security.
- They must be refuelled every 7 to 10 years.
- The waste produced after seven years of operation is approximately the size of a softball and is a good candidate for fuel recycling."
- It will be on sale within next five years.
- They will cost approximately $25m to $35m.

Super-safe, small, and simple (4S) reactor developed by Toshiba has the following features [8].

- The 4S is based on a smaller 10 MW design that can last 30-40 years before refueling.
- The 4S is sodium-cooled, and uses liquid lithium-6 to moderate the reactor, instead of conventional control rods.
- Like Hyperion's design, the reactor is totally sealed and requires no maintenance or operation.
- The actual reactor would be located in a sealed, cylindrical vault 30 m (98 ft) underground
- The 4S is planned to be online in 2012.

Chapter 5

Nuclear Power Plant Pre-feasibility Study: Economy

The pre-feasibility study is carried out in comparison with coal power plants which are the current solution for Sri Lankan electricity needs.

5.1. Economics of Coal Power

The cost analysis of Puttalam coal power plant is taken for this purpose, as this project is currently in implementation. Following figures are taken from the project data of the Puttalam Coal power plant (first phase of constructing a 300MW unit) [11].

Assumptions in this analysis are;

- Official discount rate is 10%
- Loan duration is 20 years at a concessionary rate of 3.5%
- Price escalation during the construction period not considered.
- Current average exchange rate of 1US$=115 Rs.

Economic Life of the power plant	= 30 Yars
Total project cost (Including infrastructure)	= 455 US$
Capital cost	= 1.77 UScts/kWh
Fuel Cost (100 US$/Ton)	= 4.2 UScts/kWh
Maintenance Cost	= 1.25 UScts/kWh
Therefore total cost of Electricity Produced	= 7.22 UScts/kWh
	= 8.3 Rs./kWh

Environmental cost due to various pollution emissions is not added for the above calculation. Main emission is CO_2 and considering internationally accepted figure of 14 US$ for 1 Ton of CO_2 the total economic cost of electricity produced can be obtained.

Emission of CO_2 per kWh	= 0.915 kg
Environmental cost	= 1.28 UScts
Total economic cost of Electricity Produced	= 8.50 UScts/kWh
	= 9.78 Rs./kWh

5.2. Economics of Nuclear Power

For this calculation, basic data from a recently built nuclear power plant is taken. The reference project is Qinshan CANDU Project (Phase III) in China where the NPP is in operation since year 2002.

The following data is taken from the reference project.

The construction cost including heavy water fill and first fuel loading is 1827 million. US$.

Assumptions in this analysis are;

- Official discount rate is 10%
- Project is started in the current year.
- Loan duration is 25 years including 5 year grace period at 5% interest.
- Price escalation during the construction period not considered.
- Current average exchange rate of 1US$=115 Rs.
- Equity ratio between foreign and local components is 85:15.
- During the 5 years of construction period only the interest for loan components will be paid.
- Profit component taxes are not included in this analysis.
- Total availability factor of 0.95 at a capacity factor of 0.9 is considered.
- Total maximum electricity output is 700MW and system 14% loss to be considered.

Economic Life of the power plant is 60 years (With slight refurbishment at the mid of life span). Discounted LUEC (Levelized Unit Energy Cost) is calculated from the formula as given below.

$$LUEC = \sum\left[(I_t + M_t + F_t)(1+r)^{-t}\right] / \sum\left[E_t(1+r)^{-t}\right]$$

Where: I_t = Investment expenditures in the year t
M_t = Operations and maintenance expenditures in the year t
F_t = Fuel expenditures in the year t
E_t = Electricity generation in the year t
r = Rate used to discount expenses and revenues to a present value

From the above formula investment expenditure or capital cost per unit energy is calculated as;

$$Capital\ Cost = \sum\left[I_t(1+r)^{-t}\right] / \sum\left[E_t(1+r)^{-t}\right]$$

The other components of expenditures are taken internationally accepted values as mentioned in the relevant references. Capital cost per unit energy is calculated using above formula Refer (Appendix 2).

Capital cost per unit energy	= 4.80 UScts/kWh
Fuel cost (Refer Appendix 2)	= 0.70 UScts/kWh
Operation & maintenance cost [13]	= 1.83 UScts/kWh
Decommissioning cost [13]	= 0.20 UScts/kWh
Used fuel handling [13]	= 0.87 UScts/kWh
Cost of Electricity (LUEC)	= 8.40 UScts/kWh
	= 9.66 Rs. /kWh

5.3. Comparison and Sensitivity Analysis of Unit Cost

In sensitivity analysis two criteria are considered.

- Fuel price increases due to the limited availability and increased use.
- Due to advance technologies like modularization and miniaturization and project management the construction cost of power plants can be reduced.

Following table summarize the sensitivity study based on above two criteria.

Fuel price	Cost Rs./kWh		
	Coal Powered (without CO2 compensation)	Coal Powered (with CO2 compensation)	Nuclear powered
Current	8.30	9.78	9.66
1.5 times	10.72	12.19	10.06
2 times	13.13	14.61	10.47
3 times	17.96	19.44	11.27
4 times	22.79	24.27	12.08
Reduction of construction cost and maintaining current fuel cost			
5% reduc.	8.20	9.67	9.38
10% redu.	8.10	9.57	9.10
20% redu.	7.90	9.37	8.56

Table 5.1 – Sensitivity Analysis

Upon extinction of the fossil fuel oil and gas it is obvious that the coal price will go up rapidly. From the above analysis it is clear that the unit energy cost from nuclear power plant is less sensitive to fuel price increase. Moreover the unit energy cost of nuclear power is more sensitive to the construction cost.

5.4. Possible International Financing Sources and Contractors

There are number of options available for possible financing. Some of the financing sources discussed here have already contributed nuclear power projects in China, Japan, Canada, India etc. Following are the main sources [15] of financing.

5.4.1. Export Credit

(a) Export credit agencies (ECAs)

ECAs, are private or quasi-governmental institutions that act as intermediaries between national governments and exporters to issue export financing. The financing can take the form of credits or credit insurance and guarantees (pure cover) or both, depending on the mandate the ECA has been given by its government. ECAs can also offer credit or cover on their own account. This does not differ from normal banking activities. Some agencies are government-sponsored, others private, and others a bit of both. Following are examples of ECA.

- Canada: Export Development Corporation (EDC).
- France: Compagnie francaise d'assurance pour le commerce exterieur (COFACE), Banque francaise du commerce exterieur (BFCE).
- Germany: Hermes Kreditversicherungs AG, Ausfuhrkredit-Gesellschaft mbH (AKA), Kreditanstalt fur Wiederaufbau (KfW).
- Japan: Export-Import Bank of Japan, Ministry of International Trade and Industry (MITI).
- Sweden: Exportkreditnamnden (EKN), AB Svenska Export Kredit (SEK).
- United Kingdom: Export Credits Guarantee Department (ECGD).
- United States of America: Export-Import Bank of the United States (EXIM),
- Private Export Funding Corporation (PEFCO), Overseas Private Investment Corporation (OPIC).

(b) Equipment supplier's credit

5.4.2. Multilateral Development Institutions

(a) The World Bank Group

- The IBRD: International Bank for Reconstruction and Development
- The International Development Association (IDA),
- The International Finance Corporation (IFC),
- The Multilateral Investment Guarantee Agency (MIGA).

(b) Regional development banks and organizations

- The African Development Bank/Fund (AFDB/AFDF),
- The Asian Development Bank (ADB),
- The Inter-American Development Bank (IDB),
- The European Investment Bank (EIB),
- The European Bank for Reconstruction and Development (EBRD).

(c) Other institutions

- The Islamic Development Bank (ISDB),
- The Arab Fund for Economic and Social Development,
- The Saudi Fund for Development,
- The Kuwaiti Fund for Development.

5.4.3. International Markets

- Commercial loans,
- International bonds (Eurobonds).

5.4.4. Alternative Method – BOO/BOT Approach

BOT approach is developed as follow. A number of foreign investors form a consortium, which establishes a joint venture company (JVC) with a local utility. This JVC sells the electricity generated to the utility. The foreign investors procure most of the funds for the project, which are used to:

- Build a power plant with foreign engineering expertise
- Operate and manage the plant (by foreign investors/operators) for a certain period of time until all costs, debt service and equity are recovered by means of electricity tariffs; and then
- Transfer ownership of the plant to the country in which it is built.

Another variant of BOT is the build-own-operate (BOO) approach, which does not involve transferring the plant to the host country. The BOO plant can, in principle, continue to remain in private hands throughout the useful life of the project or up to some earlier date agreed upon by the host government and the private owners.

5.4.5. Possible Contractors and Equipment Suppliers

Below indicated is a list of main nuclear power plant contractors and equipment suppliers.

- General Electric Nuclear Energy (GE Nuclear Energy) – USA
- Toshiba – Japan
- Westinghouse – Pennsylvania
- Doosan Heavy Industries and Construction – Korea
- Hitachi Limited – Japan
- Mitsubishi Heavy Industries – Japan
- Ansaldo Camozzi – Italy
- AECL – Canada

5.5. Nuclear Fuel Market and Availability

At present Uranium is mainly used as the fuel for almost all the reactors. Thorium is a possible option for replacing Uranium fuel but the research and development are still going on to develop Thorium fuel cycle especially in India. The reason behind this is that Thorium is not directly a fissile material. More details of these fuel types and their reactions are given in Appendix - 3 of this document.

5.5.1. Uranium Market

Uranium does not trade on an open market like other commodities. Buyers and sellers negotiate contracts privately. Prices are published by independent market consultants Ux Consulting and TradeTech [16]. Before Uranium is ready for use as a nuclear fuel in reactors, it must undergo a number of intermediary processing steps identified as the front end of the nuclear fuel cycle:

1. Mining and milling to produce U_3O_8;
2. Refining and conversion to produce UF_6 and UO_2;

3. Enrichment to produce low-enriched Uranium; and,
4. Fuel fabrication to produce fuel assemblies or bundles.

The ultimate users of nuclear fuel purchase Uranium in all of these intermediate forms. Typically, a fuel buyer from power utilities will contract separately with suppliers at each step of the process. Sometimes, the fuel buyer may purchase enriched Uranium product, the end product of the first three stages, and contract separately for fabrication, the fourth step.

Production from world Uranium mines supplies only 62% of the requirements of power utilities. The balance comes from secondary sources. Secondary supply is essentially inventories of various types and includes inventories held by utilities and other fuel cycle companies, inventories held by governments, used reactor fuel that has been reprocessed, recycled materials from military nuclear programs and Uranium in depleted Uranium stockpiles.

Major Uranium Producers (million lbs U_3O_8)	
Producer	**2007 Production**
Cameco - Canada	20
Rio Tinto – UK, Australia	19
Areva - France	16
Kazatomprom - Kazakhstan	12
TVEL - Russia	10
BHP Billiton - UK, Australia	9
Navoi - Uzbekistan	6
Uranium One -Canada	2
General Atomics - USA	2
Other	13

Table 5.2 – World Uranium Production

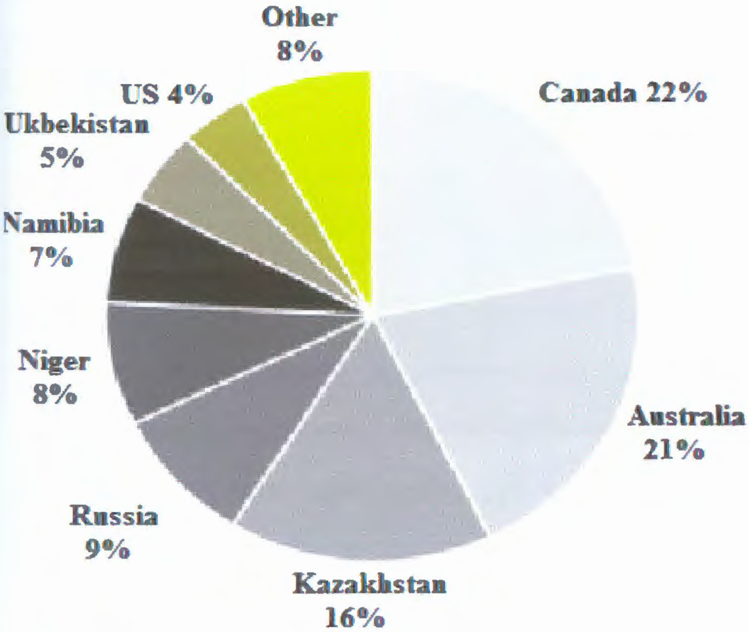

Figure 5.1 – World Uranium Production

Uranium and Coal Price Variation

Uranium average spot prices for last 20 years are given in figure 5.2.

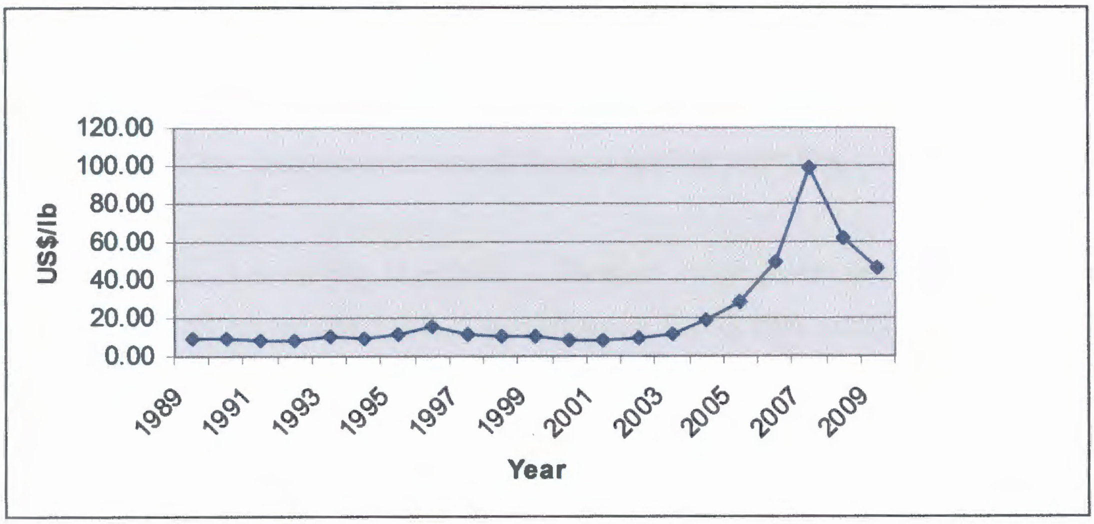

Figure 5.2 – Uranium Spot Prices – Cameco (Canada)

Average coal prices for the last 20 years are shown in figure 4.2.

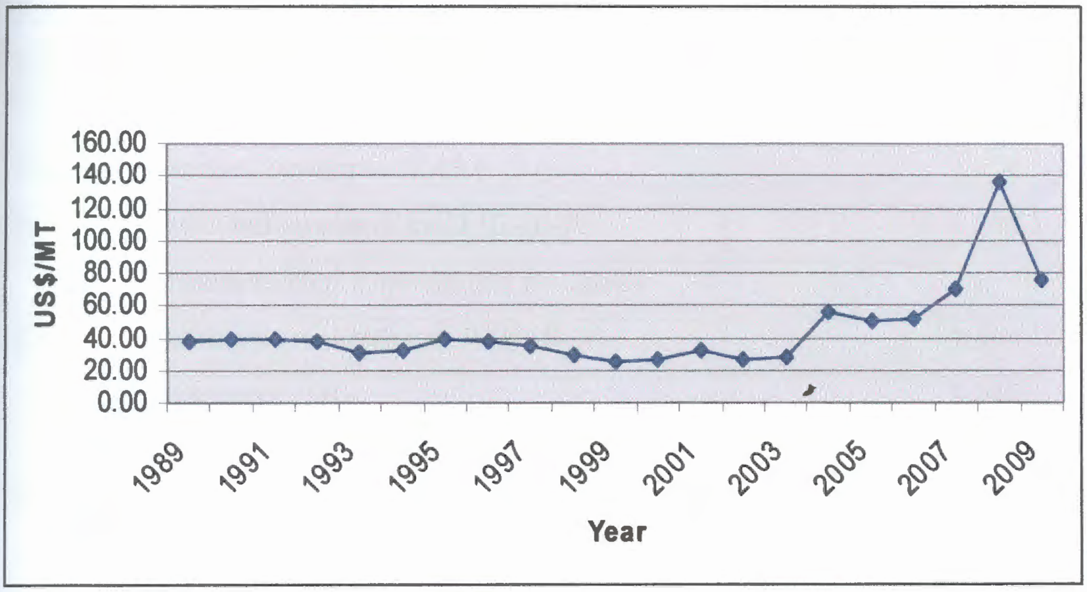

Figure 5.3 – Australian Thermal Coal Prices (Low Sulpher)

The above price variation graphs clearly show that beyond 2003 there is a marked trend of price increase for both fuels.

5.5.2. Thorium Market

Since Thorium fuel cycle is still a developing technology, there are no well known suppliers for the commodity. However domestic producers in some countries are supplying the small demand of the current market. Most of the Thorium produced in this way is used for research reactors and for non-nuclear activities.

Today, Thorium is relatively expensive – Thorium oxide prices per kilogram were $82.50 for 99.9% purity and $107.25 per kilogram for 99.99% purity. However, this is only because there is currently a little demand for Thorium, so as a special metal, it is expensive [17].

5.5.3. Availability and Sustainability to the Future (Uranium)

Current consumption of the Uranium fuel all over the world is about 77,000 MT per year which is used to produce 2.6 trillion kilowatt-hours (installed capacity 303GWe) of electricity from nuclear power plants - the share of about 15% of the world total electricity production of 17 trillion kilowatt-hours (2008 data).

5.5.3.1. Uranium Availability

Following are the estimated quantities of Uranium [19].

Resources type	Estimate (1000 MT)
(1.) Known conventional resources	
Reasonably assured resources (RAR)	2,850
Estimated additional resources cat. I (EAR-I)	1,080
(2.) Undiscovered conventional resources	
Estimated additional resources cat. II (EAR-II)	2,330
Speculative resources (SR)	9,940
(3.) Secondary sources	
Commercial inventories	220
Surplus defence inventories	250
Re-enrichment	440
(4.) Unconventional resources	
In phosphates	22,000
In seawater	4,000,000
Total	4,039,110

Table 5.3 – Uranium Availability

Meaning of Key Terms

Known conventional resources: These are readily accessible resources, i.e. resources that are known to exist and are inexpensive to exploit using conventional mining techniques.

Reasonably assured resources (RAR): The Uranium that occurs in known mineral deposits of such size, grade, and configuration which could be recovered within the given production cost ranges, with available mining and processing technology and priced less than 80 US$/U kg.

Estimated additional resources cat. I (EAR-I): That is basically, geometrically less known extensions (larger drilling patterns) of the previous (RAR), but are likely to have similar geological, technical and economic characteristics.

Estimated additional resources cat. II (EAR-II): The resources that are evaluated on the basis of indirect evidences within known Uranium bearing areas.

Speculative resources (SR): the resources that are thought to exist in geologically documented but poorly explored areas with respect to Uranium "on the basis of indirect evidence and geological extrapolations".

5.5.3.2. Availability at the Current Consumption Rate (Uranium)

Resource	**No. of Years of Availability**
Resource Type (1) above	51
Resource Type (1) + (2) above	210
Resource Type (1) + (2) + (3) above	222
Resource Type (1) + (2) + (3) + (4) above (Excluding from Sea*)	507

Table 5.4 – Uranium Availability: No. of Years

* Uranium extraction from sea water is feasible but estimated at a price of about ten times the current uranium production price [19]. However, even if 1% of Uranium from the sea water is extracted, the number of years of availability will increase further 500 years.

With recycling and using advance technologies like fast breeder reactors the above figures could be increased further giving the sense of sustainability.

5.5.3.3. Thorium Availability

Although the Thorium cycle is not still fully developed, the research and developments are going on (Especially in India) to harness it as a main nuclear fuel. In the case of India, they have been using Thorium as a fuel in seven PHWR and four research reactors [20]. Therefore it is important to discuss the Thorium fuel availability.

Thorium is 3 to 4 times more abundant in the earth crust than Uranium [20]. Data for reasonably assured and inferred resources recoverable at a cost of $80/kg provide an estimation of 2,110,000 tons of Thorium fuel availability [19]. However data from China, Central and Eastern Europe, and the former Soviet Union are not available. Therefore the actual amount of Thorium resource availability could be much higher than the above figure.

5.5.3.4. Thorium Fuel Availability in Sri Lanka

Thorium resources are found to be in south west costal region as per the studies carried out by M.S. Rupasinghe in1983 [21]. This study shows that Thorium content in the monazite thus found is 10% (average) and is more than the commercial monazite from sources elsewhere in the world. A quantitative assessment has not been done for Thorium resources in Sri Lanka but it is well known for its monazite placer deposits which are believed to exist in considerable quantity.

On the contrary to above following data exist for information [22].

Availability of Monazite in Sri Lanka	- 12,000 MT
Monazite Production in year 1994/95 each	- 120 MT

Chapter 6

Nuclear Power Plant Pre-feasibility Study: Site Survey

Selecting a suitable location for the NPP is a challenge because Sri Lanka is a small country and the population is distributed all over. However indicated in Table 1.6 of this document, even countries smaller in sizes than Sri Lanka have successfully adopted nuclear power plant technologies.

The site studies will include:

- Ease of integration into the electric system
- Geology and tectonic
- Seismology
- Heat removal capability
- Hydrology
- Demography
- Meteorology
- Risks from man-made events
- Availability of local infrastructure
- Legal aspects
- Public acceptance

The site survey may be further subdivided into three distinct stages:

- Regional analysis and identification of potential sites
- Screening of potential sites and selection of candidate sites
- Comparison of candidate sites.

6.1. Regional Analysis and Identification of Potential Sites

A general analysis is carried out in relation to whole of Sri Lanka.

6.1.1. Ease of Integration into the Electrical System

Figure 6.1 – Sri Lankan Electrical Transmission System
(CEB Annual Report 2005)

As shown in figure 6.1, the transmission lines and locations of grid substations are not well distributed all over the country. In case of selecting a remote location for NPP site the development of transmission system up to that point and capacity enhancement of existing system should be analyzed. In the planning stage of the NPP, designer and the CEB should consider this matter working together in cooperation.

6.1.2. Geology and Tectonic

Geology is the science and study of the solid and liquid matter that constitutes the Earth. The field of geology encompasses the study of the composition, structure, physical properties, dynamics, and history of Earth materials, and the processes by which they are formed, moved, and changed.

Plate tectonics is a theory which describes the large scale motions of Earth's lithosphere (lithosphere includes the crust and the uppermost mantle).

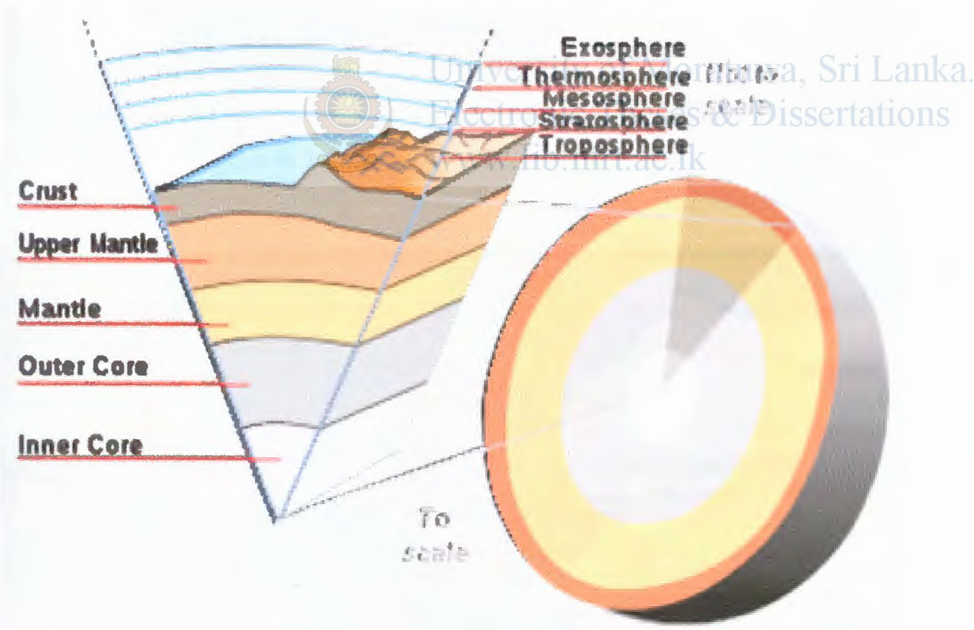

Figure 6.2 – Geological Layers of Earth

The lithosphere is broken up into what are called tectonic plates. In the case of Earth, there are currently eight major and many minor plates. Sri Lanka is in Indian Plate which is currently moving northeast at 5 cm/yr speed.

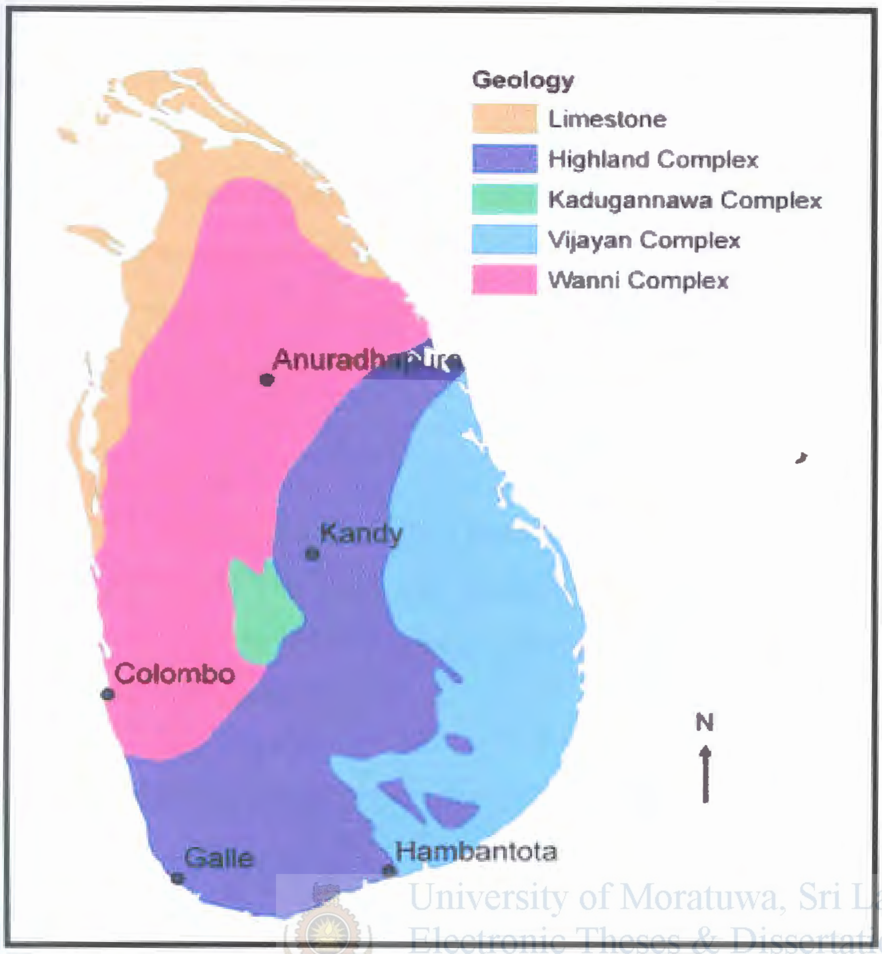

Figure 6.3 – Geology of Sri Lanka

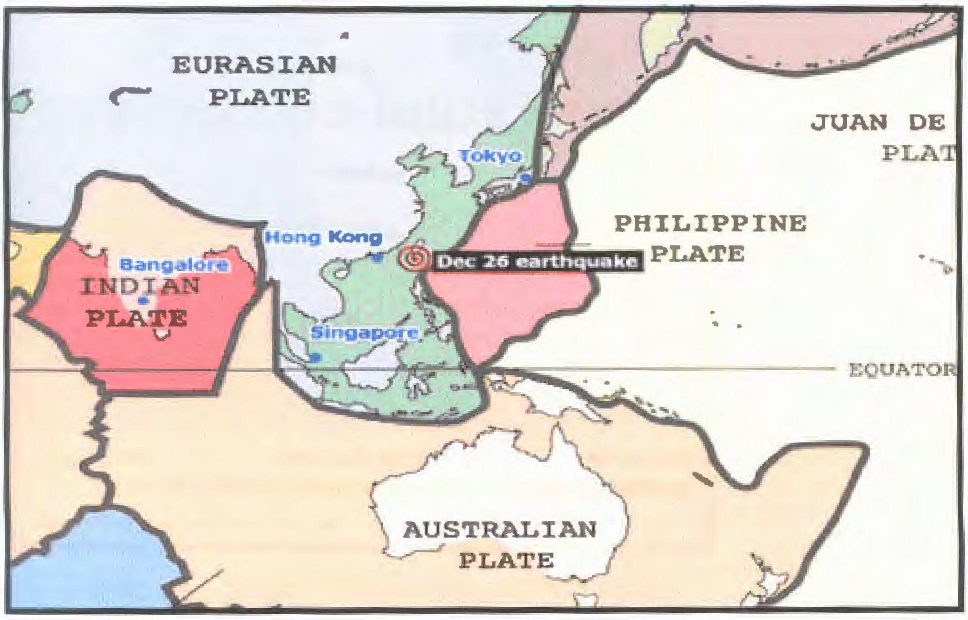

Figure 6.4 – Indian Plate

Composition of layers of geological areas is shown in figure 6.3 and these needed to be studied further.

The following data should be analyzed for proposed sites as a basic approach to consider geo-technical aspects [28].

- Geological information ;
- Descriptions of the extent and nature of subsurface materials;
- Characterizations of soil and rock (in terms of properties);
- Information on groundwater (the groundwater regime, locations and characteristics of the hydrological units).

6.1.3. Seismology

Seismology is the scientific study of earthquakes and the propagation of elastic waves through the Earth. The field also includes studies of earthquake effects, such as tsunamis as well as diverse seismic sources such as volcanic, tectonic, oceanic, atmospheric, and artificial processes.

Figure 6.5 - Seismic Hazard Map of Sri Lanka

As per the figure 6.5, seismic hazard level of Sri Lanka is very low since it does not lie near any of plate boundaries. In the last decades, however this plate has began to rotate on account of accumulation of run off from the Himalayas in the Bay of Bengal and other reasons; leading to a fissure between the "Australian" and "Indian" plates. Some scientists believe that this is leading to a new plate boundary across the Southern Indian Ocean. This boundary is still approximately a 1000 km from the south of Sri Lanka. Further research is needed to decide the consequences of compressions set up in the India plate and the impact of the recent earthquake on the regional hazards and also more precisely an estimate of the probability of the risk of earthquakes closer to Sri Lanka.

6.1.4. Heat Removal Capability

The available technologies for NPPs permit limits on efficiency probably around 33%. Therefore the excess heat needs to be removed from the plant. For this purpose huge amount of water is used. Therefore the availability of cooling water is a major factor for setting up a NPP. Sri Lanka is an island and having long costal area around it. The rivers, lakes and reservoirs are well distributed all over the country with abundance of water resource.

6.1.5. Hydrology

Under this, flood hazard on river sites and coastal sites and underground water system should be studied. In general Sri Lanka does not experience major effects in river flooding on banks in costal and low land areas. But in highland areas like Ratnapura the river flooding is becoming a major disaster.

For coastal sites (sea, lakes and semi-enclosed water bodies) the flood hazard is related to the most severe among the following types of flood, where applicable [29].

- The flood resulting from the probable maximum storm surge
- The flood resulting from the probable maximum tsunami resulting from an earthquake and also from landslides (including landslides under the sea), undersea volcanoes and falling ice.
- The flood resulting from the probable maximum seiche. (Oscillation of closed or semi closed water body)
- The flood resulting from wind and wave effects.

However the worst Sri Lankan experience was the tsunami of December 2004, with a maximum reported wave height of about 6m and the horizontal thrust so created was adequate to move a railway engine out of track.

The maximum tide variation is around 0.4-0.6m and the seasonal range of sea level change around Sri Lanka is about 20 -30 cm [30]

6.1.6. Demography

Demography is the statistical study of population. The present population in Sri Lanka is around 20 million and the natural growth is around 1.28%. Figure 6.6 gives an idea about the population distribution of the country.

6.1.7. Meteorology

Meteorology is the science of weather. The extreme values of the meteorological variables and the rare meteorological phenomena listed below should be investigated for every nuclear power plant site [31].

- wind, precipitation, temperature
- tornadoes, tropical cyclones and lightning.

Wind

Analysing the last 50 years of wind data the maximum wind speeds on costal areas are 4m/s to 8m/s where the maximum values occurring on south specially in Hambanthota District [32].

Precipitation

Annual average rainfall ranges from 2540 mm to over 5080 mm in the South West of the Island and less than 1250 mm in the North West and South East of the Island [33]. The rain often comes in relatively short but dramatic bursts even in dry zones. Habarana, for example, located in the Dry Zone between Polonnaruwa and Anuradhapura received 1,240 mm (nearly 50") of rain in 3 days around Christmas in 1975. Relative Humidity varies from 70% during the day to 90% at night.

Temperature

Average mean temperature along the coast is 26.7 C (80 F) and 19.7 C (66.50 F) in the hill country. But the temperature in costal areas may vary from 23^0 C to 33^0 C.

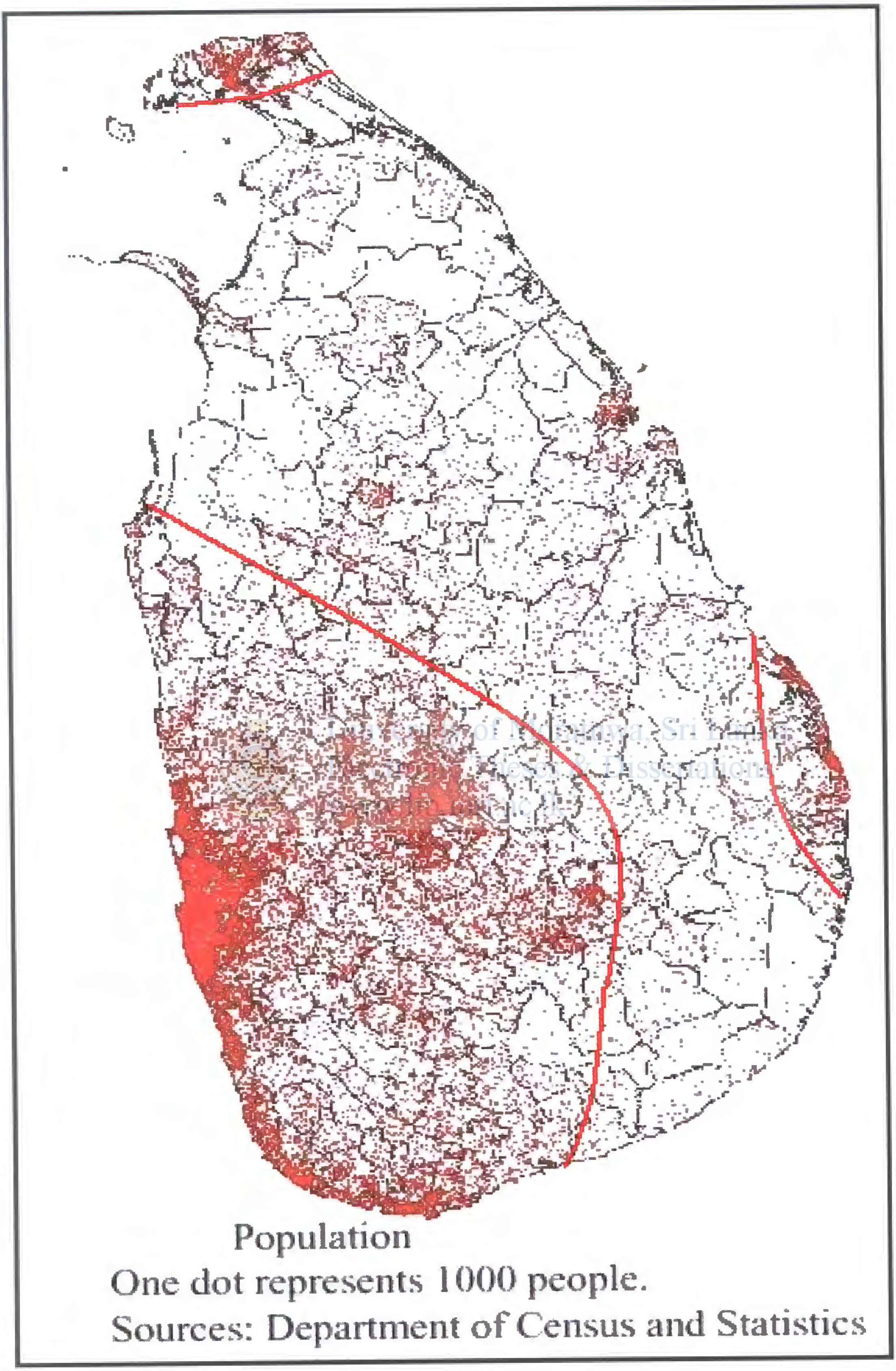

Figure 6.6 – Population Distribution of Sri Lanka

Tornadoes

The majority of tornadoes occurring in Asia have been reported in northeastern India, Bangladesh, Asiatic Russia, Japan, China and Philippines. There are no historical evidences for tornadoes in Sri Lanka and in the vicinity of the Indian Ocean [34]

Tropical Cyclones

There are several evidences of tropical cyclones in Sri Lanka in recent past. The following data exist for the reference.

- Cyclone in year 2000 December – Wind Speed 120km/h – Entered from east and left the Island
- Cyclone in year 1978 - Wind Speed 175km/h (hurricane strength)

Threfore there is a strong possibility of cyclone occurance in the island although it is occational.

Lightning

The isokeraunic level being high as 30 to 100, the severe lightning conditions exists in most of the areas of country. The current flow (mainly in **return** stroke) may carry currents as high as 200 kA, although the average current is about 20 kA.

6.1.8. Risks from Man-made Events

The major man made hazard may be due to terrorist activities and the aircraft impacts. Bombing, usage of heavy guns and missile attacks can be considered as terrorist activities. Instability in man made structures like huge dams, buildings and mines should also be considered when designing the NPP facility.

6.1.9. Availability of Local Infrastructure

Following items should be further analyzed for assessing the availability of local infrastructure for each proposed locations.

- Road network and their capacity to transport very heavy vehicles and material
- Bridges
- Sea Ports
- Water and electricity accessibility
- Stores and temporary accommodations.

6.1.10. Public Acceptance

Public acceptance for a NPP site is a major challenge because the perception of the general public on NPP is not favorable. They have the right to fear due to the knowledge of historical events like Hiroshima, Nagasaki events and Chernobyl accident. The only way of getting public acceptance is by educating them on new improved technologies, risks and benefits and reasons for NPP accidents that were taken place in the history.

6.2. Population Distribution and Zoning Criteria

When selecting a suitable site for a NPP the most critical factor is the population distribution. This is important to minimise the effect on general public in a worst case scenario.

The population distribution map of Sri Lanka is given in Figure 6.6. This figure shows that the south-west, major part of south and western provinces are densely populated. Jaffna and some small parts of east are also highly populated. Therefore these areas have to be excluded from the consideration. The hilly area is not suitable for a NPP due to rapid dispersion of radioactive material through wind in case of a radioactive material release. Even in areas having very low population density, the population centres or towns need to be considered when selecting a site.

In American systems the exclusion area and the low population area are the zones related to NPP location. The radii of these zones from the location of reactor are calculated considering radiation dose exposed by the workers and public [24].

The Indian system [25] consists of three zones as described below, which are more appropriate and adaptable to Sri Lanka.

Exclusion zone

An exclusion zone of 1.5 km radius around the plant is established (irrespective of the size of the plant), which is under the exclusive control of the operating organization, and no public habitation is permitted in the area. The dose limits to a member of the public, under normal operating conditions and under design basis accident conditions specified, are applied at the boundary of this exclusion zone.

Sterilized zone

With the help of administrative measures, efforts are made to establish a sterilized zone up to a 5-km radius around the plant (Irrespective of plant size). This is the annulus around the exclusion zone, which has the potential for extensive contamination in case of a severe accident. Development activities within this area are controlled so as to check an uncontrolled increase in the population. In this area, only natural growth of the population is permitted.

Emergency planning zone (EPZ)

This is the zone defined around the plant up to a 16-km radius and provides for the basic geographical framework for decision making on implementing measures as part of a graded response in the event of an off-site emergency. The EPZ is examined in great detail while drawing up an offsite emergency plan and arranging logistics for the same. The entire EPZ is divided into 16 equal sectors. The objective is to optimize the emergency response mechanism and to provide the maximum attention and relief to the regions most affected during an offsite emergency.

In assessing the above zones the Atomic Energy Regulatory Board of India has conformed to the requirement of IAEA safety standard. However the above criteria should be verified using a methodology described in Safety Report Series No.19 of IAEA [26] and Standards for dose limits as described in Reference [23].

6.3. Identification of Potential Sites

The author selected nine locations based on most of the above criteria as potential NPP sites. Special considerations were given to population distribution and elevation from the sea level. However this is a very preliminary study and needs to be further screened for best possible locations. These 9 locations are shown in Figure 6.7. More information on these locations is given under Appendix-5.

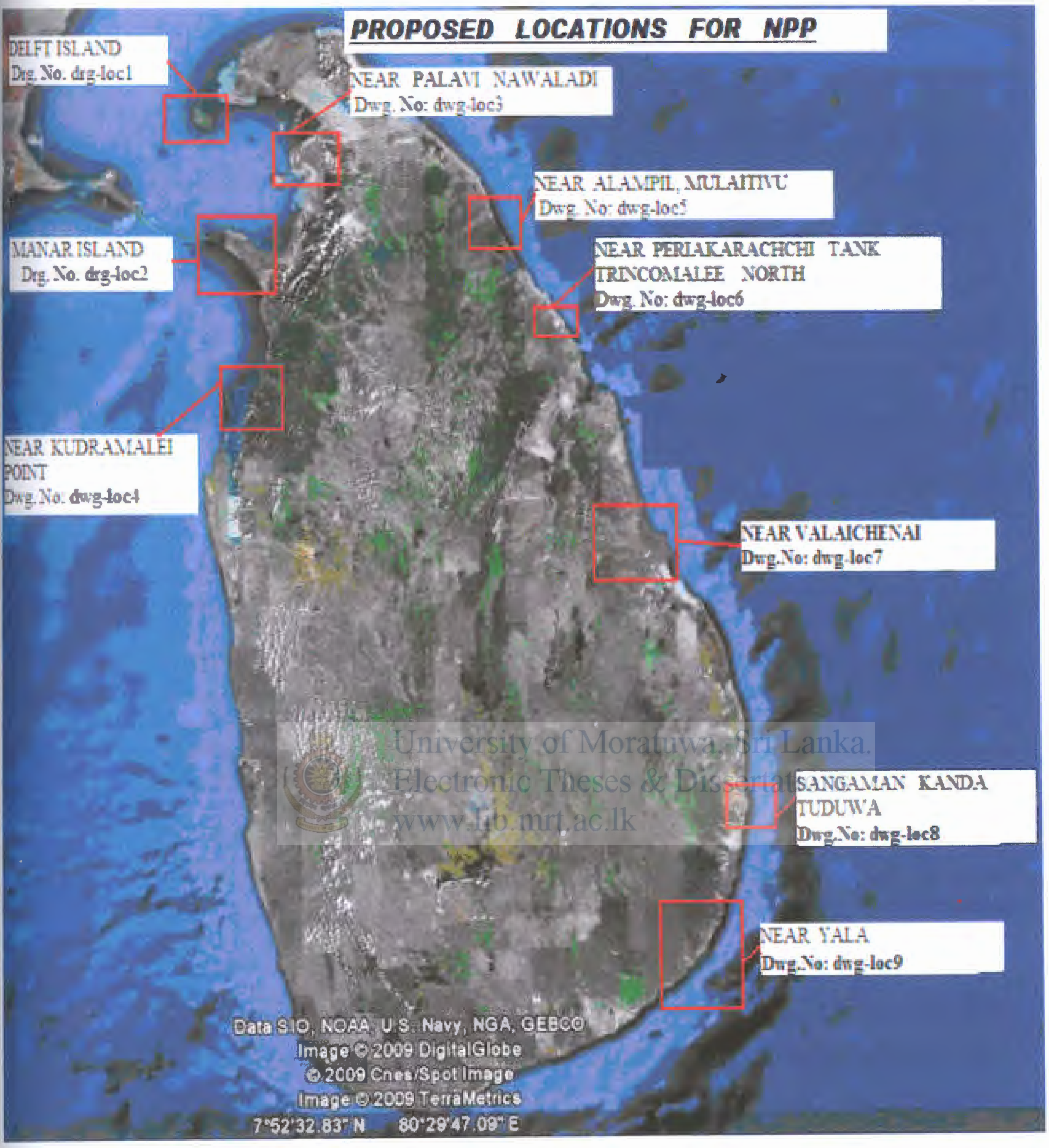

Figure 6.7 – Proposed Site Locations for NPP

Chapter 7

Nuclear Power Plant Pre-feasibility Study: Environmental Impact Assessment

Environmental impact assessment with relating to nuclear power plant construction and operation could be analyzed in following areas.

- Impact on land use
- Impact on water systems and the fishing industry
- Impact of radioactive and other emissions
- Impact on flora, fauna and protected sites
- Impact on the soil, bedrock and groundwater
- Impact on the landscape and cultural environment
- Impact on living conditions, comfort and health
- Impact on waste management and final disposal
- Impact on decommissioning of the power plant

7.1. Impact on Land Use

The area of the power plant site (with future expansion up to 1500MW) which covers the central power plant functions will be about 10 hectares (0.1 sqkm or nearly 25 Acre). The plant activities in the preliminary plans, excluding cooling water intake and discharge structures, harbour quay, and accommodation and parking areas, are expected to require an area of about 100 hectares (247 Acre) at each alternative location. Ground area will also be required for new road connections to be built. The power line leading to the plant will restrict land use on a strip 80–120 meters wide, depending on the column type.

The construction of the nuclear power plant will restrict land use in the plant's safety zone, but enable new constructions in settlements and villages and along roads. Authority will define the safety zone for the plant later, but, in the inspection work, it has been assumed to extend to a distance of about five kilometres from the plant.

The population of all selected locations as per Figure 6.7 are very few. (or no population at all). Sometimes there may be a few numbers of houses which needed to be relocated. The majority of the area is unused land, forest or agricultural lands. In case of agricultural lands, the effects due to loss of these lands are to be assessed. In case of forest or preserved wild life area the effects to the wild life are to be analysed.

7.2. Impact on Water Systems and the Fishing Industry

The conduction of the cooling water used at the power plant to the sea will increase the water temperature close to the discharge site. The extent of the warming sea area will be defined by the size of the power plant and, to some extent, by the chosen intake and discharge options.

As per the Sri Lankan regulations [37] temperature of the discharge to the coastal surface water should be less than 45 degrees centigrade (Normal average temperature of the surface sea water around Sri Lanka is about 28 degree centigrade). The practical temperature increase of the coolant water could be limited to ensure this value. Considering the typical plant, the temperature increase can mainly be observed in the surface sea layer (at a depth of 0–1 m).

Possible adverse impacts on fishing include the build-up of slime in nets and decreased catching efficiency of traps in the affected area of cooling waters. Slight temperature increase of the surface sea water will not have a significant effect on fish migration.

7.3. Impact of Radioactive and Other Emissions

Design of the NPP should be done so that the environmental radioactive emissions to comply with the effective dose values stated in Appendix 4 (A.4.5). The discharges to surface water bodies should be limited as per the values stated in list-1 to 5 of the reference [37] as follows.

- To inland surface water – Alpha emitters: 10^{-8} micro curie/ml, max, Beta emitters: 10^{-7} micro curie/ml, max.

- On land for irrigation purpose - Alpha emitters: 10^{-9} micro curie/ml, max, Beta emitters: 10^{-8} micro curie/ml, max.
- Into marine coastal areas - Alpha emitters: 10^{-8} micro curie/ml, max, Beta emitters: 10^{-7} micro curie/ml, max.

Traffic during construction will increase emissions significantly in all of the alternatives. However, traffic will only be especially frequent during the fourth or fifth year of construction. In other construction years, traffic volumes and emissions will be considerably lower.

In all the options, traffic to the plant runs mostly along highways or motorways. The traffic during the nuclear power plant's operating stage will not cause a significant change in the volumes and, as a result, in traffic emissions and air quality. The nuclear power plant's traffic emissions can be assessed to have an impact on air quality mostly along smaller, less operated roads leading to the nuclear power plant. The nuclear power plant's traffic emissions will not reduce the air quality so significantly that it would have adverse impacts on people or the environment.

7.4. Impact on Flora, Fauna and Protected Sites

Most of the proposed site locations are not within the protected zones (see figure 7.1). Two of the proposed locations are very near or within the Wilpattu National Park and Yala National Park. All other locations are well away from the protected areas.

Noise and other operations during the construction stage may disturb fauna close to the power plant site. Construction work is to be scheduled so that they will cause as little damage as possible to nesting bird stocks. Protection sites or areas for protected species should be avoided when locating buildings and other infrastructure.

In case of forest areas the considerable amount of land areas will be needed to clear. Approximate land areas are given in Section 7.1 of this Chapter. Project benefit with regard to reduction of green house gas emission should be considered versus amount of flora lost and alternative fuel options.

Figure 7.1 – National Parks and Sanctuaries

7.5. Impact on the Soil, Bedrock and Groundwater

The most significant impact on soil, bedrock and groundwater will be caused during the nuclear power plant's construction stage. Construction work should be planned so that there will be as few adverse impacts as possible. During construction, all earth-moving, excavation and dredging masses are to be utilized on the site in different landfills and landscaping work.

The foundation waters and rain waters drained from the construction site may contain more solids and any oil and nitrogen compounds than waters normally drained. The quality and volume of water drained to the sea from the construction site should be monitored. The project will not have any adverse impacts on usable groundwater.

7.6. Impact on the Landscape and Cultural Environment

The nuclear power plant will alter the landscape considerably. The nuclear power plant would impact the cultural landscapes of provincial value and the surroundings, scenery and position in the overall setting. The landscape status of nationally important fishing villages will change.

Since all the proposed locations are well outside the historically important places, the impact to valuable historical places will be minimal.

7.7. Noise Impacts

The noisiest stage during the construction of the nuclear power plant will be the first years of construction when functions that cause significant noise include the rock crushing plant and concrete mixing plant. During the operating phase, the most significant noise impact will occur in the immediate vicinity of the turbine hall and the transformer.

However the noise level during construction and operational stages should be maintained as per the reference [38].

7.8. Impact on People and Society

The nuclear power plant project will have significant impacts on the regional economy, employment, the property market in the surroundings of the location site, the population, industrial structure and services. The employment impact of the construction stage on the economic area will be 500–800 man-years. The arrival of new residents will boost business and escalate building activities. The population and residence bases will grow and, as a result, the demand for private and public services will increase.

A number of people will move close to the nuclear power plant during the construction stage and the demand for services will increase. The accommodation of a large group of employees in a new municipality may also include negative impacts.

Increased traffic and noise caused by construction work may have a local impact on comfort.

Normal operation of the nuclear power plant will have no radiation-related, detectable impact on the health, living conditions or recreation of people living in the vicinity. Access to the power plant area will be prohibited and the area cannot be used for recreational purposes.

The opinions of those living and operating in the surrounding areas of the location sites on the nuclear power plant site will be identified through group interviews and resident surveys. Opposition is often based on risks and fears associated with nuclear power plants and on the belief that nuclear power is ethically questionable. The supporters emphasize its positive economic impacts and environmental friendliness.

7.9. Impact on Waste Management and Final Disposal

Regular waste created at the nuclear power plant will be sorted, sent for treatment, utilization and final disposal in a manner required by waste legislation and environmental license decisions. Waste handling at the plant will not cause any significant environmental impacts. Sufficient facilities for the handling and disposal of low- and medium-level power plant waste will be built at the nuclear power plant. The facilities will contain systems for the safe handling and transportation of waste and the monitoring of the amount and type of radioactive substances. The disposal facilities for low- and medium-level waste can be built in underground facilities and the disposal facilities for very low-level waste can also be built in facilities located in the ground. Once the use of the final disposal facilities is terminated, the connections will be sealed and will not require any supervision afterwards. Any radioactive substances contained in the waste will become safe for the environment over time. Careful planning and implementation will help to eliminate significant environmental impacts caused by the treatment and final disposal of operating waste.

7.10. Impact of Decommissioning the Power Plant

The new nuclear power plant's estimated operating life is at least 60 years. The most significant environmental impacts of decommissioning will arise from the handling and transport of radioactive decommissioning waste generated during dismantling of the controlled area of the plant. The most radioactive portion of such waste will be treated and disposed of similar to operating waste. As many of the dismantled contaminated plant parts and equipment as possible will be cleaned so that they can be released from the radiation authority's control and either recycled or disposed of at a general landfill site. The plant's systems will be sealed so that radioactive substances cannot spread into the environment.

Chapter 8

Local Regulations & International Obligation

A wide range of legislation is expected to be in place in a country that has decided to implement nuclear power, the key elements of such legislation being nuclear safety, security, safeguards and liability for nuclear damage.

8.1. Existing Local Regulations and Laws on Nuclear Technologies

The basic legislation, Atomic Energy Authority Act No. 19 of 1969, needed to establish the regulatory authority, has existed since 1969. The legislation established the Regulatory Authority, the Atomic Energy Authority (AEA) in 1970 and provided adequate empowerment to the AEA to license inspect and enforce regulated activities. The AEA functions under the Ministry of Science & Technology. The functions of the AEA include providing scientific services, conducting manpower development programs demonstrating the applications of this technology to potential users, undertaking research and development in areas of national relevance and ensuring that all uses of radiation and radioisotopes are carried out according to internationally accepted safety standards.

The Authority has promulgated new regulations titled "Ionizing Radiation Protection Regulation" in July 2000. The new regulations are based on IAEA Basic Safety Standard – 115.

The other areas of local laws relating to the establishment of NPP are as follows.

- Land Usage
- Costal area management
- Agricultural lands
- Water usage
- Fisheries
- Environment

8.2. Local Legal Framework Required

Under the above Act and the AEA the required regulations should be made for obtaining first nuclear power plant. These regulations should be based on the following principle [35].

(a) The safety principle

(b) The security principle

(c) The responsibility principle

(d) The permission principle

(e) The continuous control principle

(f) The compensation principle

(g) The sustainable development principle

(h) The compliance principle

(i) The independence principle

(j) The transparency principle

(k) The international co-operation principle.

A separate regulatory body should be formed to carry out regulatory functions relating to establishment of NPP. The regulatory functions are,

a) Establishing safety requirements and regulations
b) Preliminary assessment
c) Authorization (licensing, registration, etc.)
d) Inspection and assessment
e) Enforcement
f) Public information
g) Co-ordination with other bodies

More comprehensive description on local legal framework and regulatory body is described in "Safety Standard Series No. GS-R-1, Legal and Governmental Infrastructure for Nuclear Radiation, Radioactive Waste and Transport Safety, IAEA, 2000".

8.3. International Obligation

Verification of compliance of safety principles and verification of non-nuclear weaponry activities are intended by compliance to international obligations. Sri Lanka is a member country of IAEA (Nuclear Non-Proliferation Treaty was signed by Sri Lanka on 1st July 1968) and the Safeguard Agreement is in force from 6th August 1984 as per the INFCIRC-320 of IAEA.

In general following agreements, protocols and conventions are to be adopted by the country to fulfill the international obligation [36].

- Comprehensive Safeguards Agreement pursuant to INFCIRC/153 (Corr.)
- Additional Protocol pursuant to INFCIRC/540 (Corr.)
- Convention on Early Notification of a Nuclear Accident
- Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency
- Convention on Nuclear Safety
- Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, reproduced in document INFCIRC/546
- Convention on Physical Protection of Nuclear Material, and Amendment
- Vienna Convention on Civil Liability for Nuclear Damage
- Joint Protocol Relating to the Application of the Vienna Convention and the Paris Convention, reproduced in document INFCIRC/402
- Protocol to Amend the 1963 Vienna Convention on Civil Liability for Nuclear Damage and Convention on Supplementary Compensation for Nuclear Damage
- Revised Supplementary Agreement Concerning the Provision of Technical Assistance by the IAEA

8.3.1. Safeguards

Under the Safeguards the IAEA can verify that a country is living up to its international commitments not to use nuclear programmes for nuclear-weapons purposes. Verification measures include on-site inspections, visits, and ongoing monitoring and evaluation [36].

In comprehensive safeguard agreement the objective of safeguard is defined as the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or other nuclear devices or for purposes unknown and deterrence of such diversion by means of early detection.

Safeguards agreements are negotiated on the governmental level, while the utility/owner in charge of the NPP project becomes involved in the implementation of the agreements. Thus, the utility's main tasks consist of performing detailed nuclear materials accountancy, reporting and providing counterparts at the plant to the safeguards inspectors.

8.4. IAEA Assistance

IAEA can assist the country in following ways.

- Implementing the construction and operational stage of a NPP to the extent that the country has demonstrated that it has established the essential elements of a national framework. Advice and guidance on obligations and commitments can be provided during all stages of a nuclear programme.
- Technical support for the owner operator for the assessment of potential technology, the managerial approaches that can be used in the implementation of a project, and issues related to ensuring the safe and economic operation of a NPP.

The Revised Guiding Principles and General Operating Rules to Govern the Provision of Technical Assistance by the Agency is given in INFCIRC/267 March 1979 of IAEA.

Chapter 9

Analysis of Past Nuclear Accidents

Nuclear powered electricity generation has a history of around 55 years up to date (First nuclear power plant: Obninsk NPP of USSR – 1954 – Officially in Operation). Since then there are considerable amount of NPP accidents happened (23 Accidents – See Apendix-6) and from those very few number of accidents can be considered as severe. In this chapter the most sever nuclear power plant accident in the history is analyzed.

The categorization of nuclear power plant accident (International Nuclear Event Scale –INES) is given in Appendix – 6.

Hiroshima Nagasaki disaster is not considered as an accident. It is an incident purposely made during the Second World War by military actions against Japan.

Chernobyl Accident

The worst nuclear power plant accident in the world history is the Chernobyl Power Plant accident which occurred in April 26, 1986 in Ukraine (part of former USSR). This accident is considered as the only Level-7 accident in the INES scale. In this accident power excursion, explosion and complete meltdown of the reactor core took place.

The Chernobyl Power Plant consisted of four RBMK-1000 nuclear reactors, each capable of producing 1 GW of electric power. Two more reactors, no. 5 and 6, also capable of producing 1 GW each, were under construction at the time of the disaster. The accident occurred in reactor number 4.

9.1. Effect to Human [40]

9.1.1 Deaths

- Two people died during the accident itself; one was killed by the explosion and one suffered a heart attack.
- A third person died early the next morning from thermal burns (he was scalded by steam.)

- 237 people were initially diagnosed as suffering from acute radiation exposure and were hospitalized for treatment. From those 21 died in spite of intensive medical attention.
- From 237 people suffered from acute radiation sickness, of whom 31 died within the first three months. Most of these were fire and rescue workers trying to bring the accident under control, who were not fully aware of how dangerous the radiation exposure.
- 11 more deaths - possibly caused by radiation - have occurred among the population of highly exposed people, bringing the total death to 42.
- However 56 direct deaths were reported due to the accident.

Importantly none of the highly exposed people were members of the general public; all received their exposure because of occupational responsibilities related to the nuclear plant or casualty control.

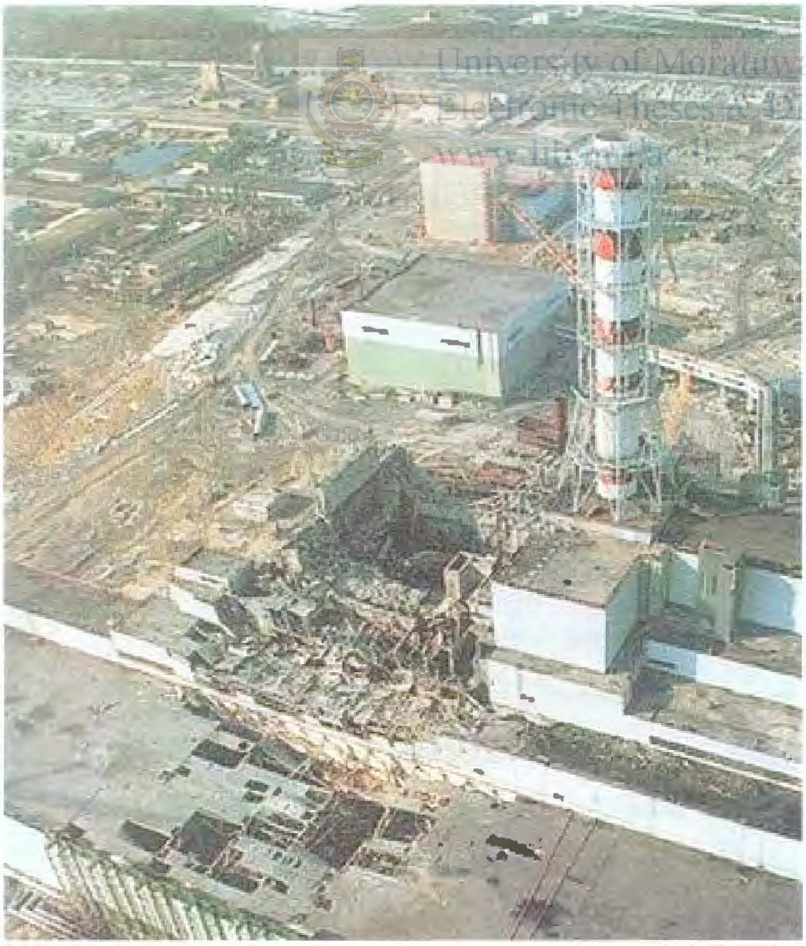

Figure 9.1 – Chernobyl Site after the Disaster

9.1.2. Long Term Radiation Effects

- There have been approximately 500-600 excess cases of thyroid cancer, mostly in children, in the areas most affected by the radioactive fallout.
- As of early 1996, three deaths have been associated with this thyroid cancer.
- There have been no excess leukemia, congenital abnormalities, adverse pregnancy outcomes or any other radiation induced disease in the general population.
- Unconfirmed data: Around 600,000 suffered radiation exposure, which **may** result in **as many as** 4,000 cancer deaths over the lifetime of those exposed, in addition to the approximately 100,000 fatal cancers to be expected due to all other causes in this.

9.1.3. Other Effects

- Increase in stress related illnesses due to fear of radiation and to the severe dislocation of people caused by government ordered evacuations.
- As many as 200,000 women decided to abort otherwise healthy unborn babies, because of the concern that they might have been damaged in the womb by minor radiation exposures. There is no evidence of any birth defects caused by the radiation levels experienced by expectant mothers after the accident.
- Evacuation and resettlement of over 336,000 people.

9.2. Affected Areas

- The evacuation began at 14:00, 27 April. An exclusion zone of 30 km/19 mi within radious of the plant remains in place today. Exclusion Zone around Chernobyl is where officially nobody is allowed to live, but people do. These "resettlers" are elderly people who lived in the region prior to the disaster. Today there are approximately 10,000 people between the ages of 60 and 90 living within the Zone around Chernobyl. Younger families are allowed to visit, but only for brief periods of time.
- The affected area includes Russia, Belarus and Ukraine, European part of Turkey, Greece, Moldova, Romania, Bulgaria, Lithuania, Finland, Denmark, Norway, Sweden, Austria, Hungary, the Czech Republic and the Slovak Republic, Slovenia, Croatia, Poland, Switzerland, Germany, Italy, Ireland, France, Canada and the United Kingdom (UK).

- ❖ In Sweden, on April 27 workers at the Forsmark Nuclear Power Plant (approximately 1100 km from the Chernobyl site) were found to have radioactive particles on their clothes.
- ❖ Radioactive fallout carried by the wind was later found on clothing worn by people throughout Europe, and in rain in the United States.

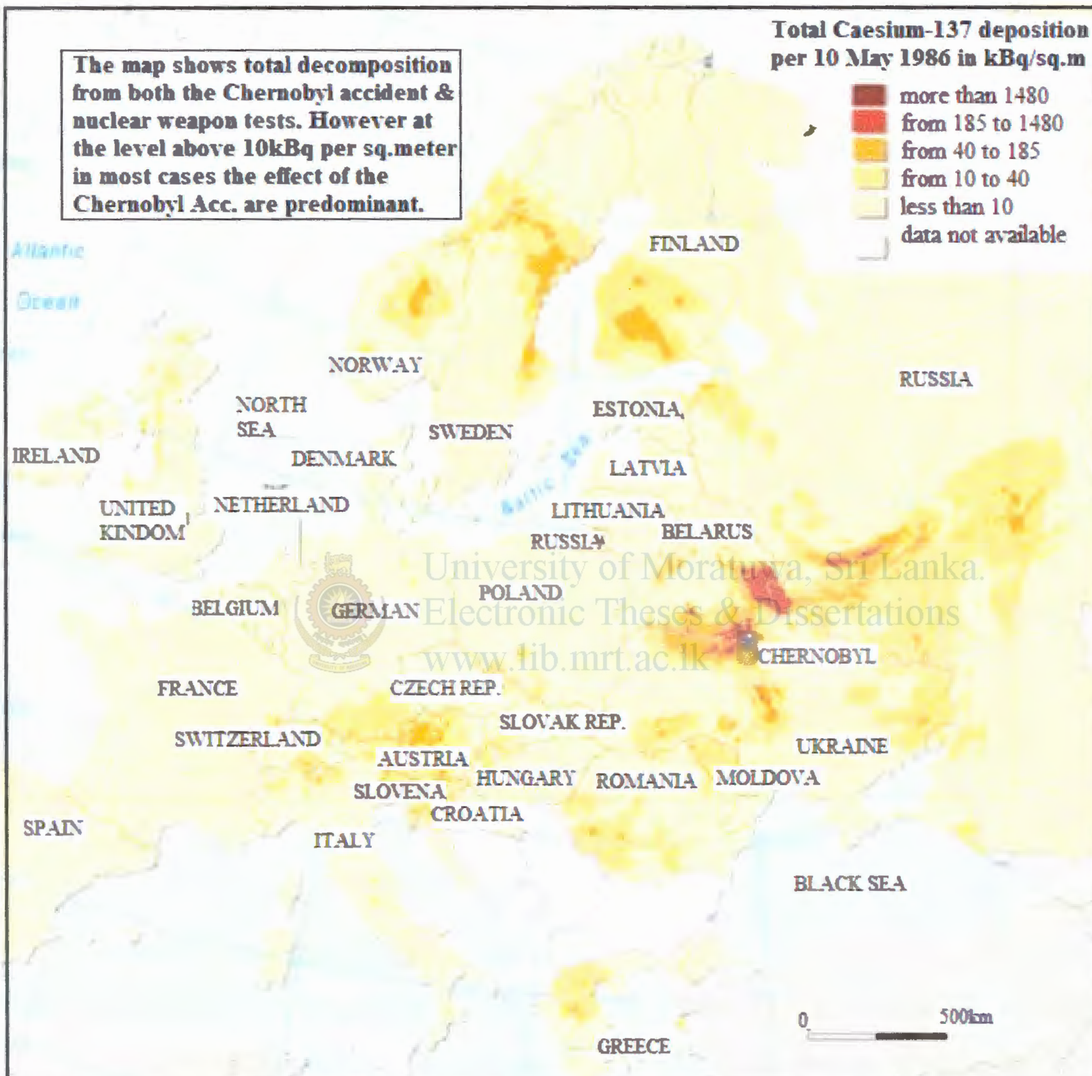

Figure 9.2 – Continental Scale of the Chernobyl Accident [41]

Notes:

- The most hazardous isotopes released in this accident are known to be Cs-137, I-131, and Sr-90.
- Regions of heaviest fallout from the effluents from the fire at Chernobyl are shown in the figure below (Map shows borders in 1986). In these regions radiation exposure exceeded 100 mrads/h (0.1mrem/hr or 0.001mSv/hr) – 20 to 400 times the allowable limit.

- The effect of radioactive dispersion from the Chernobyl nuclear power plant accident seems to have spreaded even to 1200km distance from the Chernobyl site.

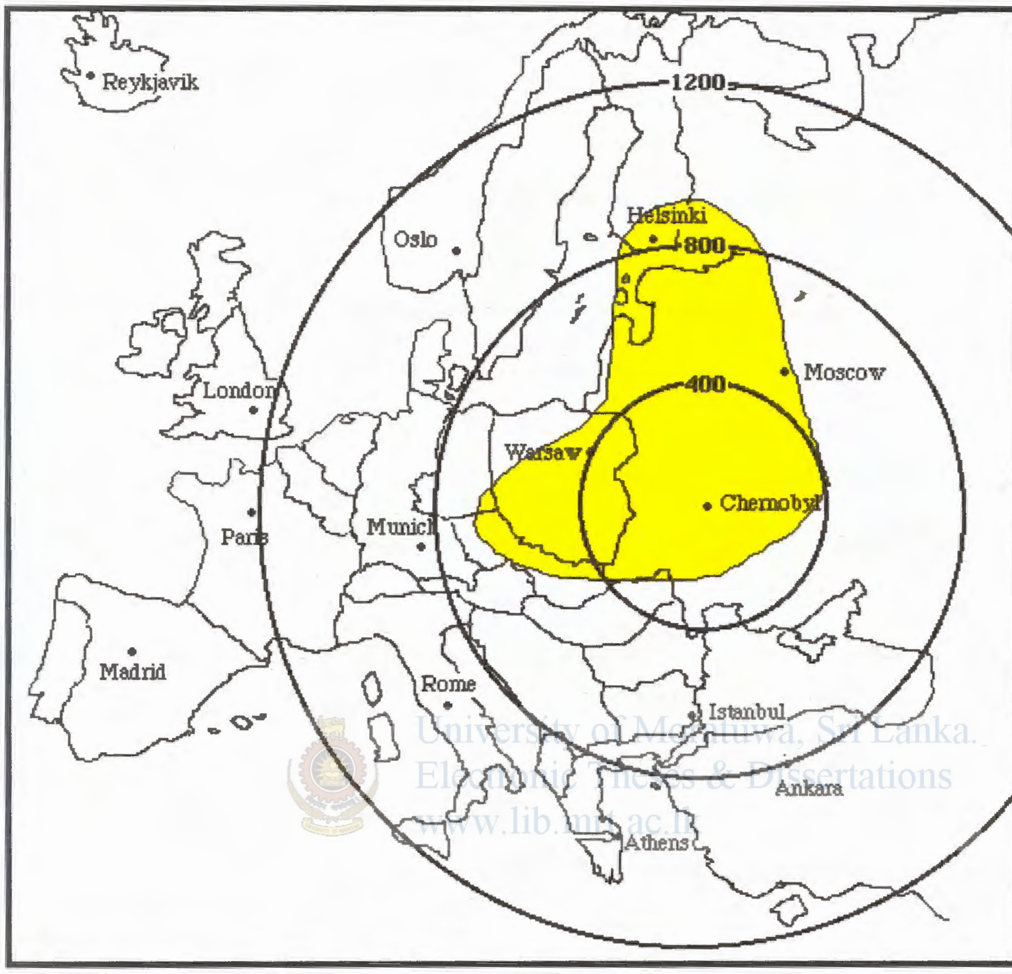

Figure 9.3 – Continental Scale of the Chernobyl Accident

9.3. Reasons for the Chernobyl Accident

There were many investigations to find out the reason behind the accident. One notable incident is that during the daytime of 25 April 1986, reactor 4 was scheduled to be shut down for maintenance as it was near the end of its first fuel cycle. An experiment was proposed to test a safety emergency core cooling feature during the shut down procedure.

The soviet specialists point out serious breach of the safety operational principles by the operating staff as the reason for the accident. Those violated principles are,

- Operation of the reactor at a very low operative reactivity surplus (ORS) – prohibited the operation below 700MW thermal due to thermal hydraulic instability.
- Conducting of the experiment by the power below the level provided for test.
- Blocking of the protection system relaying on water level and steam pressure in steam-separators.
- Blocking of the protection system relaying on shutdown signal from two turbo generators.
- Connection of all the main circulating pumps to the reactor.
- Switching off the emergency core cooling system (ECCS).

According to the findings by the International Nuclear Safety Advisory Group report INSAG-1 and INSAG-7 [42] following is the summary of the the possible reasons.

- Design fault: Extremely high positive void coefficient in the reactor. (When the steam air bubbles are formed in the cooling water, the reactivity increased rapidly due to the presence of the graphite moderator giving increased formation of the steam bubbles.)
- The reactor was not contained by any kind of hard containment vessel unlike most modern NPPs.
- Defects in the design of control and safety rods.
- Violation of safety procedures by the operating staff.
- Departure from the specified test procedure.
- Deficiencies in the regulatory regiom.

Chapter 10

Analysis of NPP Status of the India

Since India is very close to Sri Lanka, it is important for us to be conscious about the nuclear power status of the neighbor. In this chapter the India's nuclear energy programs for electricity generation will be discussed [43].

10.1. Government Bodies and Institutions

India has a very good structure of government institutions for nuclear related activities. Following is a list of main institutions and brief description of their functions.

- **Department of Atomic Energy (DAE)** - The **Department of Atomic Energy (DAE)** is a department directly under the Prime Minister of India. The department is responsible for nuclear technology, including nuclear power and research.
- **Atomic Energy Commission** - The **Atomic Energy Commission** is a governing body functioning under the Department of Atomic Energy.
- **Nuclear Power Corporation of India Limited (NPCIL)** - **NPCIL** is a government-owned corporation in India. One of the public sector undertakings, it is wholly owned by the Union Government and is responsible for the generation of nuclear power for electricity.
- **Nuclear Command Authority (NCA)** - NCA of India is the nodal agency for all command, control and operational decisions regarding India's nuclear weapon stockpile.
- **Atomic Minerals Directorate for Exploration and Research (AMD** - The principal mandate of the organization is to carry out geological exploration and discover mineral deposits required for nuclear power programme of India.

10.2. General Picture of Nuclear Energy (Electricity) Production

- Total Power Generation -680 billion kWh in 2006 of which 76% Thermal (Coal, Gas, Oil), 21% Hydro and 4% Nuclear.
- Total installed capacity 147,000 MW of which 4,120 MW is nuclear power.

India's Future for Nuclear Power

- Current installed capacity – 4,120 MW (Table 10.1)
- Planned increase in year 2010 – up to 6,000 MW. (total nuclear)
- Planned increase in year 2020 – up to 45,000 MW (total nuclear)

Nuclear Power Plants in Operation

Type	Capacity (MW)	No. of Units
PHWR (CANDU)	540	2
PHWR (CANDU)	220	11
PHWR (CANDU)	200	1
PHWR (CANDU)	100	1
BWR	160	2
Total Installed	**4,120 MW**	

Table 10.1 – Nuclear Plants in Operation - India

Nuclear Power Plants under Construction

Type	Capacity (MW)	No. of Units
PHWR (CANDU)	220	3
VVER-1000	1000	2
PFBR	500	1
Total Construction	**3,160 MW**	

Table 10.2 – Nuclear Plants under Construction

Note that in India, out of 17 operating nuclear power plants, 15 plants are having CANDU or CANDU derived technology as per the Table 10.1.

Figure 10.1 – Atomic Power Stations in India

<u>Nuclear Power Plants – Planed Projects</u>

Type	Capacity (MW)	No. of Units
PHWR (CANDU)	640	8
VVER-1200	1200	2
PWR	1500	1
PWR	1000	3
EPR	1600	4
PFBR	470	4
AHWR (Thorium Based)	300	1
Total Planned	**20,600 MW**	

Table 10.3 – Planned Nuclear Power Plants

Figure 10.2 – Koodankulam Atomic Power Station, India

Nuclear Power Plants – Firmly Proposed Projects

Type	Capacity (MW)	No. of Units
VVER	1200	4
EPR	1600	2
PWR	2000	1
PWR	8800	
Total	**18,800 MW**	

Table 10.4 - Firmly Proposed Projects

10.3. India's Nuclear Power Stations nearest to Sri Lanka

10.3.1. Koodankulam Atomic Power Station

The nearest NPP to Sri Lanka in India is the Koodankulam Atomic Power Station and yet power units are being constructed and some are proposed. The details of the power station are as follows.

Type	Capacity(MW)	Nos.
VVER	1000	2
VVER	1200	6
Total	**9200MW**	

Table 10.5 - Koodankulam Atomic Power Station

After completion of all units of the power plant this will be the biggest power plant in the South Asia (The Chernobyl power plant was only 4000MW capacity – 4 nos. of 1GW units)

Figure 10.3 - Koodankulam Atomic Power Station, India

In case of possible major release of radioactive material from this plant, Sri Lanka will be well within the affected area (in comparison with Chernobyl disaster) according to prevailing weather conditions.

Figure 10.4 - Madras Atomic Power Station, India

10.3.2. Madras Atomic Power Station

This is the second nearest power station to Sri Lanka in India. Following are the details of reactor units in the power plant.

Type	Capacity(MW)	Nos.
PHWR (CANDU) -Active	220	2
PHWR (CANDU) –Under Construction	500	1
Total	**940MW**	

Table 10.6 - Madras Atomic Power Station

For this power plant too, in case of possible major release of radioactive material, Sri Lanka will be within the affected area (in comparison with Chernobyl disaster) according to prevailing weather conditions.

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Appendix - 1

Nuclear Power Plant Classification

In this document very basic classification is given covering all available type of NPPs.

A1.1. Classification by Reaction Type

A1.1.1. Nuclear Fission

Most reactors, and all commercial ones, are based on nuclear fission. They generally use uranium and its product plutonium as nuclear fuel, though a thorium fuel cycle is also possible. This article takes "nuclear reactor" to mean fission reactor unless otherwise stated.

- **Thermal reactors**; use slowed or thermal neutrons. Almost all current reactors are of this type. These contain neutron moderator materials that slow neutrons until their neutron temperature is *thermalized*, that is, until their kinetic energy approaches the average kinetic energy of the surrounding particles.
- **Fast neutron reactors;** directly use fast neutrons to fission their fuel. They do not have a neutron moderator, and use less-moderating coolants. Maintaining a chain reaction requires the fuel to be more highly enriched in fissile material (about 20% or more) due to the relatively lower probability of fission versus capture by U-238. Fast reactors have the potential to produce less transuranic waste because all actinides are fissionable with fast neutrons, but they are more difficult to build and more expensive to operate.

A1.1.2. Nuclear Fusion

Fusion power is an experimental technology, generally with hydrogen as fuel. While not currently suitable for power production

A1.1.3. Radioactive Decay

Examples include radioisotope thermoelectric generators and atomic batteries, which generate heat and power by exploiting passive radioactive decay.

A1.2. Classification by Moderator Material

A1.2.1. Graphite Moderated Reactors

Graphit is used as the moderator material in the reactor core.

A1.2.2. Water Moderated Reactors

- Heavy Water Reactor; D_2O is used as the moderator material.
- Light Water Moderated Reactors (LWRs); Light water reactors use ordinary water to moderate and cool the reactors.

A1.2.3. Light Element Moderated Reactors

- Molten Salt Reactors (MSRs); are moderated by a light elements such as lithium or beryllium, which are constituents of the coolant/fuel matrix salts LiF and BeF_2.
- Liquid Metal Cooled Reactors; such as one whose coolant is a mixture of Lead and Bismuth, may use BeO as a moderator.
- Organically Moderated Reactors (OMR); use biphenyl and terphenyl as moderator and coolant.

A1.3. Classification by Coolant

A1.3.1. Water Cooled Reactor

Water cooled reactors use the water as the heat carring media from the reactor vessal to the steam genrator.

- Pressurized water reactor (PWR); A primary characteristic of PWRs is a pressurizer, a specialized pressure vessel. Most commercial PWRs and naval reactors use pressurizers. During normal operation, the pressurizer is connected to the primary reactor pressure vessel (RPV) and the pressurizer "bubble" provides an expansion space for changes in water volume in the reactor.
- Boiling water reactor (BWR); BWRs are characterized by boiling water around the fuel rods in the lower portion of primary reactor pressure vessel. During normal operation, pressure control is accomplished by controlling the amount of steam flowing from the reactor pressure vessel to the turbine.

A1.3.2. Liquid Metal Cooled Reactor.

Since water is a moderator, it cannot be used as a coolant in a fast reactor. Liquid metal coolants have included sodium, NaK, lead, lead-bismuth eutectic, and in early reactors, mercury. Populer reactor types are,

- ❖ Sodium-cooled fast reactor
- ❖ Lead-cooled fast reactor

A1.3.3. Gas Cooled Reactors

Gas Cooled Reactors are cooled by a circulating inert gas, usually helium. Nitrogen and carbon dioxide have also been used. Utilization of the heat varies, depending on the reactor. Some reactors run hot enough that the gas can directly power a gas turbine. Older designs usually run the gas through a heat exchanger to make steam for a steam turbine.

A1.3.4. Molten Salt Reactors (MSRs)

MSRs are cooled by circulating a molten salt, typically a eutectic mixture of fluoride salts, such as LiF and BeF_2. In a typical MSR, the coolant is also used a matrix in which the fissile material is dissolved.

A1.4. Classification by Generation

- Generation I reactor
- Generation II reactor (most current nuclear power plants)
- Generation III reactor (evolutionary improvements of existing designs)
- Generation IV reactor (technologies still under development)

A1.5. Classification by Phase of Fuel.

- Solid fueled
- Fluid fueled
- Gas fueled

A1.6. Classification by Use

- ❖ Electricity production: NPPs
- ❖ Propulsion: marine propulsion, proposed forms of rocket propulsion
- ❖ Desalination

- Heat for domestic and industrial heating
- Hydrogen production
- Production reactors for transmutation of elements: fast breeder reactors, weapons-grade plutonium creation
- Research reactor.

A1.7. Current Technologies

Pressurized Water Reactors (PWR)

- Pressure vessel to contain the nuclear fuel, control rods, moderator, and coolant.
- Cooled and moderated by high pressure liquid water.
- Primary loop (pressuried water) and secondary loop (steam from stem generator)
- Newest design of this type are Advanced Pressurized Water Reactor, European Pressurized Reactor and United States Naval reactor.

Boiling Water Reactors (BWR)

- A BWR is like a PWR without the steam generator.
- Cooled and moderated by water like a PWR, but at a lower pressure.
- Only one loop, no separate steam generator.
- Thermal efficiency of these reactors can be higher, and they can be simpler.
- The newest designs are Advanced Boiling Water Reactor and the Economic Simplified Boiling Water Reactor.

Pressurized Heavy Water Reactor (PHWR)

- Canadian design – CANDU, use of heavy water
- Instead of using a single large pressure vessel as in a PWR, the fuel is contained in hundreds of pressure tubes.
- Fuelled with natural uranium.
- On power refuelling.

Reaktor Bolshoy Moshchnosti Kanalniy (High Power Channel Reactor) (RBMK)

- Soviet Union design, built to produce plutonium as well as power.
- RBMKs are water cooled with a graphite moderator.
- Very unstable and too large to have containment buildings, making them dangerous in the case of an accident.
- The Chernobyl plant had four RBMK reactors.

Gas Cooled Reactor (GCR) and Advanced Gas Cooled Reactor (AGR)

- Generally graphite moderated and CO_2 cooled.
- High thermal efficiency compared with PWRs.
- Decommissioning costs can be high due to large volume of reactor core.

Liquid Metal Fast Breeder Reactor (LMFBR)

- Cooled by liquid metal, totally unmoderated.
- Produces more fuel than it consumes.
- Lead Cooled Type: lead as the liquid metal provides excellent radiation shielding. Lead-bismuth eutectic mixture is ussed: lead may be problematic from toxicology and disposal points of view.
- Sodium Cooled Type: Sodium is relatively easy to obtain and work with. Sodium explodes violently when exposed to water.

A1.8. Future and Developing Technologies

A1.8.1. Advanced Reactors

Advanced reactor designs are in various stages of development.

- Advanced Boiling Water Reactor (ABWR)
- ESBWR - Economic Simplified Boiling Water Reactor
- AP1000 – Passively safe PWR, Compat and more safe, Generation III+ reactor.
- High Temperature Gas Cooled Reactor (HTGCR), or Pebble Bed Reactor
- SSTAR - Small, Sealed, Transportable, Autonomous Reactor, researched and developed in the US, intended as a fast breeder reactor that is passively safe.

- Clean And Environmentally Safe Advanced Reactor (CAESAR) - nuclear reactor concept that uses steam as a moderator. This design is still in development.
- Advanced Heavy Water Reactor - next generation design of the PHWR type under development.
- FBTR - fast breeder thorium reactor

A1.8.2. Generation IV Reactors

Set of theoretical nuclear reactor designs currently are being researched. These designs are generally not expected to be available for commercial construction before 2030. The primary goals being to improve nuclear safety, improve proliferation resistance, minimize waste and natural resource utilization, and to decrease the cost to build and run such plants.

- Gas cooled fast reactor
- Lead cooled fast reactor
- Molten salt reactor
- Sodium-cooled fast reactor
- Supercritical water reactor
- Very high temperature reactor

A1.8.3. Generation V+ Reactors

Designs which are theoretically possible, but which are not being actively considered or researched at present.

- Liquid Core reactor - closed loop liquid core nuclear reactor, where the fissile material is molten uranium cooled by a working gas pumped in through holes in the base of the containment vessel.
- Gas core reactor - closed loop version of the nuclear lightbulb rocket, where the fissile material is gaseous uranium-hexafluoride contained in a fused silica vessel. A working gas (such as hydrogen) would flow around this vessel and absorb the UV light produced by the reaction.
- Gas core EM reactor - As in the Gas Core reactor, but with photovoltaic arrays converting the UV light directly to electricity.

Appendix - 2

Capital Cost of Unit Energy

Year	Opening Balance (M US$)	Interest at 5% (M US$)	Loan Payment (M US$)	Closing Balance (M US$)	Total Capital Expen. (M US$)	Present Value (M US$)	Energy Produced (GWh)	Present value (GWh)
0	1827.00	91.35	Grace Period	1827.00	91.35	91.35		
1	1827.00	91.35		1827.00	91.35	83.05		
2	1827.00	91.35		1827.00	91.35	75.50		
3	1827.00	91.35		1827.00	91.35	68.63		
4	1827.00	91.35		1827.00	91.35	62.39		
5	1827.00	89.07	91.35	1735.65	180.42	112.02	4508.86	2799.647
6	1735.65	84.50	91.35	1644.30	175.85	99.26	4508.86	2545.134
7	1644.30	79.93	91.35	1552.95	171.28	87.89	4508.86	2313.758
8	1552.95	75.36	91.35	1461.60	166.71	77.77	4508.86	2103.416
9	1461.60	70.80	91.35	1370.25	162.15	68.77	4508.86	1912.197
10	1370.25	66.23	91.35	1278.90	157.58	60.75	4508.86	1738.361
11	1278.90	61.66	91.35	1187.55	153.01	53.63	4508.86	1580.328
12	1187.55	57.09	91.35	1096.20	148.44	47.30	4508.86	1436.662
13	1096.20	52.53	91.35	1004.85	143.88	41.68	4508.86	1306.056
14	1004.85	47.96	91.35	913.50	139.31	36.68	4508.86	1187.324
15	913.50	43.39	91.35	822.15	134.74	32.26	4508.86	1079.385
16	822.15	38.82	91.35	730.80	130.17	28.33	4508.86	981.2593
17	730.80	34.26	91.35	639.45	125.61	24.85	4508.86	892.0539
18	639.45	29.69	91.35	548.10	121.04	21.77	4508.86	810.9581
19	548.10	25.12	91.35	456.75	116.47	19.04	4508.86	737.2346
20	456.75	20.55	91.35	365.40	111.90	16.63	4508.86	670.2133
21	365.40	15.99	91.35	274.05	107.34	14.50	4508.86	609.2848
22	274.05	11.42	91.35	182.70	102.77	12.62	4508.86	553.8953
23	182.70	6.85	91.35	91.35	98.20	10.97	4508.86	503.5412
24	91.35	2.28	91.35	0.00	93.63	9.51	4508.86	457.7647
Net Present Expenditure/ Total present Energy						1,257.16		26218.47

Table A2.1 – Discounted Project Cost & Energy

Project Cost	1827	M USD
Debt Equity Ratio	85:15	
Loan	1552.95	M USD
Equity	274.05	M USD
Loan period	25	years
Interest rate	5%	

Table A2.2 – Loan Schedule

Fuel cost is calculated as follows [13].

Uranium Price [12], (1.05kg of U_3O_8 x 153.2 US$)	= 160.86 US$
Conversion (1.05 kg of U_3O_8 x 12 US$)	= 12.6 US$
Fuel fabrication (per kg)	= 240 US$
Transport (assume 2% of Uranium price)	= 3.2 US$
Total for one kg of fuel	= 416.66 US$

Thermal energy of 1kg of UO_2 [14]	= 180 MWh
Electrical Energy (at 33% efficiency)	= 59,400 kWh
Therefore fuel cost	= 0.7 UScts /kWh

Appendix - 3

Nuclear Fuel

There are four basic nuclear "fuels" found in nature: deuterium, lithium, thorium, and uranium. Deuterium is an isotope of hydrogen that is found wherever hydrogen is found (such as water). Lithium is a light metal found in lake evaporates. In a traditional fusion reactor, lithium is converted to tritium (another hydrogen isotope) and then fused with deuterium, releasing energy and additional neutrons. But fusion is fundamentally difficult because unsolved technological problems at present. So the nuclear fuels which uses fission reaction are used in the reactors at present.

Fissile Material : a fissile material is one that is capable of sustaining a chain reaction of nuclear fission. Fissile nuclides in nuclear fuels include:

- Uranium-235 which occurs in natural uranium and enriched uranium
- Plutonium-239 bred from uranium-238 by neutron capture
- Plutonium-241 bred from plutonium-240 by neutron capture. The Pu-240 comes from Pu-239 by the same process.
- Uranium-233 bred from thorium-232 by neutron capture

In general, most actinide isotopes with an odd neutron number are fissile.

Fissionable Materal: Fissionable material are any materials with atoms that can undergo nuclear fission.

Notably, uranium-238 is fissionable but not fissile. Neutrons produced by fission of e.g. U-235 have an energy of around 1 MeV (100 TJ/kg, i.e. a speed of 14,000 km/s) and usually do not cause fission of U-238, but neutrons produced by the deuterium-tritium fusion reaction have an energy of 14.1 MeV (1400 TJ/kg, i.e. a speed of 52,000 km/s), and they can easily cause fission U-238 and other non-fissile actinides. The neutrons produced by this fission are again not fast enough to produce new fissions, so U-238 does not sustain a chain reaction.

Fertile Material: is a term used to describe nuclides which generally themselves do not undergo induced fission (fissionable by thermal neutrons) but from which fissile material is generated by neutron absorption and subsequent nuclei conversions. Fertile materials that occur naturally which can be converted into a fissile material by irradiation in a reactor include:

- Thorium-232 which converts into Uranium-233
- Uranium-234 which converts into Uranium-235
- Uranium-238 which converts into Plutonium-239

Artificial isotopes formed in the reactor which can be converted into fissile material by one neutron capture include:

- Plutonium-238 which converts into Plutonium-239
- Plutonium-240 which converts into Plutonium-241

Some other actinides need more than one neutron capture before arriving at an isotope which is both fissile and long-lived enough to probably be able to capture another neutron and fission instead of decaying:

- Plutonium-242 to Americium-243 to Curium-244 to Curium-245
- Uranium-236 to Neptunium-237 to Plutonium-238 to Plutonium-239
- Americium-241 to Curium-242 to Curium-243 (or, more likely, Curium-242 decays to Plutonium-238, which also requires one additional neutron to reach a fissile nuclide)

A3.1. Uranium Fuel

In nature, Uranium atoms exist as Uranium-238 (99.284%), Uranium-235 (0.711%), and a very small amount of Uranium-234 (0.0058%).

So in a metric ton of natural Uranium fuel, the fissile material (U-235 O_2) content is only 7.11kg which is used in thermal reactors for nuclear chain reaction.

The most common forms of Uranium oxide are U_3O_8 and UO_2. Both oxide forms are solids that have low solubility in water and are relatively stable over a wide range of environmental conditions. Tri-Uranium octa-oxide (U_3O_8) is the most stable form of Uranium and is the form most commonly found in nature. Uranium dioxide (UO_2) is the form in which Uranium is most commonly used as a nuclear reactor fuel. At ambient temperatures, UO_2 will gradually convert to U_3O_8. Because of their stability, Uranium oxides are generally considered the preferred chemical form for storage or disposal.

Uranium metal is heavy, silvery white, malleable, ductile, and softer than steel. It is one of the densest materials known (19 g/cm^3), being 1.6 times more dense than lead.

Uranium metal is not as stable as U_3O_8 or UO_2 because it is subject to surface oxidation. It tarnishes in air, with the oxide film preventing further oxidation of massive metal at room temperature. Water attacks uranium metal slowly at room temperature and rapidly at higher temperatures. Uranium metal powder or chips will ignite spontaneously in air at ambient temperature.

A3.2. Thorium Fuel

Thorium is estimated to be about three to four times more abundant than Uranium in the earth's crust. Naturally occurring Thorium is composed mainly of one isotope: Th-232. Th-232 is fertile material wich aborb neutrons to produce fissle U-233.

$$^{232}Th \xrightarrow{n} {}^{233}Th \xrightarrow{\beta, 23\,\text{min}} {}^{233}Pa \xrightarrow{\beta, 27\,days} {}^{233}U$$

$$^{233}U \xrightarrow{n} fission\ products + 197.9\,MeV \qquad 1MeV = 1.6 \times 10^{-13}\,J$$

Thorium is found in small amounts in most rocks and soils. Soil commonly contains an average of around 12 parts per million (ppm) of thorium. Thorium occurs in several minerals including Thorite ($ThSiO_4$), Thorianite ($ThO_2 + UO_2$) and Monazite. The latter is most common and may contain up to about 12% Thorium oxide. Thorium-containing Monazite(Ce) occurs in Africa, Antarctica, Australia, Europe, India, North America, and South America.

Appendix - 4

Radiation and Radiation Measurement.

Radiation

In physics, **radiation** describes any process in which energy emitted by one body travels through a medium or through space, ultimately to be absorbed by another body. Non-physicists often associate the word with ionizing radiation (e.g., as occurring in nuclear weapons, nuclear reactors, and radioactive substances), but it can also refer to electromagnetic radiation (i.e., radio waves, infrared light, visible light, ultraviolet light, and X-rays) which can also be ionizing radiation, to acoustic radiation, or to other more obscure processes. What makes it radiation is that the energy *radiates* (i.e., it travels outward in straight lines in all directions) from the source. This geometry naturally leads to a system of measurements and physical units that are equally applicable to all types of radiation. Some radiations can be hazardous.

A4.1. Ionizing Radiation

Some types of radiation have enough energy to ionize particles. Generally, this involves an electron being 'knocked out' of an atom's electron shells, which will give it a (positive) charge. This is often disruptive in biological systems, and can cause mutations and cancer.

A4.1.1. Alpha Radiation

Alpha (α) decay is a method of decay in large nuclei. An alpha particle (helium nucleus, He^{2+}), consisting of 2 neutrons and 2 protons, is emitted. Because of the particle's relatively high charge, it is heavily ionizing and will cause severe damage if ingested. However, due to the high mass of the particle, it has little energy and a low range; typically alpha particles can be stopped with a sheet of paper (or skin).

A4.1.2. Beta(+/-) Radiation

Beta-minus (β-) radiation consists of an energetic electron. It is more ionizing than alpha radiation, but less so than gamma. The electrons can often be stopped with a few centimeters of metal. It occurs when a neutron decays into a proton in a nucleus, releasing the beta particle and an antineutrino.

Beta-plus (β+) radiation is the emission of positrons. Because these are antimatter particles, they annihilate any matter nearby, releasing gamma photons. Therefore, they pose no direct risk, although the gamma photons released do.

A4.1.3. Gamma Radiation

Gamma (γ) radiation consists of photons with a frequency of greater than 10^{19} Hz. Gamma radiation occurs to rid the decaying nucleus of excess energy after it has emitted either alpha or beta radiation.

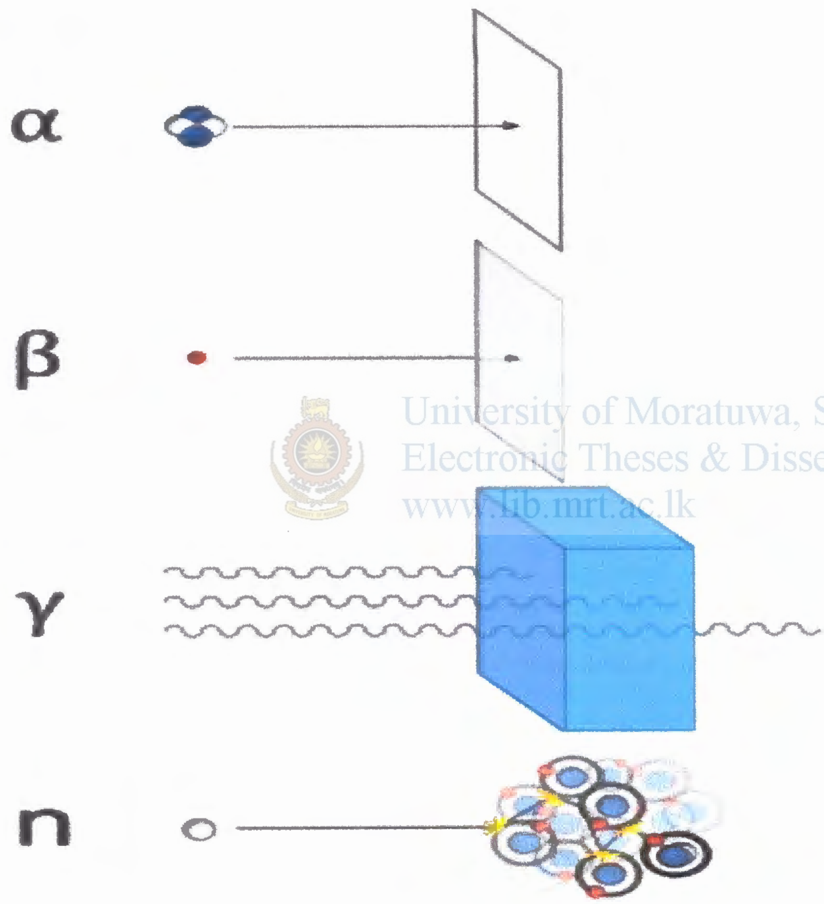

Figure A4.1 : Radiation

Neutron (n) radiation consists of free neutrons which are blocked using light elements, like hydrogen, which slow and/or capture them.

A4.2. Non-ionizing Radiation

Non-ionizing (or non-ionising) radiation, by contrast, refers to any type of radiation that does not carry enough energy per quantum to ionize atoms or molecules. Most especially, it refers to the lower energy forms of electromagnetic radiation (i.e., radio waves, microwaves, terahertz radiation, infrared light, and visible light). The effects of these forms of radiation on living tissue have only recently been studied. Instead of producing charged ions when passing through matter, the electromagnetic radiation has sufficient energy only for excitation, the movement of an electron to a higher energy state. Nevertheless, different biological effects are observed for different types of non-ionizing radiation

A4.3. X-Ray

X-radiation (composed of X-rays) is a form of electromagnetic radiation. X-rays have a wavelength in the range of 10 to 0.01 nanometers, corresponding to frequencies in the range 30 petahertz to 30 exahertz (3×10^{16} Hz to 3×10^{19} Hz) and energies in the range 120 eV to 120 keV. They are shorter in wavelength than UV rays.

X-rays can penetrate solid objects, and their largest use is to take images of the inside of objects in diagnostic radiography and crystallography. As a result, the term *X-ray* is used to refer to a radiographic image produced using this method, in addition to the method itself. X-rays are a form of ionizing radiation, and exposure to them can be a health hazard.

X-rays from about 0.12 to 12 keV are classified as soft X-rays, and from about 12 to 120 keV as hard X-rays, due to their penetrating abilities.
The X-rays and gamma rays of radiation are now usually distinguished by their origin: X-rays are emitted by electrons outside the nucleus, while gamma rays are emitted by the nucleus.

A4.4. Units of Measurement of Ionizing Radiation

The ionizing effects of radiation are measured by units of exposure:

- The coulomb per kilogram (C/kg) is the SI unit of ionizing radiation exposure, and measures the amount of radiation required to create 1 coulomb of charge of each polarity in 1 kilogram of matter.

However, the amount of damage done to matter (especially living tissue) by ionizing radiation is more closely related to the amount of energy deposited rather than the charge. This is called the **absorbed dose**.

- The gray (Gy), with units J/kg, is the SI unit of absorbed dose, which represents the amount of radiation required to deposit 1 joule of energy in 1 kilogram of any kind of matter.
- The rad (Roentgen absorbed dose), is the corresponding traditional unit which is 0.01 J deposited per kg. 100 rad = 1 Gy.

Equal doses of different types or energies of radiation cause different amounts of damage to living tissue. For example, 1 Gy of alpha radiation causes about 20 times as much damage as 1 Gy of x-rays. Therefore the equivalent dose was defined to give an approximate measure of the biological effect of radiation. It is calculated by multiplying the absorbed dose by a weighting factor which is different for each type of radiation.

- The sievert (Sv) is the SI unit of equivalent dose. Although it has the same units as grays, J/kg, it measures something different. It is the dose of a given type of radiation in Gy that has the same biological effect on a human as 1 Gy of x-rays or gamma radiation.
- The rem (Roentgen equivalent man) is the traditional unit of equivalent dose. 1 sievert = 100 rem. Because the rem is a relatively large unit, typical equivalent dose is measured in millirem (mrem), 10^{-3} rem, or in microsievert (μSv), 10^{-6} Sv. 1 mrem = 10 μSv.

For comparison, the 'background' dose of natural radiation received by a US citizen is around 3 mSv (300 mrem) per year. The lethal full-body dose of radiation for a human is around 4 - 5 Sv (400 - 500 rem) instantaneously. For comparison, the average 'background' dose of natural radiation received by a person is around 2.4 millisieverts (240 mrem) per year.

A4.5. Radiation Exposure Limits

The radiation exposure limits are given in IAEA safety standard [23] as given below.

A4.5.1. Dose Limit: Occupational Exposure

The occupational exposure of any worker shall be so controlled that the following limits be not exceeded:

(a) an effective dose of 20 mSv per year averaged over five consecutive years

(b) an effective dose of 50 mSv in any single year;

(c) an equivalent dose to the lens of the eye of 150 mSv in a year; and

(d) an equivalent dose to the extremities (hands and feet) or the skin of 500 mSv in a year.

For apprentices of 16 to 18 years of age who are training for employment involving exposure to radiation and for students of age 16 to 18 who are required to use sources in the course of their studies, the occupational exposure shall be so controlled that the following limits be not exceeded:

(a) an effective dose of 6 mSv in a year;

(b) an equivalent dose to the lens of the eye of 50 mSv in a year; and

(c) an equivalent dose to the extremities or the skin of 150 mSv in a year.

A4.5.2. Dose Limit: Public Exposure

The estimated average doses to the relevant critical groups of members of the public that are attributable to practices shall not exceed the following limits:

(a) an effective dose of 1 mSv in a year;

(b) in special circumstances, an effective dose of up to 5 mSv in a single year provided that the average dose over five consecutive years does not exceed 1 mSv per year;

(c) an equivalent dose to the lens of the eye of 15 mSv in a year; and

(d) an equivalent dose to the skin of 50 mSv in a year.

Dose limitation for comforters and visitors of patients

The dose limits set out in this part shall not apply to comforters of patients, i.e., to individuals knowingly exposed while voluntarily helping (other than in their employment or occupation) in the care, support and comfort of patients undergoing medical diagnosis or treatment, or to visitors of such patients. However, the dose of any such comforter or visitor of patients shall be constrained so that it is unlikely that his or her dose will exceed 5 mSv during the period of a patient's diagnostic examination or treatment. The dose to children visiting patients who have ingested radioactive materials should be similarly constrained to less than 1 mSv.

A4.6. Definitions of important terms

Radioactive decay (Radioactivity) : process in which an unstable atomic nucleus spontaneously loses energy by emitting ionizing particles and radiation.

Becquerel (symbol **Bq**) : the SI derived unit of radioactivity. One Bq is defined as the activity of a quantity of radioactive material in which one nucleus decays per second. It is therefore equivalent to s^{-1}.

Curie (symbol **Ci**) : a unit of radioactivity, defined as

$$1 \text{ Ci} = 3.7\times10^{10} \text{ decays per second or becquerels.}$$

Appendix - 5

Proposed NPP Sites

Figure A5.1 – Delft Island

Delft Island		
Population density	Persons/sqkm	-
Elevation From Sea Level	m	1-9
Distance to nearest populated area	km	13
Nearest Grid substation (GS)	Chunnakam (132kV)	
Straight Distance to GS	km	50
Nearest Road (NR)	A9	
Straight Distance to NR	km	40
How far from the sea	km	Very Near

Figure A5.2. – Manar Island

Mannar Island		
Population density	Persons/sqkm	<100
Elevation From Sea Level	m	3-10
Distance to nearest populated area	km	Small population within the Island
Nearest Grid substation (GS)	Vavuniya	
Straight Distance to GS	km	80
Nearest Road (NR)	A14	
Straight Distance to NR	km	30
How far from the sea	km	Very Near

Figure A.5.3. – Near Palavi Nawaladi

Near Palavi, Nawaladi		
Population density	Persons/sqkm	<100
Elevation From Sea Level	m	6-13
Distance to nearest populated area	km	8
Nearest Grid substation (GS)	Kilinochchi (not in operation)	
Straight Distance to GS	km	38
Nearest Road (NR)	A32	
Straight Distance to NR	km	9
How far from the sea	km	Very Near

Figure A.5.4. – Near Kudramalei Point

Near Kudramalei Point, Wilpattu		
Population density	Persons/sqkm	<100
Elevation From Sea Level	m	10-18
Distance to nearest populated area	km	30
Nearest Grid substation (GS)	Puttalam	
Straight Distance to GS	km	50
Nearest Road (NR)	A14	
Straight Distance to NR	km	39
How far from the sea	km	Very Near

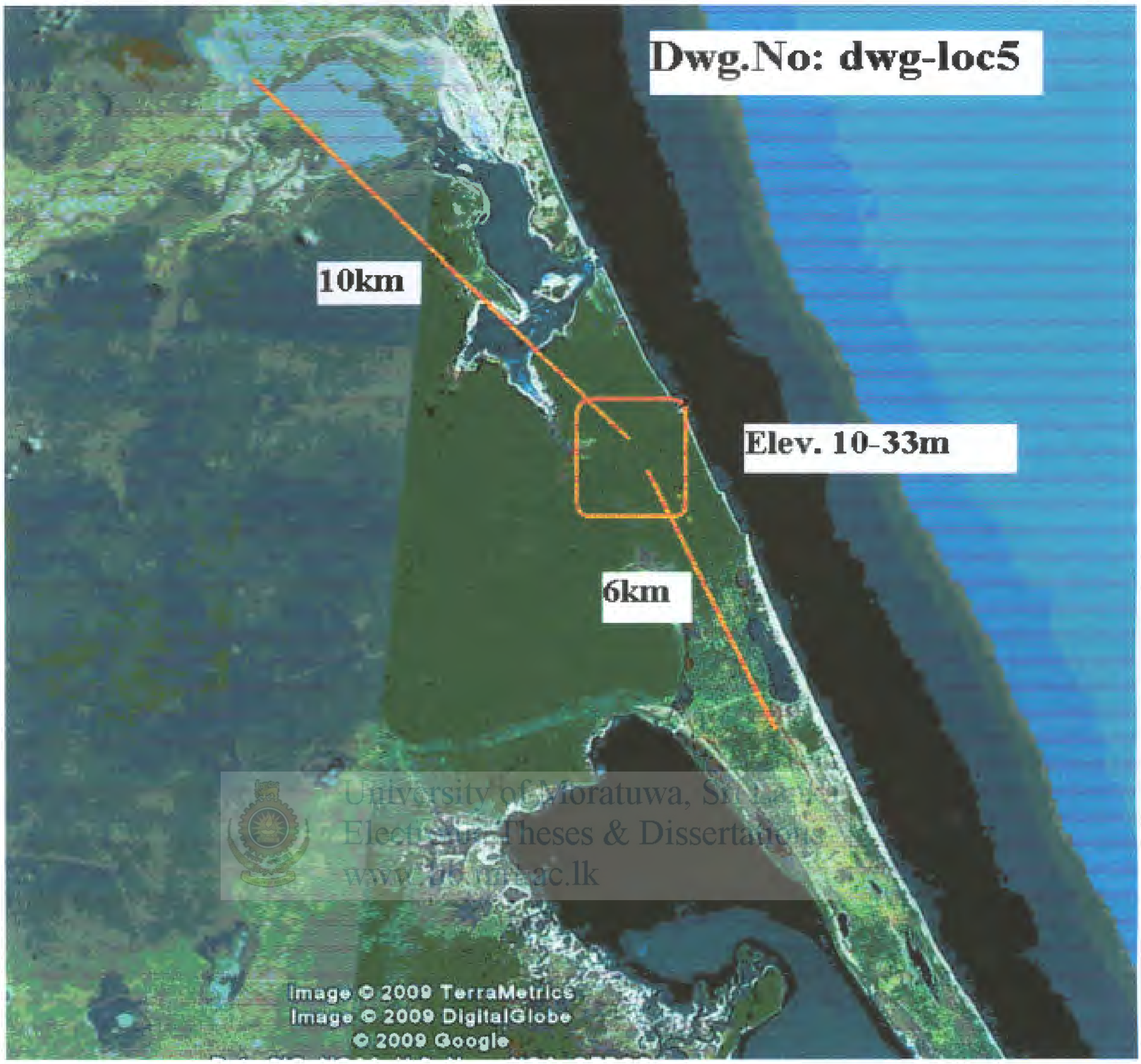

Figure A.5.5. – Near Alampil Mulaitivu

Near Alampil, Mulaitivu		
Population density	Persons/sqkm	<100
Elevation From Sea Level	m	10-33
Distance to nearest populated area	km	6.0
Nearest Grid substation (GS)	Vavuniya	
Straight Distance to GS	km	58
Nearest Road (NR)	A34	
Straight Distance to NR	km	21
How far from the sea	km	Very Near

Figure A.5.6. - Near Periyakarachchi Tank, Trincomalee North

Near Periyakarachchi Tank, Trincomalee North		
Population density	Persons/sqkm	<100
Elevation From Sea Level	m	7-50
Distance to nearest populated area	km	5.5
Nearest Grid substation (GS)	Trincomalee	
Straight Distance to GS	km	28
Nearest Road (NR)	Puttalam Road	
Straight Distance to NR	km	13
How far from the sea	km	Very Near

Figure A.5.7. – **Near Valaichchenai**

Near Valaichchenai		
Population density	Persons/sqkm	<100
Elevation From Sea Level	m	6-15
Distance to nearest populated area	km	17
Nearest Grid substation (GS)	Valaichchenai	
Straight Distance to GS	km	20
Nearest Road (NR)	Batticalo Raod	
Straight Distance to NR	km	2
How far from the sea	km	Very Near

Figure A.5.8. - **Sangaman Kanda Tuduwa**

Sangaman Kanda Tuduwa			
Population density	Persons/sqkm	101-1000	
Elevation From Sea Level	m	8-18	
Distance to nearest populated area	km	2(about 20 houses)	
Nearest Grid substation (GS)	Ampara		
Straight Distance to GS	km	38	
Nearest Road (NR)	CRWB high way		
Straight Distance to NR	km	2.8	
How far from the sea	km	Very Near	

Figure A.5.9. - **Near Yala**

Near Yala		
Population density	Persons/sqkm	<100
Elevation From Sea Level	m	6-15
Distance to nearest populated area	km	25
Nearest Grid substation (GS)	Hambanthota	
Straight Distance to GS	km	85
Nearest Road (NR)	A4 – CRWB Road	
Straight Distance to NR	km	15
How far from the sea	km	Very Near

Appendix - 6

International Nuclear Event Scale (INES)/Record of Past Accidents

The **INES** was introduced in 1990 by the IAEA in order to enable catogarization of nuclear accidents regarding to its impact on workers, site premises, general public and environment [39].

There are 7 levels on the INES scale; 3 incident-levels and 4 accident-levels. The level on the scale is determined by the highest of three scores: Off site effects, on site effects, and Defence in depth degradation.

A6.1. Level 7 – Major Accident

A large off-site impact with widespread health and environmental effects. External release of a significant fraction of reactor core inventory can be considered. It is required to implement emergency plans. Only major accident reported in the history which belong to Level-7 is the Chernobyl Disaster.

A6.2. Level 6 – Serious Accident

Significant off-site release, likely to require full implementation of planned countermeasures. The Kyshtym disaster at Mayak (former Soviet Union) – 1957 can be considered as an accident of Level-6.

A6.3. Level 5 – Accident with Wider Consequences

Limited off-site release, likely to require partial implementation of planned countermeasures or severe damage to a reactor core/radiological barriers. The Windscale fire (United Kingdom) – 1957 and Three Mile Island accident (United States) – 1979 can be considered as level-5 accidents.

A6.4. Level 4 – Accident with Local Consequeces

Minor off-site impact resulting in public exposure of the order of the prescribed limits, significant damage to a reactor core/radiological barriers or the fatal exposure of a worker.

Examples:

- Sellafield (United Kingdom) - 5 incidents 1955 to 1979
- SL-1 Experimental Power Station (United States) - 1961
- Saint-Laurent Nuclear Power Plant (France) - 1980
- Buenos Aires (Argentina) - 1983
- Jaslovské Bohunice (Czechoslovakia) - 1977
- Tokaimura nuclear accident (Japan) - 1999

A6.5. Level 3 – Serous Incident

A very small off-site impact, public exposure at levels below the prescribed limits or severe spread of contamination on-site and/or acute health effects to one or more workers.

Examples:

- THORP plant Sellafield (United Kingdom) - 2005.
- Paks Nuclear Power Plant (fuel rod damage in cleaning tank) (Hungary) - 2003.

A6.6. Level 2 - Incident

This is an incident with no off-site impact, a significant spread of contamination on-site may have occurred, This can be an overexposure of a worker or Incidents with significant failures in safety provisions.

Examples:

- Ascó Nuclear Power Plant, (Catalonia, Spain) April 2008; radioactive contamination
- Forsmark Nuclear Power Plant (Sweden); backup generator failure.

A6.7. Level 1 - Anomaly

This is an anomaly beyond the authorized operating regime.

Example:

- Gravelines (Nord, France), August 8, 2009; during the yearly exchanging of fuel bundles in reactor #1, one bundle kept hung to the upper handling structure, stopping the operations and causing the evacuation and isolation of the reactor's building.

- SOCATRI (Drôme, France), July 2008; leak of 6000 litres of water containing 75 kg of Uranium into the environment.

A6.8. Level 0 – No safety significance

This is a "below-scale event" of no safety significance.

Following is a table which described the event scale more fully.

INES Level	People and Environment	Radiological Barriers and Control	Defence-in-Depth
Major Accident Level - 7	Major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures.		
Serious Accident Level - 6	Significant release of radioactive material likely to require implementation of planned countermeasures.		
Accident with Wider Consequences Level - 5	• Limited release of radioactive material likely to require implementation of some planned countermeasures. • Several deaths from radiation	• Severe damage to reactor core. • Release of large quantities of radioactive material within an installation with a high probability of significant public exposure. This could arise from a major criticality accident or fire.	

Accident with Local Consequences Level - 4	• Minor release of radioactive material unlikely to result in implementation of planned countermeasures other than local food controls. • At least one death from radiation	• Fuel melt or damage to fuel resulting in more than 0.1% release of core inventory. • Release of significant quantities of radioactive material within an installation with a high probability of significant public exposure.	
Serious Incident Level - 3	• Exposure in excess of ten times the statutory annual limit for workers. • Non-lethal deterministic health effect (e.g., burns) from radiation	• Exposure rates of more than 1 Sv/h in an operating area. • Severe contamination in an area not expected by design, with a low probability of significant public exposure.	• Near accident at a nuclear power plant with no safety provisions remaining. • Lost or stolen highly radioactive sealed source. • Mis-delivered highly radioactive sealed source without adequate procedures in place to handle it.
Incident Level - 2	• Exposure of a member of the public in excess of 10 mSv. • Exposure of a worker in excess of the statutory annual limits.	• Radiation levels in an operating area of more than 50 mSv/h. • Significant contamination within the facility into an area not expected by design.	• Significant failures in safety provisions but with no actual consequences. • Found highly radioactive sealed orphan source, device or transport package with safety provisions intact. • Inadequate packaging of a highly radioactive sealed source.
Anomaly Level - 1			• Overexposure of a member of the public in excess of statutory annual limits. • Minor problems with safety components with significant defence-in-depth remaining. • Low activity lost or stolen radioactive source, device or transport package.

Table A6.1 – General Description of INES Levels

A6.9. Record of Past Accidets (Up to 2006)

1) December 12, 1952 — INES Level 5 - Chalk River, Ontario, Canada - Reactor core damaged. – **No Immediate fatalities were reported.**
2) May 24, 1958 — INES Level needed - Chalk River, Ontario, Canada - Fuel damaged.- **No injuries.**
3) October 25, 1958 - INES Level needed - Vinča, Yugoslavia - Criticality excursion, irradiation of personnel. - **1 person died, 6 hospitalized.**
4) July 26, 1959 — INES Level needed - Santa Susana Field Laboratory, California, United States - Partial meltdown. - **No injuries.**
5) October 5, 1966 — INES Level needed - Monroe, Michigan, United States - Partial meltdown. - **No injuries.**
6) Winter 1966-1967 (date unknown) – INES Level needed – location unknown – loss of coolant accident (Surface Ship – USSR) – **30 crew of the ship were killed.**
7) May 1967 — INES Level needed - Dumfries and Galloway, Scotland, United Kingdom - Partial meltdown. - **No injuries.**
8) January 21, 1969 — INES Level needed - Lucens, Canton of Vaud, Switzerland – Explosion. **No injuries.**
9) February 22, 1977 — INES Level 4 - Jaslovské Bohunice, Czechoslovakia - Fuel damaged. - **No injuries.**
10) March 28, 1979 — INES Level 5 - Middletown, Dauphin County, Pennsylvania, United States - Partial meltdown. (Three Mile Island Accident) - **No injuries.**
11) March 13, 1980 - INES Level 4 - Orléans, France - Nuclear materials leak.- **No injuries.**
12) March, 1981 — INES Level 2 - Tsuruga, Japan - Overexposure of workers. - **No injuries.**
13) September 23, 1983 — INES Level 4 - Buenos Aires, Argentina - Accidental criticality. – **1 died**
14) April 26, 1986 — INES Level 7 - Prypiat, Ukraine (then USSR) - Power excursion, explosion, complete meltdown (Chernobyl Accident). – **56 deaths and 237 hospitalized.**

15) May 4, 1986 – INES Level needed - Hamm-Uentrop, Germany (then West Germany) - Fuel damaged. - **No injuries.**

16) November 24, 1989 — INES Level needed - Greifswald, Germany (then East Germany) - Fuel damaged. - **No injuries.**

17) April 6, 1993 — INES Level 4 - Tomsk, Russia – Explosion. - **No injuries.**

18) June, 1999 — INES Level needed - Ishikawa Prefecture, Japan - Control rod malfunction. - **No injuries.**

19) September 30, 1999 — INES Level 4 - Ibaraki Prefecture, Japan - Accidental criticality. – **2 workers died.**

20) April 10, 2003 — INES Level 3 - Paks, Hungary - Fuel damaged. - **No injuries.**

21) April 19, 2005 — INES Level 3 - Sellafield, England, United Kingdom - Nuclear material leak. - **No injuries.**

22) November 2005 — INES Level needed - Braidwood, Illinois, United States - Nuclear material leak. - **No injuries.**

23) March 6, 2006 — INES Level needed - Erwin, Tennessee, United States - Nuclear material leak. - **No injuries.**