THE FUTURE OF NUCLEAR POWER

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INTRODUCTION

This work is an overlook on the perspective of nuclear power as source of electricity. The increasing concern about global warming is moving electrical energy generation towards the use of sources different from fossil fuels.

This report is mainly based on an interdisciplinary study performed by MIT (Massachusetts Institute of Technology) and evaluates the problems that should be faced in order to maintain nuclear power as one of the significant options for meeting future world energy needs at low cost and with environmental care.

In the first part, after a brief explication of the fission process, there is a description of the present generators technology and an overview of the feasible future technologies till generation IV and thorium and hydrogen reactors. There is also a short analysis on safety: the 1979 Three Mile Island and 1986 Chernobyl reactor accidents, but also accidents at fuel cycle facilities in the United States, Russia, and Japan, leaded to the perception of adverse safety, environmental, and health effects.

Then the attention is focused on economics: MIT results reveal that nuclear power has higher overall lifetime costs compared to natural gas with combined cycle turbine technology (CCGT) and coal only in the absence of a carbon tax or an equivalent “cap and trade” mechanism for reducing carbon emissions. The method used to perform this comparison is based on the Levelized Cost Of Electricity (LCOE), that is the cost per MWh that allows to cover all generation costs (costs of capital, O&M costs, construction costs, etc). MIT evaluations are also enriched with data provided by an University of Chicago study that shows nuclear costs in other OECD countries.

The following section describes nuclear power unresolved challenges in long-term management of radioactive wastes. The goal is to implement final disposition of spent fuel or high level radioactive waste streams created at various stages of the nuclear fuel cycle.

Finally, the last part describes security risks connected with nuclear power, focusing on proliferation: actually, the acquisition of nuclear weapons capability is strictly connected with the possible misuse of nuclear facilities and operations to acquire nuclear technology or materials. There is also growing concern about the safe transportation of nuclear materials and the security of nuclear facilities from terrorist attack.

1 TECHNICAL ANALYSIS

1.1 Introduction

The target of the first part of this work is to explain how and in what direction technical and scientific researches are moving in order to obtain an answer to the problems posed by nuclear energy.

After a brief review on actual reactors, the focus will be posed on technologies that now seem to promise a better future development and on nuclear safety.

1.2 How a nuclear reactor works

In order to understand what are the features of nuclear reactors and what are the technical breakthroughs lately happened, is important to know how a reactor works and by what parties is composed.

A low speed neutron impacts against an atom with a gross nucleus; the nucleus splits in more fragments and releases energy. The origin of this energy is due to the difference of mass between initial and final products; according to the Einstein equation, in effect, mass can not be destroyed but can be transformed:

$$E=mc^2.$$

Reaction control, that normally is explosive, is done with a reactor: in latest fifty years many kinds of reactors were built but all are made with the following parts: core, fuel, moderator, coolant, poison.

Core: it is an iron structure and it is considered the first safety barrier; it contains all the others nuclear reactors parts.

Fuel: it has a pellet form with a defined percentage of fissile material, generally uranium 235, but many reactors are fuelled with different elements like plutonium 239. Rods manufacturing is a complex industrial process which allows to raise the quantity of fissile material and to have the right chemical physical form.

Moderator: neutrons emitted by a fission reaction have a high speed; in order to raise the probability to have other collisions, they must be slow down; moderator is the material that allows the neutrons to have a low speed.

Coolant: it is the fluid that allows the transportation of the heat generated by the fission; usually it is water but can also be helium, molten salt or metal.

Poison: it is the material that can stop neutrons; its function is to control and adjust fission reaction.

1.3 Present reactors

The nuclear power industry has been developing and improving reactor technology for almost five decades and is preparing for the next generations of reactors to fill orders expected in the next five to twenty years.

Several generations of reactors are commonly distinguished. Generation I reactors were developed in 1950-60s and relatively few are still running today. Generation II reactors are typified by the present US fleet and most in operation elsewhere. Generation III are the Advanced Reactors under construction or ready to be ordered at present (see Table 1). Generation IV designs are still on the drawing board and will not be operational before 2010 at the earliest.

Third-generation reactors have:

- a standardized design for each type to expedite licensing, reduce capital cost and reduce construction time,
- a simpler and more rugged design, making them easier to operate and less vulnerable to operational upsets,
- higher availability and longer operating life - typically 60 years,
- reduced possibility of core melt accidents,
- minimal effect on the environment,
- higher burn-up to reduce fuel use and the amount of waste,
- burnable absorbers ("poisons") to extend fuel life.

The greatest departure from second-generation designs is that many of them incorporate passive or inherent safety features which require no active controls or operational intervention to avoid accidents in the event of malfunction, and may rely on gravity, natural convection or resistance to high temperatures.

Generation III has many types of reactors: some are cooled by light water, some by heavy water; others use pressurized gas technology. Fast breeder reactors are in an earlier development level: the main features of this technology are to use a fuel with a low percentage of U-235 and to transform U-238 in fissile material in order to improve the fuel exploitation.

The table below illustrates the main features of generation III nuclear reactors.

Table 1- Advanced thermal reactors being marketed

Country and developer	**Reactor**	**Size MWe**	**Design Progress**	**Main Features**
US-Japan (GE-Hitachi-Toshiba)	ABWR	1300	Commercial operation in Japan since 1996-7. In US: NRC certified 1997, FOAKE.	• Evolutionary design • More efficient, less waste • Simplified construction (48 months) and operation
South Korea (derived from Westinghouse)	APR-1400 (PWR)	1400	NRC certified 1997, Further developed for new S. Korean Shin Kori 3 & 4, expected to be operating 2010.	• Evolutionary design • Increased reliability • Simplified construction and operation
USA (Westinghouse)	AP-600 AP-1000 (PWR)	600 1100	AP-600: NRC certified 1999, FOAKE. AP-1000 NRC design approval 2004.	• Passive safety features • Simplified construction and operation • 3 years to build • 60-year plant life
Japan (utilities, Westinghouse, Mitsubishi)	APWR	1500	Basic design in progress, planned at Tsuruga	• Hybrid safety features • Simplified Construction and operation
France-Germany (Framatome ANP)	EPR (PWR)	1600	Confirmed as future French standard, French design approval, To be built in Finland	• Evolutionary design • Improved safety features • High fuel efficiency • Low cost electricity
USA (GE)	ESBWR	1390	Developed from ABWR, pre-certification in USA	• Evolutionary design • Short construction time • Enhanced safety features
Germany (Framatome ANP)	SWR-1000 (BWR)	1200	Under development, pre-certification in USA	• Innovative design • High fuel efficiency • Passive safety features
Russia (OKBM)	V-448 (PWR)	1500	Replacement for Leningrad and Kursk plants	• High fuel efficiency • Enhanced safety
Russia (Gidropress)	V-392 (PWR)	950	Two being built in India, Likely bid for China	• Evolutionary design • 60-year plant life • Enhanced safety features
Canada (AECL)	CANDU-9	925-1300	Licensing approval 1997	• Evolutionary design • Single stand-alone unit • Flexible fuel requirements • Passive safety features
Canada (AECL)	ACR	700 1000	ACR-700: pre-certification in USA, ACR-1000 proposed for UK	• Evolutionary design • Light water cooling • Low-enriched fuel • Passive safety features

South Africa (Eskom, BNFL)	PBMR	165 (module)	prototype due to start building, pre-certification in USA	Modular plant, low cost Direct cycle gas turbine High fuel efficiency Passive safety features
USA-Russia et al (General Atomics - Minatom)	GT-MHR	285 (module)	Under development in Russia by multinational joint venture	Modular plant, low cost Direct cycle gas turbine High fuel efficiency Passive safety features

1.4 Future technologies

1.4.1 Generation IV

After some two years' deliberation, the Generation IV International Forum (GIF) representing ten countries announced the selection of six reactor technologies (see Table 2)which they believe represent the future shape of nuclear energy. These are selected on the basis of being clean, safe and cost-effective means of meeting increased energy demands on a sustainable basis, while being resistant to diversion of materials for weapons proliferation and secure from terrorist attacks.

Most of the six systems employ a closed fuel cycle to maximize the resource base and minimize high-level wastes to be sent to disposal. Three of the six are fast reactors and one can be built as a fast reactor, one is described as epithermal, and only two operate with slow neutrons like today's plants.

Only one is cooled by light water, two are helium-cooled and the others have lead-bismuth, sodium or fluoride salt coolant. The latter three operate at low pressure, with significant safety advantage. The last one has the uranium fuel dissolved in the circulating coolant. Temperatures range from 510°C to 1000°C, compared with less than 330°C for today's light water reactors, and this means that four of them can be used for thermochemical hydrogen production.

At least four of the systems have significant operating experience already in most respects of their design, which may mean that they can be in commercial operation well before 2030.

Gas-cooled fast reactors. Like other helium-cooled reactors which have operated or are under development, these will be high-temperature units - 850°C, suitable for power generation, thermochemical hydrogen production or other process heat. For electricity, the gas will directly drive a gas turbine (Brayton cycle). Fuels would include depleted uranium and any other fissile or fertile materials. Spent fuel would be reprocessed on site and all the actinides recycled to minimize production of long-lived radioactive wastes.

Lead-cooled fast reactors. Liquid metal (Pb or Pb-Bi) cooling is by natural convection. Fuel is depleted uranium metal or nitride, with full actinide recycle from regional or central reprocessing plants. A wide range of unit sizes is envisaged, from factory-built "battery" with 15-20 year life for small grids or developing countries, to modular 300-400 MWe units and large single plants of 1400 MWe. Operating temperature of 550°C is readily achievable but 800°C is envisaged with advanced materials and this would enable thermochemical hydrogen production.

Molten salt reactors. The uranium fuel is dissolved in the sodium fluoride salt coolant which circulates through graphite core channels to achieve some moderation and an epithermal neutron spectrum. Fission products are removed continuously and the actinides are fully recycled, while plutonium and other actinides can be added along with U-238. Coolant temperature is 700°C at very low pressure, with 800°C envisaged. A secondary coolant system is used for electricity generation, and thermochemical hydrogen production is also feasible.

Sodium-cooled fast reactors. This builds on more than 300 reactor-years experienced with fast neutron reactors over five decades and in eight countries. It utilizes depleted uranium in the fuel and has a coolant temperature of 550°C enabling electricity generation via a secondary sodium circuit, the primary one being at near atmospheric pressure. Two variants are proposed: a 150-500 MWe type with actinides incorporated into a metal fuel requiring pyrometallurgical processing on site, and a 500-1500 MWe type with conventional MOX fuel reprocessed in conventional facilities elsewhere.

Supercritical water-cooled reactors. This is a very high-pressure water-cooled reactor which operates above the thermodynamic critical point of water to give a thermal efficiency about one third higher than today's light water reactors from which the design evolves. The supercritical water (25 MPa and 510-550°C) directly drives the turbine, without any secondary steam system. Passive safety features are similar to those of simplified boiling water reactors. Fuel is uranium oxide, enriched in the case of the open fuel cycle option. However, it can be built as a fast reactor with full actinide recycle based on conventional reprocessing. Most research on the design has been in Japan.

Very high-temperature gas reactors. These are graphite-moderated, helium-cooled reactors, based on substantial experience . The core can be built of prismatic blocks such as the Japanese HTTR and the GTMHR under development by General Atomics and others in Russia, or it may be pebble bed such as the Chinese HTR-10 and the PBMR under development in South Africa, with international partners. Outlet temperature of 1000°C enables thermochemical hydrogen production via an intermediate heat exchanger, with electricity cogeneration, or direct high-efficiency driving of a gas turbine (Brayton cycle)

Table 2 - Generation IV reactors

	Neutron spectrum (fast/ thermal)	Coolant	Temperature (°C)	Pressure*	Fuel	Fuel cycle	Size(s) (Mwe)	Uses
Gas-cooled fast reactors	fast	helium	850	high	U-238	closed, on site	288	electricity & hydrogen
Lead-cooled fast reactors	fast	Pb-Bi	550-800	low	U-238	closed, regional	50-150** 300-400 1200	electricity & hydrogen
Molten salt reactors	epithermal	fluoride salts	700-800	low	UF in salt	closed	1000	electricity & hydrogen
Sodium-cooled fast reactors	fast	sodium	550	low	U-238 & MOX	closed	150-500 500-1500	electricity
Supercritical water-cooled reactors	thermal or fast	water	510-550	very high	UO_2	open (thermal) closed (fast)	1500	electricity
Very high temperature gas reactors	thermal	helium	1000	high	UO_2 prism or pebbles	open	250	hydrogen & electricity

* high = 7-15 Mpa

** 'battery' model with long cassette core life (15-20 yr) or replaceable reactor module.

1.4.2 Thorium

Thorium, as well as uranium, can be used as a nuclear fuel. Although not fissile itself, thorium-232 (Th-232) will absorb slow neutrons to produce uranium-233 (U-233), which is fissile. Hence like uranium-238 (U-238) it is fertile.

In one significant respect U-233 is better than uranium-235 and plutonium-239, because of its higher neutron yield per neutron absorbed. Given a start with some other fissile material (U-235 or Pu-239), a breeding cycle similar to but more efficient than that with U-238 and plutonium (in slow-neutron reactors) can be set up.

Over the last 30 years there has been growing interest in utilising thorium as a nuclear fuel since it is three times as abundant in the earth's crust as uranium. Also, all of the mined thorium is potentially useable in a reactor, compared with the 0.7% of natural uranium, so some 40 times the amount of energy per unit mass might be available.

The thorium-plutonium fuel claims four advantages over MOX: proliferation resistance, compatibility with existing reactors. In addition a lot more plutonium can be put into a single fuel assembly than with MOX. The spent fuel amounts to about half the volume of MOX and is even less likely to allow recovery of weapons-useable material than spent MOX fuel.

Many problems brake a fast development of the thorium based fuel cycle: high cost of fuel fabrication, due partly to the high radioactivity of U-233; the similar problems in recycling thorium due to highly radioactive Th-228; some weapons proliferation risk of U-233; and the technical problems (not yet satisfactorily solved) in reprocessing.

Much development work is still required before the thorium fuel cycle can be commercialised, and the effort required seems unlikely while (or where) abundant uranium is available.

1.4.3 Small reactors

As nuclear power generation has become established since the 1950s, the size of reactor units has grown from 60 MWe to more than 1300 MWe, with corresponding economies of scale in operation. At the same time there have been many hundreds of smaller reactors built both for naval and scientific use. Today, due partly to the high capital cost of large power reactors generating electricity via the steam cycle and partly to consideration of public perception, there is a move to develop smaller units. These may be built independently or as modules in a larger complex, with capacity added incrementally as required. Economies of scale are provided by the numbers produced. There are also moves to develop small units for remote sites.

The most prominent modular project is the South African-led consortium developing the Pebble Bed Modular Reactor of 110 MWe. A US-led group is developing another design with 285 MWe modules. Both of them drive gas turbines directly, using helium as a coolant and operating at very high temperatures.

1.4.4 Nuclear power and hydrogen

A new use is approaching to the nuclear world: hydrogen production. Thermo-chemical cycle water-splitting processes offer the potential for making hydrogen at temperatures in the range of 700 to 900ºC. The basic cycle involves the thermal decomposition of water into hydrogen and oxygen using an ionic solution to mediate the reaction.

The most promising of these cycles are the calcium-bromine process and the sulfuriodine process. Currently, neither of these thermo-chemical processes has progressed to the point of commercial viability, perhaps partly because there has not been the economic incentive to do so. Recently, however, interest in environmental benefits and energy independence has increased attention to these methods. Recent estimates indicate that thermo-chemical production costs could be 60 percent of current electrolysis costs using nuclear reactors dedicated to hydrogen production (Forsberg 2003, p. 1075).

Thermo-chemical processes would be conducted from nuclear reactors dedicated to hydrogen production. The greater proportion of the heat generated by the reactor would be used for the hydrogen production, but the waste heat could be used to power a steam turbine which would generate electricity that could be sold outside the hydrogen production facility. In this production process, the ability to sell electricity from a hydrogen facility would reduce the cost of hydrogen production.

1.4.5 Safety in nuclear power plants

To achieve optimum safety, nuclear plants operate using a 'defence-in-depth' approach, with multiple safety systems. Key aspects of the approach are:

- high-quality design & construction;
- equipment which prevents operational disturbances developing into problems;
- redundant and diverse systems to detect problems, control damage to the fuel and prevent significant radioactive releases;
- provision to confine the effects of severe fuel damage to the plant itself.

The safety systems include a series of physical barriers between the radioactive reactor core and the environment, the provision of multiple safety systems, each with backup and designed to accommodate human error. These include control rods which are inserted to absorb neutrons and regulate the fission process, and the back-up cooling systems to remove excess heat.

In addition, most reactors are designed with an inherent feature called a negative void coefficient. This means that beyond an optimal level, as the temperature increases the efficiency of the reaction decreases (especially if any steam has formed in the cooling water). This is due to a decrease in moderating effect so that fewer neutrons are able to cause fission and the reaction slows down automatically.

Other physical features also enhance safety. For instance, in a typical reactor the fuel is in the form of solid ceramic (UO_2) pellets, and radioactive fission products remain bound inside these pellets as the fuel is burned. The pellets are packed inside zirconium alloy tubes to form fuel rods. These are confined inside a large steel pressure vessel with walls about 20 cm thick, which, in turn, is enclosed inside a robust concrete containment structure with walls at least one meter thick.

Investigations following the accident led to a new focus on the human factors in nuclear safety. No major design changes were called for in western reactors, but controls and instrumentation were improved and operator training was overhauled.

Since the World Trade Centre attacks in New York various studies have looked at similar attacks on nuclear power plants. They show that nuclear reactors would be more resistant to such attacks than virtually any other civil installations. The latest and most thorough study was undertaken by the Electric Power Research Institute.

The analyses used a fully-fuelled Boeing 767-400 of over 200 tonnes as the basis, at 560 km/h - the maximum speed for precision flying near the ground. The wingspan is greater than the diameter of reactor containment buildings and the 4.3 tonne engines are 15 metres apart. Hence analyses focused on single engine direct impact on the centreline and on the impact of the entire aircraft if the fuselage hit the centreline (in which case the engines would ricochet off the sides). In each case no part of the aircraft or its fuel would penetrate the containment. Looking at spent fuel storage pools, similar analyses showed no breach. Dry storage and transport casks retained their integrity.

One mandated safety indicator is the calculated frequency of degraded core or core melt accidents. The US Nuclear Regulatory Commission (NRC) specifies that reactor designs must meet a 1 in 10,000 year core damage frequency, but modern designs exceed this. US utility requirements are 1 in 100,000, the best currently operating plants are about 1 in 1 million and those likely to be built in the next decade are almost 1 in 10 million. The Three Mile Island accident in 1979 was the only one in a reactor conforming to NRC safety criteria, and this was contained as designed, without radiological harm to anyone.

The IAEA (International Atomic Energy Agency) has given a high priority to addressing the safety of nuclear power plants in eastern Europe, where deficiencies remain. However, energy demand in these countries is such that there is little flexibility for closing even those plants which are of most concern, though the European Union is bringing pressure to bear, particularly in countries which aspire to EU membership.

A major international program of assistance has been carried out by the OECD, IAEA and Commission of the European Communities to bring early Soviet-designed reactors up to near western safety standards, or at least to effect significant improvements to the plants and their operation.

Modifications have been made to overcome deficiencies in the 13 RBMK (Chernobyl reactor) reactors still operating in Russia and Lithuania. Among other things, these have removed the danger of a positive void coefficient response.

The other class of reactors which has been the focus of international attention for safety upgrades is the first-generation of pressurised water VVER-440/230 reactors. These were designed before formal safety standards were issued in the Soviet Union and they lack many basic safety features. Eleven are operating in Bulgaria, Russia, Slovakia and Armenia, under close inspection.

Many occupational accident statistics have been generated over the last 40 years of nuclear reactor operations in the US and UK. These can be compared with those from coal-fired power generation. All show that nuclear is a distinctly safer way to produce electricity. Two simple sets of figures are quoted in the Table below. A major reason for coal's unfavorable showing is the huge amount which must be mined and transported to supply even a single large power station. Mining and multiple handling of so much material of any kind involves hazards, and these are reflected in the statistics.

Table 3 - Comparison of accident statistics in primary energy production.

Fuel	**Immediate fatalities 1970-92**	**Who?**	**Normalised to deaths per TWy* electricity**
Coal	6400	workers	342
Natural gas	1200	workers & public	85
Hydro	4000	public	883
Nuclear	31	workers	8

*Basis: per million MWe operating for one year, not including plant construction, based on historic data which is unlikely to represent current safety levels in any of the industries concerned.

Source: Ball, Roberts & Simpson, Research Report #20, Centre for Environmental & Risk Management, University of East Anglia, 1994; Hirschberg et al, Paul Scherrer Institut, 1996; in: IAEA, *Sustainable Development and Nuclear Power*, 1997; *Severe Accidents in the Energy Sector*, Paul Scherrer Institut, 2001).

2 ECONOMICS

2.1 Introduction

This chapter focuses primarily on the economic analysis elaborated by MIT (Massachusetts Institute of Technology) in order to evaluate the costs of nuclear power.

The ever growing energy demand and the pervasiveness of global warming makes non-fossil fuels an interesting alternative source of energy. Whilst the scarce economic competitiveness and technological know-how make the development of renewable sources not feasible yet, it is interesting evaluating benefits and limits of an hypothetical nuclear power exploitation.

The following analysis depicts an hypothetical development scenario, describes the existing different nuclear fuel cycles and compares the costs of electricity generated from gas, coal and nuclear by using the LCOE (Levelized Cost of Electricity, see Appendix). All these technical and economical considerations are enriched with observations on waste management and public opinion attitude.

2.2 The scenario

These years the growing energy demand, mostly due to developing countries contribute, has been satisfied thanks to fossil fuels; the intensive usage of these energy sources has been the main cause of GHG production increase. Actually, electricity generation has a leading role in global GHG emissions, with a contribution of about one third of the global emissions.

There are sectors, such as transports, where an effective solution to this problem is very far from being found; on the other hand, the electric world can reduce its contribution to global warming acting in several ways:

- Increasing generation and utilization efficiency;
- Increasing renewable sources based technology (wind, solar, biomass e geothermic)
- Using carbon sequestration technologies at fossil fuels power plants (coal first of all);
- Increasing nuclear fission utilization (hoping in a future with nuclear fusion).

The importance of electrical power in this kind of analysis is due to the continuous growth of energy demand: in the next years, while developed countries demand will probably be interested by a slight increment, a different trend is going to take place in developing countries (China, Mexico, Brazil, India), where an increment of 2-3% of annual consumption is foreseen.

In this scenario, there are many factors justifying nuclear power utilization: first of all, nuclear technology is well known, then there’s a wide primary source (uranium) availability and mining resources have a wide geographical distribution, especially in politically stable countries (Australia, Canada); last but not least, nuclear power is a base load kind of generation: in developing countries population tends to concentrate in big urban agglomerations, requiring big productive units, that can be easily provided by nuclear power plants.

Together with these observations, other features should be considered: Actually, there are several obstacles not only facing a rapid spread of nuclear power but also causing a nuclear plants dismissing in areas where this technology had found large agreements in the past:

- Economic convenience: high fixed costs and low operating costs cannot bear the competitiveness of coal and natural gas power plants, until external costs aren’t internalized.
- Public opinion suspicion and fear, especially after global accidents (Three Mile Island, Chernobyl).
- Proliferation: fission products can be used in non conventional weapons construction;
- Waste management: waste harmfulness needs a correct management system both in temporary storage structures and in geological disposal facilities.

Table 4 - Global growth scenario

REGION	PROJECTED 2050 Gwe CAPACITY	NUCLEAR ELECTRICITY MARKET SHARE	
		2000	**2050**
Total World	1000	17%	19%
Developed world	625	23%	29%
U.S.	300		
Europe and Canada	210		
Developed East Asia	115		
FSU	50	16%	23%
Developing world	325		
China, India, Pakistan	200		
Indonesia, Brazil, Mexico	75		
Other developing countries	50		

Projected capacity comes from a global electricity demand scenario which entails growth in global electricity consumption from 13.6 to 38.7 trillion kWhrs from 2000 to 2050 (2.1% annual growth). The market share in 2050 is predicated on 85% capacity factor for nuclear power reactors. Note that China, India, and Pakistan are nuclear weapons capable states. Other developing countries includes as leading contributors Iran, South Africa, Egypt, Thailand, Philippines, and Vietnam.

On the basis of these considerations, wide nuclear power utilization can be a valid solution to purchase benefits in GHG emission reduction; MIT scenario (see Table 4) predicts the construction of one thousands 1000 MWe nuclear power plants by 2050, in different geographical areas, according to the energy demand and population growth forecasts.

2.3 The Levelized Cost of Electricity (LCOE)

Any analysis of the costs of nuclear power must take into account an important consideration: while all the nuclear power plants operating today were developed by vertically-integrated utility monopolies (state-owned or regulated investor-owned), in the future nuclear power will have to compete with alternative generating technologies in competitive wholesale markets. These changes in the structure of the electric power sector have important implications for investment in generating capacity: investors should bear the risk of uncertainties associated with obtaining construction and operating permits, construction costs and operating performance.

The LCOE (Levelized Cost of Electricity) is a very effective tool to evaluate the electricity costs of the alternative generation options. It consists on the constant real wholesale price of electricity that would be necessary over the life of the plant to cover all operating expenses, interest and principal repayment obligations on project debt, taxes and provide an acceptable return to equity investors over the economic life of the project.

In its analysis, MIT developed and utilized an alternative model, in order to overcome typical calculation which provide levelized nominal cost values rather than levelized real cost values, obscuring the effects of inflation and making capital intensive technologies look more costly relative to alternatives than they really were. A deep description of the calculation of the LCOE is attached in Appendix.

Since nuclear power plants have relatively high capital costs and very low marginal operating costs, nuclear energy will compete with alternative electricity generation sources for “baseload” (high load factor) operation. As a consequence, in the following paragraphs the costs of nuclear power will be compared to fossil fuel (coal and gas) generating alternatives in base-load applications. There have been assumptions of both a 25-year and 40-year capital recovery period and 85% and 75% lifetime capacity factors.

The MIT analysis proceeds examining the relative costs of new nuclear power plants, pulverized coal plants, and combined-cycle gas turbine (CCGT) plants in base-load operations in the United States. Three different cases have been examined: first of all, a “base case”, that examines the levelized real life-cycle costs of nuclear, coal, and CCGT generating technology at present; then a comparison assuming a change of the real levelized cost of nuclear generated electricity, due to additional technology improvements; finally, an assessment internalizing the social costs of coal and CCTG generation.

2.3.1 Base case

The base case reflects reasonable estimates of the current perceived costs of building and operating the three generating alternatives in 2002 U.S. dollars. All the cost valuations are based on recent nuclear plant construction experience, in order to have reliable estimates; actually, if late 1980s plant costs were considered, the average overnight construction cost would have been much higher.

The following assumptions have been made (see Table 5): for nuclear, the overnight capital cost is \$2000/kWe and O&M costs are 15 mills/kWe-hr (according with the recent performance of operating nuclear plants in the U.S., but lower than the the average nuclear plant costs); for CCGT and coal plants, the construction costs are in line with experience and EIA (Energy Information Administration) estimates; for coal plants construction costs reflect NOx and SO2 controls as required to meet the actual standards.

For CCGT plants, four cases are presented:

1. low gas price (\$3.50/MMBtu), rising at a low real rate (0.5% per year);
2. low gas price (\$3.50/MMBtu), rising at a moderate real rate (1.5% per year);
3. high gas price (\$4.50/Mmbtu), rising at a high real rate (2.5% per year);
4. high gas price and advanced CCGT design (with a roughly 10% improvement in its heat rate).

The base case results show that nuclear power is not convenient at present: it’s much more costly than the coal and gas alternatives even in the high gas price cases. Besides, investors probably will prefer coal technology because, together with high gas price volatiliy and gas resources shortage, there are regions of the country with below average coal costs where coal would be less costly than gas As regards gas, only in the low gas price case CCGT is cheaper than coal.

An important assessment should been made: this analysis examines the relative costs of new nuclear power plants, pulverized coal plants, and CCGT plants in the United States, where abundant coal and gas resources are avilable. A similar analysis for countries with an unlike geopolitical situation would lead to different results. For instance, a recent comparatory OECD study (see Table 6) shows theat in some countries (like China) the gap between nuclear and coal reduces, while in other nations (like France and Russia) overturns.

Table 5 - Base case assumpions

Nuclear
Overnight cost: $2000/kWe
O&M cost: 1.5 cents/kWh (includes fuel)
O&M real escalation rate: 1.0%/year
Construction period: 5 years
Capacity factor: 85%/75%
Financing: Equity: 15% nominal net of income taxes Debt: 8% nominal Inflation: 3% Income Tax rate (applied after expenses, interest and tax depreciation): 38% Equity: 50% Debt: 50%
Project economic life: 40 years/25 years
Coal
Overnight cost: $1300/kWe
Fuel Cost: $1.20/Mmbtu
Real fuel cost escalation: 0.5% per year
Heat rate (bus bar): 9300 BTU/klWh
Construction period: 4 years
Capacity factor: 85%/75%
Financing: Equity: 12% nominal net of income taxes Debt: 8% nominal Inflation: 3% Income Tax rate (applied after expenses, interest and tax depreciation): 38% Equity: 40% Debt: 60%
Project economic life: 40 years/25 years
Gas CCGT
Overnight cost: $500/kWe
Initial fuel cost: Low: $3.50/MMbtu ($3.77/MMbtu real levelized over 40 years) Moderate: $3.50/MMbtu ($4.42/MMbtu real levelized over 40 years) High: $4.50/MMbtu ($6.72/MMbtu real levelized over 40 years)
Real fuel cost escalation: Low: 0.5% per year Moderate: 1.5% per year High: 2.5% per year
Heat rate: 7200 BTU/kWh Advanced: 6400 BTU/kWh
Construction period: 2 years
Capacity factor: 85%/75%
Financing: Equity: 12% nominal net of income taxes Debt: 8% nominal Inflation: 3% Income tax rate (applied after expenses, interest and tax depreciation): 38% Equity: 40% Debt: 60%
Project economic life: 40 years/25 years

2.3.2 Nuclear costs improvements

This scenario examines how the cost of electricity generated by nuclear power plants would change, if the following actions would be taken:

- construction time reduction from 5 years to 4 years;
- construction costs reduction by 25 %;
- operation and manteinance (O&M) costs to 13 mills/Kwe-hr;
- nuclear plants financing under the same conditions (cost of capital) as a coal or gas plants.

These cost improvement are not proven but plausible, according to the expectations of technological progress.

As shown in Table 7 and Table 8, these analysis suggests that nuclear power could be quite competitive with CCGT, if gas prices gets higher, and would be only slightly more costly than coal, under the hypothesis of significant improvements in the costs of building, operating, and financing nuclear power plants, and continued excellent operating performance (85% capacity factor).

Table 6 - OECD analysis results: LCOE in $ 2003 per MWh, with 75% capacity factor and 40 years plant life-cycle.

COUNTRY	PLANT TYPE	DISCOUNT RATE = 8%	DISCOUNT RATE = 10%
CHINA	Pulverized Coal Combustion	43	48
CHINA	Nuclear with Reprocessing	39-50	47-61
CHINA	Nuclear, Spent Fuel Disposal	44	54
FRANCE	Gas Turbine Combined Cycle	59	63
FRANCE	Pulverized Coal Combustion	66	74
FRANCE	Nuclear with Reprocessing	50	60
RUSSIA	Gas Turbine Combined Cycle	42	46
RUSSIA	Pulverized Coal Combustion	57	64
RUSSIA	Nuclear with Reprocessing	45	55

2.3.3 External costs internalization

All the previous scenarios show that coal is more competitive than nuclear, but they do not consider that all external social costs of electricity generation should be reflected in the price. In the third scenario, considering the cost of CO_2 emissions, nuclear looks more attractive: unlike gas and coal-fired plants, nuclear plants produce no carbon dioxide during operation and do not contribute to global climate change. Accordingly, it is natural to explore what the comparative social cost of nuclear power would be, if carbon emissions were “priced” to reflect the marginal cost of achieving global carbon emissions stabilization and reduction targets.

Recognizing that there is enormous uncertainty about the costs of deploying CO2 capture, transport, and storage on a large scale, reducing carbon emissions to meet aggressive global emissions goals, three different levels of severities of carbon emissions restrictions have been examined:

- a carbon tax of $50/tC, consistent with an EPA estimate of the cost of reducing U.S. CO2 emissions by about 1 billion metric tons per year;
- a carbon tax of $100/tC and $200/tC, on the basis of the range of values that appear in the literature regarding the costs of carbon sequestration.

With this assumptions, the situation has radically changed (see Table 7 and Table 8): nuclear would be significantly less costly than all of the alternatives with carbon prices at this level and if all of the cost reduction specifications discussed earlier could be achieved.

However, it is quite difficult thinking about a common global policy about internalization of social costs, despite the recent ratification of Kyoto protocol. Actually, in USA, a non signatory country, the future policies regarding carbon emissions are uncertain at the present time; nevertheless, many investments have been made in order to improve CO_2 sequestration technology. As regards UK, nuclear is treated like fossil fuels generation techniques and it is associated with a carbon tax even if it is not responsible of CO_2 emissions.

Table 7 - Costs of Electric Generation Alternatives : Real Levelized Cents/kWe-hr (85% capacity factor)

<table>
<tr><th>Base Case</th><th colspan="2">25 YEARS</th><th colspan="2">40 YEAR</th></tr>
<tr><td>Nuclear</td><td colspan="2">7.0</td><td colspan="2">6.7</td></tr>
<tr><td>Coal</td><td colspan="2">4.4</td><td colspan="2">4.2</td></tr>
<tr><td>Gas (low)</td><td colspan="2">3.8</td><td colspan="2">3.8</td></tr>
<tr><td>Gas (moderate)</td><td colspan="2">4.1</td><td colspan="2">4.1</td></tr>
<tr><td>Gas (high)</td><td colspan="2">5.3</td><td colspan="2">5.6</td></tr>
<tr><td>Gas (high) Advanced</td><td colspan="2">4.9</td><td colspan="2">5.1</td></tr>
<tr><td>Reduce Nuclear Costs Cases</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>Reduce construction costs (25%)</td><td colspan="2">5.8</td><td colspan="2">5.5</td></tr>
<tr><td>Reduce construction time by 12 months</td><td colspan="2">5.6</td><td colspan="2">5.3</td></tr>
<tr><td>Reduce cost of capital to be equivalent to coal and gas</td><td colspan="2">4.7</td><td colspan="2">4.4</td></tr>
<tr><td>Carbon Tax Cases (25/40 year)</td><td>$50/tC</td><td colspan="2">$100/tC</td><td>$200/tC</td></tr>
<tr><td>Coal</td><td>5.6/5.4</td><td colspan="2">4.3/4.3</td><td>4.6/4.7</td></tr>
<tr><td>Gas (high)</td><td>5.8/6.1</td><td colspan="2">5.3/5.6</td><td>6.8/6.6</td></tr>
<tr><td>Gas (moderate)</td><td>4.9/4.8</td><td colspan="2">5.1/5.2</td><td>6.4/6.7</td></tr>
<tr><td>Gas (high)</td><td>5.8/6.0</td><td colspan="2">9.2/9.0</td><td>5.9/5.9</td></tr>
<tr><td>Gas (high) advanced</td><td>6.2/6.2</td><td colspan="2">7.4/7.7</td><td>6.7/7.0</td></tr>
</table>

Table 8 - Costs of Electric Generation Alternatives : Real Levelized Cents/kWe-hr (75% capacity factor)

<table>
<tr><th>Base Case</th><th colspan="2">25 YEARS</th><th colspan="2">40 YEAR</th></tr>
<tr><td>Nuclear</td><td colspan="2">7.9</td><td colspan="2">7.5</td></tr>
<tr><td>Coal</td><td colspan="2">4.8</td><td colspan="2">4.6</td></tr>
<tr><td>Gas (low)</td><td colspan="2">4.0</td><td colspan="2">3.9</td></tr>
<tr><td>Gas (moderate)</td><td colspan="2">4.2</td><td colspan="2">4.3</td></tr>
<tr><td>Gas (high)</td><td colspan="2">5.5</td><td colspan="2">5.7</td></tr>
<tr><td>Gas (high) Advanced</td><td colspan="2">5.0</td><td colspan="2">5.2</td></tr>
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<tr><td>Coal</td><td>6.0/5.8</td><td colspan="2">7.2/7.0</td><td>9.6/9.4</td></tr>
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<tr><td>Gas (high) advanced</td><td>5.5/5.7</td><td colspan="2">5.9/6.2</td><td>6.8/7.1</td></tr>
</table>

2.4 Fuel cycles

All the previous cost values refer to the civil nuclear industry and are comprehensive both of the power plants management and of fuel production plants and high technology disposal facilities costs.

As regards fuel technologies, two main systems can be identified:

- open or once-through fuel cycle, where the spent fuel discharged from the reactor is treated as waste;
- closed fuel cycle, where the spent fuel discharged from the reactor is reprocessed in order to be used back again into a reactor.

Closed cycles have an advantage over the once-through cycle in terms of resource utilization, because the recycled actinides reduce the requirement for enriched uranium; on the other hand, the open cycle has an advantage in terms of cost and proliferation resistance, since there is no reprocessing and separation of actinides. The closed cycle option seems to be more economical only in the limit of very high ore prices; anyway, since the cost of uranium represents only a small fraction of the busbar cost of nuclear electricity, even large increases in the former may not substantially increase the latter.

MIT report analyzes three different fuel management options, examining good and bad points as regards economics, technical safety and proliferation:

- open fuel cycle – the process consists in three main phases: uranium, after its enrichment through diffusion, is treated in order to obtain special fuel bars ready to be used in the power generation; then the spent fuel is disposed, firstly in cooling pools and lastly in geological disposal facilities;

- closed cycle (MOX option – one recycle) - the spent fuel discharged from the reactor is reprocessed, the products are partitioned into uranium (U) and plutonium (Pu) suitable for fabrication into oxide fuel or mixed oxide fuel (MOX) for recycle back into a reactor; the rest of the spent fuel is treated as high-level waste (HLW).
- closed fuel cycle with complete actinides recycle - this reactor (fast breeder) may be used as a breeder to produce new fissile fuel by neutron absorption at a rate that exceeds the consumption of fissile fuel by the neutron chain reaction; in such fuel cycles the lower containt of actinides will signifi-cantly reduce the long-term radioactivity of the nuclear waste.

Table 9 - Fuel Cycle Parameter comparison. Annual Amounts for 1500 GWe Deployment

	OPTION 1A ONCE THROUGH LOW BURN UP	**OPTION 1B ONCE THROUGH HIGH BURN UP**	**OPTION 3 LWR + FAST REACTOR**	
			LWR	**Fast reactor**
Capacity, GWe	1,500	1,500	815	685
Enrichment, %	4.5	8.2	4.5	25
Burn up, GWd/MTIHM	50	100	50	120
Uranium ore	306	286	166	
per year, 103 MT/yr	9.45	8.76	5.96	
cumulative, 106 MT	29.9	14.9	Repr.: 20.9 (12.3 LHEc)	
Spent or repr. Fuel	922 (13.7 YME)	516 (7.4 YME)	Spent : 4.1 YMEs	
per year, 103 MTIHM/yr	Not applicable	Not applicable	FP: 1398; MA+Pu: 1.0	
cumulative, 103 MTIHM	397	294	0.7 (repr. losses)	
HLW, MT/yr	1.1·104	1.1·104	2.8·103	
Pu, MT/yr	6.9·1011	5.3·1011	2.2·107	
Waste decay heatd	306	1,500	Repr.: 20.9 (12.3 LHEc)	
W/GWeY (100 yrs)	9.45	8.2	Spent : 4.1 YMEs	
Waste ingestion hazard	29.9	100	FP: 1398; MA+Pu: 1.0	
m3/GWeY (1,000 yrs)	922 (13.7 YME)	286	0.7 (repr. losses)	

a. Thermal efficiency 33% for LWRs and 40% for FRs, capacity factor 90%, enrichment tails assay 0.3%. Capacity is assumed to increase linearly.
Fast reactors start deployment in 15 years.
b. Intended as generic fast reactor; data from ANL IFR.
c. LHE means La Hague equivalent (1,700 MTHM/year)
d. The decay heat and radiotoxicity are computed from and MCODE/ORIGEN run and expressed on a per GWe-y basis to establish a fair comparison between the various fuel cycles. The decay heat and radiotoxicity per unit mass can be obtained by dividing by the mass of spent fuel discharged per GWe-y. The spent fuel discharge for option 1A is 22.1 MTIHM/y, giving a decay heat at 100 years of 5.0·102 W/MTIHM and a radiotoxicity at 1000 years of 3.1·1010 m3/MTIHM, as shown in Figures 7.2 and 7.3.

On the basis of this analysis, the open cycle can be considered more advantageous than the closed one as regards both costs and poliferation resistance: actually, it does not require complex power plants using radioactive materials and it does not separate plutonium, which is the potential basis of non conventional weapons construction.

On the other hand, closed cycles are more effective in fuel exploitation and they produce less waste. In particular, fast breeder reactors allow a complete actinides recycle, reducing waste long term radioactivity.

Table 9 summarizes the technical features of the three kinds of cycles and an estimation of the waste production on the basis of the reference base scenario (year 2050, 1500 reactors sized 1000 MWe).

2.5 Public attitudes

Public attitudes have a relevant role in the decision of nuclear technology adoption in a country: for instance, in Italy a referendum in 1987 leaded to the complete elimination of the national nuclear program; in the United States, despite the presence of more than 100 working reactors, public is sceptical: on one hand, most of Americans approve of the use of nuclear power, but oppose the building of additional nuclear power plants to meet future energy needs.

In order to understand why people oppose and support specific power sources, MIT conducted a survey of 1350 adults in the United States, measuring public opinion about future use of energy sources, including fossil fuels, nuclear power, hydroelectricity, solar and wind power. The results can be summarized as follows:

- As regard nuclear, perception of environmental harms, uncertainty about the feasibility of a safe waste management system and high costs; this concern is not related to age, gendre, income or education; besides, generally nuclear power is not perceived as the optimal solution for global warming.
- General propension toward a progressive abandon of oil and coal as energy sources, keeping gas utilization at present level;
- Stong support of a wide spread of wind and solar energy generation, but mostly because the public perceives these technologies to be inexpensive; when informed that solar and wind are more expensive than fossil fuels or nuclear power, survey respondents showed substantially more support for nuclear generation.

These assessments reveal the fundamental importance of the technology itself for public support. Actually, public opposition to nuclear power in the United States is due primarily to the concerns over safety, toxic waste and poor economics. While a public campaign to change perceptions about nuclear power could have only modest effect, strategic technology choices and improvements able to lower the cost of nuclear power, lessen any environmental impact and improve waste management and safety will substantially increase support for this power source.

3 WASTE MANAGEMENT

3.1 Introduction

Management and disposal of nuclear wastes is one of the most discussed aspects of nuclear industry today. These activities are under the spotlight because of a question of much concern: the harm due to radiation exposure. Actually, everyone is constantly exposed to radiation. At high levels radiation is dangerous and hence it is important to shield such radiation from people. When considering radioactive materials and especially wastes, the objective is to avoid increasing that exposure significantly. At each stage of the fuel cycle there are proven technologies to dispose of the radioactive wastes safely. In some cases, however, they are not implemented because of public concerns or because they are not presently needed.

Radioactive emission occurs naturally from the decay of particular forms of some elements (radioisotopes), as an atom disintegrates. The rate of radiation lessens with time because each disintegration reduces the number of radioactive atoms. A key factor in managing wastes is the time that they are likely to remain hazardous. This depends on the kinds of radioactive isotopes in them, and particularly the half lives characteristic of each of those isotopes. The half life is the time it takes for a given radioactive isotope to lose half of its radioactivity. There are elements with a long half-life, such as uranium 238 (half life 4.5 billion years): they give out very low levels of radiation albeit over a geological time scale, making their handling easier. On the other hand, elements with a short half life, such as radon 220 (half life 56 seconds), emit very much more radiation over a shorter time.

Eventually all radioactive wastes decay into non-radioactive elements. Radioactive waste is produced through the generation of electricity using nuclear fission. A large portion of it has radiation levels comparable to the natural background level. While this waste is relatively easy to deal with, there’s a small, highly radioactive part which requires particular attention.

The main objective in managing and disposing of radioactive waste is to protect people and the environment. This means isolating or diluting the waste so that the rate or concentration of any radionuclides returned to the biosphere is harmless. To achieve this, practically all wastes are contained and managed.

Radioactive wastes can be classified considering several features: the concentration of the radioactive material in the waste, whether the waste is heat generating and how long the waste will remain at hazardous levels. These characteristics are very important: actually, the persistence of the radioactivity determines how long the waste requires management, while the concentration and heat generation state how the waste should be handled. These considerations also inform suitable disposal methods. There isn't an unique classification of radioactive wastes: it varies slightly from country to country; anyway, internationally accepted categories can be identified:

- Very low level waste (VLLW) or exempt waste - they contain negligible amount amounts of radioactivity and may be disposed of with domestic refuse.
- Low-level waste (LLW) – Generated also from hospitals and industry and mostly made of paper, rags, tools, clothing, filters, this is the bulk of waste from the nuclear fuel cycle and contains small amounts of mostly short-lived radioactivity. It does not require shielding during handling and transport and it's suitable for shallow land burial. To reduce its volume, these wastes are often compacted or incinerated before disposal. Disposal sites for low-level waste are in operation in many countries. Worldwide they make up 90% of the volume but have only 1% of the total radioactivity of all radioactive wastes.
- Intermediate-level waste (ILW) – it usually deals with resins, chemical sludges, metal fuel cladding and contaminated materials from reactor decommissioning, all associated with a higher amounts of radioactivity and consequently requiring shielding (tipically, barriers of lead, concrete or water), in order to give protection from penetrating radiation such as gamma rays. These radioactive materials may be solidified in concrete or bitumen for disposal. They make up some 7% of the volume and has 4% of the radioactivity of all radioactive wastes. Generally, short-lived waste (mainly from reactors) is buried, but long-lived waste (from fuel reprocessing) will be disposed of underground.
- High-level waste (HLW) – arising from the use of uranium fuel in a nuclear reactor, it contains the fission products and transuranic elements generated in the reactor core which are highly radioactive and hot. High-level waste accounts for over 95% of the total radioactivity produced, even though the actual amount of material is low (as an example, a typical large nuclear reactor - 1000 MWe, light water type – has to do with 25-30 tonnes of spent fuel. or three cubic metres per year of vitrified waste).

In the civil nuclear fuel cycle the attention focuses mainly on high-level waste because of their long life, high radioactivity and technical challenge; nevertheless, at present no country has yet succeeded in disposing of this kind of waste.

3.2 High-level waste management

High level wastes (HLW) can be made of both fission products or transuranics separated from the spent fuel and spent fuel elements themselves (from the reactor core, when they are not reprocessed). Before disposal, they must be treated: HLW from reprocessing is incorporated into solid blocks of borosilicate glass (vitrification) while, regarding with direct disposal, spent fuel must be encapsulated in stainless steel or copper containers.

For reprocessing, when the fission products are first extracted from the spent fuel, they are in liquid form, having been dissolved in acid (usually nitric acid). This liquid can be safely retained in stainless steel tanks that are equipped with cooling systems until it is converted into a solid, which is a more convenient material for management, storage, transport and disposal. After drying, it is incorporated into molten borosilicate glass, which is allowed to solidify inside corrosion resistant canister. Vitrification produces a stable solid that has the high-level waste incorporated its structure.

In either case however there is a cooling period of 20 to 50 years between removal from the reactor and disposal, the wastes are retained in interim storage, in order to reduce the levels of radioactivity and heat to acceptable values.

Because of the very long toxic lifetime of the waste, the primary technical challenge is that of long-term isolation. However, shorter-term risks must also be addressed. Prior to final disposition, the waste will pass through several intermediate stages or operations, including temporary storage, transportation, conditioning, packaging, and, potentially, intermediate processing and treatment steps. There are several possible choices at each stage.

Among technical experts, the generally accepted method for disposing of radioactive waste is geologic disposal. There is a high level of confidence within the scientific community because this approach has been studied extensively for several decades, leading to:

- a deep understanding of the processes that could transport radionuclides from the repository to the biosphere;
- a quantification of the long-term environmental impact of repositories, thanks to mathematical models which consider information about specific sites and repository designs;
- natural analogue studies which help to build confidence that the analytical models can be reliably extrapolated to the very long time-scales required for waste isolation.

Nevertheless, past failures in the waste management programs of several countries have contributed to many doubts among the general public: there is a lack of confidence in the prospects for successful implementation of geologic disposal. Besides, some members of the public – especially those living in the vicinity of proposed repository sites – also question the fairness and integrity of the site selection process.

The main goals an effective waste disposal should achieve can be summarized as follows: reduction of the risks to public health and safety and the environment, both in the short and long term; cost reduction; increase of public confidence. In order to facilitate the successful implementation of waste management and disposal, several possible innovations can be considered:

1. technical modifications or improvements that could be incorporated into the once through fuel cycle:
    - Extended interim storage of spent fuel (this subject is faced in detail in the following paragraph);
    - High burnup fuel - The burnup of spent fuel is the amount of energy that has been extracted from a unit of fuel at the time of its discharge from the reactor; an increase of this parameter leads to a reduction in the volume of spent fuel per unit of electricity generated; but an higher burnup leads also to a bigger decay heat; so the fuel would need to be spaced farther apart in the repository and the advantageous reduction in the storage volume required would be modest. A further benefit of higher burnup is that the isotopic composition of the discharged plutonium would reduce its radioactivity life, making it less suitable for use in nuclear explosives. The biggest obstacle against high burnup fuel is its high cost.
    - Advances in geologic repository design - A geologic repository must provide protection against every plausible scenario, through a ‘defense in depth’ approach, relying on a combination of engineered components and natural geologic, hydrologic, and geochemical barriers to contain the radionuclides.
    - The deep borehole or sea bed approach – this alternative disposal technology consists in placing waste canisters in boreholes drilled into stable crystalline rock several kilometers deep. In fact, by these depths, vast areas of crystalline basement rock should be extremely stable, having experienced no tectonic, volcanic or seismic activity for billions of years. Bedrock or seabed at a depth of several kilometres would probably isolate radioactive substances effectively, but afterwards it would be difficult to verify the safety of these disposal methods. There is no certainty that waste canisters would remain intact in the depths of oceans or bedrock. Besides, it would most probably be difficult to win international approval for the final disposal of wastes in seabed. At last,

but not least, this solution is very costly and it is very difficult to predict the impact on public opinion of a shift in siting strategy from one large central repository to scores of widely dispersed boreholes.

2. technical modifications or improvements requiring a closed fuel cycle:
   - Waste partitioning – this process consists in separating the spent fuel in radionuclide fractions and managing each fraction according to its particular characteristics. The additional costs and near-term environmental and safety risks associated with partitioning operations make this technique not persuasive.
   - Waste partitioning and transmutation - The objective is to change long-lived actinides and fission products into significantly shorter-lived nuclides. Transmutation would be used to destroy those substances of spent nuclear fuel that have very long half-lives, even of millions of years. Among these substances there are iodine 129, technetium 99, caesium 135, selenium 79 and many substances heavier than uranium. With repeated recycle in a transmutation system, the need for a waste repository is certainly not eliminated, but the hazard posed by the disposed waste materials is greatly reduced. However, it seems to be difficult to develop industrial scale transmutation processes for nuclear waste management: all actinide partitioning and transmutation schemes currently under consideration seem likely to add significantly to the economic cost of the nuclear fuel cycle.
3. institutional or organizational innovations:
   - a strong international coordination of standards and regulations for waste life-cycle could strengthen public confidence in the safety of these activities;
   - an international sharing of waste storage and disposal facilities could lead to significant economic and safety benefits; such a condition could also reduce proliferation risks from the fuel cycle but it cannot be easily achieved in the short-term because of formidable political obstacles.

3.3 The long term storage of radioactive waste: safety and sustainability

Spent fuel is generally removed from the reactor core under water and transferred to large water filled pools where the fuel is held on racks underwater. The water function is twofold: both as a shield from the radiation and as a coolant of the spent fuel, which may be destined either long term storage or reprocessing.

Storage is a necessary step in the overall management of radioactive waste and its importance has grown in recent years, mainly because of the unavailability of permanent disposal facilities; actually, many stores, originally intended as temporary facilities, have had their lifetimes extended and some countries are seriously thinking about the use of storage as a long term management option.

In 1995 the International Atomic Energy Agency (IAEA) published The Principles of Radioactive Waste Management, Safety Series No. 111-F, facing the matter of radioactive waste management safety from "sustainable" point of view. Actually, among the nine main principles of this document, there's a sentence that states: "Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations". This implies that the generation that cause radioactive waste formation through nuclear energy production should take care of any liabilities connected with this activity, making all the arrangements needed for the disposal of the waste in order to avoid damages against future generations.

Studies on effective disposal facilities are quite recent; actually, in most countries, these researches started after nuclear power generation and other applications of radioactive materials. As a consequence, in early times, waste was most frequently stored in various types of engineered containment on the surface and at sites to which access was controlled. At present, R&D work on waste disposal shows that, in principle, all types of radioactive waste can be disposed of in a sustainable way, providing protection for the health and safety of people and the environment. For high level and long lived radioactive waste, international experts agree on disposal in deep underground engineered facilities (geological disposal) as the best, currently available option. This potential solution is under investigation in many countries, but so far only two countries, the United States and Finland, have identified specific sites for their repositories, as shown in Table 10. This is due to difficulties encountered in several countries, mainly because of public and political opposition. As a result, in such places, the waste material continues to accumulate in storage facilities, but, as the amounts of radioactive waste in surface storage have increased, concern has grown over the sustainability of storage in the long term and the associated safety and security implications. The question is quite complex: the characteristics of storage and disposal facilities may vary significantly and they are characterized by both positive and negative features. After a brief description of these two kinds of facilities, a comparison between them will follow, in order to make a constructive analysis and state whether a best solution exists.

Table 10 - Waste Management for Spent Fuel from Nuclear Power Reactors

COUNTRY	POLICY	FACILITIES AND PROGRESS TOWARD FINAL REPOSITORIES
Belgium	Reprocessing	Central waste storage & underground laboratory established Construction of repository to begin about 2035
Canada	Direct disposal	Underground repository laboratory established Repository planned for use 2025
China	Reprocessing	Central spent fuel storage in LanZhou
Finland	Direct disposal	Spent fuel storages in operation Low & intermediate-level repositories in operation since 1992 Site near Olkiluoto selected for deep repository for spent fuel, from 2020
France	Reprocessing	Two facilities for storage of short-lived wastes Site selection studies underway for deep repository for commissioning 2020
Germany	Reprocessing, but moving to direct disposal	Low-level waste sites in use since 1975 Intermediate-level wastes stored at Ahaus Spent fuel storage at Ahaus and Gorleben High-level repository to be operational after 2010
India	Reprocessing	Research on deep geological disposal for HLW
Japan	Reprocessing	Low-level waste repository in operation High-level waste storage facility at Rokkasho-mura since 1995 Investigations for deep geological repository site begun, operation from 2035
Russia	Reprocessing	Sites for final disposal under investigation Central repository for low and intemediate-level wastes planned from 2008
South Corea	Direct disposal	Central interim HLW store planned for 2016 Central low- & ILW repository planned from 2008 Investigating deep HLW repository sites
Spain	Direct disposal	Low & intermediate-level waste repository in operation Final HLW repository site selection program for commissioning 2020.
Sweden	Direct disposal	Central spent fuel storage facility in operation since 1985 Final repository for low to intermediate waste in operation since 1988 Underground research laboratory for HLW repository Site selection for repository in two volunteered locations
Switzerland	Reprocessing	Central interim storage for high-level wastes at Zwilag since 2001 Central low and intermediate-level storages operating since 1993 Underground research laboratory for high-level waste repository, with deep repository to be finished by 2020.
United Kingdom	Reprocessing	Low-level waste repository in operation since 1959. High-level waste is vitrified and stored at Sellafiled Underground HLW repository planned.
USA	Reprocessing	Three low-level waste sites in operation 2002 decision to proceed with geological repository at Yucca Mountain

3.3.1 Storage facilities

Storage facilities for high level waste and spent fuel are typically placed above ground or at very shallow depth. The waste can be stored either dry or underwater. For instance, most spent fuel, after removal from the nuclear reactor, is stored underwater for a period of at least three to five years. As said before, the water has two functions: it serves both as radiation shielding and to keep the spent fuel elements at an acceptably low temperature. The spent fuel can either be transferred to storage in dry conditions or it can be reprocessed (in this case, the resulting highly radioactive liquors are solidified by vitrification). In dry storage the waste, depending on its characteristics, may undergo conditioning before being packaged inside a container, which is designed to be extremely durable and resistant to corrosion or other forms of degradation for many years. The containers are then stored inside a suitable structure, often constructed from concrete, to provide radiation shielding and security. These structures are usually located at a secure site inside a perimeter security fence.

As regards in-ground storage, there are facilities located no more than a few metres below the surface, characterized by elaborate methods of detecting and preventing any leakage of contaminants from the packages.

An important aspect of storage is its inherent, temporary nature, with the implication that the waste material will be transferred at some future time to a permanent repository.

3.3.2 Disposal facilities

Waste emplacement at significant depths underground is commonly known as ‘geological disposal’. The main feature of disposal, as opposed to storage, is that the emplacement of the waste is intended to be permanent. It’s considered by technical experts the best method of waste management available at present because containment and isolation of harmful materials from the environment are assured by both engineered and natural barriers. Actually, there are special containers into which the waste is put before being emplaced in the repository and there’s the host rock which provides an effective obstacle against the radioactive propagation.

Geological disposal can be undertaken in several geological formations; the most commonly studied rock types are clay, salt, and hard magmatic, metamorphic or volcanic rocks such as granite, gneiss, basalt or tuff. The depth at which the disposed material would be emplaced depends to a large extent on the type of formation used and the isolation capacity of the overlying formations. Suitable clay formations, for example, tend to occur in layers of a few hundred metres thickness at a depth of a few hundred metres. Salt deposits occur as bedded slat layers or salt domes at this or greater depths. For disposal in hard rocks, the usual design depth is between 500 and 1000 m, and the aim is to use parts of the rock formation that contain very few large fracture zones or faults.

Finally, a disposal facility will be closed and sealed, and from the surface there might or might not be any indication of the existence of the facility that is at some considerable depth below. In most rock types, a repository can be designed so that closure of the facility can be delayed for a period of several tens to a few hundred years. In this period, the repository and the surrounding environment can be monitored if desired, and the facility can be designed to allow for retrieval of the emplaced material if required.

3.3.3 Factors relevant to the safety and sustainability of storage facilities

Safety: the operation of existing facilities demonstrated the feasibility of safe storage over periods of decades; the defects of some older facilities have been recognized and corrected in modern facilities and this option of correcting any problems which might occur can be seen as an advantage of surface storage. Unfortunately, there are negative features too: it is inevitable that some structural degradation of the packages and their contents will occur over time. The longer the waste is stored before transfer to another facility, the greater are the probabilities that such degradation will occur; as a consequence, greater is the potential radiation exposure for the workers who will eventually have to carry out the transfer and handling operations. Furthermore, waste stores are vulnerable: if they are not kept under close surveillance, intrusion by humans can take place. On the other hand, geological repositories are designed to provide containment and isolation of radioactive waste from the human environment for the very long periods required; besides, they are passively safe: they provide this isolation without the need for active controls.

Maintenance/institutional control - Effective maintenance is favoured by a storage facility because it easier to repair anything that needs to be repaired and it is also easier to detect deficiencies at their formative stage in a facility that is located on the surface and accessible, compared with when it is underground. On the other hand, maintenance should not be required in geological repositories: in fact, these systems are designed so that any failure in a protective barrier should not have an impact on people and the environment.

Retrieval - . The possibility of retrieving the waste preserves the option for future generations to make different decisions concerning the existing radioactive waste inventory (for instance, recycling the material by reprocessing). An advantage of surface storage is the ease of retrieving material if it should be decided to do so. However, recent work has shown that geological disposal can be developed in stages so that retrievability would be possible for both storage and disposal.

Security - Over the last few decades, especially after the events of 11 September 2001, the concerns about security of nuclear materials have heightened. The material is obviously much more vulnerable to attack if placed on the surface so putting wastes underground increases the security of them.

Costs - Storage has a significant operating cost, so sufficient funds should be set aside to maintain ongoing storage and address future management actions (refurbishments, reprocessing or disposals). On the other hand, a disposal facility is associated with a significant capital cost, especially given the long time (of the order of 20 years and more) between the start of work towards a geological disposal option and the emplacement of waste in the facility. Many jurisdictions have taken the step of requiring utilities that generate nuclear power to set aside funds on a continuing basis to pay for the future cost of disposal of the related waste , in order to internalize costs.

Community attitudes – Storage is understood to be an intermediate step in the management of wastes, so the level of acceptance of new or expanded storage facilities is greater, especially in communities that have lived alongside nuclear installations for many years (often because it is just a continuation of existing practice). As regards geological disposal, its permanence is source of much concern and opposition; besides, it’s unattractive to some because it deprives future generations of the option to choose how the wastes are managed.

Transfer or information - Long term storage of radioactive waste requires transfer of information to future generations. This information should be retained in order to be readable and understandable to future generations. Modern technologically based systems (e.g. computerized data storage) are a potential good solution to this matter, but they require constant updating and maintenance: in fact, changes in technology, and software could quickly lead to storage media obsolescence, making this information unreadable

As a conclusion, storage and disposal are complementary rather than competing activities and both are needed. However, the timing and duration of the process of moving from storage to disposal is influenced by many factors, not only the sustainability of long term storage. Strategies for storage and disposal need careful consideration in light of the many issues involved. These include transport of radioactive wastes from storage sites to disposal sites, security of the waste, retrievability of the waste from storage, safe packaging and conditioning of waste for long term storage and disposal, availability of suitable disposal sites, confidence that adequate levels of safety can be achieved, and the availability of finances.

4 PROLIFERATION

4.1 Introduction

Like many other technological innovations, from the outset nuclear technology has been ambiguous. Its birth began with production of the first weapons-usable fissionable material but it has enabled humankind to access a virtually unlimited source of energy at a time when constraints are arising on the use of fossil fuels.

Today, the objective is to minimize the proliferation risks of nuclear fuel cycle operation. The best way consists in preventing the acquisition of weapons-usable material, either by diversion (in the case of plutonium) or by misuse of fuel cycle facilities (also research reactors or hot cells) and control, to the extent possible, the know how about how to produce and process either HEU (enrichment technology) or plutonium.

4.2 Fissile materials

4.2.1 Plutonium

Plutonium consists of several different isotopes but not all are fissile. Plutonium-239 by itself is an excellent nuclear fuel but, because of its relatively low spontaneous fission rate and its low critical mass, it has also been used extensively for nuclear weapons.

Plutonium contained in spent fuel elements is typically about 60-70% Pu-239 while weapons-grade plutonium is more than 93% Pu-239.

The plutonium routinely produced in all commercial nuclear power reactors and which may be separated by reprocessing the spent fuel from them is usually called "reactor-grade". It remains in the reactor for a relatively long time so it contains a large proportion - up to 40 percent - of the heavier plutonium isotopes, especially Pu-240. This is not a particular problem for re-use of the plutonium in mixed oxide (MOX) fuel for reactors, but it seriously affects the suitability of the material for nuclear weapons. Actually, it is not and has never been used for weapons, due to the relatively high rate of spontaneous fission and radiation from the heavier isotopes. Anyway, safeguards arrangements assume that both kinds of plutonium could conceivably be used for weapons, particularly weapons designed for terror rather than military use.

The following table gives some of the important characteristics of plutonium and its use.

Table 11 - Main characteristics of plutonium and its uses

Type	Composition	Origin	Use
Reactor-grade, from high-burnup fuel	55-60% Pu-239, >19% Pu-240, typically about 30% non-fissile	Comprises about 1% of spent fuel from normal operation of civil nuclear reactors used for electricity generation	As ingredient (c 5-7%) of MOX fuel for normal reactor. (Can also be used as fuel in a fast neutron reactor.)
Weapons-grade	Pu-239 with <7% Pu-240	From military "production" reactors specifically designed and operated for production of low burn-up Pu.	Nuclear weapons (can be recycled as fuel in fast neutron reactor or as ingredient of MOX)

Commercial plutonium is a much less attractive weapons material than plutonium produced in special "production reactors" designed for producing Pu-239, and which are capable of frequent fuel changing. However, the development of laser enrichment technology may mean that it becomes feasible to enrich commercial plutonium to weapons-grade. Hence safeguards arrangements are set up accordingly to take seriously the proliferation possibilities even of reactor-grade plutonium. (Conventional enrichment cannot readily be used to separate Pu-239 from Pu-240 because the atomic mass is so similar.)

The plutonium-based fast breeder fuel cycle is seen as having features which might give rise to weapons proliferation problems. On the other hand conventional thermal reactors normally have a higher net yield of plutonium from the fuel cycle. This suggests that in the forseeable future the fast neutron reactor should be utilised more as a plutonium "incinerator", which is likely to mean less plutonium in storage or in spent fuel elements than otherwise.

4.2.2 Uranium

There are two other fissile materials that could be used for weapons and both are isotopes of uranium. The most common is uranium-235. This material is produced by enriching natural uranium in an enrichment plant. Uranium processed for electricity generation is not useable for weapons. Actually, the uranium used in power reactor fuel for electricity generation is typically enriched to about 3-4% of the isotope U-235, while weapons-grade is over 90% U-235. For safeguards purposes uranium is deemed to be "highly enriched" when it reaches 20% U-235. Few countries possess the technological knowledge or the facilities to produce weapons-grade uranium.

The other isotope of uranium suitable for use in explosives is U-233. This material is made from thorium-232 fuels in reactors in much the same way as plutonium is made from U-238 in uranium-fuelled reactors. However, the use of thorium-fuelled reactors has not moved beyond the experimental stage and U-233 is not seen as a significant proliferation problem.

Whilst the above materials can be used for explosives manufacture, they are not readily available in any practical sense, and international efforts are designed to make them even less accessible.

4.3 International safeguard

The proliferation concern has led, over the last half century, to an elaborate set of international institutions and agreements. Unfortunately, none of them have proved entirely satisfactory.

4.3.1 Non Proliferation Treaty: origins and objectives

The Nuclear Non Proliferation Treaty (NPT) is the foundation of the control regime: it aims to prevent the spread of nuclear weapons while ensuring fair access to peaceful nuclear technology under international safeguards (audits and inspections).

The NPT took effect on March 5, 1970, after being opened for signature on July 1, 1968. Beginning with 43 original parties in 1970, membership increased steadily to 96 in 1975, 132 in 1985, and 178 in 1995. By July 1998, 187 parties had joined the NPT. Cuba acceded to the treaty on November 4, 2002, thereby becoming the 188th party to the NPT. More countries have ratified the NPT than any other arms control or disarmament agreement in history. At present, only three states have not signed the treaty: India, Israel, and Pakistan. Democratic People's Republic of Korea (DPRK, also known as North Korea) announced its withdrawal from the NPT on January 10, 2003, and its withdrawal came into effect on April 10, 2003.

The NPT parties can be divided into two main categories: nuclear weapon states (NWS) and non-nuclear weapon states (NNWS).

Under the treaty, NWS are defined as the five states that exploded a nuclear device before January 1967 (the P-5: United States, Soviet Union - now Russian Federation, United Kingdom, France, and China) and, according to the trety, they may retain their nuclear arsenals, not transfer nuclear weapons to anyone, not assist any NNWS to acquire, manufacture or control nuclear weapons; and commit to pursuing negotiations in good faith towards ending the nuclear arms race and achieving nuclear disarmament.

On the other side, NNWS must not build, acquire, or possess nuclear weapons; they may research, produce, and use nuclear energy for peaceful purposes and must accept safeguards (audits and intrusive on-site monitoring) on all of their nuclear activities and materials to verify they are not being used for nuclear weapons.

The NPT is an indispensable legal and political instrument in preventing further proliferation of nuclear weapons. Its main principles can be summarized as follows:

- Member states without nuclear weapons are forbidden from developing them;
- The five member states with nuclear weapons are forbidden from transferring them to any other state;
- The application of international safeguards provides assurance that peaceful nuclear programs in NNWS will not be diverted to nuclear weapons or other nuclear explosive devices;
- Peaceful uses of nuclear energy are facilitated for all NNWS under international safeguards;
- Member states are committed to pursue good faith negotiations toward ending the nuclear arms race and achieving nuclear disarmament.

4.3.2 The International Atomic Energy Agency (IAEA)

The IAEA was set up by unanimous resolution of the United Nations in 1957 to help nations develop nuclear energy for peaceful purposes. Allied to this role is the administration of safeguards arrangements. This provide assurance to the international community that individual countries are honouring their treaty commitments to use nuclear materials and facilities exclusively for peaceful purposes.

The IAEA therefore undertakes regular inspections of civil nuclear facilities to verify the accuracy of documentation supplied to it. The agency checks inventories and undertakes sampling and analysis of materials. Safeguards are designed to deter diversion of nuclear material by increasing the risk of early detection. They are complemented by controls on the export of sensitive technology from countries such as UK and USA through voluntary bodies such as the Nuclear Suppliers' Group.

4.3.3 Recent facts

In recent years, the international community was challenged by an illicit nuclear weapons program in North Korea based on plutonium production in a research reactor and detected by IAEA safeguards inspections. The United Nations imposed a nuclear "freeze" on the country's reactors and facilities under a 1994 Agreed Framework which led to the country bowing to international pressure so that the

IAEA could reassure the UN that all nuclear materials were safeguarded and that North Korea was moving towards full compliance with its IAEA safeguards agreement. The trade-off for North Korea was that an international consortium led by USA, South Korea and Japan is building two large modern nuclear reactors for the country to provide electricity untainted by military possibilities. However, in 2002 North Korea admitted to a clandestine uranium enrichment program, which put the country doubly in default of its international treaty obligations.

Even greater concern was generated by suspicions that Iraq had developed or was developing nuclear weapons; these fears were heightened during the Persian Gulf War. After the cease-fire in 1991, the United Nations was able to confirm that Iraq, though a signatory to the NPT, had been pursuing a clandestine weapons program apart from materials and facilities covered by IAEA inspections. The major part of its illicit endeavour was based on indigenous uranium and its enrichment. This situation led to the enhancement of the safeguards regime, through the IAEA's Integrated Safeguards Program.

Questions continue as to the nuclear intentions of India, Pakistan and Israel. None of these countries are bound by the NPT. India and Pakistan have demonstrated their capability of producing nuclear weapons, and Israel is suspected of developing a nuclear weapons program.

4.4 Conclusions

NPT embodies the renunciation of nuclear weapons by all signatories except for the declared NWS and a commitment to collaborate on developing peaceful uses of nuclear energy. However, non-signatories India and Pakistan tested nuclear weapons in 1998, and signatories, such as South Africa and North Korea, have admitted to making nuclear weapons.

The NPT main objectives are to stop the further spread of nuclear weapons, to provide security for non-nuclear weapon states which have given up the nuclear option, to encourage international co-operation in the peaceful uses of nuclear energy, and to pursue negotiations in good faith towards nuclear disarmament leading to the eventual elimination of nuclear weapons.

The nonproliferation concerns previously discussed call for an international response that:

- strengthens the institutional underpinnings of the safeguards regime now, preparatory to a period of expanded nuclear power deployment;
- guides nuclear fuel cycle development in ways that reinforce shared nonproliferation objectives.

CONCLUSIONS

After this analysis, the following conclusions can be stated:

- Technology: research studies go on and general improvement in reactors performances seems to be probable: the most promising technologies are those based on higher temperature that permits hydrogen production or those based in closed cycle and high fuel burn up. Despite highly sophisticated safety methods, it is impossible to cancel the probability of a nuclear accident.
- Costs: a detailed comparison shows that nuclear power is economically competitive with coal generating technologies only if carbon taxes or cap and trade systems are adopted; as regards gas, the convenience is more probable in short time according with an high gas price and an ever growing nuclear technology.
- Waste: this is a source of great concern and uncertainty because, while most of scientists agree with geological disposal as the best way to manage nuclear waste, public opinion is skeptical about this solution. Actually only a few countries (USA and Finland) have approved a geological disposal facility realization, while most countries support long term storage plants.
- Proliferation: especially after September 11th, the misuse of reprocessing technology and nuclear materials is a threat to public security; only through an international accordance the proliferation risk can be contained. This response should strengthen the institutional role of the IAEA safeguards regime and improve nuclear fuel cycle surveillance.

In conclusion the future of nuclear power is uncertain: its independence from fossil fuel and the absence of carbon emissions is not enough to assure a wide diffusion in the short term because of problems of public concern and most of all waste management.

APPENDIX - CALCULATION OF THE LEVELIZED COST OF ELECTRICITY

The real levelized cost of electricity production is used to assess the economic competitiveness of alternative generating technologies. The real levelized cost of a project is equivalent to the constant dollar (“real”) price of electricity that would be necessary over the life of the plant to cover all operating expenses, interest and principal repayment obligations on project debt, taxes and provide an acceptable return to equity investors over the economic life of the project.

A project’s real levelized cost can be computed using discounted cash flow analysis, the method employed in the model described below. Revenues and expenses are projected over the life of the project and discounted at rates sufficient to satisfy interest and principal repayment obligations to debt investors and the minimum hurdle rate (cost of equity capital) required by equity investors.

Capital costs

Power plants require significant capital investments before electricity production can begin. The cash flow model allocates the overnight cost of the plant, C_O, specified in \$/kWe of the year production begins over the construction period, T_C, allowing for an additional period after construction for final licensing and testing. By convention, all investment expenditures are counted at the beginning of the year in which they occur, and all revenues and operating expenses are assumed to occur at the end of the year.

$$X_n = F_C C_O (1+i)^n$$

where X_n is the outlay in year n, F_n is the fraction of the overnight cost allocated to year n, and i is the rate of general inflation. In order to finance construction, the project takes on debt obligations and attracts equity investors with certain requirements. Debt and equity each have an expected minimum rate of return and debt has a specified repayment period. The interest on debt and imputed interest on equity are added to the overnight cost to find the total cost of construction.

$$C_{TOT} = \sum_{n<0} X_j (1+r_{eff})^{-n} \qquad r_{eff} = \frac{D}{V} * r_D + \frac{E}{V} * r_E$$

employing an effective interest rate r_{eff}. The total cost of construction does not represent true cash flows but is a measure of construction cost taking into account the time value of money.

Asset depreciation

Once put in service, the power plant depreciates according to a specified schedule. The treatment of depreciation is important in the calculation of the annual tax liability, since asset depreciation is a tax-deductible expense. Normally accelerated depreciation, based on Modified Accelerated Cost Recovery System (MACRS) guidelines, is used. The total capital expenditure (excluding interest and equity appreciation) during construction is used as the depreciable asset base. The depreciable asset base is based on nominal rather than real expenditures

Revenues

The sole source of revenue for the power plant is the sale of electricity. The price of electricity is determined in an iterative process such that required returns to investors are met. This price, p, is equivalent to the levelized cost of the plant. In order to represent a real levelized cost, the price of electricity escalates at the rate of general inflation.

Annual revenue is the product of the quantity of electricity produced and its price. The plant's net capacity and capacity factor determine the annual electric generation.

$$Q = \frac{L}{10^3} * \Phi * 8760 Hrs / year$$

$$R_n = Qp_n \qquad p_n = p_n (1+i)^n$$

where the rated capacity, L, is specified in MWe.

Operating expenses

Operating expenses are incurred throughout the operational life of the plant and include fuel, operating and maintenance costs, and decommissioning funds. Carbon emissions taxes and incremental capital expenditures similarly are treated as operating expenses. Non-fuel operating expenses can be broken down into fixed and variable cost components and are generally assumed to increase at the rate of inflation, though in some cases a real escalation rate is included. The assumed escalation of real fuel prices is a variable input to the model. This is particularly useful in the CCGT case where increases in natural gas prices have a large impact on the levelized cost of generation.

Total operating expenses are:

$$C_{n,Op} = C_{n,fuel} + C_{n,waste} + C_{n,omf} + C_{n,omv} + C_{n,decom}$$

Total operating expenses, $C_{n,Op}$, incremental capital expenditures, and carbon emissions taxes are subtracted from revenues before computing the annual tax liability. Two other adjustments are made to taxable income. Asset depreciation, D_n, and interest payments I_n to creditors are both treated as tax-deductible expenses and thus reduce taxable income.

The tax liability, T_n, is simply the product of taxable income and the composite marginal corporate income tax rate, assumed to be 38% in the base cases.

$$T_n = \tau\left\lfloor R_n - C_{n,Op} - C_{n,Incr} - C_{n,carbon} - D_n - I_n \right\rfloor$$

A production tax credit is available in the model to simulate, along with the carbon emissions tax, public policies to curb CO_2 emissions.

Investors return

The model solves for a constant real price of electricity sufficient to provide adequate returns to both debt and equity investors. Interest on debt accrues during construction and is repaid with the principal in equal annual payments over the specified term of the debt. Equity holders invest funds during construction and receive profits net of taxes and debt obligations during plant operation. Net profits over the life of the project are such that the internal rate of return (IRR) of the equity holders' cash flows equals the required nominal return. The model includes a constraint that the debt payment obligations specified are made in full each year. For example, assume that the model solves for a constant real price of electricity that satisfies the return required by equity holders. In most cases, the solution would be deemed the levelized cost of electricity.

However, if the resultant operating income (revenues less operating expenses) is insufficient to cover the entire debt payment in any year, the electricity price is raised until all debt payments can be made.

If the debt service constraint is binding, the realized return on equity will then exceed the minimum required return specified.

Since the purpose of the levelized cost calculation is to compare alternative generating technologies and assess their potential contribution to future energy supply, the technologies compared must generate electricity over equivalent time periods. In order to maintain the level basis for comparison, plants are not allowed to shut down prematurely when operating expenses exceed revenues, as in the case of escalating natural gas prices. The result in these situations is a cash flow stream for the project that does not reflect expected business decisions.

Model Variables

C_O	Overnight cost (\$/Kwe)
T_C	Construction time (years)
C_{TOT}	Total construction cost (\$/Kwe)
D/V	Debt fraction of initial investment
E/V	Equity fraction of initial investment
r_D	Nominal cost of debt
r_E	Nominal cost of equity
N	Plant life
Φ	Capacity factor
p_n	Nominal price of electricity in period n
τ	Marginal composite corporate income tax rate
HR	Heat rate (BTU/KWh)
C_{Fuel}	Unit cost of fuel (\$/mmBTU)
C_{waste}	Nuclear waste fee (mills/KWh)
C_{omf}	Fixed O&M (\$/Kwe/yr)
C_{omv}	Variable O&M (mills/KWh)
C_{incr}	Incremental capital cost (\$/Kwe/yr)
C_{decom}	Decommissioning cost (\$ million)
τ_{carbon}	Carbon emissions tax (\$/tonne-C)
I_{carbon}	Carbon intensity of fuel (Kg-C/mmBTU)
R_n	Revenues in period n

I_n	Interest payement in period n
$C_{n,op}$	Total operating expenses in period n

Table 12 - Symbols

Expense	Value yerar n	Notation
Fuel	$C_{fuel} * HR * Q * (1+e_f)^n$	$C_{n,fuel}$
Waste fund	$C_{waste} * Q * (1+i)^n * 10^{-3}$	$C_{n,waste}$
Fixed O&M	$C_{omf} * L * (1+e_{om})^n * 10^{-6}$	$C_{n,omf}$
Variable O&M	$C_{omv} * Q * (1+e_{om})^n * 10^{-6}$	$C_{n,omv}$
Decommissioning	$C_{decom} * (1+i)^N * SSF_0$	$C_{n,decom}$
Incremental capital	$C_{incr} * L * (1+i)^n * 10^{-3}$	$C_{n,incr}$
Carbon emission tax	$\tau_{carbon} * I_{carbon} * HR * Q * (1+i)^n * 10^{-9}$	$C_{n,carbon}$

BIBLIOGRAPHY

- Various Authors - The future of nuclear power: an interdisciplinary MIT study - MIT Press.
- Various Authors - The economic future of nuclear power: a study conducted at The University of Chicago.
- G. Perkovich, J. T. Mathews, J. Cirincione, R. Gottemoeller, J. B. Wolfsthal - Universal compliance: a Strategy For Nuclear Security.
- www.world-nuclear.com
- IAEA circular - Multilateral approaches to the nuclear fuel cycle.
- IAEA document - The long term storage of radioactive waste: safety and sustanbility.