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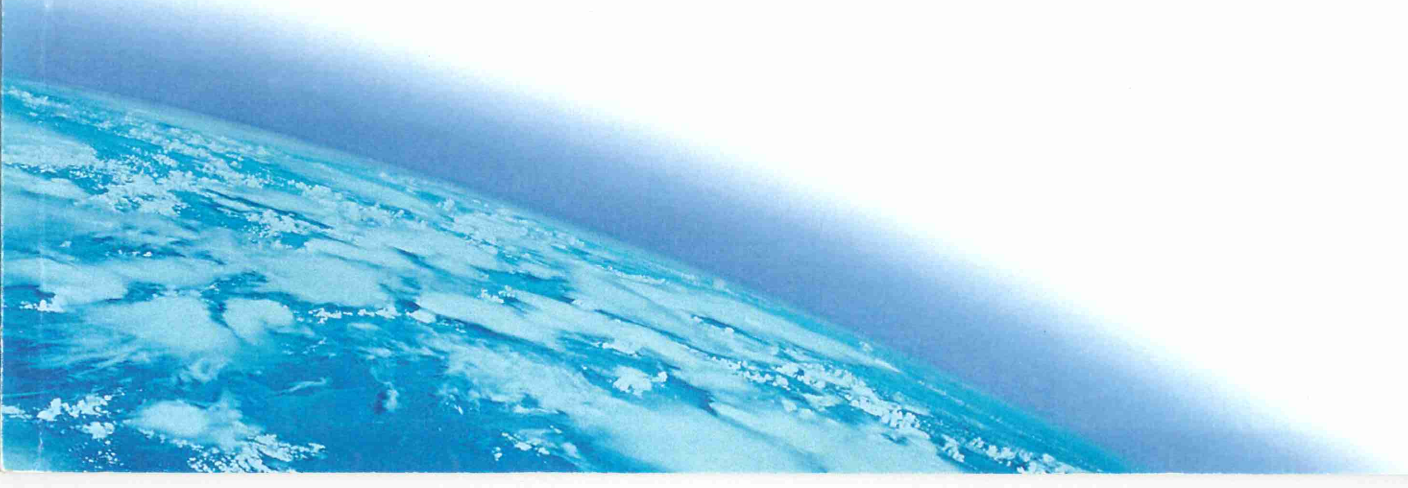
What (not) to expect from nuclear power



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What (not) to expect from nuclear power

by

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Summary

Till some years ago, the prevailing outlook for civil nuclear energy production was one of slow decline. Now, there is a widespread feeling that this may, or should change. Global issues like energy security and climate change call for different priorities. A new future for nuclear energy could be based on progress in science and technology. One often heard statement is that, once the problem of nuclear waste is solved, nothing stands in the way of rapid, large-scale deployment of nuclear. Also, large developing countries in Asia, where nuclear energy does not bear "the burden of history" are thought capable of building significant nuclear capacity in the coming decades.

In this report, we conclude that there is little reason to assume that there is a "nuclear revolution" at hand. For the coming decades, growth of the installed capacity and technological progress will be gradual. The following findings support this conclusion:

- Civil nuclear energy has not become commercially viable. It has been, and still is, a purely political choice. On a future market for carbon-free, large scale energy supply, this might change.
- New reactor technologies can not be expected to make nuclear's future look very much different from its past. Any sizable expansion of nuclear energy would have to be provided by current reactor types, with evolutionary improvements serving safety, economy and fuel efficiency.
- Reserves of natural fissionable uranium are sufficient to fuel any imaginable nuclear fleet for the next century. Costs will rise as supply becomes dependent on lower grade ores, but the impact on nuclear electricity cost is minor. On the short-to-medium term, production capacity can fail to meet a rising demand.
- In view of this, practices like fuel recycling or breeding are not justifiable by economics. Reasons to pursue them are, again, politically motivated.
- The imaginable in which nuclear can contribute to electricity generation on the 2050 horizon lies between 8 and 20% of total electricity generated.
- The promise of cheap hydrogen is not based on sound technology.
- The promise of cheap small-scale nuclear electricity is not based on sound economics.

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1. Introduction

For a number of years now, nuclear energy has been finding its way back into conversations, its virtues first rediscovered by stakeholders and lifelong proponents of the sector, later by parties with a more neutral view. More recent, the turnaround of a few nuclear-naysayers could be witnessed and at this moment the debate about nuclear energy is rapidly re-emerging in the public domain. Of course, the association between energy and global warming offers the chance for nuclear energy to shift from the dirty side to the clean side of the energy spectrum.

The debate, it should be stressed, is largely an affair of the Western world. For a number of reasons, in other areas of the world (like in France) nuclear energy has never been the subject of much dispute. But in Europe and North-America, the nuclear option slowly awakens from decades of hibernation and finds itself amidst the same controversy that sent it to sleep in the first place.

Since the sale of its 50% stake in General Atomic Co., in 1982, Shell has kept nuclear energy firmly outside its energy portfolio, now basically limited to oil and gas. Recent external developments, from the climate change issue, the dependence on fossil energy and frequent news about the 'nuclear renaissance' have many people wonder if this is a sensible position. This report addresses many of the prevailing arguments, be they supporting or questioning such a policy for an energy major. A number of popular assertions are traced back to their origin, or examined in the light of the facts.

2. Nuclear Now

At the start of 2005, there were worldwide 441 nuclear power plants in operation with a total net installed capacity of 370 GWe, or 10.4% of total installed generating capacity.

Construction was started on 27 new power plants. In the course of 2004, 6 new plants were connected to the grid, 5 units were shut down and 2 new plants came under construction.

In 2002, nuclear power generated 2650 TWh of electricity, or 16.5% of total electricity. Its share of total primary energy supply for the same year was 6.7%[1] [IEA 2004].

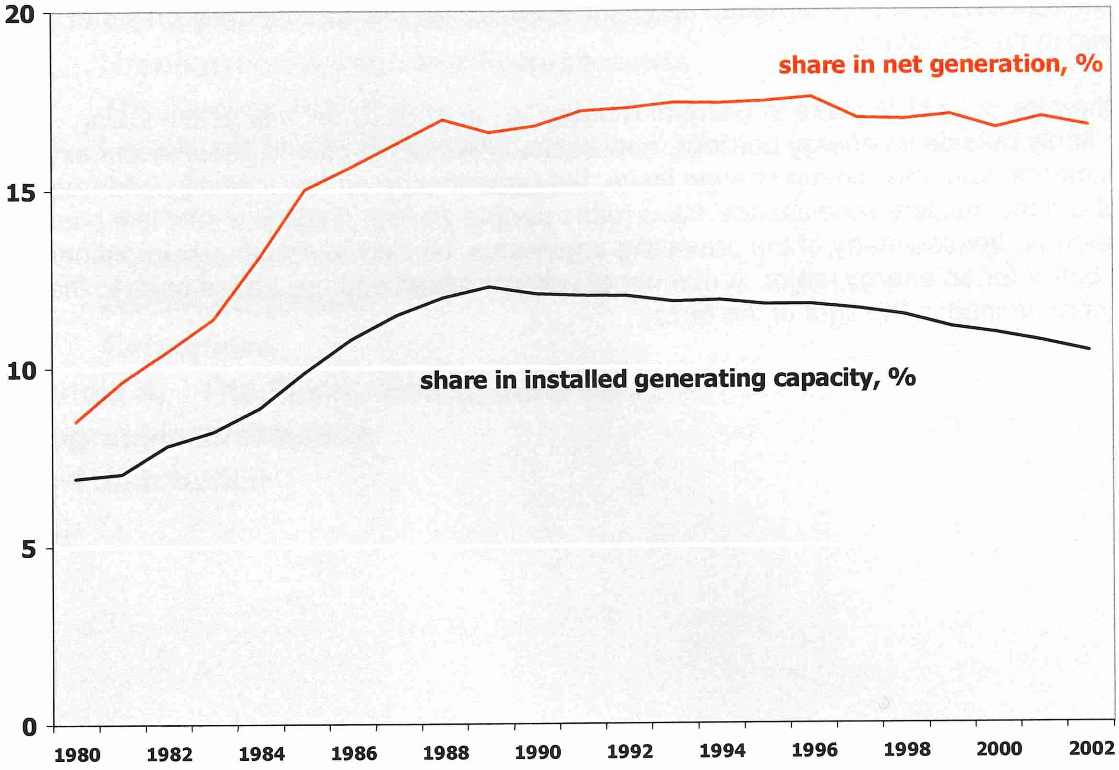

Figure 1: World nuclear share in installed capacity and generated electricity

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[1] Assuming heat is converted to electricity at 33% efficiency.

3. History

In its short history of a bit more than fifty years, nuclear energy (or more precise: generation of electricity from heat derived from nuclear reactions) has gone through dramatic phases. At present, it is often seen as a failed promise from the past which is surrounded by prickly issues, nevertheless needing to be reexamined in the light of the world's growing demand for secure energy and the threat of global warming. To get a clear picture of nuclear's future, a look at this history is a good start: it shows why nuclear is where it is today.

What started the feverish race to develop uses for "Man's New Servant, the Friendly Atom"[2]? Surely, it was not the prospect of "electrical energy too cheap to meter." This often quoted phrase was originally spoken by Lewis L. Strauss, chairman of the US Atomic Energy Commission, addressing the National Association of Science Writers in New York, on September 16th, 1954. Strauss likely knew better, and in any case much of his contemporary experts did. It was unlikely that heat produced in nuclear reactors would ever become much cheaper than that from burning coal, and even if it did, only 20% of the cost of electricity (the fuel cost part) would be affected.

The real drivers behind the development of nuclear power were political. Priorities in the second world war had forced the atomic cat out of the bag, and now it badly needed taming. In the words of Dwight D. Eisenhower:

> *"It is not enough to take this weapon out of the hands of the soldiers. It must be put into the hands of those who will know how to strip its military casing and adapt it to the arts of peace."*

On Eisenhower's strategic agenda, there were at least three considerations that played a role in the urge to pursue this adaptation. First, there was the need to gain, and regain influence in Europe, where the recovery from the war was gaining pace, and the rebuilding of the industry brought about a need for plentiful energy. The considerations were the same as those behind the Marshall Plan[3]: if we don't help out, the Russians will. In fact, Russian progress in civil nuclear technology was feared more by the U.S.A. than their advances in bomb manufacturing.

Two other factors were related to the availability of uranium. At the time it was believed that natural supplies of uranium were very limited and offering nuclear energy technology to countries like - for instance – Belgium, would ensure access to uranium resources of those countries. Furthermore, in his "Atoms for Peace" address[4], Eisenhower proposed a scheme wherein fissionable material was to be removed from the military stockpiles and placed under control of an agency under the patronage of the U.N. It would be made available for peaceful use and the U.S. would share its nuclear know-how with nations seeking this peaceful use. This noble plan was doubtlessly co-inspired by the fact that the U.S. could afford to divert far

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[2] A phrase from F. Barrows Colton, Assistant editor of National Geographic magazine in 1954.
[3] Between 1948 and 1951, the United States contributed more than $13 billion dollars (nearly $100 billion at present-day U.S. conversion rates) of economic and technical assistance toward the recovery of 16 European countries which had joined in the Organization for European Economic Cooperation (OEEC, forerunner to today's OECD) in response to Marshall's call for a joint scheme for European reconstruction [source: Wikipedia].

[4] Address by Mr. Dwight D. Eisenhower, President of the United States of America, to the 470th Plenary Meeting of the United Nations General Assembly, Tuesday, 8 December 1953

more fissionable material from its military stocks than the U.S.S.R., without jeopardizing their weapons program.[5]

U.S. nuclear technology became declassified (Eisenhower called it a “wasting asset”) and – to some extent- available to the world wide scientific community. Development of commercial nuclear technology started in the U.S., but by far not at the speed that the general public was led to believe. Charles Douglas Jackson, the President’s cold war strategist, considered the message that Americans could soon benefit from limitless cheap electricity to be of great propaganda value, and made sure it was broadcasted widely by the media.

In 1954, work was started on the Shippingport facility, a 90 MWe Pressurized Water Reactor (PWR) which was to be the USA’s first commercial nuclear power plant. Late 1957, the unit was connected to the power grid. The ‘overnight construction cost’ was around $[6] 420 million, or $4700/kW. At that time, cost of future nuclear capacity was predicted to decline along a learning curve typical for utility industrial technology [see, for instance Ullmann 1958], and in the early 60s turnkey building contracts for a cost of around $1500/kW were issued [EIA 2004]. These predictions proved to be far too optimistic however, the vendors suffered huge losses on the first projects and, from the mid-60s started offering only cost-based contracts.

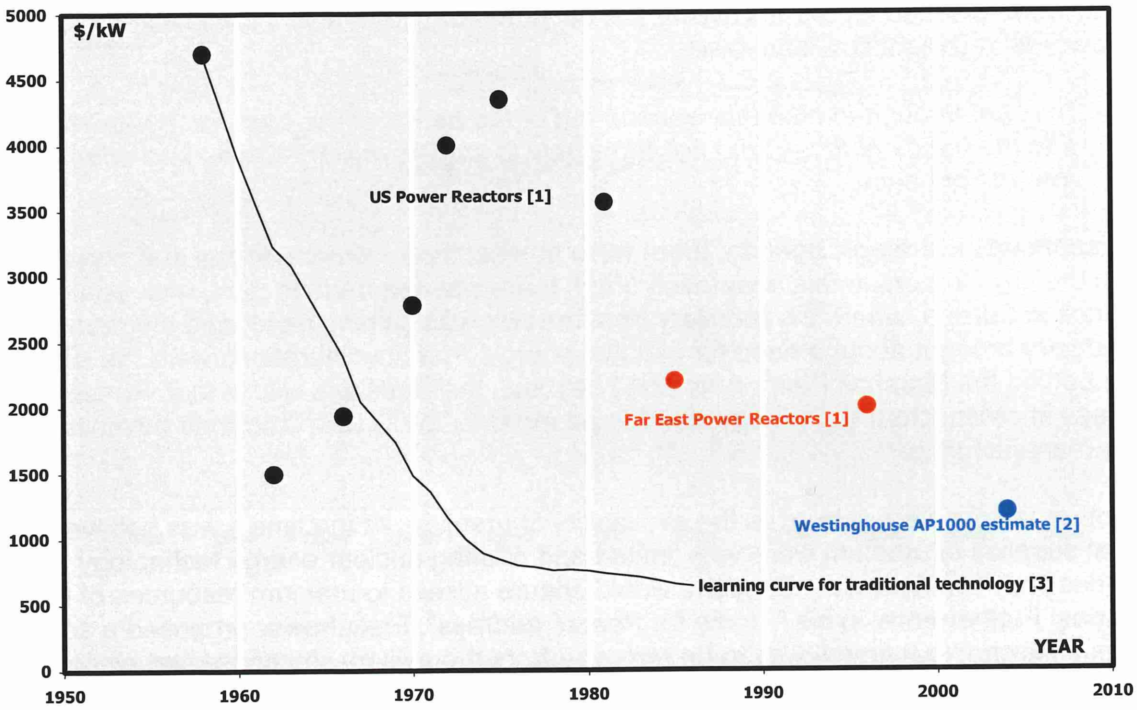

Figure 2: Overnight construction cost of nuclear power facilities

Sources: [1]US DOE/EIA, Electric Power Research Institute (EPRI); [2]Westinghouse AP1000 building cost indication, not yet realized; [3]:Ullmann 1958; *Note: the expected cost decline has been plotted as a function of the actual installed capacity.*

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[5] The Soviet Union did not take the bait: the International Atomic Energy Agency saw the light in 1957, but controls on the directing of fissionable materials was implemented only after 1970, when the Nuclear Proliferation Treaty was accepted by almost all key industrial countries.

[6] Unless otherwise indicated, all financial data in this report have been converted to 2002-dollars, using data from the United States' Bureau of Labor Statistics.

To make matters worse, government regulation and reactor design were still evolving, burdening the projects with long lead times and frequent, costly backfitting during construction. In the mid 70's, the construction cost was almost back at the level of the first plant, above $4000/kW. Cost of capital for new nuclear plants (which is needed largely up-front) became increasingly expensive, driving the total cost of ownership to unrealistic heights. After 1974, utilities stopped ordering new units and cancelled orders that had already been placed.

A much lower construction cost has since then been realized in Japan and South Korea. Also US vendors have prepared designs of modern PWR's in the (overnight) cost region of $1000/kW to $1300/kW. It appears that, with a delay of 20 years, the nuclear power plant is finally riding down the learning curve.

In many views, the blossoming nuclear industry in the western world has been maimed by public opposition and escalating environmental requirements. The above paragraphs suggest otherwise: political priorities of the USA, technology optimism and the market had already taken care of that, when on March 28, 1979 the incident at the Three Mile Island plant in Pennsylvania triggered a wave of public fear for the technology and distrust in regulating authorities see Figure 3).

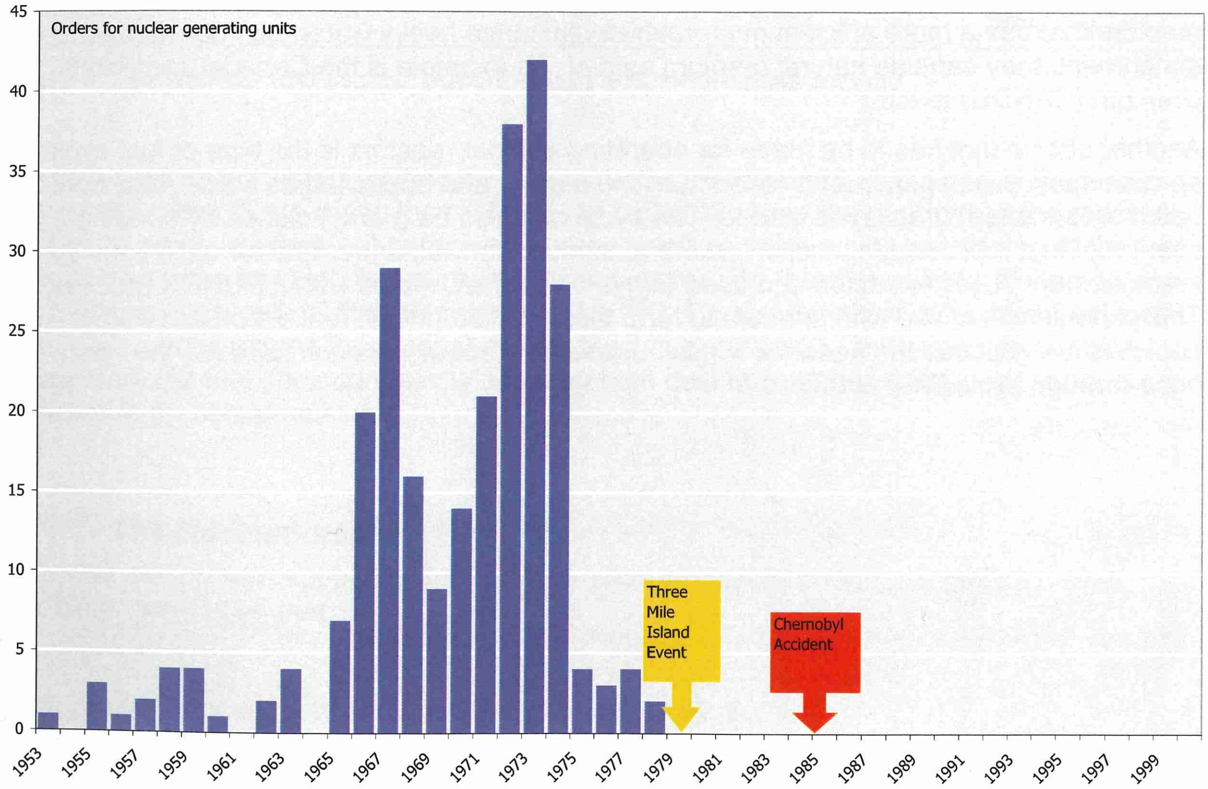


Figure 3: Timeline of nuclear events: orders from U.S. utilities for nuclear generating units and nuclear mishaps

4. The State of the Art

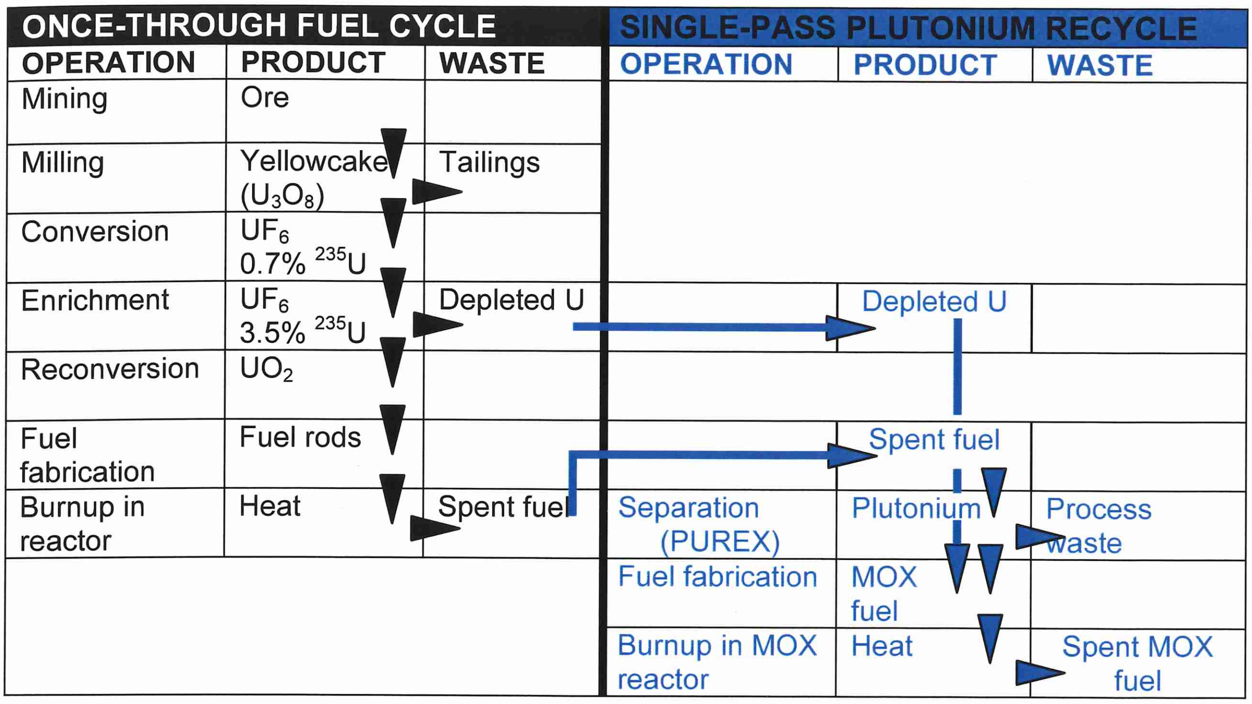
4.1 Basics

A nuclear reactor delivers heat, obtained from the fission of heavy atoms, usually ^{235}U. The fission reaction is triggered by neutrons, and produces new neutrons. This principle causes, under the right circumstances, a sustained chain reaction. One important condition is the energy, or the velocity of the neutrons in the reactor core. A moderator is used to slow down fast neutrons obtained from the fission reaction, to make it possible for them to trigger a new fission event. The heat developed by the process is removed by a coolant and transported to a heat engine (usually a turbine) for conversion to electricity. So, we have the basic ingredients of a nuclear power plant: fuel, moderator, coolant, turbine and generator.

By far the most common type of nuclear power reactor is the Pressurized Water Reactor (PWR). Water serves both as moderator and coolant, in a high-pressure primary circuit. Steam to feed the turbine is generated in a secondary circuit. Another fairly popular type is the Boiling Water Reactor (BWR). By keeping the reactor pressure lower than in a PWR, the water coolant is allowed to boil, and the steam is directly fed to the turbine.

Fuel for the PWR and BWR reactors (together called Light Water Reactors or LWRs) is uranium, ^{235}U to be more precise. This isotope is present in natural ore at ca. 0.7%. For use as fuel in a LWR, this content has to be increased to 3.5 to 4 % by a enrichment. Nuclear reactors that use a more efficient moderator, for instance heavy water, can do without enrichment: they can use natural uranium as fuel. An example is the Canada Deuterium Uranium (CANDU) reactor.

Another choice that has to be made for operating nuclear reactors is the type of fuel cycle. In an open fuel cycle, spent fuel is taken from the reactor and deposited as waste, and new batch of (enriched) uranium is loaded. The cycle can also be (partly) closed by sending the spent fuel to a reprocessing facility, where plutonium (formed under reactor conditions by irradiation of ^{238}U) is extracted and used to make new fuel, the so called PUROX process. This plutonium is mixed with uranium to form Mixed Oxide (MOX) fuel. Reprocessing of depleted fuel reduces the need for “virgin” uranium by about 15% compared to the open, once-through cycle [MIT 2003].



ONCE-THROUGH FUEL CYCLE			SINGLE-PASS PLUTONIUM RECYCLE		
OPERATION	PRODUCT	WASTE	OPERATION	PRODUCT	WASTE
Mining	Ore				
Milling	Yellowcake (U_3O_8)	Tailings			
Conversion	UF_6 0.7% ^{235}U				
Enrichment	UF_6 3.5% ^{235}U	Depleted U		Depleted U	
Reconversion	UO_2				
Fuel fabrication	Fuel rods			Spent fuel	
Burnup in reactor	Heat	Spent fuel	Separation (PUREX)	Plutonium	Process waste
			Fuel fabrication	MOX fuel	
			Burnup in MOX reactor	Heat	Spent MOX fuel

Figure 4: The nuclear fuel cycles: once-through and single-pass recycle

The light- and heavy water reactors mentioned above, and indeed all but one of the world's commercial reactors are of the thermal type, so called because the neutrons in the reactor are slowed down (moderated) to thermal energy levels. A more advanced closing of the fuel cycle can be done by using fast nuclear reactors, which can "burn" a number of elements that make up the waste of thermal reactors, like ^{238}U, Pu and Actinides. While fast reactors could thus greatly reduce the amount of long-lived nuclear waste, and extract far more energy from the fuel, their complexity and very high cost makes them, at present, unattractive for commercial use.

4.2 The Nuclear Issues

For broad stakeholder support of further expansion of nuclear energy, these five critical conditions need to be met:

1. Safety and security of nuclear facilities and operations.
2. Safeguards against adverse use of radioactive or highly toxic substances.
3. Economically competitive production of energy.
4. Safeguards against proliferation of fissionable materials.
5. An acceptable solution for disposal of radioactive and highly toxic wastes.

The type of reactor technology and operating regime for future nuclear power plants will have implications for all five issues, although not for all to the same extent. Today's most advanced LWR's could potentially offer safe operation and deliver electricity at near-competitive prices, at least when operating on a once-through fuel cycle. Reprocessing spent fuel (the PUREX-MOX route) would add significantly to the electricity cost, perhaps as much as 50% (for an extensive treatise on this see [Bunn 2003]). Also, separating plutonium from spent fuel creates stockpiles of weapons-grade material, presenting a proliferation risk. On the other hand, the once-through cycle creates more long-lived waste. A fast nuclear reactor could minimize the waste problem, but has forbidding economic consequences. This story could be continued to considerable length, but the gist is that there are options available to mitigate some of the critical problems, but usually at the expense of the remaining ones.

Different views exist on how to carry on (if at all, of course). The conventional large water-cooled reactors have shown, over the last decades, a good safety- and operational track record. For existing units, lifetimes are being extended and nameplate capacities up-rated. New design philosophies, adding passive safety systems and more standardized components can possibly bring the construction cost down to a competitive level. The technology-oriented communities in the nuclear domain are, in general, in favor of a radical new design for nuclear workhorses of the future. By an initiative from the US DOE, an international research consortium was assembled in 2000 to explore this pathway: the Generation IV International Forum (GIF) (-see next chapter-).

5. The Generations of the Nuclear Family

By age and design, nuclear power reactors are often classified into generations. Generation I were the early prototypes, often graphite moderated reactors. Virtually all commercially operated power units of today belong to Generation II: light- and heavy water reactors and some gas cooled designs. Generation III came about in the 1990s, when the outlook for new nuclear capacity in the Western world was grim. Some were built and are being planned in Japan, Taiwan and Korea, and now also in China. They present a step improvement on the water-cooled reactors of Generation II, characterized by simpler, more economical construction and passive safety systems that should virtually eliminate chances of a "loss of coolant event[7]". The optimal size for these units is in the 500-1500 MWe range. Examples of this generation are:

- Advanced Boiling Water Reactor (AWBR), supplied by General Electric, 1350 MWe, built and operating in Japan.
- AP600 and AP1000 family of advanced PWR's, designed by Westinghouse, 600/1150 MWE. The AP600 has been certified by the US Nuclear Regulatory Commission.
- SWR1000, a 1013 MWe BWR, designed by Framatome/ANP to meet European requirements.
- Advanced CANDU reactors from AECL. The Canadian company has been steadily improving (and building) their heavy water reactor. The newest design, the ACR-700 needs less heavy water and uses slightly enriched uranium fuel. The CANDU design also enables in-service refueling.

Any sizable additions of the world's nuclear power fleet within the next 25 years will have to come from this generation of plants.

Some of the advanced reactors mentioned above are, sometimes and rather arbitrarily, called Generation III+ technology. G-III+ would stand for: safe and economical operation feasible before 2010. A prominent member of this category is the Pebble Bed Modular Reactor (PMBR), a design that is considered by some to enable nuclear energy's revolutionary comeback and offer hydrogen manufacture as well. More on the PMBR, a much-hyped subject, can be found in the Appendix at the end of this report.

Finally, there is the Generation IV nuclear technology [NERAC 2002], which would have to deal with everything that went wrong in the past, and with everything that could go wrong in the future. It is to be safe, economical, resistant to proliferation and producing minimal waste streams. Solutions must be offered for electricity in small and in large grids, for production of hydrogen and other chemicals and for water desalination. G-IV reactors will also operate at temperatures much higher than previous generations (550-1000°C compared to 250-350°C), so the turbines can operate at higher Carnot efficiencies.

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[7] Loss of coolant precedes the much-feared core meltdown. The accident in the Three Mile Island plant, in March 1979, was a loss of coolant event that led to a partial meltdown.

Uranium supply issues must be met, by obtaining more energy from the same amount (see also the chapter on uranium resources). Destruction of transuranic elements (by transmutation) would be beneficial, as it –in theory- removes the nastiest parts from the waste. The Generation IV International Forum (GIF) has chosen six different concepts that hold the promise to score high on the list above, and identified the needs for enabling research work. The objective of the effort is to have systems available for wide-scale deployment before 2030.

Table I: Generation IV Nuclear Systems [NERAC 2002]

System Acronym	Neutron Spectrum Fuel Cycle	Coolant	Temperature (°C) Pressure (Mpa)	Earliest deployment[8]	Mission
Gas Cooled Fast GFR	Fast Closed	Helium	850 9	2026	Electricity Actinide Management
Lead Cooled Fast LFR	Fast Closed	Pb/Bi eutectic	550-800 0.1	2026	Electricity (Decentralized) Process heat
Molten Salt MSR	Epithermal Closed	Molten fluorides of Na, Zr and U	700 0.1	2026	Electricity Waste burndown
Sodium Cooled Fast SCR	Fast Closed	Liquid sodium	550 0.1	2021	Electricity Actinide Management
Supercritical Water Cooled SCWR	Thermal or Fast Once-through or Closed	Water	550 25	2026	Electricity
Very High Temperature VHTR	Thermal Once-through	Helium	>1000 10	2021	Process heat Hydrogen

All fast systems can operate in a closed fuel cycle and offer actinide management, mitigating the high-level waste issue. Other issues (safety, security, proliferation, economics) are addressed to varying degree by the different concepts. The MSR seems to be the most complicated and costly generation member, but it can also operate in a closed fuel cycle and has an attractive waste burndown performance. The SCR could be Generation IV's first-born, since the concept has already received attention in the past. The VHTR has the highest priority for the US DOE, based on the (unproven) option for hydrogen production through thermochemical water splitting (see section 8.3). It scores poorly on waste minimization, because of its once-through fuel cycle.

Of course, it is difficult to say what the chances are, for this fourth generation of “man's best servant”. What can be said is, that virtually all research priorities are in the field of material science, where progress is usually erratic, but seldom fast. Also, looking at research budgets that have been made available to date (US $21m, France €30m, both for 2003) there is not really a call for great optimism.

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[8] End of demonstration phase

In any case, policy makers responsible for addressing pressing energy and environment issues are unlikely to sit on their hands for another 25 years, wondering if nuclear technology development will deliver on its latest promises.

6. Uranium Resources and Requirements

Uranium, in short supply and at the same time abundantly available: in this sense, the nuclear fuel is not unlike oil. Despite the fact that scarcity of uranium is often mentioned by anti-nuclear groups and its abundance quoted by nuclear advocates, there is truth to either view.

The world's 438 power reactors require a yearly supply of 66550 t of uranium [Combs 2004]. Total production from mining and milling, for 2003 was 35783 t [WNA 2004], half of this originating from Canada and Australia combined.

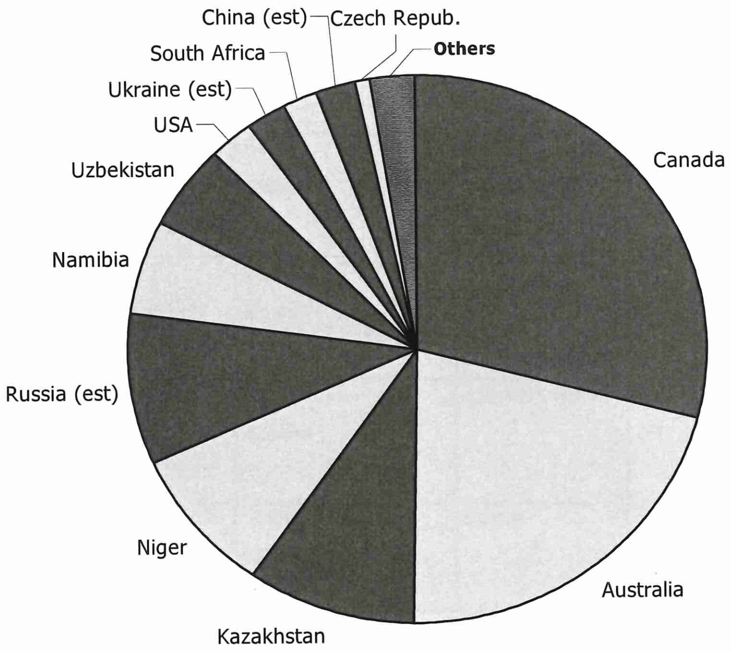

Figure V: Uranium producing countries in 2003; Total produced amount is 35783 t/U source: [UIC 2005]

The remaining 30767 t was provided from civil and government inventories. At flat demand, this situation can go on for another 8-10 years, after which the stockpile will have run out and the production from mining, including the currently planned expansions, can not meet the requirement [Steyn, 2004].

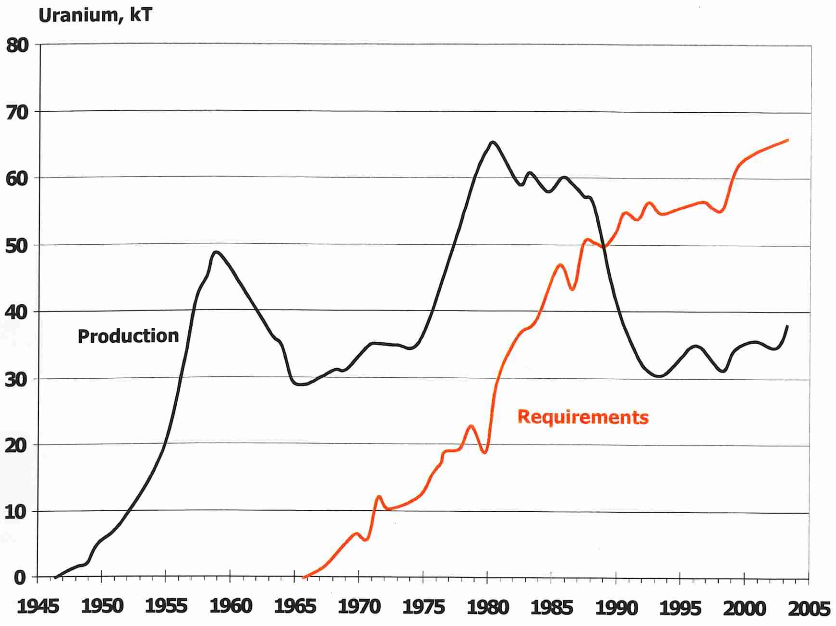

Figure VI World Uranium Production and Requirements

source: [Combs 2004]

In terms of the resource size, the OECD/IAEA Redbook [IAEA 2003] reports the worldwide uranium resource to be 3.1 Mt (Reasonably Assured Resources plus Additional Estimated Resources Cat I, cost up to \$80/kg U[9]). Adding the amount still available in stockpiles brings a total of 3.3 Mt, or 50 years at current demand. This can be longer if more costly or more speculative resources are included, but the message remains that the amount of known natural uranium ore will last for decades, and not for centuries.

If we lump together all the world's nuclear power reactors (all but one are of the thermal type and have broadly similar fuel-to-energy ratio's), using 2003 data, we can draw up the following global fuel cycle:

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[9] Current spot price is around \$50/kg U

STEP	PRODUCT	AMOUNT
Mining & Milling	U_3O_8 with 0.71% ^{235}U	66550 t U
Enrichment	Fuel: UO_2 with 3.2% ^{235}U	9275 t U
Reactor	Heat	7650 TWh
Generation	Electricity (@ 33% efficiency)	2550 TWh
Reactor discharge	Spent fuel with 0.8% ^{235}U	8950 t U 85 t Pu

Table II: Fuel Cycle for 'Global Reactor'

Of course, we are not interested in uranium, but in how much energy it can deliver. The average fuel 'burn up', the amount of thermal energy extracted per ton of fuel, amounts to 825 GWh/t. All kinds of approaches have been devised to enhance this burn up. The current average for US LWR's is 1200, the increase mainly obtained by keeping the fuel longer in the reactor, so that more fissionable ^{239}Pu is formed from ^{238}U, a mild form of breeding in the fuel core. In European and Japanese reactors, the PUREX/MOX process is used. To some extent, Pu from spent fuel is recovered and used to replace some ^{235}U in new fuel (MOX stands for Mixed Oxide). By this approach, natural uranium requirement for a given energy output is lowered by 12-15%. High temperature gas cooled reactors, especially of the fast type, can reach a significantly higher burn-up. The VHTR concept in the Generation IV portfolio is laid out for a value of 4800 GWh/t, four times higher than the LWR benchmark. And finally, of course, in true fast breeder reactors, also ^{238}U (and not just the 0.7% ^{235}U) could be turned into fissile fuel, stretching the resource by a factor of approximately 60.

The amount of natural uranium that is available (with its 0.7% ^{235}U the single source of fissile material in nature) can vary over several orders of magnitude, depending on assumptions. The Redbook reports data provided by individual countries and only deals with ores that are compatible with mining and milling as currently practiced. The numbers are classified in three cost categories and four classes of certainty:

U Resources (kt)	< US$ 40/kg U	< US$ 80/kg U	< US$ 130/kg U
Reasonably Assured[10]	1534	2242	2853
Estimated Additional I[9]	552	865	1080
Total	**2086**	**3107**	**3933**
		< US$ 80/kg U	**< US$ 130/kg U**
Estimated Additional II[9]		1480	**2332**
	< US$ 130/kg U	**Unassigned Cost**	**Total**
Speculative[9]	4438	5501	**9939**

Table III: Conventional Uranium Resources

Then there are a number of unconventional sources of uranium, for instance phosphate deposits, typically containing 40 to 150 ppm by wt. of uranium, with an often quoted total amount of 22000 kt U. But all unconventional resources are dwarfed by the estimated content of the world's oceans: 4000 Mt., at a concentration of 3 mg U/m^3 water. The latter has attracted mainly Japanese interest [Seko 2003], as its 54 nuclear power plants rely entirely on uranium imports and plutonium recycle. It is estimated that extraction from seawater can become economical at a price from \$300/kg U [IAEA 2003].

An extensive treatment of uranium resource availability and economics is available in [Bunn 2003].

To sum things up, there are no hard reasons why a nuclear expansion should be restricted by fuel resource economics, all the more so because the cost of nuclear energy is not very sensitive to fuel cost. This does not mean however that there will not be supply problems on the short-to-medium term. Over the last 20 years, the outlook for the nuclear power industry has been gloomy, uranium demand remained flat and market prices were depressed by military stockpiles, especially from the former Soviet Union, that became available. Incentives to invest in exploration and new production capacity have been accordingly low. As mentioned in the beginning of this section, even if demand remains constant, production could fall short within a decade. Whether this situation is to be avoided by extracting more uranium from the earth or more energy from the given amount, both approaches will need timely investments in view of their very long lead times.

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[10] Reasonably Assured (RAR): known deposits of delineated size, grade and configuration. Estimated Additional I (EAR-I): expected to occur in extensions of well explored deposits. Estimated Additional II(EAR-II): expected to occur in well defined geological trends, based on indirect evidence. Speculative (SR): thought to exist, based on indirect evidence and geological extrapolations.

7. The Nuclear Futures

7.1 Large-scale power generation

As said above, nuclear's future is a matter of choices that have to be made, of what reactor technologies to pursue, which fuel cycles to adopt, how to tackle or mitigate the classic critical issues. If the right decisions are made, nuclear energy could continue to deliver a sizable share of the world's energy needs. But the sheer number of options available, and consequences that are entangled in intricate ways might well turn out to be the ultimate stumbling block. Man's dealings with the 'friendly atom' cast long shadows in the fields of politics and the integrity of his environment. It is one thing that governments and stakeholders hold views that scatter over the entire spectrum, in terms of acceptability and sustainability of nuclear fission energy. The fact that this is also true for the community of experts in nuclear science and technology is more serious. In such a situation, choices and options become dilemmas, and critical problems remain unsolved.[11]

In terms of share in global primary energy demand, the imaginable bandwidth for nuclear around 2050 lies between zero and ten percent, the higher value calling for a very ambitious scheme of new construction and deployment. A convincing case for this is made in an enlightening study published by an interdisciplinary team from the Massachusetts Institute of Technology: "The Future of Nuclear Power" [MIT 2003]. It provides a sound analysis of what would be needed to make nuclear power a significant contributor to reducing CO_2 emissions. It also makes a convincing case that timely consistent choices and decisions are essential, and the presented scenario is based on these. It places a threefold expansion of current worldwide nuclear generation capacity on the 2050 horizon, calling for 1000 new reactors of 1 GWe size[12]. Some of the most prominent choices and conclusions seen as vital for this pathway:

- The once-through fuel cycle is to be adopted, for reasons of economy, safety and security.
- Light-water reactors are to remain the technology of choice, in a modernized design that offers passive safety and rationalized, economical construction methods.
- Nuclear power should not expand unless the risk of proliferation from operation of the commercial fuel cycle is made acceptably small.
- New, advanced reactor and fuel cycle technologies are not seen as capable to simultaneously overcome problems of cost, safety, waste and proliferation.
- Governments should support the construction of new facilities, by subsidizing a number of "first mover" plants and a tax credit for CO_2-free electricity.

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[11] An appropriate illustration of such a stalemate is provided by the fate of long-lived waste with high radiation and toxicity level. All material in this category that has been generated since the 1950s is still being held in "temporary storage." In 1980 US presidential candidate Ronald Reagan was quoted in the Burlington Free Press as saying: "All the waste in a year from a nuclear power plant can be stored under a desk", but this statement does little justice to the extent and urgency of the predicament. "Experts" have come up with a wide range of solutions, or even a denial that it is a problem in the first place. A pick from the menu: underground (engineered) storage with the option of future retrieval, permanent isolation in deep, stable formations, burn-up (transmutation) in dedicated reactors, keep it available until more advanced reprocessing is available and economical (it is not waste, it is fuel). But meanwhile, it stays "under the desk".

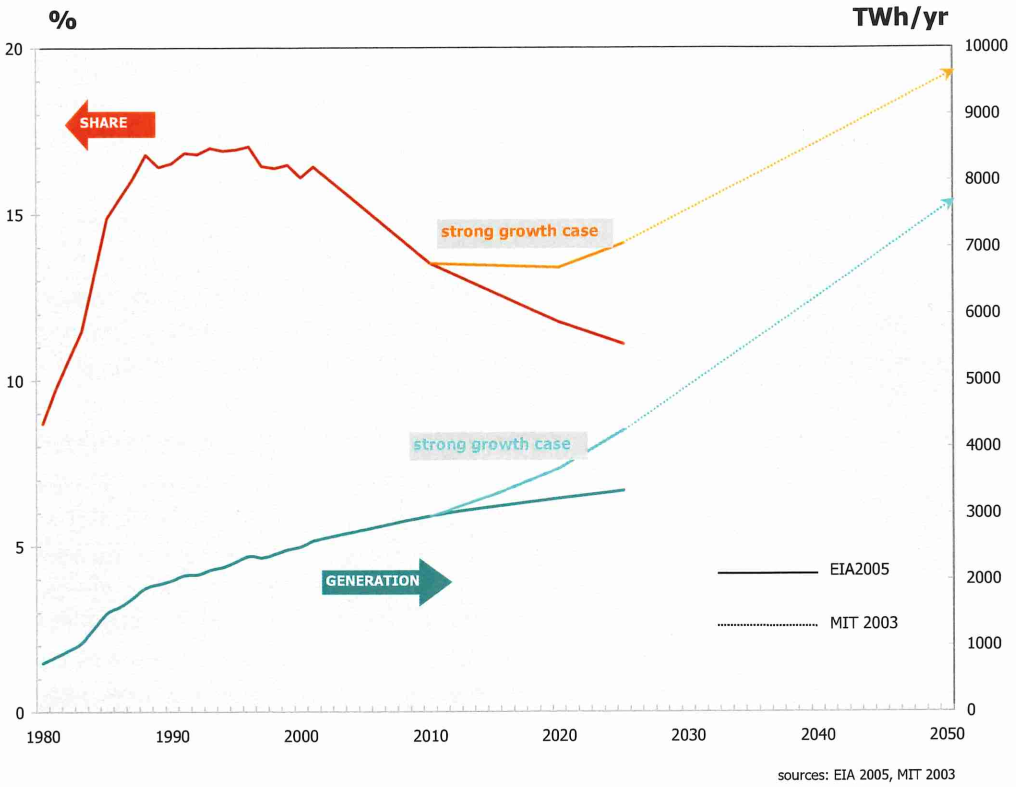
[12] Total world nuclear capacity would be 1000 GW, since most of today's plants will be retired by 2050.

As the scenario leaves out plutonium recycle and fast reactors, it depends on the availability of sufficient natural uranium at an affordable cost. Some 10 Mt of uranium is needed for the lifetime operation of one thousand 1 GW reactors. The authors of the study are confident that current reserve estimates are very conservative and that the base can be considerably extended by increased exploration. They quote the Australian Uranium Information Center, which states that a doubling of the current market price will result in a tenfold increase of the resource.

The MIT study presents a realistic picture of how nuclear can keep, or slightly expand its current share in electricity production over, and beyond the next 50 years, in which research priorities are reshuffled, and long-time favorites from technology lobbies forsaken. National and trans-national politics will have to move towards an unprecedented degree of consensus on the management of the nuclear fuel cycle. Maybe "The Future of Nuclear Power" is best considered as a likely scenario in an unlikely world.

A comparable, "nuclear revival" scenario" is found in the US Energy Information Agency's latest international outlook [EIA 2005]. There, the "strong nuclear power revival case" extends to 2025. It is based on the premises that US nuclear capacity remains flat (for lack of data on potential expansion), new growth in Western Europe (policy reversals) and Eastern Europe (economic growth), and the greatest imaginable growth in China, India and South Korea. Compared to the reference case, 37 GW of additional nuclear capacity would be available by 2025.

Both scenarios, from MIT and EIA are plotted in fig. 7, in terms of yearly nuclear electricity generated and nuclear's share in total electricity. To realize this kind of growth in electricity production, more than 10 new reactors of 1GW size have to be delivered every year, from 2010 till 2050. In terms of CO_2 emission avoidance, the amount of electricity delivered by nuclear would save about 1.8GT of C-equivalent emission in 2050, if seen to displace conventional coal fired generation.



sources: EIA 2005, MIT 2003

Figure 7: Nuclear electricity growth under two scenarios

In today's world, decisions about the use of nuclear power will always be based on guidelines from governments at the nation-state level. These will be based on expected needs for energy and resource independence and the prevailing political position (which will reflect the public attitude, albeit to a varying degree). An overview of current trends in countries that exploit nuclear energy is given in Fig. 8.

A more detailed look at countries that have a significant capacity today:

- In the United States, 103 power reactors are in operation, with a total capacity of 97.5 GWe. By 2020, almost 400 GW of new generation capacity is seen as needed, but no new nuclear plants have been ordered so far (in fact, not since 1973). Some increase of nuclear energy is expected on the short term, from better plant availability, up-rating and extended operating licenses. The 2005 Energy Policy Act has a supportive attitude towards nuclear energy, but contains no elements that have the potential to change the trend.
- France has 59 nuclear plants, with 63.5 GWe total capacity, providing over 77% of the country's electricity. State-owned utility EDF[13] has a virtual monopoly in the country, and has firm plans for new nuclear facilities. A demonstration European Pressurized Reactor is to arise within a decade, and this design is the major

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[13] At present undergoing the first stages of privatization.

candidate to replace power plants that reach the end of their lifetime from 2015 onward.

- In Japan, 54 reactors (45,5 GW) fill a quarter of electricity demand. A program for significant expansion (to 52 GWe in 2025) has come under attack amidst scandals surrounding the industry since 2002.

Three Asian countries account for the majority of nuclear capacity additions expected over the next decades, and all have plans to develop indigenous designs:

- South Korea is the only country where nuclear energy has shown consistent growth since 1978. The country's electricity demand has grown almost tenfold since then, while it is for 97% reliant on imported energy resources. The first reactors were bought as turnkey units, but with each subsequent one, local contractors were more involved. At present, there are 19 power reactors (16 GWe combined). Plans up to 2015 include 9 more units (10.2 GWe combined).
- China (mainland) has 9 power reactors with a joint capacity of 7 GW. Two more are under construction and ten units are 'on order'. Government plans for up till 2020 include a total addition of 27 reactors to bring the installed nuclear capacity to 36 GW.
- India operates 14 power reactors (27 GWe) at 6 sites. In 2008, 8 GWe is to be added from newly constructed plants. The Indian Department of Atomic Energy has a target of 20 GWe total nuclear capacity for 2020. As a non-signatory to the Nuclear Proliferation Treaty, the country is subject to export controls of nuclear suppliers. Apart from the power reactors, India has comprehensive indigenous facilities for fabrication and recycling of nuclear fuel and has started construction on a 500MWe prototype fast breeder reactor

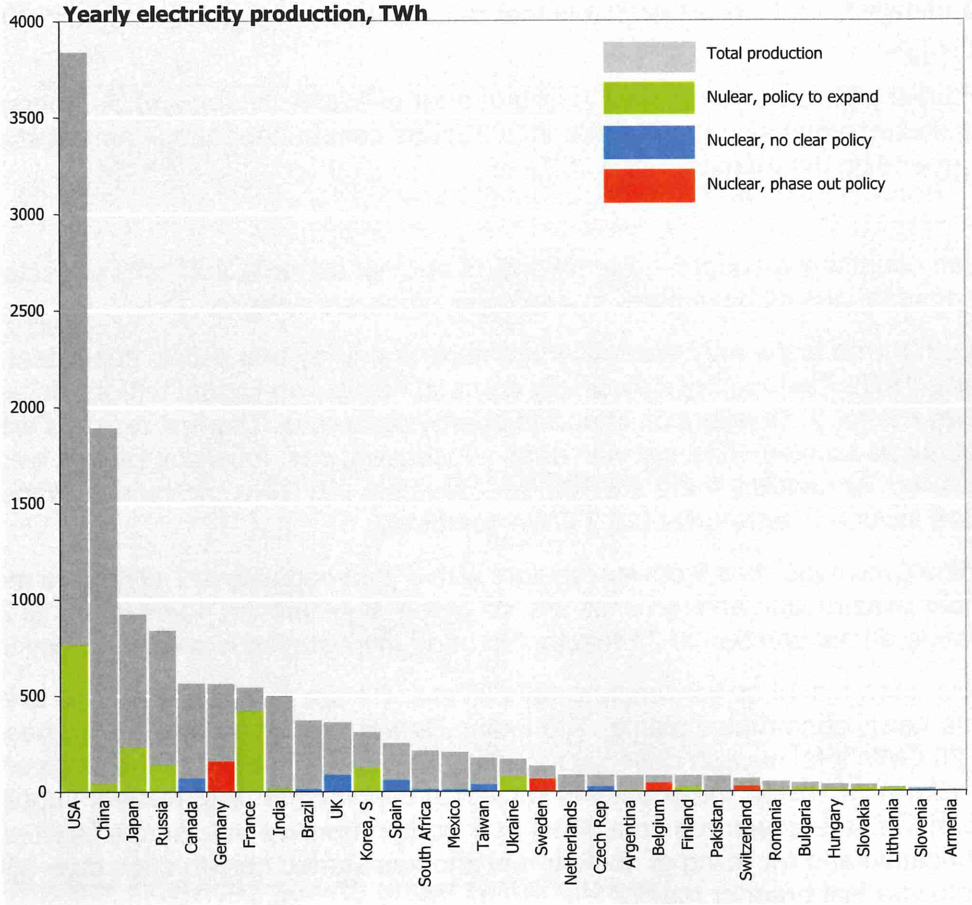

Figure 8: Electricity production, nuclear share and current policy for countries that have nuclear capacity

7.2 Small Scale

State governed institutions as well as private companies have been working to develop smaller nuclear power reactors. There are designs cooled by water, gas, molten metals and molten salts. The designs either exist on paper only, or are based on small pilot versions. Application is proposed for remote delivery of electricity or process heat, for which a suitable capacity range would be from 20 to 50MWe. One example is the 4S reactor developed by CRIEPI and Toshiba, a sodium-cooled fast reactor that could operate without refueling for up to 30 years. The 4S was designed in a 10MWe and a 50MWe version and would cost about $2500/kW. Another example, of course, is the Pebble Bed Modular Reactor (see Appendix).

The adjectives ‘cheap’, ‘simple’ and ‘safe’ usually feature in descriptions of these small nuclear plants. All these however seem to be rather speculative. Designs may be simple if compared to large nuclear plants, but these units are intended to compete with diesel- and gas fired power generation. No matter how much safety is apparent from a paper study, for a true qualification a sound safety record is indispensable. For economical production, large numbers of similar units would have to be manufactured. Without an assessment of the available market, and wide consensus on the preferred type of reactor, the economics of these smaller systems are, at best, unclear. Also, the licensing procedure may be very unfavorable for small systems. In the U.S.A., the cost and time path would be identical to one for a full-scale facility.

Thus, we feel there is little reason to expect that nuclear energy will become a player in the market for power generation under 200MWe anytime in the next 20 years.

7.3 'Nuclear' Hydrogen

Four out of the six Gen-IV designs currently on the drawing boards aim at the co-production of hydrogen, next to electricity. If this materializes, the impact of this 'nuclear' hydrogen would have a more direct impact on Shell's business than growth in the nuclear power sector. It would open up a channel for the large-scale, centralized production of carbon-free hydrogen as transportation fuel, in direct competition with hydrogen from conventional processes and feedstocks – most typically SMR – in which Shell, through its Hydrogen business, has a natural interest.

The hydrogen production process that is invoked in this context is thermolysis of water, *i.e.* the splitting of water in its constituent elements by means of high-temperature heat, in a multi-step thermochemical cycle, involving heteroelements. The general idea for such a process stems from 1960s research at General Motors' corporate R&D labs. The incentive was – then as now – the development of an alternative for electrolysis that is at once cheaper and more energy efficient. Over 500 theoretical schemes have been proposed in the literature; practical research was done on a dozen or so of these schemes in the seventies and into the early eighties, when research was stopped for both lack of progress and a decline in interest for non-fossil energy carriers. In the absence of any new ideas or technological breakthrough, the concept was dug up again around 2000 as the nuclear power sector's (more accurately the nuclear R&D sector's) ticket to ride the hydrogen bandwagon.

In order to get some feeling for the chemistry that is involved, it is illustrative to consider for a moment the most prominent example of the family of thermochemical cycle, *viz.* the Sulphur-Iodine process, which has the following three reaction steps:

$$H_2SO_4 \rightarrow SO_2 + H_2O + 1/2O_2 \ (850°C);$$
$$I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4 \ (120°C)$$
$$2HI \rightarrow I_2 + H_2 \ (450°C)$$

Of these three reactions, only the middle one, the Bunsen reaction is well researched. The other ones are essentially speculative. The decomposition of hydrogen iodide is most problematic: in the 1970s it was envisaged as simple decomposition, to occur at high-temperature (900°C) and it encountered experimental problems; now the plan foresees reactive distillation at much lower temperature, not to circumvent the previous problems, but rather to boost the efficiency. It would ideally also incorporate a yet-to-be-invented selective membrane to separate the hydrogen from the decomposing HI soup. The sulphuric acid decomposition is *qua* technological challenge in between these two reactions.

While it is admitted that such details as the thermodynamic data of the HI system are not know in sufficient detail, the industry[14] consensus is that the product hydrogen will have a production cost of 1.65 $/kg, making it cost-competitive with SMR hydrogen if oil and gas prices double, or if CO_2 taxes hit the 100 $/ton mark. Our own analysis indicates that 2$/kg is probably a fair lower bound to the ultimate cost, if (a big if indeed) the reactions can be driven to completion and side reactions will not complicate the flow scheme, which, even as it is, is rather complex.

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[14] The "industry" we speak of here is essentially a proposal-writing industry. The main players are CEA of France, JAERI of Japan and various US National Labs and DoE initiative groups.

In the final analysis, the relevance and viability of this thermochemical route to hydrogen critically depends on the claims about process efficiency. Whether or not the high expectations will be met is entirely open. Experimental programs now under way should hopefully tell us within a few years. If the outcome is positive, the industry aims to build a 600 MW_{th} demo plant, start-up date 2017 and located in Idaho (with only potatoes nearby). A decade later (?) a commercial alternative for electrolysis would exist that may be cheaper, but one where a not insignificant fraction of the operating costs are, according to a spokesman, iodine make-up cost. A process also, where nuclear power plant and thermochemical complex are a kilometer apart, or separated by a dam ‘for safety reasons’. It is expected that tritium contamination of the product hydrogen will be within legal limits.

Compared to that, coal-derived hydrogen with carbon sequestration becomes an environmentalist’s dream.

8. Conclusions

For the next 25 years, the main role of civil nuclear energy is, as it has been, in large scale electricity generation. It will remain a subject of national and political priorities, but if sufficient evidence shows that the technology has truly become a competitive option for secure, CO_2-free energy, the private sector may take up the initiative.

The imaginable range in which nuclear can contribute to electricity generation on the 2050 horizon lies between 8 and 20% of total electricity generated. The upper end of this range would call for an unprecedented degree of international cooperation and consensus.

We see no role for radical new technology. Water cooled reactors, as they are currently constructed (generation 3 or 3+), remain the preferred (if not the only) option for economical nuclear energy. New and innovative concepts for small scale heat and power, 'nuclear' hydrogen and transmutation of nuclear waste are far less mature than is suggested in many communications.

9. Aknowledgement

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Appendix A. The Pebble Bed Modular Reactor

The odd one out of the G-III family (also dubbed Generation III+) is the Pebble Bed Modular Reactor (PBMR), which is often presented as a new, revolutionary cure-all for nuclear's ailments. It is originally a German design from the 1950s, for a high-temperature helium cooled reactor, in which the fuel is encapsulated in graphite spheres, or pebbles. In a current design, each pebble of 60mm diameter holds 15000 fuel grains, embedded in the graphite matrix. The fuel grains consist of a 0.5mm uranium particle, clad with layers of silicon carbide and pyrolitic carbon, to form a 1mm pellet. The core of the reactor is to be filled with 456,000 pebbles, ¼ of which are solid graphite to form the moderator. In operation, pebbles are withdrawn at the bottom of the vessel and recirculated to the top as far as they still contain sufficient fissionable fuel. The helium coolant is pumped into the reactor top at 500°C and 70 Bar and heats up to 900°C. At the bottom it exits the vessel to expand in a turbine (Brayton cycle). This design was developed by South African Eskom corporation, which started their initial study in 1993. The reactor would be built in 110 MW_e (at present increased to 165MWe) modules, a size at which it would still be 'meltdown proof' in case of loss of coolant. The maximum temperature reached before the nuclear fission stops is not high enough to cause desintegration of the fuel pebbles, hence no radiation can escape. On one site, up to 10 modules can be operated from a single control facility.

The pebble bed's track record is not all that encouraging. A prototype, built in Jülich, Germany, was a 15 MWe unit and operated successfully for 21 years. It generated enough confidence to start on a commercial unit of 300 MWe. But the scale-up brought problems. The THTR-300 was built near Hamm (Germany), became critical in 1983, and was declared commercial in 1987. It was permanently shut down in 1990, after seven years of "teething troubles", including an accident with release of radioactivity in 1986. The real reasons for abandoning the project are difficult to reconstruct, but were most likely a combination of high costs, technological setbacks and a hostile political climate.

These days, there is renewed enthusiasm for the pebble bed, based on (again) it's elegant design features and the nice fit it provides with elements of the fashionable energy vision: decentralized, modular and simple, and the outlook of hydrogen production. But besides media attention, the PBMR only receives hands-on attention in South Africa and China.

In 1998, Eskom's study resulted in the conclusion that the PBMR would be a viable alternative to LWR-technology for South Africa's power needs, and also a profitable export article to countries about to start with nuclear energy. A project was initiated to build a demonstration unit at the Koeberg nuclear site. The venture has been wrestling to attract much needed foreign investments, and target dates keep being moved into the future. The current scheme mentions 2007 for start of construction, 2010 for completion and in 2013 (originally 2008) a "merchant nuclear module" should be available.

In China, Tsinghua University operates a demonstration pebble bed reactor, similar to the Eskom design. The HTR-10 was commissioned in 2000. Plans for a commercial prototype of 150 MWe are in an advanced state. There are no immediate plans for mass produced units however: the LWR is to remain the workhorse of the Chinese nuclear power industry.

In the US, a group at MIT's Nuclear Engineering faculty is lending support to the Chinese program. The group is also trying to show that the PBMR technology is the best near-term option for nuclear power in liberalized energy markets like the US.

An overview of cited PMBR advantages:

1. Small size makes for a smaller investment risk.
2. Meltdown proof.
3. High reactor temperature offers higher efficiency and non-power applications, like thermal water splitting for hydrogen manufacturing.
4. Graphite and SiC packaging make fuel misuse and proliferation unlikely.
5. Refueling under power.
6. Will not require a containment building.
7. Modular design makes economical, off-site fabrication possible.

Some comments on these:

1. Small size also gives a higher cost of electricity. In fact, the design capacity of the pebble bed module has been increased a number of times, in order to address this concern.
2. Does not mean intrinsically safe: the design would only exclude the possibility of a core meltdown, which may be the most feared, but certainly not the only conceivable mishap in a nuclear reactor.
3. The economics for this mode of hydrogen manufacturing are far from clear and the technological viability doubtful (see section 8.3). It is also unproven that the energy efficiency will be superior to electrolysis.
4. The packaging also greatly adds to the volume of high-level waste. There are also concerns about the fuel production: for one reactor module, hundreds of millions (6.84E9) of fuel grains have to be produced. To keep the fail rate of the ceramic coating sufficiently low will be an extremely challenging enterprise.
5. This feature is also offered by other designs, such as the CANDU reactors.
6. But the reactor modules will need protection from external events, which in conventional reactors is also provided by the containment structure.
7. Again, this advantage is not necessarily limited to PBMR technology.

Adding up the above, there is little credibility to the dominant role that is often seen for this specific technology. We can only guess why the pebble bed nevertheless gets such a good press. Much of it seems to be hype, the ignorant quoting the enthusiast. There is also a great need –for the believers in a nuclear renaissance- to have a champion technology on offer, one that promises a radical departure from nuclear's stalled development and is deployable within a decade. After all, a renaissance based on 50 years old technology is a hard sell.

Bibliographic Information

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