# Can Nuclear Power Deliver?

# The Future of the Civilian Use of Nuclear Technology

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> *If it is to benefit humanity, concern for our planet and the future of our civilization needs to be matched with an understanding of the facts*
> Richard L Garwin & Georges Charpak [Garwin, 2001]

> *Atomic energy unquestionably will be made extremely cheap – like 'free air' at the service stations. Our automobiles eventually will have atomic energy units built into them at the factory so that we will never have to refuel them. So will large airplanes . . . In a relatively short time we will cease to mine coal.*
> New York Herald Tribune, 1945

## Contents

# 1 Introduction

This article reviews the current status on arguments regarding nuclear power, and lists developments with the potential to address some of its concerns. The debate is not new – an overview article published 25 years ago in National Geographic [Weaver, 1979] is still largely relevant today. But since the 90's, a new element has been added: nuclear's potential as a low emission energy source to mitigate climate change. Nuclear power offers tremendous promise of abundant, secure and low cost energy, if only it can address its problems of nuclear waste, reactor safety and proliferation, and convince public opinion of these solutions.

Stuck between doom and dream, it is still not possible today to build an irrefutable case either way for the nuclear option on a global scale, but we need to keep in mind that there is no such thing as a perfect energy source, and nuclear power should be seen in combination with its alternatives.

| **Technology** | **Capacity** | **Fuel/yr** | **Waste** | **Availability** |
|---|---|---|---|---|
| Nuclear | 1.0 GWe | 25 tonne | 24.999 tonne | Base load |
| Coal | 1.0 GWe | 2 Mtonne | 6 Mtonne | Base load |
| Wind | 2.5 GWe | - | - | Random generation |

Table 1: Options to produce electricity for a million people (7–8 TWh/year)

Nuclear's problems are not insurmountable, and solutions are within sight, though not yet within reach. Some of these emerging technologies are highly speculative. Therefore the question is no longer whether nuclear can deliver, but when.

# 2 Nuclear peril

## Waste

In nuclear fission reactors highly radioactive waste is produced, but the volume is rather low: about 4 $m^3$ i.e. about 28 tons of irradiated fuel per GW-year. In addition , about 27 tons of the irradiated fuel can in principle be reprocessed and reused in other reactors as it consists of a mixture of about 224 kg U-235 , 26 400 kg U-238 and 170 kg Pu isotopes. The remaining fission products must be disposed of. Hence, in the strict sense only 1 ton or about 50 $dm^3$ of highly radioactive waste is produced per GW-year. The total volume after packaging for disposal becomes about 4 $m^3$. The problem of waste is well known. Thus to ensure that no significant environmental releases occur over a period of tens or thousands of years after disposal a 'multiple barrier' concept is used to immobilise the radioactive elements in high-level waste and some intermediate-level waste and to isolate them from the biosphere.

The world's 433 nuclear reactors, with 340 GWe combined capacity, produce each year close to 10 000 tonne radioactive waste in the core, as well as further amounts of light radioactive waste from operating the reactor. It takes about 50 years before waste can be moved to a permanent storage facility. At present, no political agreement has been reached yet for disposal of waste, though the technical solutions exist. With reprocessing, this waste stream can be reduced to about 340 tonne of highly radioactive waste per year for the world's current civil use of nuclear power. While this waste stream is relatively small - certainly compared to other streams, it accumulates with time, and remains radioactive over a very long time period[1].

Using nuclear power without reprocessing waste poses a problem of storing larger quantities waste over a very long time period[Meshik, 2005]. The option of a permanent geological storage in Yucca mountain has been explored in the USA, but a court action by the state of Nevada has resulted in a judgement that the risk, while small, could not be ignored over such a long time period. In the USA, where reprocessing is not being pursued for economic reasons, 200 000 tonnes of high level nuclear waste have accumulated so far.

Because of the lack of a (politically acceptable) solution for the relatively small amounts of waste, nuclear power cannot really be considered sustainable. New methods for handling waste are being developed to store it in a safe way such as disposal in plastic clay or even to eliminate it by transmutation thereby producing energy.

[1]It takes thousands of years to reach the earth's background radiation level

## Proliferation

The difference between civil and military use of nuclear technology is a matter of dose. Natural uranium contains only 0.7% of the fissile isotope U-235 that is enriched to 3.5% for use in nuclear power plants while uranium in atomic bombs is enriched to over 90% . Hence, nuclear power stations are not atomic bombs waiting to go off.

At present, about 30 000 atomic weapons can eliminate human life on our planet many times over[2]. Advocates will say that this arsenal has avoided a $3^{rd}$ world war, and has created one of the longest periods of peace and prosperity for a large part of world population. But even a very remote risk of a nuclear holocaust is difficult to accept.

Producing nuclear weapons is not an easy task and needs huge plants, advanced technology and skilled scientists. Such installations cannot be constructed and run unnoticed. Assembling an atomic bomb by individual terrorists or even terrorist organisations is highly improbable. Besides the procurement of enriched uranium or plutonium it needs special equipment and components. Handling of highly enriched uranium and plutonium is a risky business because of the health hazards of pure uranium and plutonium due to high radioactivity and toxiticy of the materials. Only a team of skilled scientists or engineers provided with the necessary equipment are able to realise such an undertaking and bring it to completion.

## Nuclear safety

Advocates of nuclear technology will place it low on the risk ladder. They will argue that the perceived risk is largely subjective, showing risk statistics to put it into perspective.

[2]Fortunately, the stock is gradually decreasing. At its peak, almost 100 000 atomic weapons existed. At present, few new bombs are being produced, and many decommissioned.

| Cause of death | Number per year | Probability per 100 000 persons.year |
|---|---|---|
| Cardiovascular diseases | 2 286 000 | 876.0 |
| Malignancies | 534 000 | 205.0 |
| Accidents | 90 000 | 34.0 |
| Motor vehicles | 42 524 | 16.0 |
| Falls | 13 450 | 5.2 |
| Accidental poisoning | 7 828 | 3.0 |
| Fire & flame | 3 986 | 1.5 |
| Drowning | 3 404 | 1.3 |
| Inhalation / ingestion | 3 065 | 1.2 |
| Medical complications | 2 700 | 1.0 |
| Firearms | 1 123 | 0.4 |
| Air & space transport | 1 075 | 0.4 |
| Water transport | 723 | 0.3 |
| Railway | 635 | 0.2 |
| Gases & vapors | 605 | 0.2 |
| Electric current | 561 | 0.2 |
| Handguns | 233 | 0.1 |
| Nuclear - Chernobyl | | 0.6 |
| Nuclear - normal cycle | | 0.02 |
| Nuclear - Three Mile Island | | 0.00007 |
| (Meteor impact) | 20 | 0.0004 |

Table 2: Deaths and death rates for 1994 in US [Garwin, 2001]

Opponents argue that the safety track record is meaningless, and that the risk of nuclear incident is simply unacceptable. The consequences of nuclear catastrophe are beyond imagination, and this uninsured risk is an external cost carried by society. Adding this cost, and the cost of waste into the equation would price nuclear power out of the market, according to the opponents.

The experience supports the advocates so far. There have been 3 incidents with nuclear power: 3-mile Island, Chernobyl and Tokai-mura. While every casualty is one too many, the risk of dying in a 3-mile Island or Tokai-mura type of incident is orders of magnitude lower than the risk of 'death by meteor impact'[3]. The margins of error on these tiny risks are so high that they become almost meaningless. But Chernobyl, with an estimated 30 000 casualties cannot be ignored [Garwin, 2001]. Chernobyl has established an image in the public mind of nuclear reactors as wild mustangs, running out of control by an operator's wrong push of a button. But in his book appearing in the context of Glasnost, Grigori Medvedev describes the incident from the inside, as a results of a decade of mismanagement, incompetence and almost criminal negligence [Medvedev, 1991].

The Chernobyl accident was the result of flawed Soviet reactor design and in addition whilst testing, numerous safety procedures were disregarded. The reactor was intended for both electricity and plutonium production. This design made the reactor unstable at low power levels. Had there been multiple layers of safety systems, like in Western reactors, the major accident that occurred in April 1986, and that was triggered by human errors, would have been contained and the disastrous consequences would not have occurred.

[3]Based on a single meteor impact with 10 km diameter. Such event can be expected once every 50 million years, and would cause a billion death, i.e. 20 deaths per year.

# 3 The nuclear promise

## The power of the atom

A fully developed world of 9 billion people using advanced energy technology would need 2-3 times more energy than we consume today, when offering globally today's 'Western' lifestyle[4]. Considering today's primary energy needs of approximately 400 EJ, equivalent to 10 000 Mtoe or 200 million barrels oil equivalent per day, this results in an expected annual demand of 1000 EJ[5].

The energy released from nuclear reactions is a million times larger than in high energy chemical reactions, such as fossil fuel combustion. Plugging the speed of light into Einstein's equation $E = m \times c^2$, with m=1 kg, results in E = 25 TWh ($9 \times 10^{16} J$), i.e. sufficient heat to run a nuclear power station for a year. However, with the current inefficient conversion of mass to energy, converting 1 kg mass into energy yields 25 tons of 'by-products'[6]. The fact that a fistful of matter holds enough energy to power a city of a million people for a year represents nuclear's tremendous promise.

While nuclear power has a million times the energy density of fossil fuel, the other possible route - renewable energy, has a much lower energy density than fossil. Considering expected energy demand, it helps to put things in perspective using (hypothetical) 100% supply scenario's for various energy technologies.

| Technology | Capacity | Status | Remark |
|---|---|---|---|
| Nuclear | 11 TWe | 400 GWe | |
| Wind | 125 TWe (5 MWe units) | 50 GWe | 12.5 million sq. km, i.e. 10% of land |
| Photovoltaics | 1.4 M sq. km | - | 5 times the area of Germany, or 200 000 1 M roof programmes |

Table 3: Hypothetical 1000 EJ scenario's

[4]Such estimate assumes no energy efficiency gain and mastering of demand to compensate growing demand of energy products and services. It is possible to build plausible scenarios resulting in a less than doubling of actual total primary energy demand, without hampering development.

[5]By the time your finish reading this paper, the world will have consumed an amount of energy equivalent to 2 million barrels of oil. It requires 450 wind turbines of 2 MW running 3000 hours at nominal power to generate this amount of energy.

[6]The major fraction is not waste but the fertile uranium isotope U-238 that can be converted into fissionable Pu-239 by bombardment (or irradiation) with fast neutrons in a breeder reactor. The major fraction of 'waste' (about 10% of total depending on the length of cycle) is Pu-239 that is converted into MOX if exhausted fuel is recycled.

## Climate Change

Governments and scientists concerned by climate change agree that it would be prudent to reduce anthropogenic greenhouse gas emissions by 50-80%[7]. There is a wide agreement among scientists that $CO_2$ as a greenhouse gas will cause the average temperature on earth to rise. What will happen to our environment is a most difficult question. Our ecosystem is very complex with many feedback loops and some buffers. There are limits to the adaptability of our ecosystem and actually nobody knows what these limits are. We are conducting a possibly irreversible large-scale geophysics experiment. Only, if the experiment fails, we cannot close the laboratory and go home, since we live inside it, and it's all we have.

Currently, the world's energy system depends 80% on fossil fuel, and various scenario's expect demand to increase by 2020 to more than 600 EJ, a 200 EJ absolute increase. If we look at roadmaps for renewable energy, successful renewable technologies such as wind and solar photovoltaics can contribute an extra 20 EJ by 2020, i.e. 10% of the increase. Considering that the scenario for renewable energy is already ambitious, and the demand scenario realistic, we can only expect the share of fossil fuel in the energy mix to become more important. This share increase of fossil energy may be further accelerated by nuclear moratoria and phaseouts planned in selected countries. From today's perspective, it looks like the $21^{st}$ century might very well use more fossil energy than the $20^{th}$[8].

The only long-term alternatives to burning fossil fuels are a step increase in energy efficiency, renewables with their fundamental problem of variability and their diffuse nature, and fission and fusion, each with their own problems. At present, we clearly have no single 'silver bullet' solution.

## Ensuring energy supply

The amount of economically minable uranium in the earth is estimated at between 5 and 6 million tons[9]. With the present reactor types the lifetime of our uranium sources is rather short - about 50 years. Using breeder technology to transform non-fissile fuel into fissile elements, we could stretch our resources by a factor 60 although the safety and environmental problems are potentially more difficult to cope with.

If we continue to consume uranium at the present rate, its demand reportedly will exceed

[7] The IPCC for example has urged for a 60% reduction.

[8] According to [Odell, 2005], fossil fuel consumption during the 21st century will be 1660 billion tonne oil equivalent, more than 3 times the 20th century consumption of 500 billion tonne.

[9] As we learned since the Club of Rome reports, 'reserves' are a very elastic concept. [Garwin, 2001] mentions 4.5 million tonnes Uranium reserve at today's prices, but hints that the exploitable resource is likely to be more in the range of 100 – 250 million tonne.

the supply. Several countries have been working to develop fast breeder reactors and international research experiments are set up to develop nuclear fusion. But before technology for these next-generation reactors can be perfected there is strong possibility that we will meet again an energy crisis. One possibility for maintaining fission as a major option is low cost extraction of uranium from seawater. The uranium concentration of sea water is low[10] but the quantity of contained uranium is vast: some 4 billions tons, thus about 700 times more than the known terrestrial economically recoverable resources. Research on a process being developed in Japan suggests that it might be feasible to recover uranium from seawater at a economically acceptable price[Sugo].

If we succeed building thorium reactors, we have yet another path to tap the power of the atom. Thorium's terrestrial reserves are 3 times as large than for Uranium[Garwin, 2001].

And finally, the dream of nuclear fusion would solve many problems (fuel, waste, proliferation), but the option of purely deuterium-based fusion is so far ahead that it represents, according to some, an irresponsible flight to the future [Reeves, 2003].

Considering the much larger energy density of nuclear fuels, it should be easier to build up stocks to cope with energy crisis.

[10] Around 3 parts-per-billion, ppb

# 4 From peril to promise

## Public opinion

Nuclear risks are incidents and proliferation. In risk comparisons, perceived risks are generally very different from actual risks, as defined by statistics. Psychology has studied the difficulty of the human mind to understand extreme probabilities. This is illustrated in table 4: opinions of experts and lay persons correlate well for assessing the risks of motor vehicles, handguns, smoking, motorcycles and alcoholic beverages. However, for nuclear power, both lay groups 'women' and 'students' selected it as the highest risk (among a list of 30 hazards), whereas experts consider it the $20^{th}$ risk, safer than railroads, but more dangerous than food coloring.

| Activity | Women | Students | Experts |
|---|---|---|---|
| Nuclear power | 1 | 1 | 20 |
| Motor vehicles | 2 | 5 | 1 |
| Handguns | 3 | 2 | 4 |
| Smoking | 4 | 3 | 2 |
| Motorcycles | 5 | 6 | 6 |
| Alcoholic beverages | 6 | 7 | 3 |
| Aviation | 7 | 12 | 12 |
| Police work | 8 | 8 | 17 |
| Pesticides | 9 | 4 | 8 |
| Surgery | 10 | 11 | 5 |
| Firefighting | 11 | 10 | 18 |
| ... | | | |
| Railroads | 24 | 23 | 19 |
| Food preservatives | 25 | 12 | 14 |
| Food coloring | 26 | 20 | 21 |
| ... | | | |

Table 4: Priority ranking from various groups on perceived risks for selected activities and technologies [Breyer, 1993]

In addition to advocates and opponents, public opinion has a 3rd group: a neutral camp. According to opinion research in UK [Grimston, 2002], the neutral camp is actually the largest, comprising about half of population, with the remaining half roughly divided equally between the other groups. Opinion research in Finland when the new reactor was being decided showed a very similar pattern. Politicians have a more pronounced opinion on the issue, while being as divided as their constituencies. But politicians perceive public opinion to be quite different than it actually is.

| Group | Favourable | Unfavourable | 'Neutral' |
|---|---|---|---|
| Public opinion | 28% | 25% | 47% |
| MP's (Members of Parliament ) | 43% | 44% | 13% |
| MP's perception of public opinion | 2% | 84% | 14% |

Table 5: Attitudes towards nuclear power among decision makers [Grimston, 2002]

Cf the table below, supporters and opponents may have more in common than they think.

| The advocates | The opponents |
|---|---|
| Belief that major elements of the future are predictable; certainty about general projections of various energy sources. (For example, renewables demonstrably have the practical potential to remain only relatively minor players in world energy supply.) | Belief that major elements of the future are predictable; certainty about general projections of various energy sources. (For example, renewables demonstrably have the practical potential to dominate world energy supply.) |
| Absolutely certain about the future role of nuclear power (a major and important one), and about issues such as nuclear waste (not a difficult technical problem). | Absolutely certain about the future role of nuclear power (no role at all), and about issues such as nuclear waste (a technically insoluble problem). |
| Arrogance born out of belief in infallibility of own analysis. | Arrogance born out of belief in infallibility of own analysis. |
| Belief that the public is irrationally frightened of nuclear power. If only people could be properly educated they would become more pronuclear and support the nuclear industry. | Belief that the public is irrationally complacent about nuclear power. If only people could be properly educated they would become more antinuclear and support antinuclear campaigns. |
| Characterisation of opponents as either fools or ill-intentioned. | Characterisation of opponents as either fools or ill-intentioned. |
| Belief that government is not to be trusted to take wise decisions as it is too much influenced by the antinuclear media and pressure groups. | Belief that government is not to be trusted to take wise decisions as it is too much influenced by the nuclear industry and its supporters. |

Table 6: What nuclear activists have in common [Grimston, 2002]

## New technology

Several generations of nuclear fission reactors are commonly distinguished. Generation I reactors were developed in 1950- 1960s and relatively few are still running today. They mostly used natural uranium as fuel and used graphite as moderator. Generation II reactors are today most in operation for commercial use and in the present US and Russian fleet. They typically use enriched uranium fuel and are mostly cooled and moderated by water.

Generation III are the Advanced Reactors, the first two of which are in operation in Japan and others under construction or ready to be ordered. The most important characteristic of this Generation is its passive safety concept. Reactors are shut down safely without human intervention, by an inviolable physical principle. Used physical principles are: gravity; migration of neutron absorber from a higher concentration to a lower concentration; a sufficiently high negative temperature coefficient (when temperature increases, reactivity decreases).

Generation IV designs are still on the drawing board and will not be operational before 2020 at the earliest and probably later. They will tend to have closed fuel cycles and burn the long lived actinides now forming part of the spent fuel, so that fission products are the only highlevel waste.

Some reactors known as Fast Neutron Reactors or 'breeders' do not have a moderator and utilise fast neutrons, generating power from plutonium while making more of it from the U238 isotope. While they get more than 60 times as much energy from the original uranium compared with normal reactors, they are expensive to build and currently await their time when resources become scarce.

Fusion power offers the prospect of an almost inexhaustible source of energy for future generations, but it also presents so far insurmountable scientific and engineering challenges. The development of nuclear fusion as an energy source is one of the most complex scientific and technical tasks ever undertaken for non-military purposes. In fusion reactors, hydrogen atoms fuse together to form helium releasing a huge amount of energy. At present two different experimental approaches are being studied : fusion energy by magnetic confinement and fusion energy by inertial confinement. Although the last years fantastic progress has been obtained in magnetic fusion it will still span a period of 30 to 35 years before an industrial demonstrating fusion reactor could be started-up. The use of fusion power could substantially reduce the environmental impacts of increasing world electricity demand and easily satisfy the energy needs associated with continued economic growth.

Although fusion generates no fission products there are other concerns about safety. Some component materials will become radioactive during lifetime of a reactor and will eventually become radioactive waste. Another hazard arises from an accident to the magnetic confining system. The total energy stored in the magnetic field would be similar to ca 45 tonnes TNT. Attention must also be drawn to the possibility of a lithium fire. In contact with air or water lithium burns spontaneously. Engineers are most concerned about the release of tritium to the environment . Tritium is a radioactive isotope of hydrogen and very difficult to contain since it can easily penetrate construction materials. As an isotope of hydrogen it is incorporated easily into water and remains a threat to health for over hundred years after it is created as a gas or in water. When fusion power clearly has much to offer when the technology is eventually developed, the problems associated with it also need to be addressed.

Finally, there is Carlo Rubbia's thorium reactor: a highly speculative concept, still on the drawing table. Nobel Price winner Physics 1984, Carlo Rubbia, is very much in favour of a subcritical Thorium reactor coupled with an accelerator as energy amplifier (600 MeV cyclotron). The Thorium cycle is proliferation-free; disintegration time constant of waste is only 500 years (only $N_p$ and $P_o$ at ppm-level in the Th-cycle, corresponding to a reduction factor 1/2000 with respect to a PWR[11]). Fuel is natural Thorium regenerated every 5 days [Rubbia, 2005].

[11] Pressurised water reactor

# 5 Conclusion

Nuclear power today is not sustainable until it addresses its problems. But if it does, nuclear power holds tremendous promise. We need to realise that nuclear power represents many options, rather than a single choice. There are options on building additional reactors[12], a moratorium (no new reactors), phaseout (reduce existing reactors), reactor type, waste processing and R&D expenditure.

R&D seems to be key in the nuclear debate. If we want nuclear power, in whatever form, action is needed to preserve and develop knowledge in this field[13].

Except for fission, none of the other possible alternatives such as renewables or fusion is at present mature enough to replace combustion of fossil fuels on a sufficiently large scale. Even fission is unfortunately only a short term solution with the current types of reactors. Furthermore it has a low level of acceptance by the general public.

Too often the energy debate is fragmented, and focuses on advantages of a particular technology and disadvantages of its alternatives. If we exclude the nuclear option portfolio, a plan is needed how to do without it. Such plan needs to be based on an understanding of facts, rather than aspirations. The fact that the world has yet to see such a (transparent) plan may relate to the fact that the numbers simply do not add up without the use of nuclear energy.

With energy professionals, a view is gradually emerging of a widely diversified energy system, which will use a mix of renewable, nuclear and fossil technologies. It will equally use a wide combination of energy carriers such as electricity, hydrogen, gas, wood pellets, ... To replace fossil fuel, the world will need everything it can get, and cannot afford to exclude any mainstream option.

## Acknowledgement

The book by Garwin & Charpak [Garwin, 2001] gives an excellent and balanced overview on nuclear energy. This article is to a large extent based on this book. We also acknowledge many comments made by Bernard Geeraert. Any errors, omissions or opinions expressed are the sole responsibility of the authors.

[12] China has decided to build at least 33 new reactors and considers eventually to add up to 220 Pressurised Water Reactors.

[13] For an example, see the European Nuclear Engineering Network (ENEN) initiative

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