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Nuclear Power and Energy Sustainability

Nuclear energy is assuming more importance in energy policies worldwide due to its basic economics coupled with energy security concerns and popular interest in reducing carbon dioxide emissions from electricity production. Its performance characteristics suit it best to continuous, reliable supply of electricity on a large scale. Its physics enable control of reactions in both moderated and fast neutron configurations. On all these fronts, having this mature technology (with over 14,500 reactor-years of civil operation in 32 countries) available at this particular time can be considered indicative of God's providence in the sense of liberality of provision for human needs. The paper relates this serendipitous situation to God's creation and addresses some common concerns. The paper contends that Christian stewardship of God's creation in applying its bounty to human needs appropriately involves utilising nuclear power more widely, among many other things.

Key words: energy, nuclear, uranium, fission, neutron, stewardship of creation.

Introduction

The features of the atomic nucleus enabling nuclear fission and giving rise to radioactivity are a wonderful and exciting aspect of God's creation. The first nuclear reactors operated naturally in a uranium deposit at Oklo in what is now Gabon about two billion years ago. About seventeen of these fossil reactors are known, and there could be many more from that era, when natural uranium orebodies had an isotopic ratio with elevated uranium-235 levels similar to today's enriched nuclear fuel and much greater than today's natural uranium.[1]

Apart from uranium (which is barely radioactive in the sense of dose from exposure to it) a number of elements forming part of the Earth have radioactive isotopes and there are also many radioisotopes which result from fission.

1 Each 'reactor' operated at about 20 kW thermal. These natural chain reactions, started spontaneously by the presence of water acting as a moderator, continued for about 2 million years before finally dying away. During this long reaction period over 5 tonnes of fission products as well as 1.5 tonnes of plutonium together with other transuranic elements were generated in the orebody and remained in place. Information on the Oklo natural reactors is on the Swedish Nuclear Fuel and Waste Management Company (Svensk Kärnbränslehantering, SKB) website (www.skb.se). See also Gurban, I. & Laaksoharju, M. 'Uranium transport around the reactor zone at Okelobondo (Oklo), Data evaluation with M3 and HYTEC', SKB Technical Report TR-99-36 (December 1999).

All these emit radiation as each atomic nucleus decays towards stable forms.

The main nuclear fuel, uranium, is a fairly abundant metal in the Earth's crust, as detailed below. This means that any limits to energy provision for human need from this source will not be reached for much more than a century, by which time nuclear fusion might possibly be an option.

However, like many other things based on God's good creation, nuclear technologies are ambiguous and capable of great destruction in warfare or by evil intent. Hence, since the use of two nuclear weapons to end the Second World War in the Pacific, we have seen a huge build-up of nuclear arsenals in the Cold War, and then some dismantling of these with material recycled into power generation. The constraint on diversion to nuclear weapons is beyond the technology itself, though increasingly some support of this constraint is built into policies for development of civil nuclear power.

Nuclear power is available now as a mature technology at a time when world demand for electricity is expected to double over the next twenty years, when concerns about carbon emissions from energy use – and particularly from the generation of electricity – are driving policy; and when energy security concerns mean that continued dependence on Middle East oil and gas and Siberian gas would be reckless. On these grounds nuclear power is politically providential in its role and potential for human well-being.[2]

Providential features in the physics

Nuclear power as harnessed today has several features that make it very valuable for these times. It produces an extremely concentrated form of energy, which is controllable, and the control of it is inherent in the physics. As its mysteries unfolded in the 1940-50s it was evident that the very high energy density possible with nuclear power meant that safety had to be a prime requirement of engineering. But that engineering had some important God-given physical aspects of fission to work with.[3]

The concentrated nature of the energy release is used today in relatively dilute form, limited by the materials science available for building commercial plants, so that transfer of heat is mostly by water at up to about 330°C (in the UK: some by CO2 at 650°C). The first modern commercial-scale plant using higher temperatures (750-950°C) with helium coolant is ready to be constructed. In the future, one can readily envisage using that concentrated energy at those much higher temperatures for industrial purposes such as thermochemical hydrogen production.

2 Hore-Lacy, I. *Nuclear Energy in the 21st Century*, London: World Nuclear University Press (2010), 2nd edn (actually 9th edn – former title: *Nuclear Electricity*).
3 WNA 2010: *Physics of Uranium and Nuclear Energy*, http://www.world-nuclear.org/education/phys.htm.

Not only is the energy release concentrated, but nuclear fission produces a lot of energy from very little material – 20,000 times as much per kilogram, when comparing natural uranium (from the mine) with coal, or 160,000 times as much for the actual respective fuels as used (fabricated enriched uranium fuel, and washed coal).[4]

A remarkable feature of nuclear energy, suggesting that it is given for a benign purpose, is the delayed neutron release, enabling control of reactors. While most of the energy released is due to the kinetic energy of the fission fragments, some is from the two or three neutrons released in each nuclear fission. Some of these are immediate (so-called prompt neutrons), but a small proportion (0.7% for U-235, 0.2% for Pu-239) is delayed, as these are associated with the radioactive decay of certain fission products. The longest delayed neutron group has a half-life of about 56 seconds. The delayed neutron release is a crucial factor enabling a chain reacting system (reactor) to be controllable and able to be held precisely critical. At criticality the chain reacting system is exactly in balance, such that the number of neutrons produced in fissions remains constant (one neutron from each fission causing one more fission). Without this extraordinary delayed neutron feature, nuclear fission would be good for little more than bombs.

Commercial power reactors are usually designed to have two features giving a measure of inherent safety. The significance of the first is that if the fuel temperature should rise beyond its normal operating level, the reactivity is diminished. The balance of the chain reaction is affected so as to reduce the rate of fission and hence reduce the temperature – a natural negative feedback.[5] Fast reactors have a strong negative temperature coefficient that is the basis of automatic power regulation and even load-following. This is achieved due to the reactivity feedback – reduced coolant flow leads to higher core temperature which slows the reaction.

The second mechanism, in the common light water reactors, is that formation of steam voids within the water moderator in the actual core will reduce its density and hence its moderating effect, and this again will tilt the neutron balance towards subcritical, since fast neutrons do not cause much fission.

These natural physical phenomena – negative fuel temperature coefficient and negative void coefficient – incorporated into reactor design are a wonderful provision for safe human use of this abundant energy source.

An extreme safety test on the small Chinese HTR-10 pebble-bed reactor was conducted in 2004, relying on the negative fuel temperature coefficient. Circu-

4 Coal typically 25 MJ/kg, natural uranium in light water reactor (LWR) about 500 GJ/kg and 3.5% enriched uranium about 3900 GJ/kg.

5 One mechanism involved is the nuclear Doppler effect, whereby U-238 absorbs more neutrons as the temperature rises, thereby pushing the neutron balance towards subcritical.

lation of the helium coolant was deliberately shut off at full power without the reactor being shut down. The temperature increased steadily, but the physics of the fuel meant that the reaction progressively diminished and eventually died away over three hours. At this stage a balance between decay heat in the core and heat dissipation through the steel reactor wall was achieved, the temperature never exceeded a safe 1600°C, and there was no fuel failure.

An early Russian design tragically showed that it was possible to negate these intrinsic safety aspects and build in the possibility of positive feedbacks instead. Safety, in the sense of controlling decay heat after shutdown, also failed substantially in the triple Fukushima accident in March 2011 as a result of a major tsunami which killed some 25,000 people. The Chernobyl disaster and Fukushima accident are discussed in a later section.

One further example of how one might see God's provision for human need through nuclear power while avoiding adverse implications is this. In a normal reactor, the primary reaction is fission of the uranium-235 isotope. A secondary reaction is breeding plutonium-239, similarly fissile, from the non-fissile uranium-238 which comprises most of the fuel. This process uses some of the surplus neutrons. In fact about one third of the energy from a typical power reactor is from Pu-239 fission. There are concerns about this plutonium isotope since it is the basis of many nuclear weapons. However, as well as Pu-239, a much smaller amount of the non-fissile plutonium-240 is also formed progressively in a power reactor. By the time used fuel is removed from a civil reactor (after c3 years), most of the Pu-239 has been burned, and about one third of the overall plutonium inventory is non-fissile, mostly Pu-240. This means that if anyone has access to the plutonium from the civil nuclear fuel cycle it is entirely unsuitable for weapons (and in fact plutonium with more than 20% Pu-240 has never been made to explode). This reactor-grade plutonium however is very useful for recycling in mixed-oxide fuel, and doing so extends the original uranium resource by about 30%.

The next step up in utilising uranium more thoroughly is in fast neutron reactors, which are well-proven but not widely used as yet, though most countries with major nuclear power programmes expect to be using them in a big way by mid century. They are capable of utilising the much more abundant uranium-238 isotope (99.3% of natural uranium) by breeding fissile plutonium as described, rather than simply the readily-fissile U-235 used today, where only about 0.6% of the natural uranium is actually 'burned'. A fast reactor can potentially use some sixty times as much of the natural uranium.

Fast reactors: While there are about 300 reactor-years experience with fast reactors, their slightly higher cost and the relative cheapness of uranium have favoured the popular light water reactor so far. There are also challenges with materials, since they operate at higher temperatures – 500-550(C, and mostly have liquid metal (sodium) cooling. However, this is at relatively low pressure, which simplifies engineering on that front. Only a few operate today, in Russia, Japan, India and China.[6] France is the other country with a lot of experience of them and a strong commitment to the technology for the future. A distinct benefit of the technology is that long-lived actinides created in the fuel can be burned, producing shorter-lived fission products.

Nuclear and nature

One of the popular prospects for renewable energy in some parts of the world is hot dry rock geothermal, where holes are drilled to unusually hot rocks about four kilometres under the surface so that water can be injected and return as steam to drive a turbine. The main source of heat in these crustal rocks – mostly granites – is the decay of uranium-238. They often have 15-40 ppm uranium and/or thorium, but the level may be ten times this, yielding typically 11 milliwatts per tonne quoted by the main company aiming to commercialise the heat.[7] This sounds modest, but the insulation due to depth means that temperatures of up to 250°C are found, and there are billions of tonnes of hot rock there. Only one such project is operational, the Geox 3 MWe plant at Landau, Germany, using hot water (160°C) pumped up from 3.3 km down (and maybe should be classed as conventional geothermal). A 50 MWe Australian plant is envisaged as having nine deep wells – four taking water down and five bringing steam up.

Indeed, a significant source of heat in the mantle beneath the earth's lithosphere is the radioactive decay of uranium, thorium and potassium remaining from the supernovae in which the solar system originated,[8] though convection in the Earth's crust is also driven by plumes of material from the core. And of course the Sun is a large nuclear reactor, albeit involving fusion, not fission.

Nuclear power produced by human technology recaptures the potential of wet uranium deposits from two billion years ago, when the ratio of uranium isotopes was about the same as in today's enriched fuel, and rainwater func-

6 WNA 2010, *Fast Neutron Reactors*, http://www.world-nuclear.org/info/inf98.html.
7 Geodynamics quotes a range of 3-100 mW/t.
8 In the present Earth, most of the energy generated is from the decay of U-238 (c 10^{-4} watt/kg) and its serial decay products. At the time of the Earth's formation, however, decay of both U- 235 and K-40 would have been important and both would have exceeded the heat production of U-238.

tioned as moderator, as described in the introductory paragraph. The same radioactive fission products and transuranic elements are produced. The human technology involved today replicates this and includes ensuring that radiation exposure to people is limited and that this 'hot' waste is managed so as to cause no problems.

People with routine occupational exposure to radiation in any part of the nuclear fuel cycle receive, with very rare and newsworthy exceptions, doses well below regulatory limits, which are themselves never more than half the natural levels experienced without adverse effects by people in several regions of the world.[9] Radiation is not increased significantly for anyone outside the industry.[10] Most parts of our environment – and we ourselves – are radioactive to some extent. There is a developing debate around radiation hormesis – the proposition based on a lot of observation over many decades – that low doses and low dose rates are beneficial in reducing cancer incidence. The scientific jury is still out on this, though many are persuaded, and hormesis is known in relation to low levels of chemical carcinogens.

God's abundant provision on two fronts: electricity and uranium supply

Electricity is the fastest-growing form of energy worldwide, but around 1.5 billion people do not have any; another two billion have very inadequate supplies. In the UK, as elsewhere, electricity is basic to many aspects of existence – in transport, industry, homes and commerce. The problem is that more than half is generated from fossil fuels (notably coal) and it is widely accepted that we need to reduce our dependence on these fuels whilst meeting the demand for a continuous, reliable supply of electricity on a large scale. The main alternatives for generation are nuclear and hydro, with wind providing a useful but fickle and expensive supplement. There is little scope for increasing hydro capacity, especially in the UK, so the focus shifts to nuclear power as a central part of the energy mix, as clearly recognised by many governments worldwide. Waves, tides, sun and biomass can also provide some energy, but are limited by cost or

9 Occupational regulatory limit is usually 20 mSv/yr. The highest known level of background radiation affecting a substantial population is in Kerala and Madras States in India where some 140,000 people receive doses averaging over 15 mSv/yr from gamma radiation in addition to a similar dose from radon. Comparable levels occur in Brazil and Sudan, with average exposures up to about 40 mSv/yr to many people. Several places are known in Iran, India and Europe where natural background radiation gives doses of more than 50 mSv/yr and up to 260 mSv/yr (at Ramsar in Iran). There is no evidence for increased cancer or other health consequences in these populations.
10 In the UK there has been ongoing discussion on this matter. Our clear understanding is that all the studies done show no epidemiological relationship between nuclear facilities and childhood leukaemia, and no causal relationship given that radiation dose increments are virtually undetectable and vastly less than many populations receive naturally. See also UK Health Protection Agency: COMARE http://www.hpa.org.uk/Publications/Radiation/ (especially http://www.hpa.org. uk/Publications/Radiation/HPARPDSeriesReports/HpaRpd01 9/) and also UNSCEAR www.unscear.org.

practicality, or they are simply too early in technological development to be available.[11]

Known economic resources of uranium are currently about seventy times annual usage – though that is simply a statement about knowledge, not geology. There is certainly much more to be discovered, to the extent that amounts can be quantified – known resource figures grow in line with cumulative exploration expenditure. Since 1975 known uranium resources have grown threefold, tracking relevant exploration expenditure over that whole period. We know of some 5.5 million tonnes in 'conventional' deposits economically available, double this if one changes the economic assumptions, and then up to another 20 million tonnes in 'unconventional' deposits such as phosphates.[12] Using uranium today at the rate of about 70,000 tonnes per year we only 'burn' a tiny fraction of it, so there is enormous technological potential to improve utilisation. Indeed, we can already get about sixty times as much energy from the natural uranium as we do today, with one well-proven but currently uneconomical technological step – the fast neutron reactor, as outlined earlier.

Nuclear power and uranium are every bit as much God-given as renewable sources and fossil fuels, though Christians have been less than outspoken on this. Perhaps God is speaking through others: the 2010 version of Kazatomprom's[13] corporate brochure is titled *Energy of Creation*! God's creation is repeatedly said to be 'good' in the Genesis 1 creation account, and in the Old Testament 'good' is pre-eminently an attribute of God.[14] It implies an inherent or intrinsic value that does not require any useful dimension or purpose. I believe that this establishes an obligation for us to respect it and consider how God wants us to use it. The final part of creation, and completing it, is humankind – created from the earth (or Earth) in God's own image and made responsible in terms of Genesis1:26f, as steward reflecting God's character and concerns. It means that a utilitarian dimension of stewardship to serve the needs of people must be taken seriously as an expression of both God's love and God's purpose.[15]

The 'providence of God' in Christian writing and theology is normally applied to the understanding of God's sustaining and directing his creation, rather than drawing attention to the purpose and liberality of his provision, which is the emphasis here. Applying the resources of the Earth to human need for an ever-increasing population is a clear human priority – one implicit in the

11 WNA 2010, *Renewable Energy and Electricity*, http://www.world-nuclear.org/info/inf10.html.
12 OECD NEA & IAEA, *Uranium 2009: Resources, Production and Demand* (2009, also 2007 version), also WNA 2010, *Supply of Uranium*, http://www.world-nuclear.org/info/inf75.html.
13 Kazatomprom is the state-owned entity responsible for Kazakhstan's uranium mining. The country is the world's largest producer of uranium, accounting for a quarter of world production.
14 See Mark 10:18.
15 All this is argued more fully in my book: Hore-Lacy, I, *Responsible Dominion, a Christian approach to Sustainable Development*, Vancouver: Regent College Press (2006), two chapters of which concern energy.

mandate to 'go forth and multiply'. The technology for this application is based on the science which gives us an insight into the working of God's creation. Both the science and the technology are derived from his creation – the world with its natural resources and humankind with our inbuilt intellectual resources. Technology has long been understood in the Reformed tradition as a tool of stewardship in the service of God.[16] Given the proper application of both science and technology there is no foreseeable limit to the abundance of God's provision of resources and energy for all people on Earth, though there are many challenges in utilising those resources. I have devoted a book to the particular issues.[17]

The Bible is written with pastoral and agricultural rather than industrial imagery, though the Bronze and Iron Ages framed much of it. A major transition from nomadic life is consolidated in the entry to Canaan when the people were reassured that there they would lack nothing, and more specifically that it was 'a land where the rocks are iron and you can dig copper out of the hills' (Deut. 8:9). This implies the technology to smelt them and turn them into tools and weapons, and in fact copper smelting had probably developed before this time in that part of the world. We now know that uranium was also provided there, but it needed a few millennia before tamed neutrons could make it a meaningful resource. The point is that mineral resources for human use were provided in creation and continue to be made available today as a result of the technological aptitude with which humans were created. Our stewardship of these, and particularly of fossil fuels, has become a major public policy issue of huge importance, requiring competent and wise Christian input both scientifically and technologically.

The Deuteronomy passage proceeds to a note of caution: 'You may say to yourself, "My power and the strength of my hands have produced this wealth for me." But remember the Lord your God, for it is he who gives you the ability to produce wealth, and so confirms his covenant' (Deut. 8: 17-18). In providing not only the resources but also the ability to create wealth from them, God provides ever more possibility, even incentive, for us to get carried away with a delusion of autonomy, not to mention scientific and technological hubris. That is all too evident in our material and technological world today, built beyond the wildest imaginings of those refugees upon this very wealth to which God refers. These temptations however do not detract from God's fundamental provision.

16 This is emphasised by John Stott:

> In all their research and resourcefulness… [humans] have been exercising the dominion God gave them. Developing tools and technology, farming the land, digging for minerals, extracting fuels, damming rivers for hydro- electric power, harnessing atomic energy – all are fulfilments of God's primeval command. God has provided in the earth all the resources… we need, and he has given us dominion over the earth in which these resources have been stored. Stott, J. *New Issues facing Christians Today*, London: Marshall Pickering, UK (1999), p. 132.

17 Hore-Lacy *op. cit*., (15).

Today's energy policies

Renewed interest in nuclear power is driven by three factors: improvement in the basic economics of it (due both to higher fossil fuel prices and better nuclear technology); the prospect of carbon emission costs on fossil-fuelled alternatives; and energy security – the sources of uranium are diverse politically and geographically, and several years' supply for a whole country can be warehoused easily and cheaply.

As briefly mentioned earlier, nuclear power generation is today a mature technology, with a track record stretching back fifty years and more than 14,500 reactor-years of civil operational experience (plus about the same in naval experience, which is relevant due to similarity of plants and transfer of expertise). This technological maturity contrasts with carbon capture and storage (CCS), which provides the main hope for continued coal dependence.

Reduced carbon emissions and energy security considerations are also properties of renewable sources. The problem with them is that wind and sun cannot provide the continuous reliable supply available from nuclear and coal-fired plants, and hence require substantial back-up capacity – usually gas-fired. Experience in Germany and elsewhere indicates that the input of high levels of intermittent renewable energy is difficult to manage in a grid system, not to mention very expensive. Western Denmark with 650 MWe of wind capacity manages much better due to its 1000 MWe interconnector with Norway's abundant hydro power.

There is increasing popular pressure to limit carbon emissions from burning fossil fuels, and it is good that Christians have been prominent in advocating such policies. It is widely agreed that it would be irresponsible to continue to use the atmosphere as a dump for our waste from burning fossil fuels. One of the most readily-available disincentives is to put a price on such activity. On the basis of the EU Emissions Trading Scheme transactions, it seems we need to factor in about two Euro cents per kWh for carbon cost with coal generation, and half that for gas, hence about €20 per tonne of CO_2. Nuclear has zero cost for carbon emissions, and a 1000 MWe nuclear plant would save the emission of about seven million tonnes of CO_2 per year from an equivalent coal plant (half that from a gas-fired plant). Put another way, every 22 tonnes of mined uranium that is used will save the emission of one million tonnes of CO_2, relative to coal.

Even without carbon value, nuclear power is economically competitive in many parts of the world[18] and is taxed in some countries because it is too prof-

18 See WNA 2010, *Economics of Nuclear Power* www.world- nuclear.org/info/inf02.htm which presents all recent studies on comparative economics. See particularly the 2003 Finnish bar chart showing data which was the basis of a 3 billion investment decision. However, the OECD studies are most often cited.

itable compared with alternatives.[19] Wind power is the main no-carbon alternative, typically costing about twice as much per kWh generated and needing government coercion to succeed – both because of cost, which consumers must subsidise, and the need for back-up capacity because of its intermittent availability. Decisions in the last few years to build large new reactors have basically been economic ones. Keeping electricity costs low is prima facie a social good – the UK government has focused attention on energy poverty in recent years.

Nuclear power plants operate in thirty countries and produce 14% of the world's electricity (24% of electricity in the Organisation for Economic Co-operation and Development (OECD) countries). More nuclear plants are being built or are about to be built in some twenty countries.[20] China is planning to increase nuclear capacity almost tenfold by 2020 (26 large new reactors are under construction as of 30/12/10) because this is an important way of meeting its rapidly escalating electricity demand while taking steps to improve air quality.[21] India aspires to similar growth in nuclear provision.[22]

Advanced third-generation reactors are now being built. These have greater standardisation, simpler engineering, expedited approvals in several countries, longer operating life and are one or two orders of magnitude safer than the well-proven second generation units.[23] While many of these depend on economies of scale and are around 1400-1700 MWe, others likely to be built soon depend on economies of replication and factory construction, and are 45-300 MWe each.[24]

Security and safety

Energy security is increasingly coming to the fore in public consciousness. There is no technical problem and relatively little cost in a country or electrical utility holding a few years' supply of nuclear fuel, either as mined natural uranium, as enriched uranium, or as fabricated fuel. Being subject to long distance sea transport or at the end of a gas pipeline from Siberia or the Middle East through a variety of countries with little interest in the UK's welfare, can cause considerable unease – both civic and economic. Japan and France are two countries that got that general message in the 1970s. France for some years has obtained 75% of its electricity from nuclear power and is the world's largest

19 In Sweden about one third of the operating cost of nuclear power is a special tax on it. Belgium is introducing a tax of EUR 0.5 cents/kWh on nuclear power, and Germany has just introduced taxes amounting to about EUR 2.5 c/kWh on nuclear power production.
20 WNA 2010, *Emerging Nuclear Energy Countries*, http://www.world-nuclear.org/info/inf102.html.
21 WNA 2010, *Nuclear Power in China*, http://www.world-nuclear.org/info/inf63.html.
22 WNA 2010, *Nuclear Power in India*, http://www.world-nuclear.org/info/inf53.html.
23 WNA 2010, *Advanced Nuclear Power Reactors*, http://www.world-nuclear.org/info/inf08.html.
24 WNA 2010, *Small Nuclear Power Reactors*, http://www.world-nuclear.org/info/inf33.html.

net exporter of electricity; Japan gets about one third of its power from nuclear and is moving towards 50% by 2030.

There has never been any public harm to health from any western-type reactor and as with most technologies, operations today have generally much enhanced safety margins compared with decades ago. New plants are much safer and older ones have been upgraded in varying degrees.[25] This includes resistance to terrorism, and certainly to any adverse local effects arising from it. Nuclear power reactors are very robust steel and concrete structures, and materials arising from nuclear power are intrinsically unattractive for 'dirty bombs' compared with radioactive stuff from elsewhere.

Until 2011, the nuclear industry had had only one accident causing public harm in more than 14,500 reactor-years of civil experience and that was of little applicability to any reactor licensable in the West.[26] The US Three Mile Island power plant accident in 1979 was the one most relevant for ongoing safety and much was learned and applied. Moreover, no one was harmed by it, due to the way the plant (in common with all plants in the West) was designed and constructed.

The major accident to three reactors at Fukushima Daiichi in March 2011 has cast doubt on the safety resilience of some older western reactors. While the reactors shut down safely as designed when the major earthquake hit, the huge tsunami an hour later disabled their cooling systems and back-up power provisions so that decay heat (about 1.5% of operating heat at that stage) could not be removed. The fuel apparently melted and volatile decay products in the fuel were vented with steam and hydrogen as internal pressure rose to about twice design levels. A large amount of radioactive iodine (with short half-life) and caesium (much longer) were deposited up to 50 km from the plant. Well before this the inhabitants had been evacuated, but there is massive inconvenience to some 100,000 people, in addition to the direct effects of the tsunami in the area. After more than three months there have been no deaths or serious radiation exposures from the accident and hundreds of people working on the radioactively-polluted site are cleaning it up, restoring proper cooling (for ongoing decay heat removal) and treating some 110,000 cubic metres of contaminated water. It may be some time before the three written-off reactors are brought to 'cold shutdown' and everyone can go home.[27]

The Chernobyl disaster in 1986[28] was largely irrelevant to any nuclear

25 WNA 2010, *Safety of Nuclear Power Reactors*, http://www.world-nuclear.org/info/inf06.html.
26 Apart from Russian submarines, there have been eleven reactor accidents or serious incidents, six of them to commercial nuclear power units (the others to military – e.g. Sellafield 1957 – or experimental reactors). Three resulted in no or very minor radiation release, the other three are discussed here.
27 WNA 2011, *Fukushima Accident*, http://www.world-nuclear.org/info/fukushima_accident_inf129.html.
28 WNA 2010, *Chernobyl Accident*, http://www.world-nuclear.org/info/chernobyl/inf07.html.

power plant outside the Soviet bloc. It involved a Soviet reactor design with many features that would render it far from being licensable in the West then, or anywhere today. As well as having a positive void coefficient large enough to overwhelm all other influences, the design had no containment structure and the operators did not understand the basic characteristics of the plant. (The examples of this Reactor Bolshoy Moshchnosty Kanalny (RBMK) design that continue to operate have been highly modified, though they still do not satisfy western safety standards.) It tragically underlined the reasons why such plants could never be built outside the Soviet Union.[29]

Waste and decommissioning

Waste management and disposal costs are the responsibility of operators. These are internalised and passed on to the power consumer as 2-3% of the generation cost, although it is more in the UK due to British Energy's contracts with the British Nuclear Group which were part of the privatisation arrangement in 1996. Technically, storage and disposal are straightforward. The waste from nuclear power is modest (even less than before, with newer reactors) and is contained and managed, not dispersed to the environment. Compared with any other process involving the conversion of fuel to energy, the quantities of hazardous residues are very small.[30] This is a significant feature relevant to the ethics of energy choices, given that the waste is easily manageable.

In Europe, radioactive waste (including that from medicine, etc) comprises about one per cent of all toxic industrial waste, and the radioactivity of the high-level nuclear waste diminishes to 0.1% of the original level after about forty years. There have been no significant problems from storage, handling and transport of civil nuclear waste in the first fifty-five years of industry experience anywhere in the Western world. In the UK however there was for many years a conspicuous failure of political will to formulate and implement policies for dealing with radioactive waste (among others). This is in marked contrast with most other countries relying significantly on nuclear power.[31]

Decommissioning costs are normally met from a levy on current production, and in most cases the amount generated by the levy has been found more than adequate as experience has caught up with projections. Over 120 nuclear

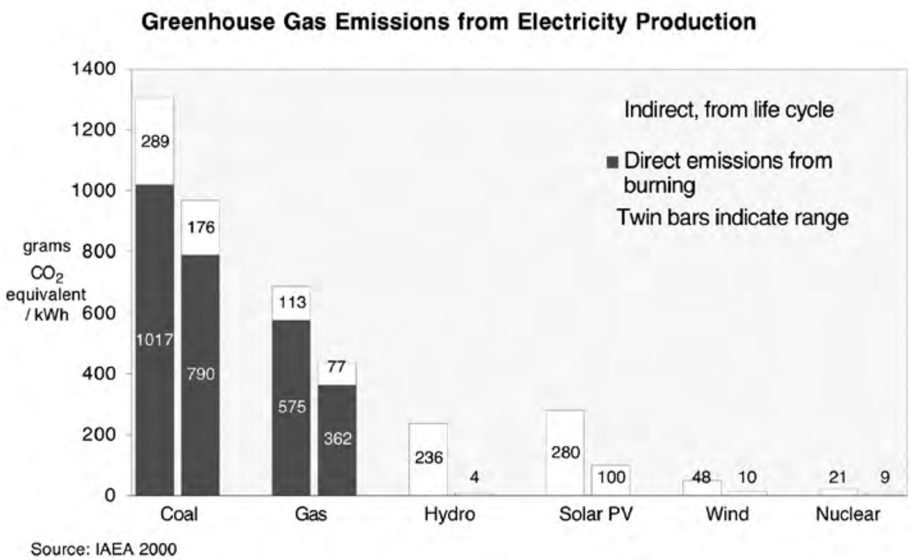
29 The Chernobyl Forum report in 2005, from three governments and 8 UN agencies is a recent account of the effects of the accident: IAEA 'Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience', *Report of the UN Chernobyl Forum Expert Group 'Environment'*, (2006).

30 From a typical 1000 MWe power unit operating for one year the quantities of waste are about 200 m3 of low-level waste (requiring no shielding to be handled), about 70 m3 of intermediate- level waste (requiring shielding) and 10 m3 of used fuel (requiring shielding and cooling) or 2.5 m3 if as vitrified high- level waste from reprocessing that used fuel. See also http://www.world-nuclear.org/info/inf04.htm.

31 WNA 2009, *National Policies – Radioactive waste management Appendix 3*, http://www.world-nuclear.org/info/inf04ap3.html.

power reactors have so far been decommissioned. (The UK historical situation[32] is unique, at least outside Russia.) Political problems regarding selection of sites for geological disposal hamper the industry – NIMBY (not in my backyard) being a ubiquitous social reflex. That is a challenge for people of principle and integrity in the political process, to balance narrow self-interest with the wider community good, and one which merits attention from Christians.[33]

Nuclear energy is essentially carbon-free: when the whole nuclear fuel cycle from mining through enrichment to waste disposal is taken into account, the carbon emissions are usually less than two per cent of those from coal.[34] Audited life cycle figures are available for several plants and range from 3 to about 20 g/kWh CO_2. Energy input to the whole fuel cycle is less than two per cent of output (up to 3% likely with very low grade ores).



32 Huge costs are estimated for dealing with UK's legacy of waste and decommissioning of plants from early in the nuclear era. These are due to the pre-1960 nexus with military programmes, early decisions regarding technology and successive government decisions to put funds set aside for waste into general revenue. See also fuller description in *Nuclear Development in the UK*, http://www.world-nuclear.org/info/inf84a_nuclear_development_UK.html.

33 In Finland a community has willingly accepted the location of a deep geological repository, in Sweden two communities competed to host one, elsewhere there is some ambivalence and in USA Nevada politically blocked the proposed Yucca Mountain repository located between a nuclear weapons test site and a USAF bombing range!

34 They depend on energy inputs especially to mining and enrichment, and the source of those energy inputs. E.g. in France the energy input to enrichment is about 50 times higher than normal (until a new plant comes on line) but all the electricity for that comes from nuclear power, so has no CO2 implication.

Avoiding weapons proliferation

Proliferation of nuclear weapons has been an acknowledged problem for at least fifty years and is largely addressed internationally by measures under the Nuclear Non-Proliferation Treaty (NPT). Instead of over thirty nuclear weapons states at the turn of the century as widely predicted in the 1960s, there were eight, three of them outside the NPT. The constraint can be directly attributed to the NPT. Civil nuclear power has not been the cause of or route to nuclear weapons in any country, and all uranium traded for electricity production is subject to international accounting and auditing provisions known as safeguards. None has ever been diverted for military use. All nuclear weapons programmes have either preceded or risen independently of civil nuclear power,[35] as shown most recently by North Korea and, apparently, Iran. No country is without plenty of uranium in the small quantities (say ten tonnes) needed for a few weapons. There is no chance that the problem of nuclear weapons proliferation will be solved by turning away from nuclear power or by ceasing trade in the tens of thousands of tonnes of uranium needed for it annually. There is scope in the international safeguards regime to consolidate further steps in line with NPT principles of international transparency, accountability and interdependence.

It is also relevant to note and be thankful for the fact that a lot of military high-enriched uranium (mined in the 1950-60s) is today coming out of weapon stockpiles and is being used in civil power programmes to generate electricity. Half of the uranium now used in the USA is from Russian nuclear weapons demobilised since the Cold War! The first military plutonium is now being used similarly. There is an echo here of Ezekiel 39: 9-10, where the people of God use the figurative enemy's weapons of war as fuel after God acts to remove the military threat: 'For seven years they will use them for fuel. They will not need to gather wood… because they will use the weapons for fuel.' The Russian-US programme spans twenty years, to 2013.

External and opportunity costs

External costs are those incurred in relation to health and the environment. They are quantifiable but not built into the cost of electricity to the consumer; they are borne by society at large. They are an important ethical as well as practical consideration, and arguably should be a concern for Christians since they can tend to be 'paid' by those who do not enjoy the benefits arising from their being incurred. A major European study (ExternE report, 2001)[36] shows that

35 See also individual case studies in WNA 2010, *Nuclear Proliferation Case Studies*, http://www.world-nuclear.org/info/inf73.html.
36 The European Commission launched the project in 1991 in collaboration with the US Dept of Energy (which subsequently dropped out), and it was the first research project of its kind 'to put plausible financial figures against damage resulting from different forms of electricity production for the entire EU'.

nuclear energy incurs about one tenth of the costs of coal-fired electricity, and much the same as wind. If these external costs were included, the EU price of electricity from coal would double and that from gas would increase around 30%.

Opportunity costs also raise ethical issues where one would expect to see Christians being vocal. Natural gas is touted as a CO_2-reduction strategy relative to coal (it can approximately halve emissions per kWh), but it is most unlikely that our grandchildren will thank us for profligate use of it in large-scale power generation. Such use has driven up the price of electricity and has made natural gas less affordable for fuel uses for which it is better suited, such as comprising the main chemical feedstock for nitrogen fertilisers.[37] Uranium has no other uses than concentrated energy production.

Future opportunities for nuclear benefits

Doubling the world's nuclear contribution would eliminate twenty-five to thirty per cent of the CO_2 emissions from power generation. This could be achieved relatively quickly: for instance in 1984, 39 nuclear reactors came on line in a single year, and through the 1980s, 218 power reactors started up, an average of one 923 MWe unit every 17 days (201 GWe total). So it is not hard to imagine that over a decade – plus a bit of lead time – the present 376 GWe nuclear capacity could be more than doubled.[38]

It is likely that we will see this expansion occurring at the same time as weapons proliferation concerns are reduced; ironically Iran's two decades of evasion under the NPT and that country's subsequent intransigence will have achieved a major paradigm shift towards greater security and better use of resources.

In the longer term nuclear power may well be used to make hydrogen for transport fuel, initially by high-temperature electrolysis, then thermochemical processes using high-temperature (950˚C) reactors. However in the short term the role of nuclear power in road transport is more likely to be through increased base-load provision for overnight charging of plug-in electric and electric-hybrid vehicles.[39]

37 Using the Haber-Bosch process. Some 100 million tonnes of nitrogen fertiliser is now produced annually by this process, using about half the world's hydrogen production. The hydrogen is made by steam reforming of natural gas, and each tonne of hydrogen produced gives rise to 11 tonnes of CO2.

38 The WNA's Nuclear Century Outlook projection for 2030 is in the range 602 to 1350 GWe.

39 Base-load (24/7 power) is generally about half of maximum capacity of grid systems. With a large proportion of motor vehicles being electric or plug-in hybrid, overnight charging of these is likely to take the base-load proportion of supply to 75-90%, thereby lowering the unit cost of electricity for all. The UK Department of Transport and the Royal Academy of Engineering (2010) have both estimated that if the UK switched to battery electric vehicles, electricity demand (kWh) would rise about 16%, filling in overnight low demand. Royal Academy of Engineering, May 2010, *Electric vehicles:charged with potential*.

Ten years ago the environmental lobby was noisy in opposition to nuclear power, but today some of the highest profile environmentalists are speaking very clearly for nuclear power, not because they love it, but because it represents much less of a problem or threat than global warming. The great question before us is not whether nuclear energy will grow, but whether it will grow rapidly enough to play its needed role. Patrick Moore,[40] a founder of Greenpeace, has said 'we need not 440 nuclear reactors but maybe 5000… to really make a dent in (consumption of) fossil fuels'.

For base-load power – continuous, reliable supply on a large scale – there are generally no carbon-free alternatives to nuclear power. Non-hydro renewables have a valuable place – but only at the margin, and requiring significant subsidy. There is thus a strong case for using nuclear energy fully, carefully and gratefully. Failure to do so will certainly impose resource constraints and environmental costs which are arguably incompatible with faithful stewardship of God's creation. These constraints and costs are likely to fall most heavily on those already in poverty and least able to cope with them.

Concerns raised in opposition to nuclear power

Despite the demonstrated track record over fifty-five years, concerns continue to be raised about greater use of nuclear power. These include costs, safety, weapons proliferation and waste.[41] All are discussed above, but are now more specifically addressed.

Costs

Nuclear power plants cost a lot more than others to build, but are less expensive to run. The economics of any project are addressed by the proponent, and if the figures do not add up, some other means of power generation is employed. This is hardly a credible public concern, though it is commonly voiced.

Safety

Nuclear power involves a very high concentration of energy with associated radioactivity that needs to be securely contained and controlled under all circumstances, including malign attacks. Early concerns about the effects of core melting and atmospheric release of radionuclides have been modified over fifty years of experience and are addressed in the design of power plants. The dangers of nuclear power are much fewer than many others accepted in our technological age from industry and energy production. Just sharing a main road

40 http://www.greenspirit.com/.
41 WNA 2009, *The Nuclear Debate*, http://www.world-nuclear.org/info/inf50.html.

with a petrol tanker reminds one of this, let alone living near an LNG terminal.

Weapons proliferation

This continues to be a legitimate concern for the industry and governments worldwide. However, no proliferation has occurred from the base of civil nuclear power; all the particular concerns today (e.g. Iran, North Korea) have arisen apart from any nuclear power programme, and it is not clear that any curtailment of nuclear power would help resolve today's concerns or avoid new ones – arguably the contrary would be the case.

Waste

The longevity of (particularly) high-level nuclear waste is put forward as a problem. However, nuclear waste has not proved to be a problem or hazard in practical terms over half a century; it is the only toxic industrial waste that becomes more benign with age. With new fuel cycles the longevity can be greatly reduced and it is a very small fraction of all toxic industrial waste (e.g. about 1% in the EU). The only problems that have arisen are political, relating to repository location. In addition, the management and disposal of nuclear waste is very well funded, much more so than for most (perhaps all) other forms of waste disposal.

Fears from folklore

Some opposition to nuclear power comes from those with an ideological antipathy to innovations and/or to economic growth and a technology-enabled way of life.[42] Folklore, misrepresentation and fear-mongering are sometimes deployed in their cause, as with opposition to genetically-modified organisms. While passionately-held beliefs are not necessarily groundless, the basis for them requires teasing out. Many popular fears of nuclear power arise not from science, but out of such ideas, shaped into ideologies. It is sometimes said that all energy derived from substances within the earth is abhorrent ('brown energy') and that only 'green energy', obtained from the earth's surface or above it, should ever be employed. Such a distinction is entirely without any scientific or theological basis. All of God's creation is good.

42 Christian Ecology Link is a UK organisation in this category. After delivering an anti-nuclear message to 10 Downing Street in 2008, a statement said: 'Christian Ecology Link believes the question we should be asking is how best should we be living with justice, joy and humility on the one planet we have available to us. The answer to this question is in a low-energy, low-carbon and renewably-powered economy.' This is elaborated in a 2006 CEL document entitled *Faith and Power*: http://www.christian-ecology.org.uk/fp.pdf. While the section on Christian Principles to underpin Energy Strategy is unexceptional, that on Assessing the Nuclear Option has many errors and misrepresentations.

At a trivial level, we find the notion that anything labelled 'nuclear' must necessarily be bad or harmful. For this reason the medical profession omits the word from what should properly be called '*nuclear* magnetic resonance imaging' (MRI). Some ideological objections, however, are more explicit and structured. Herein lies a big challenge for Christians: moving the discussion to where integrity in handling the facts can be demonstrated and sustained.

There is a view that radioactivity and nuclear reactions generally are somehow 'unnatural' and therefore to be eschewed. To this it may be replied that many 'unnatural' things are beneficial, and in any case nuclear reactions and radioactivity are part of the fabric of the universe and are merely being applied and deployed to serve human needs.

Finally it is sometimes argued that Christian stewardship of the world must not involve going beyond nature's bounds in creating new elements and actually destroying atoms, which are the 'God-given building blocks of the universe'. Yet atoms are not eternal, and may be changed by all manner of nuclear processes in nature, from the supernovae in which they were made to the fission at Oklo, never mind the normal process of radioactive decay continually going on in the rocks, soil and masonry.

Theologically, harnessing nuclear power is as justifiable as harnessing fossil fuels, wind, tide or animal power. All are gifts from God, provided as part of his bounteous creation. In the New Testament the timid servant was castigated because his gift was left in the ground rather than being employed to create more wealth.[43] Christian stewardship of God's creation in addressing human needs appropriately involves not leaving uranium in the ground but utilising nuclear power thankfully and responsibly as with any other gift from our bountiful Creator.

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43 Luke 19:11-27.