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WHY NUCLEAR POWER CANNOT BE A MAJOR ENERGY SOURCE

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It takes a lot of fossil energy to mine uranium, and then to extract and prepare the right isotope for use in a nuclear reactor. It takes even more fossil energy to build the reactor, and, when its life is over, to decommission it and look after its radioactive waste.

As a result, with current technology, there is only a limited amount of uranium ore in the world that is rich enough to allow more energy to be produced by the whole nuclear process than the process itself consumes. This amount of ore might be enough to supply the world's total current electricity demand for about six years.

Moreover, because of the amount of fossil fuel and fluorine used in the enrichment process, significant quantities of greenhouse gases are released. As a result, nuclear energy is by no means a 'climate-friendly' technology.

Nuclear power promises much. It is based on a process which does not produce carbon dioxide. It is produced in a relatively small number of very large plants, so that it fits easily onto the national grid. And there is even the theoretical prospect of it being able to breed its own fuel. So, what's the problem?

The form of nuclear power available to us at present comes from nuclear fission, fuelled by uranium. Uranium-235 is an isotope of uranium with the rare and useful property that, when struck by a neutron, it splits into two and, in the

A quick guide to nuclear terms

- A "proton" is a particle with a positive electrical charge, found in the nucleus (centre) of every atom.
- A "neutron" is a particle with a neutral charge (that is, no charge at all) found in the nucleus of every atom except that of the simple form of hydrogen.
- The "atomic number" of an element is the number of protons in the nucleus of an atom: this is what gives an element its characteristic properties.
- The "atomic mass" of an atom is the sum of neutrons and protons in the nucleus.
- "Isotopes" of an element are atoms which have the same atomic number as each other, but different numbers of neutrons and therefore different atomic masses. They are identified by the sum of protons and neutrons, so that, for instance, "uranium-235" has 92 protons and 143 neutrons, whereas uranium-238 has 92 protons and 146 neutrons.
- "Radioactive isotopes" are isotopes whose nuclei are unstable. This means that at a random moment the nucleus may release energy in the form of radiation, and decay (change) into a different element.
- The "half-life" is the time it takes, statistically, for half the atoms of a given radioactive isotope to decay.
- "Radioactivity" is the ionizing radiation which has the ability to break up and rearrange cellular DNA, and even the atomic structures of elements. It is a property of minute and mobile particles in the dust, food and water which we take into our bodies every day. Some is natural background radiation, released by local rocks or by particles, and in most cases our bodies have had millions of years' practice in coping with them or secreting them; but some is quite new, released from elements which are exceedingly rare – in some cases they did not even exist before being made by accident or design, beginning in the 1940s. These are live, radioactive materials which animal and plant life has never had to cope with before.[1]

process, produces more neutrons which then proceed to split more atoms of uranium-235 in a chain of events which produces a huge amount of energy. We can get an idea of how much energy it produces, by looking at Einstein's famous equation, $E=mc^2$, which says that the energy produced is the mass multiplied by the square of the speed of light. A little bit of mass disappears in the process – we can think of this as the material weighing slightly less at the end of the process than at the beginning – and it is that "missing" mass which turns into energy which can be used to make steam to drive turbines and produce electricity. Neutrons from the reaction which strike one of the other isotopes of uranium: uranium-238, are more likely to be absorbed by the atom which transforms it into plutonium-239. Plutonium-239 shares with uranium-235 the property that it, too, splits when struck by neutrons, so that the plutonium-239 then begins to act as a fuel as well.[2]

The process has to be controlled; otherwise, it would be a bomb. The control is provided by a "moderator", in the form of large quantities of, for instance, water or graphite, whose presence means that the neutrons cannot so easily find the next link in the chain, so the sequence slows down or stops. Eventually, however, the uranium gets clogged with radioactive impurities such as the barium and krypton produced when uranium-235 decays, along with "transuranic" elements such as americium and neptunium, and a lot of the uranium-235 gets used up. It takes a year or two for this to happen, but eventually the fuel elements have to be removed, and a fresh ones inserted.

The used fuel elements are very hot and radioactive (stand close to one for a second or two and you are dead), so there are some tricky questions about what to do with them. Sometimes they are recycled (reprocessed), to extract some of the remaining uranium and plutonium to use again, although you don't get as much fuel back as you started with, and the bulk of the impurities remains. Alternatively, the whole lot is disposed-of – but there is more to this than just dumping it somewhere, for it never really goes away. The half-life of an element is the time it takes for half of it to decay; the half-life of uranium-238, which is the largest constituent of the waste, and which keeps the whole thing radioactive, is about the same as the age of the earth: 4.5 billion years.[3]

Those are the principles. Now for a closer look at what nuclear power means. It is quite important that we should do this, because nuclear power cannot be sensibly discussed on the basis of popular misconceptions such as the one about nuclear energy producing almost no carbon dioxide.

The principal source for the discussion that follows is the work of Jan Willem Storm van Leeuwen and Philip Smith, but the interpretation of their work, and its application in the context of current energy options, is the author's. The paper relies centrally, but not exclusively, on work from this one source, and the implications of this are discussed in the concluding section.[4]

1. WHAT IS REALLY INVOLVED IN NUCLEAR POWER?

Mining and milling

Uranium is widely distributed in the earth's crust but only in minute quantities, with the exception of a few places where it has accumulated in concentrations rich enough to be uses as an ore. The main deposits of ore, in order of size, are in Australia, Kazakhstan, Canada, South Africa, Namibia, Brazil, the Russian Federation, the USA, and Uzbekistan. There are some very rich ores; concentrations as high as 1 percent have been found, but 0.1 percent (one part per thousand) or less is usual. Most of the usable "soft" (sandstone) uranium ore has a concentration in the range between 0.2 and 0.01 percent; in the case of "hard" (granite) ore, the usable lower limit is 0.02 percent. The mines are usually open-cast pits which may be up to 250m deep. The deeper deposits require underground workings and some uranium is mined by "*in situ* leaching", where hundreds of tonnes of sulphuric acid, nitric acid, ammonia and other chemicals are injected into the strata and then pumped up again after some 5-25 years, yielding about a quarter of the uranium from the treated rocks and depositing unquantifiable amounts of radioactive and toxic metals into the local environment and aquifers.[5]

When it has been mined, the ore is milled to extract the uranium oxide. In the case of ores with a concentration of 0.1 percent, the milling must grind up approximately 1,000 tonnes of rock to extract just one tonne of the bright yellow uranium oxide, called "yellowcake". Both the oxide and the tailings (that is, the 999 tonnes of rock that remain) are kept radioactive indefinitely by, for instance, uranium-238, and they contain all thirteen of its radioactive decay products, each one changing its identity as it decays into the next, and together forming a cascade of heavy metals, with spectacularly varied half-lives (box 1).

Once these radioactive rocks have been disturbed and milled, they stay around to cause trouble. They take up much more space than they did in their undisturbed state, and their radioactive products are free to be washed and blown away into the environment by rain and wind. These tailings ought therefore to be treated: the acids should be neutralised with limestone and made insoluble with phosphates; the mine floor should be sealed with clay before the treated tailings are put back into it; the overburden should be replaced and the area should be replanted with indigenous vegetation. In practice, all this is hardly ever done. It is expensive, and it also requires approximately four times

Box 1

As old as the earth

The decay sequence of uranium-238

The sequence starts with uranium-238. Half of it decays in 4.5 billion years, turning as it does so into thorium-234 (24 days), protactinium-234 (one minute), uranium-234 (245,000 years), thorium-230 (76,000 years), radium-226 (1,600 years), radon-222 (3.8 days), polonium-218 (3 minutes), lead-214 (27 minutes), bismuth-214 (20 minutes), polonium-214 (180 microseconds), lead-210 (22 years), bismuth-210 (5 days), polonium-210 (138 days) and, at the end of the line, lead-206 (non-radioactive).

the amount of energy that was needed to extract the ore in the first place.[6]

> *Once radioactive rocks have been disturbed and milled, they stay around to cause trouble. Their radioactive products are free to be washed and blown away by rain and wind.*

Preparing the fuel

The uranium oxide then has to be enriched. Yellowcake contains only about 0.7 percent uranium-235; the rest is mainly uranium-234 and -238, neither of which directly support the needed chain reaction. In order to bring the concentration of uranium-235 up to the required 3.5 percent, the oxide is reacted with fluorine to form uranium hexafluoride (UF_6), or "hex", a substance with the useful property that it changes – "sublimes" – from a solid to a gas at 56.5°C, and it is as a gas that it is fed into an enrichment plant. About 85 percent of it promptly comes out again as waste in the form of depleted uranium hexafluoride. Some of that waste is chemically converted into depleted uranium metal, which is then in due course distributed back into the environment via its use in armour-piercing shells, but most of it is kept as uranium hexafluoride in its solid form. It ought then to be placed in sealed containers for final disposal in a geological depositary; however, owing to the cost of doing this, and the scarcity of suitable places for it, much of it is put on hold: in the United States, during the last fifty years, 500,000 tonnes of depleted uranium have accumulated in cool storage (to stop it subliming), designated as "temporary".[7]

The enriched uranium is then converted into ceramic pellets of uranium dioxide (UO_2) and packed in zirconium alloy tubes which are finally bundled together to form fuel elements for reactors.[8]

Generation

The fuel can now be used to produce heat to raise the steam to generate electricity. In due course the process generates waste in the form of spent fuel elements and, whether these are then reprocessed and re-used or not, eventually they have to be disposed of. But first they must be allowed to cool off, as the various isotopes present decay, in ponds for between 10 and 100 years – sixty years may be taken as typical. Various ideas about how to deal with them finally are current, but there is no standard, routinely-implemented practice. One option is to pack them, using remotely-controlled robots, into very secure containers lined with lead, steel and pure electrolytic copper, in which they must lie buried for millions of years in secure geological depositaries. It may turn out in due course that there is one best solution, but there will never be an ideal way to store waste which will be radioactive for millions of years and, whatever least-bad option is chosen, it will require a lot of energy: it is estimated that the energy cost of making the lead-steel-copper containers needed to package the spent fuel produced by a reactor is about the same as the energy needed to construct the reactor.[9]

A second form of waste produced in the generation process consists of the routine release of very small amounts of radioactive isotopes such as hydrogen-3 (tritium), carbon-14, plutonium-239 and many others into the local air and water. The significance of this has only recently started to be recognised and investigated.[10]

A third, less predictable form of waste occurs in the form of accidental emissions and catastrophic releases in the event of accident. The nuclear industry has good safety systems in place; it has to have them, because the consequences of an accident are so extreme. However, it is not immune to accident. The work is routine, and the staff at some reactors have been described by a nuclear engineer as "asleep at the wheel". There is also the prospect, rising to certainty with the increase in numbers and the passage of time, of sabotage by staff, of the flooding of reactors by rising sea levels, and poor training and systems, particularly if a nuclear programme were to be developed in haste by governments eager to produce energy as fast as possible to make up for the depletion of oil and gas. Every technology has its accidents. The risk never goes away; society bears the pain and carries on but, in the case of nuclear power, there is a difference: the consequences of a serious accident – another accident on the scale of Chernobyl, or greater, or *much* greater. It is accepted that the damage could be so great that it was far beyond the capacity of the world's insurance industry to cover. It has therefore been agreed that governments should step in and meet the costs of a nuclear accident once the damage goes beyond a certain limit. In Britain, the Nuclear Installations Act of 1965 requires a plant's operator to pay a maximum of £150 million in the ten years after the incident. The government would cover any excess and pay for any damage that arose between ten and thirty years afterwards. Under international conventions, the government would also cover any cross-border liabilities up to a maximum of about £300 million. These figures seem to grossly understate the problem. If Bradwell power station in Essex blew up and there was an east wind, London would have to be evacuated. Perhaps even the whole of southern England. The potential costs of a nuclear accident could be closer to £300 trillion rather than £300 million, six orders of magnitude greater.

A fourth type of "waste" is the plutonium itself which, when isolated and purified in a reprocessing plant, can be brought up to weapons-grade, making it the fuel needed for nuclear proliferation. This is one of two ways in which the nuclear industry is used as the platform from which the proliferation of nuclear weapons can be developed; the other one is by enriching the uranium-235 to around 90 percent, rather than the mere 3.5 percent required by a nuclear reactor.

The reactor

The maximum full-power lifetime is 24 years, but most reactors fall short of that. During that time, they require regular maintenance and at least one major refurbishing; towards the end of their lives, corrosion and intense radioactivity make reliable maintenance impossible. Eventually, they must be dismantled, but experience of this, particularly in the case of large reactors, is limited. As a first step, the fuel elements must be removed and put into storage; the cooling system must be cleaned to reduce radioactive CRUD (Corrosion Residuals and Unidentified Deposits). These operations, together, produce about 1,000 m^3 of high-level waste. At the end of the period, the reactor has to be dismantled and cut into small pieces to be packed in containers for final disposal. The total energy required for decommissioning has been estimated at about double the energy needed in the original construction.[11]

2. GREENHOUSE GASES AND ORE QUALITY

The present

Every stage in the process of supporting nuclear fission uses energy, and most of this energy is derived from fossils fuels. Nuclear power is therefore a massive user of energy and a very substantial source of greenhouse gases. In fact, the delivery of electricity into the grid from nuclear power produces, on average, roughly one third as much carbon dioxide as the delivery of the same quantity of electricity from gas...[12]

... or, rather, it *should* do so, because the calculation of the energy cost of nuclear energy is based on the assumption that the high standards of waste management outlined above, including the energy used in decommissioning, are actually carried out. Unfortunately, that is not the case: the nuclear power industry is living on borrowed time in the sense that it is has not yet had to find either the money or the energy to reinstate its mines, bury its wastes and decommission its reactors; if those commitments are simply left out of account, the quantity of fossil fuels needed by nuclear power to produce a unit of electricity would be, on average, only 16 percent of that needed by gas. However, these are commitments which must eventually be met. The only reasonable way to include that energy cost in estimating the performance of nuclear power is to build them into the costs of electricity that is being generated by nuclear power now.[13]

There will never be an ideal way to store waste which will be radioactive for millions of years. Whatever least-bad option is chosen will require a lot of energy.

Another assumption contained in the calculation of the carbon emissions of nuclear power is that the reactors last for the practical maximum of 24 full-power years. For shorter-lived reactors, the quantity of carbon dioxide emissions per unit of electricity is higher; when the energy costs of construction and decommissioning are taken into account, nuclear reactors, averaged over their lifetimes, produce more carbon dioxide than gas-fired power stations (per unit of electricity generated), until they have been in full-power operation for about seven years.

These estimates of carbon dioxide emissions understate the actual contribution of nuclear energy to greenhouse gas emissions, because they do not take into account the releases of other greenhouse gases which are used in the fuel cycle. The stage in the cycle in which other greenhouse gases are particularly implicated is enrichment. As explained above, enrichment depends on the production of uranium hexafluoride, which of course requires fluorine – along with its halogenated compounds – not all of which can by any means be prevented from escaping into the atmosphere. As a guide to the scale of problem: the conversion of one tonne of uranium into an enriched form requires the use of about half a tonne of fluorine; at the end of the process, only the enriched fraction of uranium is actually used in the reactor: the remainder, which contains the great majority of the fluorine that was used in the process, is left as waste, mainly in the form of depleted uranium. It is worth remembering here, first, that to supply enough enriched fuel for a standard 1GW reactor for one full-power year, about 160 tonnes of natural uranium has to be processed; secondly, that the global warming potential of halogenated compounds is many times that of carbon dioxide: that of freon-114, for instance, is nearly 10,000 times greater than that of the same mass of carbon dioxide. Moreover, other halogens, such as chlorine, whose compounds are potent greenhouse gases, along with a range of solvents, are extensively used at various other stages in the nuclear cycle, notably in reprocessing.[14]

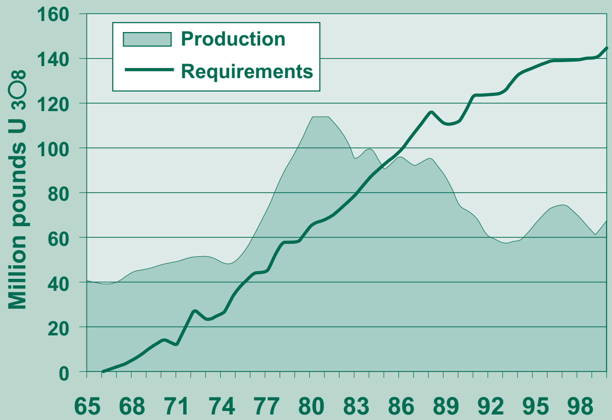
There is no readily-available data on the quantity of these hyper-potent greenhouse gases regularly released into the atmosphere by the nuclear power industry, nor on the actual, presumably variable, standards of management of halogen compounds among the various nuclear power industries around the world. There has to be a suspicion that this source of climate-changing gases substantially reduces any advantage which the nuclear power industry has at present in the production of emissions of carbon dioxide, but no well-founded claim can be made about this. It is essential that reliable research data on the quantity of freons and other greenhouse gases released from the nuclear fuel cycle should be researched and made available as a priority.

The future

The advantage of nuclear power in producing lower carbon emissions holds true only as long as supplies of rich uranium last. When the leaner ores are used – that is, ores consisting of less than 0.01 percent (for soft rocks such as sandstone) and 0.02 percent (for hard rocks such as granite), so much energy is required by the milling process that the total quantity of fossil fuels needed for nuclear fission is greater than would be needed if those fuels were used directly to generate electricity. In other words, when it is forced to use ore of around this quality or worse, nuclear power begins to slip into a negative energy balance: more energy goes in than comes out, and more carbon dioxide is produced by nuclear power than by the fossil-fuel alternatives.[15]

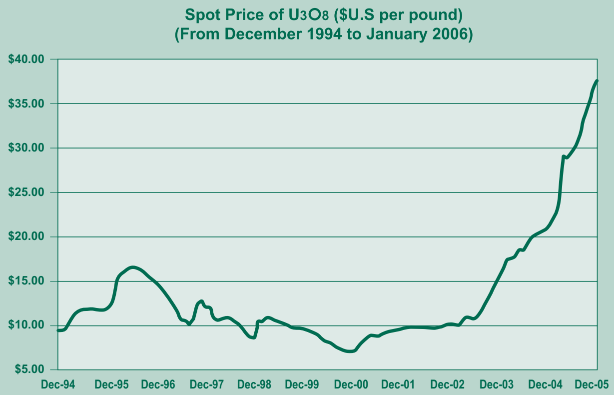
There is doubtless some rich uranium ore still to be discovered, and yet exhaustive worldwide exploration has been done, and the evaluation by Storm van Leeuwen and Smith of the energy balances at every stage of the nuclear cycle has given us a summary. There is enough usable uranium ore in the ground to sustain the present trivial rate of consumption – a mere 2 $^{1}/_{2}$ percent of all the world's final energy demand – and to fulfil its waste-management obligations, for around 45 years. However, to make a difference – to make a real contribution to postponing or mitigating the coming energy winter – nuclear energy would have to supply the energy needed for (say) the whole of the world's electricity supply. It could do so – but there are deep uncertainties as to how long this could be sustained. The best estimate (pretending for a moment that all the needed nuclear power stations could be built at the same time and without delay) is that the global demand for electricity could be supplied from nuclear power for about six years, with margins for error of about two years either way. Or perhaps it could be more ambitious than that: it could supply all the energy needed for an entire (hydrogen-

Uranium production failing to meet demand



The world's annual production of uranium oxide has been lagging behind its use in nuclear reactors for the past twenty years. The shortfall has been made up from military stockpiles.
Source: http://www.uxc.com/cover-stories/uxw_18-34-cover.html

Uranium prices triple in two years



The rise in the price of uranium oxide ("yellowcake") has soared recently. One reason is the higher cost of the fossil energy needed to mine and concentrate it.
Source: www.uex-corporation.com/s/UraniumMarket.as

fuelled) transport system. It could keep this up for some three years (with the same margin for error) before it ran out of rich ore and the energy balance turned negative.[16]

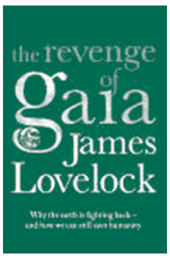
If, as an economy measure, all the energy-consuming waste-management and clean-up practices described above were to be put on hold while stocks of rich ore last, then the energy needed by nuclear energy might be roughly halved, so that global electricity could be supplied for a decade or so. At the end of that period, there would be giant stocks of untreated, uncontained waste, but there would be no prospect of the energy being available to deal with it. At the extreme, there might not even be the energy to cool the storage ponds needed to prevent the waste from being released from its temporary containers.

But it is worse than that. There is already a backlog of high-level waste, accumulated for the last sixty years, and now distributed around the world in cooling ponds, in deteriorating containers, in decommissioned reactors and heaps of radioactive mill-tailings. Some 1/4 million tonnes of spent fuel is already being stored in ponds, where the temporary canisters are so densely packed that they have to be separated by boron panels to prevent chain reactions. The task of clearing up this lethal detritus will require a great deal of energy. How much? That is not known, but here is a very rough guideline. Energy equivalent to about one third of the *total* quantity of nuclear power produced – in the past and future – will be required to clear up past and future wastes. And the whole of this requirement will have to come from the usable uranium ore that remains, which is not much more than half the entire original endowment of usable ore.[17]

This means that, if the industry were to clear up its wastes, only about one third of the present stock of uranium would be left over as a source of electricity for distribution in national grids. To put it another way, the electricity that the industry would have available for sale in the second half of its life – if at the same time it were to meet its obligation to clear up the whole of its past and present wastes – would be approximately 70 percent less than it had available for sale in the first half of its life. On that calculation, the estimates given earlier for the useful contribution that nuclear power could make in the future must be revised: nuclear energy, if it cleared up all its wastes, could supply enough power to provide the world with all the electricity it needed for some three years. And remember that this is no mere thought-experiment: those wastes do have to be cleared up; the energy required for this will reduce the contribution that can be expected from nuclear power from the trivial to the negligible.

And we should not forget the *cost* of this. If the nuclear industry in the second part of its life were to commit itself to clearing up its current and future wastes, the cost would make the electricity it produced virtually unsaleable. Bankruptcy would follow, but the waste would remain. Governments would have to keep the clear-up programme going, whatever the other priorities. They would also have to keep training programmes going in a College of Nuclear Waste Disposal so that, a century after the nuclear industry has died, the skills they will require to dispose of our waste will still exist. And yet, Government itself, in an energy-strapped society, would lack the funds. The disturbing prospect is already opening up of massive stores of unstable wastes which no one can afford to clear up.

The implication of this is that nuclear power is caught in a depletion trap – the depletion of rich uranium ore – at least as imminent as that of oil and gas. So the question to be asked is: as the conventional uranium sources run low, are there alternative sources of fuel for nuclear energy?



3. ALTERNATIVE SOURCES OF FUEL

Earlier this year, James Lovelock, the originator of the Gaia Hypothesis, argued in his book *The Revenge of Gaia* that the threat of climate change is so real, so advanced and potentially so catastrophic that the risks associated with nuclear power are trivial by comparison – and that there really is no alternative to its widespread use. Nuclear power, he insisted, is the only large-scale option: it is feasible and practical; a nuclear renaissance is needed without delay. He robustly dismissed the idea that the growth of nuclear power was likely to be constrained by depletion of its raw material. This is how he put it:

Another flawed idea now circulating is that the world supply of uranium is so small that its use for energy would last only a few years. It is true that if the whole world chose to use uranium as its sole fuel, supplies of easily-mined uranium would soon be exhausted. But there is a superabundance of low-grade uranium ore: most granite, for example, contains enough uranium to make its fuel capacity five times that of an equal mass of coal. India is already preparing to use its abundant supplies of thorium, an alternative fuel, in place of uranium.[18]

Every technology has its accidents but, in the case of nuclear power, there is a difference: the consequences of a serious accident – another accident on the scale of Chernobyl, or greater, or much greater.

Lovelock added that we have a readily-available stock of fuel in the plutonium that has been accumulated from the reactors that are shortly to be decommissioned. And he might also have added that another candidate as a source of nuclear fuel is seawater. So, if we put the supposed alternatives to uranium ore in order, this is what we have: (1) granite; (2) fast-breeder reactors using (a) plutonium and (b) thorium; and (3) seawater.

1. Granite

It has already been explained above that granite with a uranium content of less than 200 parts per million (0.02%) cannot be used as a source of nuclear energy, because that is the borderline at which the energy needed to mill it and to separate the uranium oxide for enrichment is greater – and in the case of even poorer ores, much greater – than the energy that you get back. But Lovelock is so insistent and confident on this point that it is worth revisiting.

Storm van Leeuwen, basing his calculations on his joint published work with Smith on the extraction of uranium from granite, considers how much granite would be needed to supply a 1 GW nuclear reactor with the 160 tonnes of natural uranium it would need for a year's full-power electricity production. Ordinary granite contains roughly 4 grams of uranium per tonne of granite. That's four parts per million. One year's supply of uranium extracted from this granite would require 40 million tonnes of granite. So, Lovelock's granite could indeed be used to provide power for a nuclear reactor, but there are snags. The minor one is that it would leave a heap of granite tailings (if neatly stacked) 100 metres high, 100 metres wide and 3 kilometres long. The major snag is that the extraction process would require some 530 PJ (petajoules = 1,000,000 billion joules) energy to produce the 26 PJ electricity provided by the reactor. That is, it would use up some 20 times more energy that the reactor produced.[19]

2. Fast breeder reactors

(a) Plutonium,

Lovelock's proposal that we should use plutonium as the fuel for the nuclear power stations of the future can be taken in either of two ways. He might be proposing that we could simply run the reactors on plutonium on the conventional "once-through" system which is standard, using light-water reactors. This can certainly be done, but it cannot be done on a very large scale. Plutonium does not exist in nature; it is a by-product of the use of uranium in reactors and, when uranium is no longer used, then in the normal course of things no more plutonium will be produced. There is enough reactor-grade plutonium in the world to provide fuel for about 80 reactors. That is just about realistic, but there are another two theoretical but highly unrealistic possibilities. The first is that all weapons-grade plutonium could be converted into enough fuel for about 60 more reactors; the second is that all the spent fuel produced by all nuclear power stations in the world could be successfully reprocessed (despite the substantial failure and redundancy of reprocessing technology at present) and used to provide the fuel for the reactors of the future. That would provide fuel for another 600 reactors – making a total of 740 operating with plutonium alone.[20]

But since we're trying to be realistic here, let us concentrate on what could actually be done, and stay as close as we can to what Lovelock seems to be suggesting: we could, using the plutonium that we actually have, build 80 reactors worldwide. At the end of their life (say, 24 full-power years), the plutonium would have been used up, though supplemented by a little bit over from the final generation of ordinary uranium-fuelled reactors, but soon all reactors would be closed down and not replaced, because at that time there will be no uranium to fuel them with, either. This would scarcely be a useful strategy, so it is more sensible to suppose that Lovelock has in mind the second possibility: that the plutonium reactors should be breeder reactors, designed not just to produce electricity now, but to breed more plutonium for the future.

Breeders are in principle a very attractive technology. In uranium ore, a mere 0.7 percent of the uranium it contains consists of the useful isotope – the one that is fissile and produces energy – uranium-235. Most of the uranium consists of uranium-238, and most of that simply gets in the way and has to be dumped at the end; it is uranium-238 which is responsible for much of the awesome mixture of radioactive materials that causes the waste problem. And yet, uranium-238 does also have the property of being fertile. When bombarded by neutrons from a "start-up" fuel like uranium-235 or plutonium-239, it can absorb a neutron and eject an electron, becoming plutonium-239. That is, plutonium-239 can be used as a start-up fuel to produce more plutonium-239, more-or-less indefinitely. That's where the claim that nuclear power would one day be too cheap to meter comes from.

But there is a catch. It is a complicated technology. It consists of three operations: breeding, reprocessing and fuel fabrication, all of which have to work concurrently and smoothly. First, breeding: this does not simply convert uranium-238 to plutonium-239; at the same time, it produces plutonium-241, americium, curium, rhodium, technetium, palladium and much else. This mixture tends to clog up and corrode the equipment. There are in principle ways round these problems, but a smoothly-running breeding process on a commercial scale has never yet been achieved.[21]

Secondly, reprocessing. The mixture of radioactive products that comes out of the breeding process has to be sorted, with the plutonium-239 being extracted. The mixture itself is highly radioactive, and tends to degrade the solvent, tributyl phosphate. Here, too, insoluble compounds form, clogging up the equipment; there is the danger of plutonium accumulating into a critical mass, setting off a nuclear explosion. The mixture gets hot and releases radioactive gases; and significant quantities of the plutonium and uranium are lost as waste. As in the case of the breeder operation itself, a smoothly-running reprocessing process on a commercial scale has never yet been achieved.

Box 2

The safety/cost trap

The complexity of in-depth defence against accident can make the system impossible

There is a systemic problem with the design of breeder reactors. The consequences of accidents are so severe that the possibility has to be practically ruled out under all circumstances. This means that the defence-in-depth systems have to be extremely complex, and this in turn means that the installation has to be large enough to derive economies of scale – otherwise it would be hopelessly uneconomic. However, that means that no confinement dome, on any acceptable design criterion, can be built on a scale and structural strength to withstand a major accident. And that in turn means that the defence-in-depth systems have to be even more complex, which in turn means that they becomes even more problem-prone than the device they were meant to protect.

A study for the nuclear industry in Japan concludes: "A successful commercial breeder reactor must have three attributes: it must breed, it must be economical, and it must be safe. Although any one or two of these attributes can be achieved in isolation by proper design, the laws of physics apparently make it impossible to achieve all three simultaneously, no matter how clever the design."[23]

The third operation is to fabricate the recovered plutonium as fuel. The mixture gives off a great deal of gamma and alpha radiation, so the whole process of forming the fuel into rods which can then be put back into a reactor has to be done by remote control. This, too has yet to be achieved as a smoothly-running commercial operation.

And, of course, it follows from this, that the whole fast-breeder cycle, consisting of three processes none of which have ever worked as intended, has itself never worked. There are three fast-breeder rectors in the world: Beloyarsk-3 in Russia, Monju in Japan and Phénix in France; Monju and Phénix have long been out of operation; Beloyarsk is still operating, but it has never bred.

But let us look on the bright side of all this. Suppose that, with 30 years of intensive research and development, the world nuclear power industry could find a use for all the reactor-grade plutonium in existence, fabricate it into fuel rods and insert it into newly-built fast-breeder reactors – 80 of them, plus a few more, perhaps, to soak up some of the plutonium that is being produced by the ordinary reactors now in operation. So: they start breeding in 2035. But the process is not as fast as the name suggests ("fast" refers to the speeds needed at the subatomic level, rather than to the speed of the process). Forty years later, each breeder reactor would have bred enough plutonium to replace itself and to start up another one. By 2075, we would have 160 breeder reactors in place. And that is all we would have, because the ordinary, uranium-235-based reactors would by then be out of fuel.[22]

The nuclear power industry is living on borrowed time in the sense that it is has not yet had to find either the money or the energy to reinstate its mines, bury its wastes and decommission its reactors.

(b) Thorium

The other way of breeding fuel is to use thorium. Thorium is a metal found in most rocks and soils, and there are some rich ores bearing as much as 10 percent thorium oxide. The relevant isotope is the slightly radioactive thorium-232. It has a half-life three times that of the earth, so that makes it useless as a direct source of energy, but it can be used as the starting-point from which to breed an efficient nuclear fuel. Here's how:

- Start by irradiating the thorium-232, using a start-up fuel – plutonium-239 will do. Thorium-232 is slightly fertile, and absorbs a neutron to become thorium 233.
- The thorium-233, with a half-life of 22.2 minutes, decays to protactinium-233.
- The protactinium-233, with a half-life of 27 days, decays into uranium-233.
- The uranium-233 is highly fissile, and can be used not just as nuclear fuel, but as the start-up source of irradiation for a blanket of thorium-232, to keep the whole cycle going indefinitely.[24]

But, as is so often the case with nuclear power, it is not as good as it looks. The two-step sequence of plutonium breeding is, as we have seen, hard enough. The four-step sequence of thorium-breeding is worse. The uranium-233 which you get at the end of the process is contaminated with uranium-232 and with highly-radioactive thorium-228, both of which are neutron-emitters, reducing its effectiveness as a fuel; it also has the disadvantage that it can be used in nuclear weapons. The comparatively long half-life of protactinium-233 (27 days) makes for problems in the reactor, since substantial quantities linger on for up to a year. Some reactors – including Kakrapar-1 and -2 in India – have both achieved full power using some thorium in their operation, and it may well be that, if there is to be a very long-term future for nuclear fission, it will be thorium that drives it along.

However, the full thorium breeding cycle, working on a scale which is large-enough and reliable-enough to be commercial, is a long way away.[25] For the foreseeable future, its contribution will be tiny. This is because the cycle needs some source of neutrons to begin. Plutonium could provide this but (a) there isn't very much of it around; (b) what there is (especially if we are going to do what Lovelock urges) is going to be busy as the fuel for once-through reactors and/or or fast-breeder reactors, as explained above; and (c) it is advisable, wherever there is an alternative, to keep plutonium-239 and uranium-233 – an unpredictable and potentially incredibly dangerous mixture – as separate as possible. It follows that thorium reactors must breed their own start-up fuel from uranium-233. The problem here is that there is practically no uranum-233 anywhere in the world, and the only way to get it is to start with (say) plutonium-239 to get one reactor going. At the end of forty years, it will have bred enough uranium-233 both to get another reactor going, and to replace the fuel in the original reactor. So, as in the case of fast-breeders, we have an estimated 30 years before we can perfect the process enough to get it going on a commercial scale, followed by 40 years of breeding. Result: in 2075, we could have just two thorium reactors up and running.[26]

Seawater

Seawater contains uranium in a concentration of about thirty parts per billion, and advocates of nuclear power are right to say that, if this could be used, then nuclear power could in principle supply us with the energy we need for a long time to come. Ways of extracting those minute quantities of uranium from seawater and concentrating them into uranium oxide have been worked out in some detail. First of all, uranium ions are attracted – "adsorbed" – onto adsorption beds consisting of a suitable material such as titanium hydroxide, and there are also some polymers with the right properties. These beds must be suspended in the sea in huge arrays, many kilometres in length, in places where there is a current to wash the seawater through them, and where the sea is sufficiently warm – at least 20°C. They must then be lifted out of the sea and taken on-shore, where, in the first stage of the process, they are cleansed to remove organic materials and organisms. Stage two consists of "desorption" – separating the adsorbed uranium ions from the beds. Thirdly, the solution that results form this must be purified, removing the other compounds that have accumulated in much higher concentration than the uranium ions. Fourthly, the solution is concentrated, and fifthly, a solvent is used to extract the uranium. The sixth stage is to concentrate the uranium and purify it into uranium oxide yellowcake, ready for enrichment in the usual way.[27]

Nuclear power could supply all the energy needed for an entire (hydrogen-fuelled) transport system for some three years before it ran out of rich ore and the energy balance turned negative.

But the operation is massive and takes a lot of energy. Very roughly, two cubic kilometres of sea water is needed to yield enough uranium to supply one tonne, prepared and ready for action in a reactor. A 1 GW reactor needs about 160 tonnes of natural uranium per annum, so each reactor requires some 324 cubic kilometres of seawater to be processed – that is, some 32,000 cubic kilometres of seawater being processed in order to keep a useful fleet of 100 nuclear reactors in business for one (full-power) year.[28]

And what is the energy balance of all this? One tonne of uranium, installed in a light water reactor, is taken as a rule-of-thumb also to produce approximately 162 TJ (1 terajoule = 1,000 billion joules), *less* the roughly 60-90 TJ needed for the whole of the remainder of the fuel cycle – enrichment, fuel fabrication, waste disposal, and the deconstruction and decommissioning of the reactor – giving a net electricity yield of some 70-90 TJ. The energy needed to supply the uranium from seawater, ready for entry into that fuel cycle, is in the region of 195-250 TJ. In other words, the energy required to operate a nuclear reactor using uranium derived from seawater would require some three times as much energy as it produced.

4. PUTTING NUCLEAR ENERGY IN CONTEXT

It is now decision-time for many nations, confronting the fierce certainty of climate change, the depletion of oil and gas, and the ageing of its electricity generators. Why should the decision-makers take any notice of this analysis, written from a global perspective? A decision by, say, Britain to build one or two token reactors, doubtless presented as "a contribution to our energy mix along with a vigorous programme to develop renewables and to reduce the demand for energy" – certainly isn't going to deplete uranium ores sufficiently to require any consideration of breeders or seawater – so what are the problems?

Well, one of the problems is that it is not a decision that can be made in isolation. Nuclear power could in theory be adopted by a few individual nations: they could perhaps export their wastes, and the absence of competition for rich ores would mean that the supply of uranium could be spun out for a long time. So, for an individual nation looking at the choice in isolation, the nuclear option may seem to be attractive. But there is a "fallacy of composition" here: an option that is available to one cannot be supposed to be available to many; on the contrary, it may only be available to one *because* it is not adopted by many – and if it *is* adopted by many, then everyone is in trouble, deep trouble.

The priority for the nuclear industry now should be to use the electricity generated by nuclear power to clean up its own pollution and to phase itself out before events force it to close down abruptly. Nuclear power is a solution neither to the energy famine brought on by the decline of oil and gas, nor to the need to reduce emissions of greenhouse gases. It cannot provide energy solutions, however much we may want it to do so.

But the conclusion that nuclear power cannot provide the energy we need over the next three of four decades means that we have a problem. An energy gap – an energy chasm – lies before us, for two reasons. First the damage done to the self-regulating systems of the climate is already so great that we are at or near the tipping point at which global heating will get out of control, moving relentlessly but quickly towards a new equilibrium state probably lethal to the majority of the inhabitants of the planet and to its civilisations. Secondly, we are at or near the "oil peak" at which supplies of oil and (slightly later) gas will turn down into a relentless decline whose consequences will be on a scale comparable to those of climate change. In this situation, we have little choice. If there is any energy source at all which could operate on the scale and in the time needed to fill this energy gap, then we must take it, even if it comes with enormous disadvantages.

Nuclear power certainly has disadvantages, quite apart from the clincher problem of fuel depletion. It is a source of low-level radiation which, as is now beginning to be recognised, may be incomparably more damaging than was previously thought. It is a source of high-level waste which has to be sequestered. Every stage in the process produces lethal waste, including the mining and leaching processes, the milling, the enrichment and the decommissioning. It is very expensive. It is a terrorist target and its enrichment processes are stepping stones to the production of nuclear weapons.[29]

World Nuclear Power Reactors and Uranium Requirements

As at 4 January 2006

	NUCLEAR ELECTRICITY GENERATION 2004		REACTORS OPERABLE Jan 2006		REACTORS under CONSTRUCTION Jan 2006		REACTORS PLANNED Jan 2006		REACTORS PROPOSED Jan 2006		URANIUM REQUIRED 2006
	billion kWh	% e	No.	MWe	No.	MWe	No.	MWe	No.	MWe	tonnes U
Argentina	7.3	8.2	2	935	1	692	0	0	0	0	134
Armenia	2.2	39	1	376	0	0	0	0	0	0	51
Belgium	44.9	55	7	5728	0	0	0	0	0	0	1075
Brazil	11.5	3.0	2	1901	0	0	1	1245	0	0	336
Bulgaria	15.6	42	4	2722	0	0	2	1900	0	0	253
Canada*	85.3	15	18	12595	0	0	2	1540	0	0	1635
China	47.8	2.2	9	6587	2	1900	9	8200	19	15000	1294
Czech Rep	26.3	31	6	3472	0	0	0	0	2	1900	540
Egypt	0	0	0	0	0	0	0	0	1	600	0
Finland	21.8	27	4	2676	1	1600	0	0	0	0	473
France	426.8	78	59	63473	0	0	0	0	1	1600	10146
Germany	158.4	32	17	20303	0	0	0	0	0	0	3458
Hungary	11.2	34	4	1755	0	0	0	0	0	0	251
India	15.0	2.8	15	2993	8	3638	0	0	24	13160	1334
Indonesia	0	0	0	0	0	0	0	0	4	4000	0
Iran	0	0	0	0	1	950	2	1900	3	2850	0
Israel	0	0	0	0	0	0	0	0	1	1200	0
Japan	273.8	29	55	47700	1	866	12	14782	0	0	8169
Korea, Nth	0	0	0	0	1	950	1	950	0	0	0
Korea, Sth	124.0	38	20	16840	0	0	8	9200	0	0	3037
Lithuania	13.9	72	1	1185	0	0	0	0	1	1000	134
Mexico	10.6	5.2	2	1310	0	0	0	0	0	0	256
Netherlands	3.6	3.8	1	452	0	0	0	0	0	0	112
Pakistan	1.9	2.4	2	425	1	300	0	0	2	1200	64
Romania	5.1	10	1	655	1	655	0	0	3	1995	176
Russia	133.0	16	31	21743	4	3600	1	925	8	9375	3439
Slovakia	15.6	55	6	2472	0	0	0	0	2	840	356
Slovenia	5.2	38	1	676	0	0	0	0	0	0	144
South Africa	14.3	6.6	2	1842	0	0	1	165	24	4000	329
Spain	60.9	23	9	7584	0	0	0	0	0	0	1505
Sweden	75.0	52	10	8938	0	0	0	0	0	0	1435
Switzerland	25.4	40	5	3220	0	0	0	0	0	0	575
Turkey	0	0	0	0	0	0	0	0	3	4500	0
Ukraine	81.1	51	15	13168	0	0	2	1900	0	0	1988
U.K.	73.7	19	23	11852	0	0	0	0	0	0	2158
USA	788.6	20	103	97924	1	1065	0	0	13	17000	19715
Vietnam	0	0	0	0	0	0	0	0	2	2000	0
WORLD**	2618.6	16	441	368,386	24	18,816	41	42,707	113	82,220	65,478
	billion kWh	% e	No.	MWe	No.	MWe	No.	MWe	No.	MWe	tonnes U

Sources:

Reactor data: WNA to 28/11/05.
IAEA- for nuclear electricity production & percentage of electricity (% e) 7/7/05.
WNA: Global Nuclear Fuel Market (reference scenario) - for U. Operating = Connected to the grid;
Building/Construction = first concrete for reactor poured, or major refurbishment under way;
Planned = Approvals and funding in place, or construction well advanced but suspended indefinitely;
Proposed = clear intention but still without funding and/or approvals.
TWh = Terawatt-hours (billion kilowatt-hours), MWe = Megawatt net (electrical as distinct from thermal), kWh = kilowatt-hour.

Nuclear power is caught in a depletion trap at least as imminent as that of oil and gas. So the question to be asked is: as the conventional uranium sources run low, are there alternative sources of fuel for nuclear energy?

And yet, so great is the need for some way of closing down demand for fossil fuels and filling the energy gap, and so serious are the consequences of not doing so, that Lovelock can argue that it would be better to develop nuclear power, even with all these disadvantages, than to fail to stop carbon emissions – or else fall into the energy gap and take the consequences. Lovelock writes: "We need emission-free energy sources immediately, and there is no serious contender to nuclear fission".[30] He suggests that the decision is much clarified for us if we recognise the risk of climate change for what it is, and he adds that we will not succeed in doing this if we do not in the process move beyond the intellectual analysis and, instead, feel the fear:

> Few, even among climate scientists and ecologists, seem yet to realise fully the potential severity, or the imminence, of catastrophic global disaster; understanding is still in the conscious mind alone and not yet the visceral reaction of fear. We lack an intuitive sense, an instinct, that tells us when Gaia is in danger.[31]

Lovelock's argument is persuasive. But there are three grounds on which it is open to criticism.

1. The nuclear fuel cycle.

Uranium depletion is not a "flawed idea"; it is a reality that is just a little way ahead. As we he seen, Lovelock's otherwise brilliant analysis of climate change displays no knowledge of the nuclear fuel-cycle. His optimism about the feasibility of nuclear power in the future is simply a case of whistling in the dark.

2. Alternative energy strategies

Lovelock may underestimate the potential of the fourfold strategy which can be described as "Lean Energy":

1. a transformation in standards of energy conservation and efficiency;
2. structural change to build local economic and energy systems; and
3. renewable energy; all within
4. a framework, such as emissions permits or tradable energy quotas (TEQs),

leading to deep reductions in energy demand.[32] It cannot be expected that this strategy would fill the energy gap completely, or neatly, or in time, but nor is Lovelock suggesting that nuclear power could do so. Even if there were no uranium-supply problem to restrain the use of nuclear power, and even if it were the overriding priority for governments around the world, it would still fall well short of filling the gap. It would be impossible to build all the nuclear power stations needed in time, and the energy required would mean that a rapidly-growing nuclear-power industry would be using more

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A NOTE ON SOURCES

As readers will of course be aware, there are risks in relying heavily on a single source in any field, and particularly in a subject in which the debate is as polarised as it is in nuclear power. There is no doubt that the ground-breaking work of Jan Willem Storm van Leeuwen and Philip Smith (SLS) needs to be examined in detail and replicated. Unfortunately, that has not yet happened. However, the work is evidently of high quality; it is deeply-rooted in the expert literature of nuclear technology; all ground-breaking work comes from pioneering individuals or teams who break ranks with the received vision; and there is in any case no alternative but to rely heavily on this single source.

And there are other good reasons for taking their work seriously. First, the data they use is entirely standard. It comes from the World Nuclear Association (WNA) and the Atomic Energy Agency (AEA). That is not to say that the data supplied by these agencies is infallible, but it is the best we have. The purpose of these agencies' work is broadly in support of confident, even bullish, expectations of the future of the industry; if SLS is biased, therefore, it is unlikely to be biased in the direction of *under*estimating the quantity of uranium that will be available in the future.

Secondly, there is not in fact an enormous disagreement between the conventional, broadly-agreed expectations of uranium supply produced by the industry, and the conclusions produced by SLS. For instance, a paper has recently been produced by Future Energy Solutions (FES), an operating division of AEA Technology plc, as part of the Sustainable Development Commission's submission to the U.K. Energy Review. It cites widely-shared industry expectations of the supply of uranium in the future: "Institutions across the nuclear industry are confident that reserves are sufficient to meet the needs of the next 100 years." Fine – so the next question is: how much will the industry have expanded in that time? Well, one useful forecast for expansion comes from the U.S. Energy Information Administration (EIA), which foresees nuclear generation growing by 17 percent by 2025. It now accounts for about 2$^1/_2$ percent of global final energy consumption, so the scale of expansion foreseen for it suggests that by 2025 it may account for slightly under 3 percent (assuming that final energy demand does not grow over that time).[33]

So, what does SLS say about this? They say that there are very substantial uncertainties around their numbers, but they conclude that there is enough uranium to continue at the present rate (2$^1/_2$ percent of total final demand) for roughly 75 years. Not much difference there, then. Is there a consensus beginning to emerge here? It looks rather like it: Mr Neville Chamberlain's long and distinguished record as chief executive of British Nuclear Fuels Limited (BNFL) entitles him to be listened-to as a trusted spokesperson for the industry. He estimates that there are sufficient supplies of uranium to carry on roughly as we are for another 80 years, an estimate which is practically identical with that of SLS.[34]

SLS's critical contribution is that they point out the significance of this. If the nuclear power industry were to produce the electricity for a really useful, grown-up purpose, such as *all* electricity or *all* transport, it could only keep going for half a dozen years or so. But no one, least of all, spokesmen for the industry itself, is really claiming that it can do any better than that. You would think, given the heat of the debate, that there is real disagreement about this but – except in terms of the rhetoric – there is no real dispute about the fact that the industry is, and will remain, marginal in terms of the global mixture of energy supplies, ineffective as a means of reducing carbon emissions, and just as dependent on sustained gas supplies to keep the electricity grid functioning as are gas power stations themselves. The only things that are big about nuclear power are its problems and, above all its effect in stopping people thinking clearly about the coming energy chasm, since at the back of their minds there is the sense that "if all else fails, we can always fall back on nuclear." Well, we can't. Not even the industry thinks so.

Thirdly, SLS make the major contribution of bringing the energy-cost of waste-disposal into the frame. At present, the industry is not making the large investment that is required to clear up current and future wastes to a standard required by any reasonable understanding of "sustainability". If those standards were followed, all high-, medium- and low-level waste, including the vast stores of depleted uranium, would be sequestered; reactors would in due course be dismantled and sequestered; the tailings produced by the mining and milling of uranium would be stabilised, and the land rehabilitated. SLS have pioneered an analysis of the energy cost of the comprehensive waste-treatment that lies ahead; this work, as we have seen, needs to be replicated and analysed in detail, but a conservative and provisional estimate is that if full waste management were to be sustained by the industry, the energy-cost of this would amount to almost one third of the energy delivered to the grid, plus another one third to deal with the backlog. Any dissent from this needs to be based on research into the detail of the nuclear fuel cycle as exhaustive as the work done by SLS themselves.

Of the need for further research there is no doubt. For instance, there are some stages in the nuclear fuel life-cycle on which there is no data at all – such as the global warming potential of the halogen compounds and solvents released by the nuclear energy industry. So far, all estimates of greenhouses gases released by the nuclear fuel cycle, including until very recently that of SLS themselves, have simply overlooked the contribution of escaping halogens compounds – and "overlooked" has generally meant pretending they don't exist. Just the fact of studying this question will immediately start to raise estimates of the climate impact of nuclear power out of the bath of ignorance and fudge in which it has luxuriated so far.

The absence of a definitive, replicated judgment on the whole fuel cycle and climate impact of nuclear power at present does not mean no judgment at all is possible. We know enough to say decisively that nuclear power can never come anywhere near filling the energy gap that is opening in front of us. Unless the industry focuses first of all on dealing with its past and present wastes – while supplying to the grid whatever energy it has left over after it has done that – then we will soon be left with the nightmare ticket: an inheritance of 75 years of untreated, unstable nuclear waste, and a lack of the energy and the money to deal with it. That prospect is real; thanks to the work of SLS, we can now clearly recognise it. It is the aim of this paper, in the light of all this, to encourage everyone who is thinking about, talking about or deciding on nuclear power to see it as the energy source that claims significance and causes trouble far beyond the scale of the energy it produces. It is a distraction from the need to face up to the coming energy chasm and to fill it as much as possible and as quickly as possible with pragmatic and practical solutions of the kind described in this paper as Lean Energy.

NOTES AND REFERENCES

1. For instance, radium-226 is naturally-occurring, and our bodies can repair the DNA damage it causes in small doses. Plutonium-239 is man-made; there is no safe dose. See Chris Busby (1995), *Wings of Death*, Aberystwyth: Green Audit, chapters 6-7.
2. See Gordon Edwards (2004), "Health and Environmental Issues Linked to the Nuclear Fuel Chain", Section A: Radioactivity, at www.ccnr.org/ceac_B.html. For a concise citizen's introduction to the basics of nuclear fission, see *Chemistry for Dummies*; the chapter heading of the on-line version is (unfortunately) "Gone (Nuclear) Fission".
3. See Ian Hore-Lacy (2003), "Nuclear Electricity", World Nuclear Association (WNA) website, "Nuclear Electricity", http://www.world-nuclear.org/education/ne/ne.htm, chapter 4 (referenced below as WNA).
4. Jan Willem Storm van Leeuwen. and Philip Smith (2004), Nuclear Power: The Energy Balance", at www.stormsmith.nl (referenced bellow as SLS).
5. WNA, chapter 3, and SLS, chapter 2, pp 8-9.
6. For more detail on the decay products of uranium-238, see Edwards (2004), Section A. Treatment of tailings: SLS, chapter 4, p 5; chapter 2, p 9.
7. See WNA, chapter 4, SLS, chapter 4, p 5; chapter 2, p 9.
8. WNA, chapter 4; SLS, chapter 2, pp 11-12.
9. A variant is "GeoMelt", which melts a mixture of nuclear waste and soil at 3000°C to form a solid block with the properties of exceedingly hard glass, which is then placed in a secure container for burial. However, there is controversy as to whether this is a suitable treatment for nuclear waste. The case for the treatment is made in www.geomelt.com. Disposal of high-level waste: See WNA, chapter 5; SLS, chapter 4, p 6. For a description of the latest thinking on the disposal on high-level nuclear waste, see Rolf Haugaard Nielsen (2006), "Final Resting Place", *New Scientist*, No 2541, 4 March, pp 38-41.
10. See Report of the Committee Examining Radiation Risks of Internal Emitters (Cerrie), (2004), at www.cerrie.org
11. SLS, chapters 3; 4. WNA chapter 5.
12. This summary relies substantially on SLS. Their work is based on exhaustive reference to original research in nuclear energy; nonetheless, it is clear that it should be independently assessed and replicated. The criticism it has received so far has not evidently damaged their case (see http://www.stormsmith.nl/Rebuttal_WNA.PDF). It is in fact a typical pattern: decisively-important work, strongly at variance with the received wisdom, is produced by a small number of (often vilified) pioneers. The work of Storm van Leeuwen and Smith is similar in many ways with that of Colin Campbell on oil depletion. In both cases, the pioneers have pointed out a depletion problem; the response is that there is much more of the resource yet to be discovered, and that the whistle-blowers are being alarmist.
13. 16 percent: this is easily calculated from SLS figures, and is confirmed by Jan Willem Storm van Leeuwen, personal communication.
14. For a listing of the global warming potential of freon and other gases, see US. Department of Environment Protection, "Greenhouses gases and their global warming potential relative to CO2" at http://www.state.me.us/dep/air/emissions/ghg-equiv.htm
15. SLS, Summary, and chapter 2, pp 12-17. Storm van Leeuwen (2006), "Energy from Uranium", Appendix A, in Evidence to the IPCC Working Group III, Fourth Assessment Report First Order Draft for Expert Review (referenced below as WSL/IPCC).
16. As previous note.
17. Storage ponds: see Rolf Haugaard Nielsen (2006).
18. Lovelock (2006), p 103.
19. e.g. S. Huwyler, L Rybach and M Taube (1975), "Extraction of uranium and thorium and other metals from granite", EIR-289, Technical Communications 123, Eidgenossische Technische Hochschule, Zurich, September, translated by Los Alamos Scientific Laboratory, LA-TR-77-42, 1977). Cited and discussed in Storm van Leeuwen (2006), "Uranium Resources and Nuclear Energy", Appendix E, in WSL/IPCC.
20. Storm van Leeuwen (2006), "Breeders", Appendix C, in WSL/IPCC.
21. *Ibid.*
22. *Ibid.*
23. Lawrence M. Lidsky and Marvin M Miller (1998), "Nuclear Power and Energy Security": A Revised Strategy for Japan", at www.nautilus.org/archives/papers/energy/LidskyPARES.pdf
24. Uranium Information Council (2004), Briefing Paper 67, "Thorium", at www.uic.com.au/nip67.htm
25. *Ibid.*
26. Storm van Leeuwen (2006), "Breeders", Appendix C, in WSL/IPCC.
27. Storm van Leeuwen (2006), "Uranium from Seawater", Appendix E2, in WSL/IPCC.
28. *Ibid.*
29. Low-level waste: see note 11.
30. Lovelock (2005), p 99.
31. Lovelock (2005), p 103.
32. See David Fleming (2006), *Energy and the Common Purpose*, London: The Lean Economy Connection.
33. Future Energy Solutions, an operating division of AEA Technology plc (2006), Paper 8, "Uranium Resource Availability", in Sustainable Development Commission, *The Role of Nuclear Power in a Low Carbon Economy*, p 3. The US. Energy Information Administration (2005), "International Energy Outlook", is cited on p 20.
34. Neville Chamberlain (2005), in a Today Programme debate with the author, 21 May.

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energy than it provided throughout most of the period of growth – the more rapid the growth, the deeper the energy deficit it would produce.

There are good reasons to believe that Lean Energy could do better. The delay that elapsed before it began to get results would be shorter. It would be able to call on the skill and cooperation of the entire population of the world. It is reasonable to expect that it would be cheaper, per unit of energy-services produced, by an order of magnitude or so. It would be flexible and responsive to local sites, conditions and skills. And it would be integral to a new environmental and practical ethic, in which reduced transport, environmental protection and local self-reliance come together as a joined-up programme.

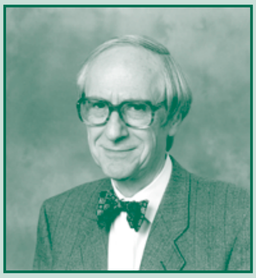
3. The oil peak

Lovelock may not give enough weight to the significance of the oil peak. As this weighs in, it will establish conditions in which there is no choice but to conserve energy, whether the urgency of climate change is recognised or not. Without the oil peak to concentrate the mind, action to save the climate could be leisurely at best. With the oil peak reminding us, by repeatedly turning out the lights and stopping us filling up our cars, we have an incentive to follow the one available option with all the will and determination we can find.

What appears to follow from this is a best-of-both-worlds strategy: to develop nuclear power as far as the uranium supply allows, and at the same time to develop Lean Energy. There is clearly a discussion to be had about this, but here again there is a catch. The problem is that the two strategies are substantially incompatible. A dash for nuclear power would reduce the funds and other resources, and the concentrated focus, needed for Lean Energy. Nuclear power depends on the centralised grid system, which depends on a reliable flow of electricity from gas-powered stations if it is to function at all; Lean Energy is organised around local minigrids. Nuclear power inevitably brings a sense of reassurance that, in the end, the technical fix will save us; Lean Energy depends on the recognition that we shall need, not only the whole range of technology from the most advanced to the most labour intensive, but the whole range of opportunities afforded by profound change – in behaviour, in the economy, and in society. Nuclear power, even as only a short-term strategy, is about conserving the bankrupt present; Lean Energy is about inventing and building a future that works.

For these reasons, the best-of-both-worlds strategy of backing both nuclear power and Lean Energy could be expected to lead to worst-of-both-worlds consequences. Lean Energy would be impeded by nuclear power; nuclear power would be hopelessly ineffective without Lean Energy. Result: paralysis. This should not be overstated: a few token nuclear power stations to replace some of those that are about to be retired would make it harder to develop Lean Energy with the single-minded urgency and resources needed, without necessarily ruling out progress towards Lean Energy entirely. But the defining reality of the energy future – equivalent to the reality of oil in the Oil Age – has to be an acknowledgment that no large-scale technical fix is available. Energy cannot any longer be delegated to experts. The future will have to be a collective, society-transforming effort.

David Fleming



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NUCLEAR ENERGY
A Lean Guide

1. Nuclear energy could sustain its present minor contribution of some $2\frac{1}{2}$ percent of global final energy demand for about 75 years, but only by postponing indefinitely the expenditure of energy that would be needed to deal with its waste.
2. Each stage in the nuclear life-cycle, other than fission itself, produces carbon dioxide.
3. The depletion problem facing nuclear power is as pressing as the depletion problem facing oil and gas.
4. The depletion of uranium becomes apparent when nuclear power is considered as a major source of energy. For instance, if required to provide all the electricity used worldwide – while clearing up the new waste it produced – it could (notionally) do so for about six years before it ran out of usable rich uranium ore.
5. Alternative systems of nuclear fission, such as fast-breeders and thorium reactors, do not offer solutions in the short/medium term.
6. The overall climate impact of the nuclear industry, including its use of halogenated compounds with a global warming potential many times that of carbon dioxide, needs to be researched urgently.
7. The option that a nation such as the United Kingdom has of building and fuelling a nuclear energy system on a substantial and useful scale is removed if many other nations attempt to do the same thing.
8.. The response must be to develop a programme of "Lean Energy". Lean Energy consists of: (1) energy conservation and efficiency; (2) structural change to build local energy systems; and (3) renewable energy; all within (4) a framework, such as tradable energy quotas (TEQs), leading to deep reductions in energy demand.
9. That response should be developed at all speed, free of the false promise and distraction of nuclear energy.