The Oil Drum
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

Is Nuclear Power a Viable Option for Our Energy Needs?

Posted by Prof. Goose on August 8, 2006 - 3:34pm
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Tags: eroei, light water fission, nuclear, nuclear energy [list all tags]

[editor's note, by Prof. Goose] This is a guest post by Martin Sevior, Associate Professor, School of Physics, University of Melbourne. (also, forget not the reddit and digg buttons...)

In the middle of the last year it became clear to me that the Australian Government was interested in having a debate about Nuclear Energy for Australia. I decided that we, in the School of Physics, could make a positive contribution to the debate and organized a study group to investigate this. We constructed a wiki-based website (http://nuclearinfo.net) where we placed our findings. We went live last December but have updated the website as we've learned more about energy issues and Nuclear Power.

In this post I draw heavily on website and restrict myself to talking about light water fission reactors. There are a variety of different and more advanced reactor schemes that could be addressed in a future post. There are more details on our website on all of the topics covered here.

Nuclear Fission Basics

A nuclear fission reaction occurs when a 235U or 239Pu nucleus captures a neutron, splits into two smaller nuclei and releases 2 - 3 more neutrons. These neutrons can be used to initiate further reactions. From an energy standpoint, the significant feature is that the release is around 200 Million Electron Volts per reaction. A typical chemical process such as the oxidation of hydrogen, emits 20 electron volts per reaction. Thus nuclear fission provides around 10 million times more energy than chemical processes. This factor of 10 million sets the scale of Nuclear Power.

Natural Uranium consists of 99.3% 238U and 0.7% 235U. Conventional light water reactors utilize fuel with an initial 235U concentration enriched to at least 3.5%. The energy released from these reactors comes from the fission of 235U and 239Pu (which is produced via neutron captures on 238U). The heat from the reaction is used to drive steam turbines with a conversion efficiency of around 33%. Typically the fuel is loaded at 3.5% 235U and replaced once the 235U concentration has fallen to 1.2%. A 1 GW light water Nuclear Power Plant consumes 30 tonnes of fuel per year. A coal-fired plant of the same magnitude consumes 9000 tonnes of coal per day.

World Uranium supply

Given that this website is devoted to the study of peak oil, I think it's appropriate to first look at the prospects for using Uranium as fuel source for at least the rest of the next century. Uranium is not a particularly rare mineral. It has an average crustal abundance of about 2.7 Parts Per

Million (PPM), which about the same as tin and zinc. There is an estimated 40 trillion tonnes of Uranium in the Earth's crust. To date we have mined less than one ten-millionth of this (as opposed to about half the world's conventional crude Oil). A typical 1 GW Nuclear reactor requires around 200 tonnes of natural Uranium per year. Current world consumption of Uranium amounts to some 65,000 tonnes per annum. Current world supply is around 40,000 tonnes per annum. The mismatch is maintained by the drawn-down of stocks and the use of fissile material available from the reduction in Nuclear Weapons in the USA and ex-Soviet Union. The combination caused a decade-long depression of World Uranium price. These stocks and secondary sources will be exhasted by the middle of the next decade. In early 2003 the price of Uranium was $23 per kg, it is currently at around $110 per kg. This price increase has triggered a rapid increase in exploration activity around the world. At $110 per kg, the price of Uranium Ore contributes about 0.22 cents per KW-HR to the price of Nuclear generated electricty.

Reasonably assured reserves (or proven reserves) refers to known commercial quantities of Uranium recoverable with current technology and for a specified price. The terms additional and speculative reserves refer to extensions to well explored deposits or in new deposits that are thought to exist based on well defined geological data.

As of the beginning of 2003 World Uranium reserves were:

- Reasonable Assured Reserves recoverable at less than $US130/kgU (or $US50/lb U3O8) = 3.10 - 3.28 million tonnes.
- Additional reserves recoverable at less than $US130/kgU (or $US50/lb U3O8) = 10.690 million tonnes.

As of the beginning of 2005 World Uranium reserves were:

- Reasonable Assured Reserves recoverable at less than $US130/kgU (or $US50/lb U3O8) = 4.7 million tonnes.
- Additional recoverable Uranium is estimated to be 35 million tonnes

The substantial increase (almost 50%) from 2003 shows the results of the world-wide renewed exploration effort spurred by the increase in Uranium prices which commenced in 2004. This increase in activity has continued through to 2006. Thus, the provable uranium resources amount to approximately 85 years supply at the current level of consumption with current technology, with another 500 years of additional reserves. It is worth noting that the numbers above do not reflect the considerable increase in Uranium exploration that has taken place in 2005 and 2006.

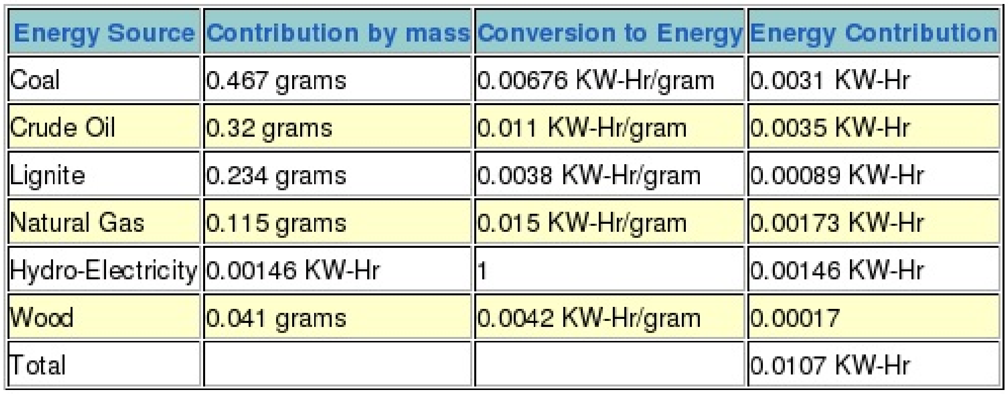
It is interesting to speculate on the ultimate size of the world Uranium resource, if it were to power light water reactors. This can be estimated by comparing the energy produced by a nuclear plant to the energy required to mine and refine the Ore. As one moves to lower grade Ore, the energy cost the mining and refining increases. However the total resource size increases at these higher dilutions. If we assume the rate at which the energy cost increases is inversely proportional to the Uranium concentration in the Ore we can estimate the ultimate size of Uranium resource if consumed in light water reactors. The Rossing mine in Nambia is a large, low grade Ore deposit. It produces around 3000 tonnes of Uranium per year. The energy cost of this process is 1 PetaJoule. Now 3000 tonnes of Uranium provides 15 GigaWatt-years of power which is about 470 PetaJoules of energy. So the energy gain from Rossing is close to a factor of 500. The grade of Uranium at Rossing is 0.035% by weight (about 350 ppm). Deffeyes & MacGregor have estimated the distribution of Uranium in different types of rock and show that shales and phosphates contain 8000 times as much Uranium as current Uranium Ore bodies at a concentration of 10 -20 PPM. These rocks are potentially minable with an energy gain of 15-30.

Consequently, unlike conventional Oil, Uranium resource exhaustion will not be an issue for the foreseeable future.

Energy Lifecycle of Nuclear Power

The performance of Nuclear Power can be compared to other energy sources by calculating the total energy required to build and run a Nuclear Power plant and comparing it to the total energy it produces. The following set of calculations is also taken from the independently audited, Vattenfall Environmental Product Declaration for its 3090 MW Forsmark nuclear power plant in Sweden. A more detailed description is here. Vattenfall have also made available the aggregated data set as a spreadsheet. You can download it from here. Vattenfall is a large European Energy utility that operates a variety of energy generation technologies including Nuclear, Hydro, Natural gas, Coal, Oil, Peat, Biomass, Wind and Photovoltaic. We chose this because it had been independently audited, and includes the entire lifecycle of the processes which includes the eventual long-term disposal of the waste. Sweden and Finland have perhaps the most developed nuclear waste disposal plans of any country.

The following table displays the source and the amount of energy required to produce 1 KW-Hr of electricity. The table includes the energy used in construction of the plant, mining the Uranium, enriching it, converting it to fuel, disposing the waste and decommissioning the plant. The plant is assumed to run for 40 years. There is an additional 0.026 grams of Uranium consumed in generating this one KW-Hr of electricity. This 0.026 grams includes the Uranium used to generate power and the Uranium consumed by the French Nuclear Power plants that produced the electricity that enriched the Fuel.



Energy Source	Contribution by mass	Conversion to Energy	Energy Contribution
Coal	0.467 grams	0.00676 KW-Hr/gram	0.0031 KW-Hr
Crude Oil	0.32 grams	0.011 KW-Hr/gram	0.0035 KW-Hr
Lignite	0.234 grams	0.0038 KW-Hr/gram	0.00089 KW-Hr
Natural Gas	0.115 grams	0.015 KW-Hr/gram	0.00173 KW-Hr
Hydro-Electricity	0.00146 KW-Hr	1	0.00146 KW-Hr
Wood	0.041 grams	0.0042 KW-Hr/gram	0.00017
Total			0.0107 KW-Hr

So the Plant produces 93 times more energy than it consumes. Or put another way, the non-nuclear energy investment required to generate electricity for 40 years is repaid in 5 months. Normalized to 1 GigaWatt electrical capacity, the energy required to construct and decommission the plant, which amounts to 4 Peta-Joules (PJ), is repaid in 1.5 months. The energy required to dispose of the waste is also 4 PJ and repaid in 1.5 months. In total this is less than 0.8% of the all the electrical energy produced by the plant.

Greenhouse Gas emissions

Although the processes of running a Nuclear Power plant generates no CO2, some CO2 emissions arise from the construction of the plant, the mining of the Uranium, the enrichment of the Uranium, its conversion into Nuclear Fuel, its final disposal and the final plant decommissioning.

The amount of CO2 generated by these secondary processes primarily depends on the method used to enrich the Uranium (the gaseous diffusion enrichment process uses about 50 times more electricity than the gaseous centrifuge method) and the source of electricity used for the enrichment process. It has been the subject of some controversy. To estimate the total CO2 emissions from Nuclear Power we also use the work of Vattenfall.

Vattenfall finds that averaged over the entire lifecycle of their Nuclear Plant including Uranium mining, milling, enrichment, plant construction, operating, decommissioning and waste disposal, the total CO2 emitted per KW-Hr of electricity produced is 3.3 grams per KW-Hr of produced power. Vattenfall measures its CO2 output from Natural Gas to be 400 grams per KW-Hr and from coal to be 700 grams per KW-Hr. Thus nuclear power generated by Vattenfall, emits less than one hundredth the CO2 of Fossil-Fuel based generation.

Nuclear Costs

The cost of generating power via nuclear energy can be separated into the following components:

- The construction cost of building the plant.
- The operating cost of running the plant and generating energy.
- The cost of waste disposal from the plant.
- The cost of decommissioning the plant

Quantifying some of these costs is difficult as it requires an extrapolation into the future.

Construction Costs

Construction costs are very difficult to quantify but dominate the cost of Nuclear Power. The main difficulty is that third generation power plants currently proposed are claimed to be both substantially cheaper and faster to construct than the second generation power plants now in operation throughout the world. The Nuclear Industry says its learned the lessons of economy-of-volume demonstrated by the French Nuclear Program, and that these will be employed for the new power plants. For example Westinghouse claims its Advanced PWR reactor, the AP1000, will cost USD $1500-$1800 per KW for the first reactor and may fall to USD $1200 per KW for subsequent reactors. They also claim these will be ready for electricity production 3 years after first pouring concrete. This should be compared to second generation plants which, in the U.S.A., had construction costs up to $6000 per KW and generally took more than five years to complete.

Meanwhile the Chinese Nuclear Power Industry has won contracts to build new plants of their own design at capital cost reported to be $1500 per KW and $1300 per KW at sites in South-East and North-East China.

Operating, Waste Disposal and Decommissioning Costs

Operating costs are much easier to quantify and are independently verified as they relate directly to the profitability of the Utilities which operate them.

Since 1987 the cost of producing electricity from has decreased from 3.63 cents per KW-Hr to 1.68 cents per KW-Hour in 2004 and plant availability has increased from 67% to over 90%. The operating cost includes a charge of 0.15 cents per KW-Hr to fund the disposal of radioactive waste and for decommissioning the reactor. This fund is currently capitalized at $24 billion dollars. The Swedish Nuclear Industry has charged 0.5 cents per KW-Hr for waste disposal and decommissioning. Sweden has well developed plans for these which appear to be adequately covered by these charges. The US plans for waste disposal at Yucca Mountain remain highly controversial. It may be that the charges levied by the US NRC are insufficient.

Sensitivity Analysis of the cost of Nuclear Power

In our study we performed a sensitivity analysis of the cost of Nuclear Power. We employed a simple model which gives a reasonable guideline to the cost in US cents of electricity per KW-Hr based on various assumptions for construction cost, operating costs, interest rates and construction time. The plant is assumed to have a 1 GW capacity.

If we assume a 7% interest rate and 4 year construction period, US operating costs in the second best quartile, the cost of electricity production for plants that cost $1.2 Billion, $1.5 Billion and$ 2.0 Billion US dollars would be 3.3, 3.8 and 4.4 US cents per KW-Hr respectively. If the AP1000 lives up to its promises of $1200 per KW construction cost and 3 year construction time, it will provide electricity fully cost competitive with Fossil Fuel based generating facilities.

Safety of Nuclear reactors

The chain reaction that provides the power-source of nuclear reactors, is controlled by adjusting the neutron multiplication factor, k. The parameter k is the overall fraction of neutrons from one fission generation that initiate further fission reactions. If $k > 1$ the number of neutrons grows with time and more power is generated. If $k < 1$, the reaction decays with time and less power is generated. In a steady operation k is adjusted to be almost precisely 1. This is possible because round 1% of the neutrons in a reactor are emitted after a delay of a several seconds even though the typical cycle time between succeeding generations in a light water reactor is of the order of 10 milliseconds (these are initiated by prompt neutrons neutrons directly from the fission). The multiplication factor is adjusted by changing the configuration of control rods which absorb neutrons within the reactor.

In addition to this active control two natural processes provide negative feedbacks which stablize the reactor. The first of these is a negative temperature coefficient. As the temperature of the fuel increases, the vibrational energy of the 238U increases which increases the rate of neutron absorption. Thus k decreases and the reaction rate slows down. The second is what is called a "negative void coefficient". What this means is that if the water that is used to cool and moderate the neutrons decreases in mass (for example via steam bubbles forming voids), it no longer is an effective neutron moderator which also slows down the reaction rate.

So light water reactors are inherently stable to first order. Of course things can and do go wrong over the course of time. These are normally corrected by routine adjustments of the reactor parameters. However the worst thing that can happen is for a massive loss of core coolant via a catastrophic accident. If this happens the nuclear reaction will stop but the fuel itself will continue to generate heat from the radioactive decay of fission products. Without the cooling water, the fuel elements will eventually melt. Should this occur, the fuel is contained within the extremely strong shell of the containment vessel. The melt-down will destroy the economic value of the reactor, however the public remains protected. To prevent meltdowns, current second generation reactors employ multiple backup cooling circuits driven by active components like pumps and valves. These are active safety systems and modern reactors are projected to have 1 major core damage incident per 100,000 years of reactor operation.

In contrast, new designs such as the Westinghouse AP1000 employ principles of physics such

such as phase change and gravity to maintain cooling water in the event of a catastrophic loss. The design is simpler, smaller and safer and cheaper than current reactors. The American NRC estimates 1 major core damage incident per 2 million years of reactor operation for the AP1000.

There are been numerous reactor incidents over the years. Some more serious than others and most recently at the Forsmark complex cited above. However Three Mile Island and the Chernobyl catastrophe are the events that most people associate with Nuclear Power accidents. The Three Mile Island accident resulted in a contained melt-down. The Chernobyl event was the result of a fundamentally unsafe reactor design (the graphite-moderated, water cooled reactor has a positive void coefficient at low power as well as no containment vessel) together with a complete lack of safety culture. The following links provide excellent descriptions of the Three Mile Island and Chernobyl events.

The Three Mile Island accident caused the US NRC to re-evaluate Nuclear Plant designs and in many cases ordered changes. These changes were both expensive and time consuming to fix but have increased the safety of US plants.

It is a condition of entry to the EU that Chernobyl style plants be shutdown.

Nuclear Waste

Spent Nuclear Fuel (SNF) from a reactor is highly radioactive. The activity can be broadly divided into two classes. Fission products, (nuclei created from the fission process) and Trans-Uranics. These are nuclei that are heavier than Uranium and are created when 238U captures a neutron. Fission products are generally short lived while TransUranics can have half-lives in the range of tens of thousands of years.

Once the SNF has been removed from the nuclear reactor it is placed in interim storage at the reactor site. Usually this consists of putting the nuclear waste into large pools of water. The water cools the radioactive isotopes and shields the environment from the radiation. Nuclear waste is typically stored in these supervised pools between 20-40 years, although this could be reduced to 5 years. As the SNF ages the radioactivity decreases, reaching the point where can be placed in dry storage facilities. Throughout this time there is a great reduction in heat and radioactivity and this makes handling of nuclear waste safer and easier. However the TransUranic component of SNF must still be isolated from the environment for 100,000 years or more. The fission products typically reach background levels after 500 years.

After this "cooling off" period the high level waste can be handled in different ways. It can be reprocessed (which invloves extracting the Uranium and Plutonium) then disposed of permanently or directly disposed permanently in a geological repository. There is also very active research into "burning" the TransUranic's in either advanced reactors or accelerator driven subcritical assemblies. However this technology has not yet been developed to work on a large scale. Finally it could be left in dry casks for "interim storage". These are predicted to be safe and stable for at least 1 century.

The most advanced concepts of long-term disposal of Nuclear waste is for deep geological burial. The Nordic countries, Sweden and Finland are perusing solutions which employ multiple barriers to provide isolation from slow-moving groundwater. Finland has selected a site for disposal, Sweden is choosing between two locations for their facility. The earliest start up date for the repositories is 2017.

Nuclear Proliferation

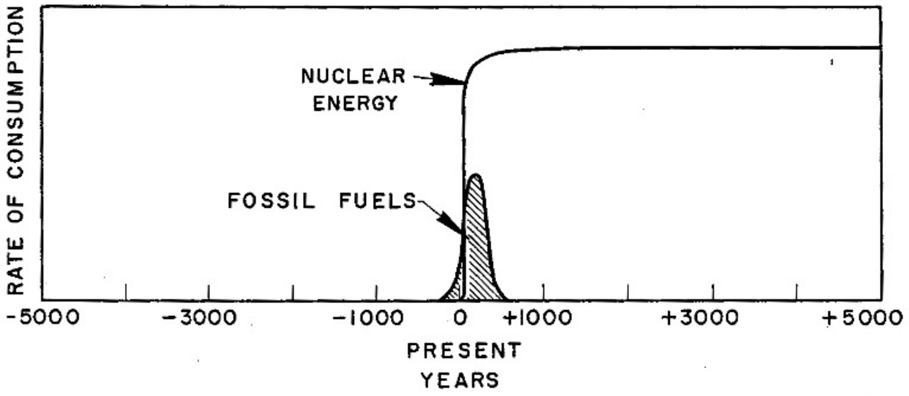
The Uranium enrichment used for light water reactors is not sufficient for a Nuclear Weapon and while light water reactors produces hundreds of kilograms of plutonium during operations, the plutonium produced has too much 240Pu for a useful Nuclear Weapon. What happens is that the 240Pu builds up in a reactor with operation. In a light-water reactor, the 240Pu exceeds useful concentration (7%) after 4 months of operation. Nuclear fuel is normally left in place for over two years. After this time the 240Pu concentration is 25% which is well beyond the militarily useful range.

For this reason, light water reactors are called proliferation resistant. Normal operations preclude the production of militarily useful Plutonium. Abnormal operations are easy to detect.

Conclusions

Technically, there appear to be no show stoppers for a considerable expansion of Nuclear Power throughout the world. It is a low carbon energy source with abundant fuel supplies. The technology works and has much potential for improvement. Whether or not a large scale expansion eventuates depends on how it competes with Coal on economic grounds and with the public on political grounds. This in turn will be determined by the performance of the nuclear industry over the next few years as these purportedly cheaper and safer plants are built.

I think it is worth showing the final graph from M. King Hubberts' seminal paper ["Nuclear Energy and the Fossil Fuels"](#).



gure 30 – Relative magnitudes of possible fossil-fuel and nuclear-
ergy consumption seen in time perspective of minus to plus 5000 years.