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The Changing Need for a Breeder Reactor

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When nuclear fission was discovered,[1] and the possibility of a neutron chain reaction was demonstrated[2] there was euphoria about the possibility for unlocking the energy of the atomic nucleus for peaceful human development. The need to win a terrible war ensured that progress was first made in the field of military explosives, but the scientists continued to ponder the use of nuclear fission as an energy source to fuel mankind. One limitation was evident. Only the rare (0.7%) isotope of uranium, U-235, was fissionable by slow neutrons and would be burnt up in a reactor. Uranium appeared to be a scarce mineral with only three known suppliers: the Joachimstal mine in Czechoslovakia, soon to be overtaken by war; Union Minière d'Haute Katanga in the Congo; and the Eldorado mining company in Canada. It seemed that although the "nuclear age" had come, it was to be short lived.

But other fissionable materials (with atomic weights $A = 4N\text{-}1$) were predicted by Bohr and Wheeler[3] in 1939, and plutonium-239 was discovered by Seaborg, McMillan, Ramannod and Wahl in 1941. Soon thereafter, Seaborg and collaborators discovered the first (U-233) of many fissionable isotopes *not* a member of Bohr and Wheeler's $4N$-1 rule. In 1951 McMillan and Seaborg received the Nobel prize in chemistry for their work on the chemistry of the transuranic elements that included this discovery. This immediately led to a possibility which I will call for brevity "Fermi's dream". By use of a breeder reactor it is possible to convert the waste U-238 into Pu-239 for burning. By this means 100 times as much energy can be obtained from the same amount of raw fuel. I note that this dream was an endeavour to achieve high efficiency in fuel use — a goal rediscovered by "environmentalists" (but not in the context of a breeder reactor), 30 years later. The development of a breeder reactor became a long term goal for all countries.

Before 1975 there were, therefore, coherent plans for a nuclear fuel cycle in the world. One starts with uranium ore, chemically processing it to extract the uranium, enriching the natural uranium in the fissile isotope U-235, burning the U-235 in an electric power producing reactor, and finally reprocessing the spent fuel to recover residual U-235 and Pu-239 for use in subsequent reactors. A fast neutron reactor is capable of producing more plutonium fuel than the uranium fuel it burns, leading to a breeder reactor. In addition, if the reactor is a fast neutron reactor, other transuranic elements can also be broken up and destroyed by fission.[4] All that would be left for subsequent waste disposal would be the fission products themselves, almost all with half lives of 30 years or less. The fast neutron reactor of preference was to be cooled with liquid sodium. With this coherent plan it was envisaged that the energy in *all* the uranium, not just in the U-235, could be unlocked. In its 1976 budget the US Energy Research and Development Administration allocated US$474 million to the breeder reactor, one third of the research and development budget and the largest sum ever for a civilian R&D project.[5]

In the early 1970s, problems appeared in the Fermi dream. It was realised that the existence of many tonnes of chemically separated plutonium might lead to the possibility of the theft, or “diversion”, of enough fissionable material to make a nuclear bomb. The presence of “weapons grade” fissionable material in the hands of a small “rogue” country, or a terrorist group, is unacceptable and would be a nightmare. This led to a study sponsored by the Ford Foundation[6] and the subsequent decision of President Carter, on 7 April 1997, to abandon the plans in the USA to reprocess spent nuclear fuel and to slow the development of the breeder reactor. Other countries did not follow the US lead and continued to reprocess nuclear fuel. While there is argument and disagreement about the dangers of reprocessing, I argue here that reprocessing is *not* necessary for the future of nuclear power over the next half century. Fossil fuel supplies are more plentiful and cheaper than anticipated, supplies of uranium ore are adequate, and the cost of the experimental breeder reactors has been greater than expected. This conclusion seems to differ from that of many others.[7] Reprocessing may be desirable — but not for fuel resource reasons.

This paper will explore the various consequences of the changes of the last 25 years, and I claim that the data demonstrate that there is no urgency for a breeder reactor. Moreover, I believe that nuclear power could regain its competitiveness and have a long-term future without a breeder reactor. However, there may be good environmental reasons for including a fast neutron reactor system as part of the world’s nuclear power complex.

The Availability of Uranium and Other Fuels

Twenty-nine years ago, Benedict[8] reported that we had “only” 500 000 tonnes of uranium at a price of US$8 per pound (which was the going price at the time), although he estimated that there were 20 million tonnes of uranium if we were willing to pay the price of US$100 per pound (Table 1). If one had paid the higher price for the uranium, the total cost for operating an LWR would have been 0.5 US cents per kWh (Table 2). At that time, the busbar cost of nuclear power was less than 1 US cent per kWh. The demand for energy — particularly electricity — was doubling every nine years, and it was predicted that the supply of the premium fuels, oil and gas, was only adequate for 20 years. Benedict’s conclusion, and that of most of the nuclear industry, at that time was that a doubling of busbar cost would be unacceptable and that it was of vital importance to develop a breeder reactor as soon as possible so that the cost of nuclear powered electricity did not increase.

However, the total quantity of uranium resources (column 2 of Table 1) does not seem to have changed.[9,10] Figure 1 (taken from Reference 11) shows the distribution of uranium reserves versus price from the OECD Red Book,[10] and Figure 2 shows the comparison with Benedict’s paper. The subsequent columns of Table 1 are merely physical calculations from the first two columns. Similarly, in 1998 the Uranium Institute reported that we have about 18 million tonnes of uranium in ore, proven reserves, reasonably assured supplies, and possible supplies, at prices up to US$200 per kgU.

There is considerably more uranium now known at the lower prices, but otherwise Table 2 is as accurate today as it was 28 years ago, and for reasons outlined below it may be pessimistic as to the overall uranium reserve. (It is in fact remarkable that the cost curve, in absolute terms, has not changed much. Since there has been inflation, the cost of uranium has gone down in “real” terms, as have the costs of many other fuels.) However, the interpretation of these data on uranium supply has changed.

In addition, the availability of fuels for a programme of thermal reactors, whether today’s light water (moderated and cooled) reactors or graphite moderated (and helium cooled) reactors, is better than Benedict suggested. A general rule about prices of any fuel has evolved. The time for depletion of reserves has stayed between 15 to 30 years for nearly a century! (Coal reserves which seem to be enough for 300 years are an exception). If enough fuel exists for 30 years there is little incentive for exploration, but if the amount falls below 15 years the profit motive ensures that exploration restarts. The present and anticipated use of nuclear power provides little incentive to explore for uranium. One can anticipate that if and when exploration restarts more uranium will be found — probably in the higher cost range. Related to this is the possibility that uranium can be extracted from seawater at a cost of perhaps US$200 per pound, which translates to 1 US cent per kWh. Although this is above the “cut-off” of Benedict’s table, it now seems reasonable.

The Thorium Cycle

All present reactors could be run on thorium fuels. Indeed, 40 years ago Indian Point unit 1 was designed explicitly to allow this.[12] There are several ideas for a fuel chain that uses thorium (since it is not closed, I use modern terminology and refuse to call the chain a cycle). There are, according to present estimates, six times as large thorium reserves as uranium reserves. I know of no good estimates for the increased fuel chain cost but it is unlikely to be as much as 0.5 US cents per kWh. While the full advantage of a thorium cycle would only be gained by reprocessing the fuel and extracting the U-233 (with the same objections to reprocessing as already noted) some advantage in fuel use can be gained by using a mixture of U-235, U-238 and thorium. The use of a thorium fuel in LWRs (in a once through system) might then postpone for a little longer the need for a plutonium breeder reactor that uses fast neutrons.[13,14,15]

Increased Cost of Both LWRs and Sodium Cooled Reactors

I first insist that nuclear energy (using LWRs) was in the past very competitive and presumably could be again. This position is not a matter of optimism brought on by believing results from a model, but is one of accepting historical fact. Twenty-five years ago, Maine Yankee nuclear power plant had just been completed for a total cost of US$180 million[16] (although another US$20 million was spent at the last moment to modify the cooling system — a cost not demanded of any coal fired plant), or US$200 per kWe of installed capacity. Electricity from Connecticut Yankee nuclear power plant was 0.55 US cents per kWh (including paying off the mortgage), and from Yankee Rowe 0.9 US cents per kWh.[17] Twenty-seven years ago, Benedict[8] (Table 2) estimated average operating costs that were a little lower than this value, and capital costs that were about 25% higher than for Maine Yankee. Taking no credit for learning, we could do as well if we could return to the optimism and procedures of 25 years ago. Allowing for inflation, the operating cost could be less than 1 US cent per kWh, and, by keeping construction times down, the capital cost could be less than 2 US cents per kWh.

Yet the average operating cost of nuclear plants in the USA today is 1.9 US cents/kWh.[18] For a well-operated plant the cost is smaller, although still higher than 25 years ago, in the range of 1.4 (South Texas) to 1.5 (Seabrook) and 1.7 (Palo Verde) US cents per kWh. The construction cost is US$1690 per kWe installed for a new GE reactor being built in Taiwan in about four years (leading to a charge for the capital of about 4 US cents per kWh). These costs are still very high, and could be more if construction takes longer than four years.

In 1955 enthusiasts (including my cousin Derek Smith who worked on breeder reactors from his PhD in 1955 until his retirement around 1990) thought that a sodium cooled fast neutron reactor might be as cheap or cheaper than a light water cooled thermal reactor. The working temperature can be higher and the thermal efficiency perhaps 40% instead of 30%. Sodium is far less corrosive than water. It does not attack steel and make it rust. On the contrary it removes oxides. It boils at a higher temperature than water enabling a high thermal efficiency without using high pressures. Even in 1973 the cost differential was not thought to be big. But the shutdown of all operating experimental breeder reactors suggests that even their operating costs are higher than the operating costs of LWRs.

Various factors have increased the cost of nuclear power until now, in the USA, the busbar cost (including paying off the mortgage) is about 5 US cents/kWh, nearly 10 times the 1973 figure. Even this high cost is competitive with most non-fossil fuel alternatives, although not with fossil fuels. The fuel cost increase which Benedict found unacceptable is only 10% of this busbar cost and an even smaller fraction of the retail cost which includes transmission and distribution costs (and some other items) of a few cents per kWh. The charge on my electricity bill is 9 US cents per kWh, compared with which 0.5 cents per kWh is small. Therefore we can afford to use the more expensive uranium resource without appreciably increasing the final electricity cost. Using Benedict’s figures, a worldwide LWR system could produce about 4×10^{15} kWh (4.6×10^{5} GW-years) of electricity, or enough for over a century at an optimistic postulated year 2030 demand of 2500 GW-years. This suggests that scarcity of affordable uranium is *not* an issue at present. An early (within 50 years) deployment of a breeder reactor must be justified by more than this.

These considerations therefore suggest that a breeder may not be cost effective for some time to come.

Reduced Demand for Energy

In 1970, the demand for energy was increasing. In particular, electricity use was doubling every nine years. US President Kennedy had publicly advocated cheap energy as a stepping stone to prosperity. Although electricity production, and various end uses of energy, were becoming more efficient (power station efficiencies of 8% in 1900 improved to 30–40% in 1970), it was considered politically and morally acceptable to “spend” energy in order to live a more comfortable life. In 1970, oil and gas prices were dropping.

Although other factors influenced the subsequent change, the change in public perception has usually been attributed to the Arab oil embargo and consequent oil price shock of October 1973. Previously, there was a perception not only that electricity was cheap but that it would get cheaper. This changed dramatically in 1973 — and even more at the start of the Iraq–Iran war in 1979 — when it became popular to believe that fuels of all sorts would become more expensive. This led to a public willingness to consider improvements in end use efficiency. It was in 1979 that my local hardware store ran out of fibreglass insulation.

Increase in the Resources of Gas and Oil

It has always been popular to cry “doom”. In 1850, distinguished scholars wrote about the coming shortage of coal — expected to run out within 30 years. In England of December 1947, for example, there was a temporary shortage of coal — due in part to a shortage of miners returning from the war and in part to a cold spell which shut down trans-Pennine railroads. There was electricity rationing. Not surprisingly, this was a time of enthusiasm for alternative energy sources. But then the oil fields of the Middle East — already known to be extensive when Winston Churchill organised the British purchase of a controlling interest in the Anglo–Iranian oil company in 1912 — were found to be extensive *and* cheap, as oil was discovered in countries such as Kuwait.

But in 1973 the prophets of doom seemed to have more facts on their side. The geologist M King Hubbert[19] argued that we had already discovered 90% of the oil to be discovered in the USA, and it was expected that we would have discovered most of the oil in the rest of the world within another 30 years. Reserves seemed to be available for only 20 years. Hubbert was right about the USA. US domestic oil output has continuously declined since 1970. But the amounts in the rest of the world continue to confound the sceptics. At a meeting in Vienna in 1978, a British cabinet minister stated categorically that production of oil from the North Sea would never exceed 1 million barrels a day and would be played out in the 1990s. Far from it. They are now producing 4 million barrels a day. It is noteworthy that a large part of this increase arises because of improved technology of secondary and tertiary recovery.

In 1973 the conventional wisdom was that natural gas came, and only came, as a by-product of oil drilling. The supply of natural gas seemed less secure than that of oil. But that has been perhaps the biggest and certainly the most important surprise of all. Natural gas has been found in many places previously thought to be unlikely. Natural gas is a premium fuel both for environmental and efficiency reasons. In the last 20 years, a combined cycle natural gas system has been introduced that increases the efficiency from 40% to 60%. There are no sulphur oxides and it is easier to control the nitrogen oxides. The effect of natural gas burning on air pollution is less than the effect of burning oil, and *far* less than the effect of burning coal. The CO_2 emissions from natural gas are a factor of four less — partly (a factor of two) because only half the energy comes from burning the carbon, and partly from the improved efficiency. Natural gas combined cycle generation is leading the deregulation of the electricity sector in the USA. For example, it is anticipated that within a year or so natural gas will generate 60% of the electricity in the eastern USA.

Nuclear Fuel Use Improvements

Nuclear fuel can stay in a reactor longer than was the case 25 years ago, when burnups of 20 000 MWd/t were usual. Although reactors were designed with the idea that 1% of the fuel rods might fail (develop leaks), the radioactivity that consequently was around the plant and released to the public caused concern (some would say unnecessary concern), and premature fuel changes were common. Since the 1970s there have been major improvements in fuel rod integrity and burnups of 40 000 MWd/t are usual. There is discussion of making fuels with even higher burnups (probably involving a higher initial uranium enrichment). This can increase the time between fuel change outages (which improves efficiency and reduces cost) and in addition enable more of the initial fuel and bred fuel to be used.

Fast Neutron Reactor Improvements

Improvements have also been made in fast neutron reactor technology. Whereas in 1970 fuel burnups in metal fuel were limited to 1%, and the plans were to use oxide fuel or nitride fuel, the Argonne National Laboratory IFR programme has demonstrated 20% burnup with metal fuel combined with “fissium” or fission products. This improves the efficiency and also the safety. With the high thermal conductivity of the metal fuel, there is less stored energy and the reactor can shut down at a temperature far below the boiling point of sodium — thereby avoiding the troubling Bethe–Tait accident. Proponents claim that the sodium cooled fast neutron reactor possesses many important features of intrinsic safety — including of course the presence of sodium to prevent the escape of dangerous iodine in an accident situation. This also lends itself to easy pyroprocessing and electrolytic processing, whereby the plutonium in the fuel is *never* separated free from fission products. This gives it a considerable degree of proliferation resistance.

Understanding the History

The above paragraphs make the case that the increase in fuel cost by using more expensive uranium ores is a small fraction of the 1999 electricity cost. But there is a possibility, which is technically obviously feasible although practically remote, that some of the reasons for the cost increases of nuclear electricity will be reversed. I will address this possibility here. It has been said that anyone who does not understand history is condemned to repeat it. For this reason alone it is important to go carefully over the decisions about nuclear energy that were made in the past and to re-examine them. This, alas, is rarely done. Even important committees[20] duck the issue and important people merely mention it.[21] I argue that understanding the history of the nuclear power programme is a primary responsibility of the nuclear industry as a whole — and by nuclear industry I include *all* segments. Academic researchers, both physicists and nuclear engineers, equipment manufacturers, electricity utility companies, regulators, legislators, and even the critics. I outline in question form a set of issues that still puzzle me:

- Is it correct that liquid sodium cooled reactors might be the conventional reactors if Admiral Rickover had not rejected them for the nuclear navy after a small sodium leak? What are the consequences of this thought?

- We have had a number of fast neutron reactors throughout the world, including a “commercial” one — Fermi-1 at Laguna Beach operated by Detroit Edison. The reactor worked and was successfully repaired after an accident. Why was it dismantled? Was it too expensive to operate? Why would any other fast neutron reactor be better?
- Nuclear electricity *was* competitive with electricity from other technologies. What has changed? Can it be changed back? Can it be partially changed back? Should it be changed back? Can it be put on a new economic track?
- What were the reasons for the choices of nuclear reactor types in the 1960s, and in particular the rejection of some promising types? Do the reasons for rejection still apply?
- It is particularly interesting to discover the reasons for the cost increases, both in construction cost and operating cost of an LWR. Why has the cost of building and running an LWR gone up?
- Is the cost increase all due to demands by the public, and if so can public perception be changed?[22]
- Can we (technically) make nuclear energy cheap again?
- A large cost is attributed to steam generators (heat exchangers) which fail more than was anticipated. Yet mass produced modular heat exchangers exist for automobiles at one-tenth the cost. Can we learn from this?

In 1973 nuclear power advocates expected that as more nuclear power plants were built and operated both the construction cost and the operating cost would follow the decreases predicted by a learning curve. But the reverse has been the case — the costs have followed a “forgetting curve”.[23] Some improvements (in fuel fabrication for example) have been made as noted above. But these must have been swamped by cost increases elsewhere. What are they?

Some people argue that the increased cost has been caused by the need for increased safety. But the safety of nuclear power in 1973 was probably better than for other comparable industrial facilities, has been steadily improved since then, and new designs promise further improvements. It is important to realise that the safety improvements have mostly come from improved analysis — which is (in principle) cheap compared with hardware modifications.

I have seen *no* careful study of the cost increases. Indeed, in 1984 when the Energy Engineering Board of the US National Academy of Sciences proposed a study of the subject it was opposed by the utility industry, perhaps for fear of adversely influencing “prudency hearings” that were in progress before public utility commissions.[24] PUCs were calling expenditures on nuclear power plants in excess of estimates as “imprudent” and disallowing them in the rate base (although I know of no similar action for a coal fired power plant).

Various ideas include the following:

- In 1970 manufacturers built turnkey plants or otherwise sold cheap reactors as loss leaders, but turnkey operations can only account for a small proportion of the capital cost.

- Construction costs generally have risen since 1970 even when corrected for inflation.
- It may be that in 1972 we had good management and good technical people; but why has management got worse when that has not been true for other technologies?
- Operating costs rose rapidly in the 1970s because the rate of expansion of nuclear energy exceeded the rate of training of good personnel.
- A sudden rise in costs came in the late 1970s after the accident at Three Mile Island. Although mandated retrofits have been blamed for cost increases, this applies to existing plants and not to new construction.

Most people seem to agree that the principal *present* limitation in nuclear power development is related to diminished public acceptance of the technology. Decreased confidence and increased risk aversion drives excessive regulation, and this in turn increases the cost. As noted above, this increased cost often reaches a factor of three even after correction for inflation. It is highly likely that nuclear power plants are safer today than they were in 1972. It would be hard to argue, however, that the actual safety improvements that have occurred have been the cause of the threefold increase in cost. Most improvements have resulted from more careful thought, using such approaches as event-tree analysis, but without excessive hardware expense.

Many people have suggested that the problem is that the regulation is more than needed for adequate safety, and this over-regulation increases the cost.[25] In particular, many claim that regulation is too prescriptive and not based upon performance. A few of the arguments related to over-prescriptive regulations are as follows:

- The response to many regulations is to increase staff. The staff numbers at the Dresden-2 power plant went from 250 in 1975 to over 1300 today.[26] This increased staffing costs money: 0.8 cents per kWh, and it is far from clear that adding personnel improves safety.
- Shut downs (always costly) for failure to meet technical specifications occur even though the technical specifications have little effect upon safety.
- Any delay in licensing can seriously increase the capital cost, as interest payments incurred during construction accrue.

A demand for safety-grade equipment in parts of the plant that have little impact on safety is unnecessarily expensive. The problem is not unique to the USA. In the UK, British Nuclear Fuels had to spend a lot of money making the THORP reprocessing plant as earthquake proof as an operating reactor, yet the inventory of dangerous material is far less than in a reactor, and the danger of re-criticality is remote.[27]

In other papers[28,29] and in Congressional testimony[30] I addressed the problem of excessive regulation; reasons why it inevitably appears and what can be done to avoid the problem. I argued that the Nuclear Regulatory Commission strongly exceeded its authority and caused vast unnecessary expense in their shut down of the Millstone reactors in 1996. There may be hope. The Chairman of the NRC recently addressed this question[31] and emphasised this area as a vital area of research and subsequent implementation. I hope that some action will be forthcoming.

Environmental Factors

The USA now emits 11% more CO_2 than in 1990. At the Kyoto Climate Change Conference the USA promised to reduce CO_2 emissions to 8% below 1990 levels in 10 years, which is a decrease of 19% below present levels. If all the electricity now generated by nuclear power were to be generated by coal, CO_2 emissions would increase by another 8%, making it more difficult to meet this commitment if nuclear power was abandoned.

About 30 years ago Dr Glenn Seaborg, then Chairman of the US Atomic Energy Commission (AEC), testified to the Joint Committee of Atomic Energy (JCAE) of the US Congress that nuclear power would be comparatively benign environmentally (in particular, not producing appreciable quantities of CO_2) and also produce electricity at a modest cost. This optimism was nationwide and worldwide. Since that time opposition to nuclear power has arisen, and nuclear power at the present moment is not being considered by most governments in the world as an option to meet energy and environmental aims and desires. Nuclear power could help the world and in particular the USA to meet the commitments made at Kyoto. Nuclear power would also be a simple way of avoiding the health effects of air pollution.[32] But for neither do we need the breeder reactor.

But we may need reprocessing and the breeder reactor for another environmentalist reason: the perceived objections to disposal of high level nuclear waste. I believe that these objections are technically unsound, but they are psychologically real and it is unlikely that they will disappear in the short term. The problem of nuclear waste might be changed if the volume were changed and if its long lifetime was reduced by transmutation. This could be plutonium recycle, burning in a fast neutron reactor (but not breeding until it were necessary), or accelerator transmutation. It is these environmentalist issues that may eventually demand the breeder reactor, assuming that the cost, safety and proliferation issues can be solved.

Breeders for the Longer Term

For a time horizon greater than 50 to 100 years a breeder reactor is probably essential. After this time there may well be a large population increase, and if fuel use per capita in developing countries approaches that of developed ones, a huge appetite for electricity. Since more of the energy in the fuel can be used it would be economic to use fuels with costs much more than US$200 per tonne. All in all, a factor of 1000 increase in effective fuel supply seems not unreasonable. It would be impudent to project the existence of the human race beyond the 100 000 years implied by these factors.

The cost estimates for a liquid metal breeder reactor are certainly smaller than the cost estimates for a fusion reactor, and are (and may remain) smaller than for renewables. A breeder programme deserves by this reckoning at least as much funding as the fusion reactor which is still far in the future. But it may be desirable (although not necessary) in the intermediate term also. It is now 50 years since the start of the nuclear age and it can be said that we are only just beginning to understand how to make a viable LWR programme. A breeder reactor development programme (including real operating demonstration plants) may give enough experience to overcome some of the cost (and weapons proliferation) problems and enable us to have the safety and environmental advantages of a metal fuel reactor and a coolant that soaks up stray fission products.

Conclusion

Allowing for a price increase of 0.5 US cents per kWh to enable us to use more expensive uranium ore, it appears we could have a future for nuclear power at several times the present level for 50 years without a breeder reactor, and possibly for many, many more. Any large scale breeder programme must be justified on a longer time scale or on definite cost or environmental advantages. It would be wise to redirect any research programme to these ends. After perhaps half a century it would be wise to be ready to use breeder and other alternate fuel cycles.

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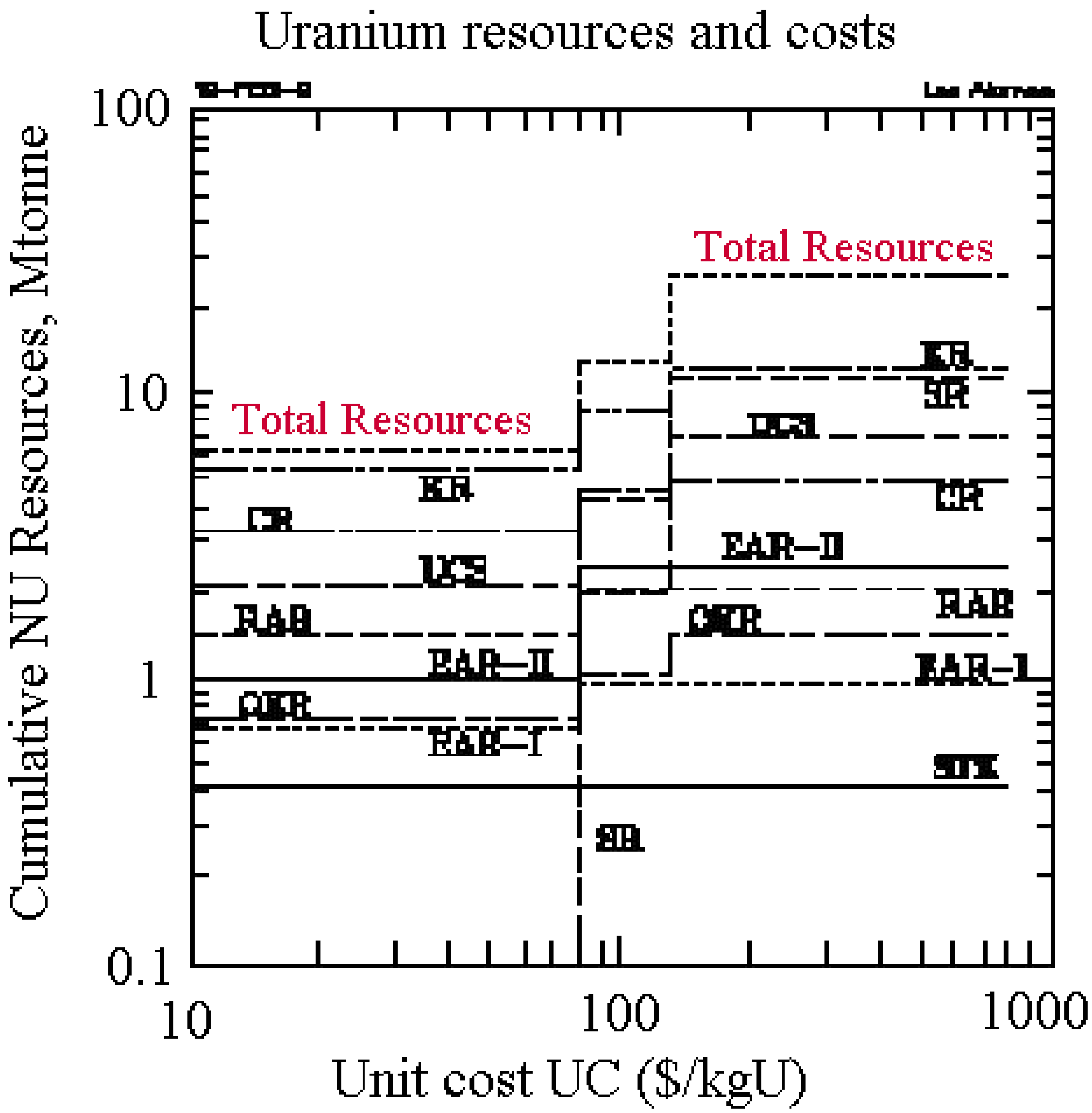
Table 1. Uranium supplies (from reference 8); resource data plotted on Figure 2.

Uranium price ($/lb U_3O_8)	**Resource tonnes**	**Cost increase (cents/kWh)**		**Electricity generated (GWe/yr)**	
		LWR	**Breeder**	**LWR**	**Breeder**
8 (base)	594 000	0.0	0.0	3 470	460 000
10	940 000	0.01	0.0	5 500	720 000
15	1 450 000	0.04	0.0	8 480	1 120 000
30	2 240 000	0.13	0.0	13 100	1 720 000
50	10 000 000	0.25	0.0	58 300	7 700 000
100	25 000 000	0.55	0.0	146 000	19 200 000

Table 2. Cost of nuclear energy in 1971 from Virginia Power & Light. (from reference 8).

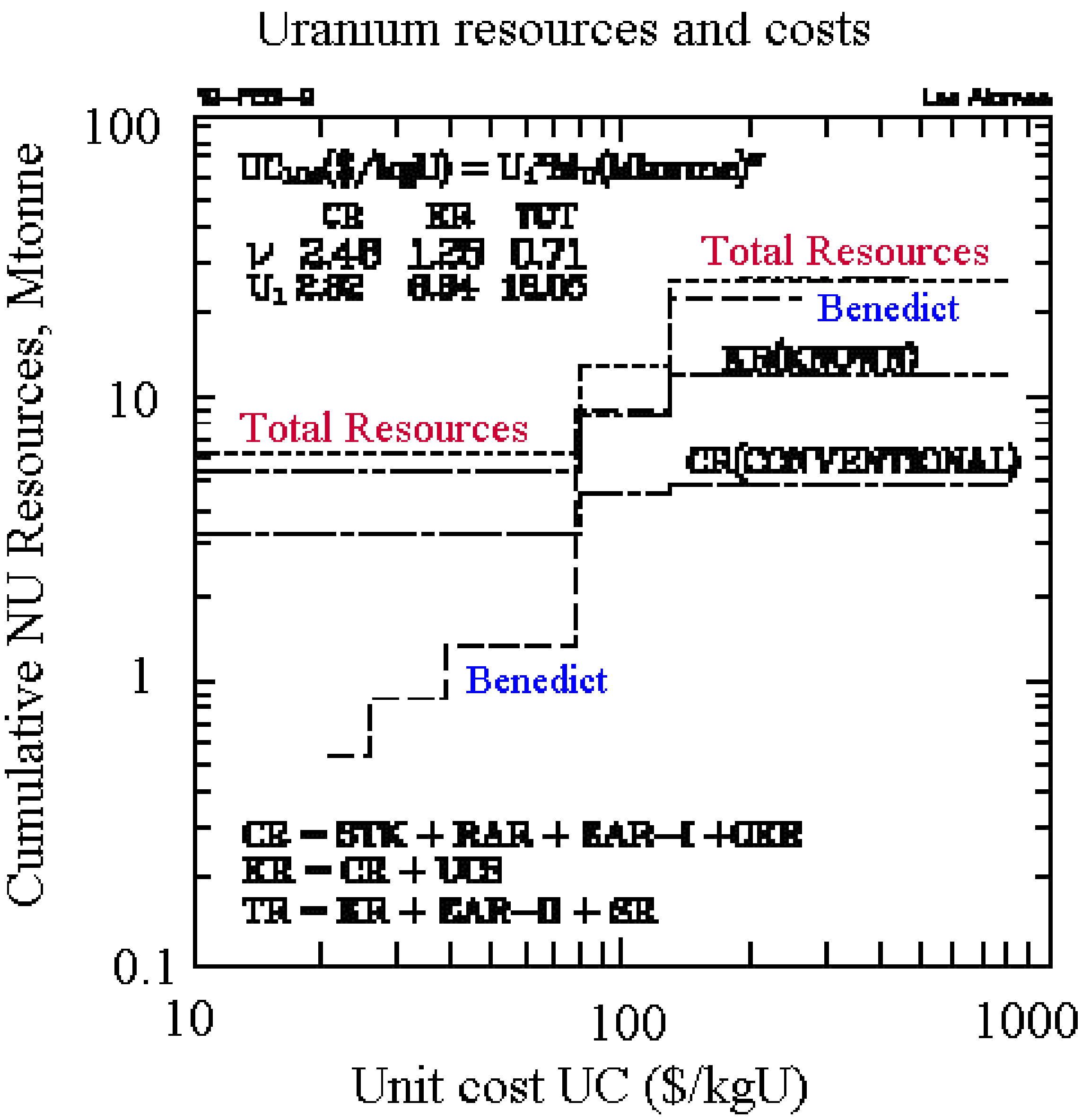
Description	**Coal**	**Nuclear**
Unit investment cost of plant (US$/kW).	202	255
Annual capital charge rate per year	0.13	0.13
Kilowatt-hours generated per year per kW capacity	5 256	5 256
Heat rate, million Btu/kWh	0.009	0.0104
Cost of heat from fuel, cents/million Btu	45	18
Cost of electricity, cents/kWh:		
Plant investment	0.500	0.631
Operation and maintenance	0.030	0.038
Fuel	0.405	0.187
Total	**0.935**	**0.856**

Figure 1. Uranium resources versus cost.



STK = reported stocks; RAR = reasonably assured resources; EAR-I = estimated additional resources; OKR = other known resources; UCS = unconventional resources; EAR-II = estimated additional resources; SR = speculative resources. And the total TR = Total Resources which is discussed in the text. Modified from Reference 11 (*Source: Reference 10)*

Figure 2. A comparison of Benedict's[8] *(long dashes) estimates of uranium resources versus cost with those of OECD*[10] *showing uranium resource cost models.*



Models used: Conventional Resource (CR = STK + RAR + EAR-I + OKR), Known Resources (KR = CR + UCS), and Total Resources with short dashes (TR = KR + EAR-II + SR). Modified from Reference 11.