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Development of the South African Pebble Bed Modular Reactor System

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South Africa has embarked on a project to build mini-nuclear power plants to address specific domestic and international electricity needs. A decision whether or not to proceed with construction is expected before the end of 1999.

The plant currently being designed is projected to produce 114 MWe, making it only some 10% the size of typical conventional PWR power reactors currently in operation. Consequently the entire nuclear generating facility can be correspondingly smaller than a conventional nuclear plant.

The reactor under design is of the high temperature gas reactor (HTGR) type, which means that its core is gas-cooled and not water-cooled. Helium is used in a closed loop Brayton cycle to power a gas turbine. In addition, this HTGR is of the "pebble bed" type, which means that the fuel is cricket ball (baseball) sized spheres of graphite containing coated uranium dioxide particles.

The reactor system is being designed in a modular fashion so that additional units can be added easily, as demand so dictates. Hence the name of the Pebble Bed Modular Reactor (PBMR). The system can accommodate ten modules to one control room.

The natural physics of the reactor system is such that it exhibits passive safety, which means that in the event of any fault occurring during reactor operations, the system, at worst, will come to a standstill and merely dissipate heat on a decreasing curve without any core failure. This means that the PBMR is inherently safe from the highly publicised public "fear factors" of reactor core meltdown and radiation release which in the public mind are associated with conventional water-cooled reactors.

At the end of its design life, fuel will be kept on site for 40 years after the plant has been shut down. At this point it can be removed and the entire PBMR can be demolished, and the site returned to greenfield status. In fact, the current costing of the project has assumed this option, and has also included the cost of long term storage of depleted fuel.

South African Circumstances

It is instructive to consider the South African circumstances that gave rise to the decision by the electricity utility Eskom to investigate the feasibility of constructing PBMRs.

About six years ago, only 30% of the South African population had access to electricity. Today the figure has risen to 60%, thanks to a concerted effort by Eskom to extend electrification.[1] By comparison, in Africa south of the equator, only 10% of persons had access to electricity six years ago, and today it is still only 10%. In other words the African challenge is great.[2] It is also interesting to note that South Africa produces and consumes over half of the electricity of the entire continent of Africa.[3,4]

Both domestically and in the rest of Africa, South Africa is seen as the regional economic powerhouse, and as such is assumed to have some moral obligation to engage in the economic uplifting of the whole region.[5]

Currently 93.5% of South Africa’s electricity is coal-fired, with one large PWR nuclear station near Cape Town providing 4.5%; a further 1.5% is hydro. There are essentially no more hydro sites that could deliver significant amounts of power, and furthermore for some years Eskom has been of the opinion that it is not an option to build another large-scale nuclear plant. However, South Africa is rich in uranium.

Most of South Africa’s coal-fired electricity is generated by large scale plants built near the pit-heads of two large coal fields, both far inland on the eastern side of the country (Figure 1).

South Africa is a large country, and the distance between Cape Town and Pretoria is the same as the distance from London to Berlin. This implies long power lines from the coal fields or long fuel delivery routes between the inland coal fields and coastal centres of electricity consumption, if the electricity were to be generated by coal in the future. The economic equations are stacked against these options.

Transporting huge quantities of coal over very long distances is just not an option, so South Africa needs to place power generation units closer to the sites that need it, to avoid having to construct very long (1000 km) high voltage transmission lines.

At the present time there is a world move against fossil-fuel power stations due to public concerns about CO_2 emissions leading to possible global warming. The United Nations sponsored conference on global warming held in Kyoto, Japan, in December 1997 gave rise to the Kyoto Protocol which sets limits on countries’ emissions of CO_2. This is in turn bringing pressure to bear on the development of fossil-fuel power stations that may produce “excessive” CO_2.[6]

Overall this general scenario led Eskom to a decision to investigate the development of a small modular pebble bed nuclear powered plant, the PBMR.

How Does the PBMR Work?

The PBMR consists of a vertical steel pressure vessel 18 m in height, and lined with 60 cm of graphite (Figure 2).

During normal operation, the pressure vessel contains a fuel load of 440 000 balls, each 60 mm in diameter. This load consists of 310 000 fuel balls containing uranium dioxide particles encased in graphite and silicon carbide, as well as an additional 130 000 pure graphite balls that serve the function of an additional nuclear moderator. The uranium dioxide particles are less than half a millimetre in size, and there are 15 000 of them in one fuel ball, totalling 9 g of uranium, which means that total uranium in one fuel load is 2.79 tonnes.

A reactor will use 10 to 15 total fuel loads in its design lifetime. The actual calculated figure, for continuous full power operation, is 13.8 fuel loads.

To remove the heat generated by the nuclear reaction, helium gas at 540°C is passed into the pressure vessel at the top. It passes between the fuel balls, and then leaves the bottom of the pressure vessel at 900°C. The hot gas then passes through a conventional gas turbine system to drive electrical generators (Figure 3). The conventional section of the turbine gas cycle can be water-cooled or air-cooled which is an important consideration, since this factor provides the plant with a great variety of site options.

Time Scale for Construction

The team developing the PBMR is hoping to obtain a decision before the end of 1999 as to whether or not Eskom intends to proceed with the construction of a demonstration unit. If so, the time scale for construction of this first unit is indicated in Table 1. A typical production PBMR module will take 24 months to construct.

The staff needed to operate such a reactor do not need to be particularly highly skilled, and furthermore relatively few staff are required. This clearly is an important factor in considering the operating costs of such a plant.

Costs

Detailed calculations of the economics and finances involved have shown that the proposed PBMR system is inexpensive to build, and inexpensive to operate. The financial calculations have not only been carried out for South African conditions but also for international scenarios as well. The PBMR has been found to be internationally cost competitive. Furthermore the costs associated with the PBMR system are competitive with the costs of South Africa’s coal-fired stations. Further details on costs of the PBMR are presented in the Appendix.

Fuel Manufacture

Fuel will be manufactured in South Africa, and there is currently a development project underway as a joint venture between the PBMR team and the South African Atomic Energy Corporation.

The fuel consists of 60 mm diameter balls of graphite that contain coated uranium dioxide particles evenly distributed throughout, as shown in Figure 4. The graphite is a mixture of 75% natural graphite and 25% synthetic graphite. The small uranium dioxide spheres are each coated with a layer of porous carbon, then high density pyrolytic carbon, silicon carbide, and then another layer of pyrolytic carbon. This is known as Triso fuel.

A function of the porous carbon is to absorb any mechanical deformation that the uranium dioxide may undergo during its lifetime, thereby enhancing the integrity of the silicon carbide containment and so ensuring that radioactive daughter products cannot escape from the particle. The inner layer of pyrolytic carbon serves the dual function of providing structural support to the silicon carbide, and also forms a barrier against the migration of some fission products. The weight of a single fuel ball is 202g, including 9 g of uranium.

The start-up fuel is enriched to a level of 4%, and the equilibrium fuel has an enrichment of 8%.

As has been explained above, each fuel particle serves as its own inherent containment boundary. Any fuel containment failure which might occur on PBMR fuel would be of small concern since there is no possibility of any type of massive simultaneous failure, as is possible in a core meltdown scenario in a conventional PWR or BWR.

Existing International Experience

When South Africa embarked on this project in 1993, there was already a considerable body of knowledge in existence in the world relating to HTGRs (see Table 2).

Eskom was therefore able to form a collection of partnerships and coalitions with various organisations that had worked on a variety of operating plants and advanced designs over the years (see Table 3). The PBMR concept is thus not an unproven new technology. In fact, the contrary is true, and Eskom has been able to collect together the “best of all worlds” and then carry out its own design on the basis of a sound body of proven knowledge and experience.

Export Opportunities

The PBMR is ideal for South Africa’s future needs, but it is also clearly ideal for other countries, both in the developing world and in the first world.

In the case of the developing world, it is easier to operate a PBMR than a coal-fired power station with twenty-first century specifications. The PBMR does not need a particularly highly skilled team of operators, and the team is small. A year’s supply of fuel can easily be stored on site, which is important in countries where road and rail supply routes can be highly unreliable. Imagine the constant transportation of coal! PBMRs can also be sited anywhere, being independent of water-cooling. In developing countries they can be sited such that they have their own localised grid, and do not need to be integrated into a major national grid.

As far as first world countries are concerned, PBMRs will be ideal. They can either be deployed individually in places where small amounts of power are required, or can be clustered on one site in modular fashion. Units can easily be added incrementally as required. First world countries could also use PBMRs to replace existing plants that come to the end of their operating lives. At that point the option could be exercised either to build a large scale modular cluster of reactors on one site, or alternatively to distribute the reactors to individual sites and close down the original large site.

Proliferation Secure

The low enriched uranium fuel is half millimetre sized particles of uranium dioxide encased in graphite and silicon carbide, which in turn is encased in the main graphite ball.[6] Not only is it expensive and difficult to process such spent fuel, but the proportion of the fuel burnt is very high.

Fuel balls are recycled through the reactor some 10 times. They are extracted, analysed to determine the amount of fissionable material left, and then either returned to the reactor or sent to depleted fuel storage.

Unlike conventional large fuel elements, the fuel balls cannot jam in reactor core housings, and so they can be burnt to depletion without any fear of mechanical deformation causing handling problems in the core. There is therefore minimal fissile material to extract from depleted fuel.

Depleted Fuel Storage

There is no low or medium level waste produced by a PBMR, except for gloves, jackets and similar items that might be used by workers in a designated radiation area.

Depleted fuel balls are planned to be stored on site for many years. However, they can either be removed to a repository, or left on site for decades, depending on the operator’s policy. The current PBMR design assumes that depleted fuel balls will be stored on site for the duration of the plant’s lifetime, and then for a further 40 years after plant shutdown and decommissioning.

Licensing

The nuclear licensing process is currently underway in South Africa, and is being carried out by the Council for Nuclear Safety (CNS) in accordance with long established norms. The CNS is an independent body formed by statute.

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REFERENCES

1. Dr X Mkhwanazi, CEO, National Electricity Regulator, reported in *Meer huise het nou electrisiteit*, Sake Beeld, p11, 11 June 1999.
2. *International Electric Power Encyclopaedia*, p144, 1998.
3. *Energy Statistics Year Book, 1995.* United Nations, New York, p432, 1997.
4. *BP Statistical Review of World Energy*, p38, 1998.
5. Inauguration speech of President Thabo Mbeki of South Africa, reported in *Pretoria News*, 16 June 1999.
6. World Coal Institute, *ECoal*, vol. 30, p4, June 1999.

Table 1. Planned dates.

July	1999	Initial regulatory licence issued
September	1999	Construction commit
July	2000	Detailed design complete
January	2003	Construction complete
April	2003	Fuel load
July	2003	First criticality
December	2004	Commercial licence

Table 2. Previous international HTGR and other programmes.

British programme		
Dragon	20MWth	1964–77
US programme		
Peach Bottom 1	40MWe	1967–74
Fort St Vrain	330MWe	1979–89
German programme		
AVR	15MWe	1967–89
THTR	300MWe	1985–89
Other national programmes		
HTTR (Japan)	30MWth	1998–
HTR-10 (China)	10MWth	1999–

Table 3. Organisations currently associated with the Eskom PBMR project.

HTR GmbH (Siemens/ABB)	(Germany)
AEA Technology PLC	(UK)
NRG	(Holland)
Kurchatov/OKBM/Minatom	(Russia)
INET	(China)

Figure 1. Position of major coalfields in South Africa.

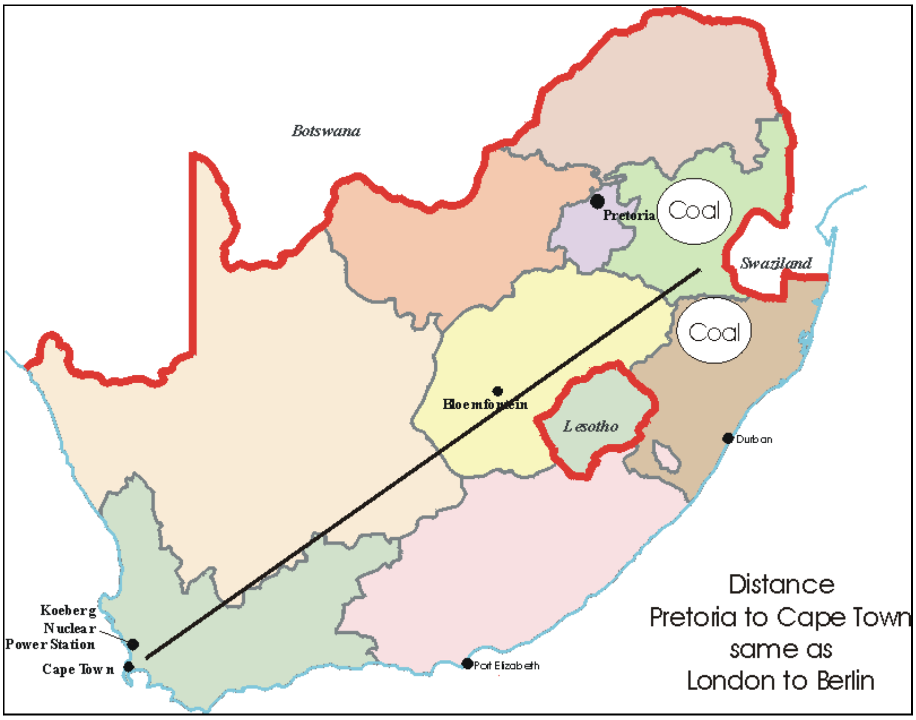


Figure 2. Main reactor power system.

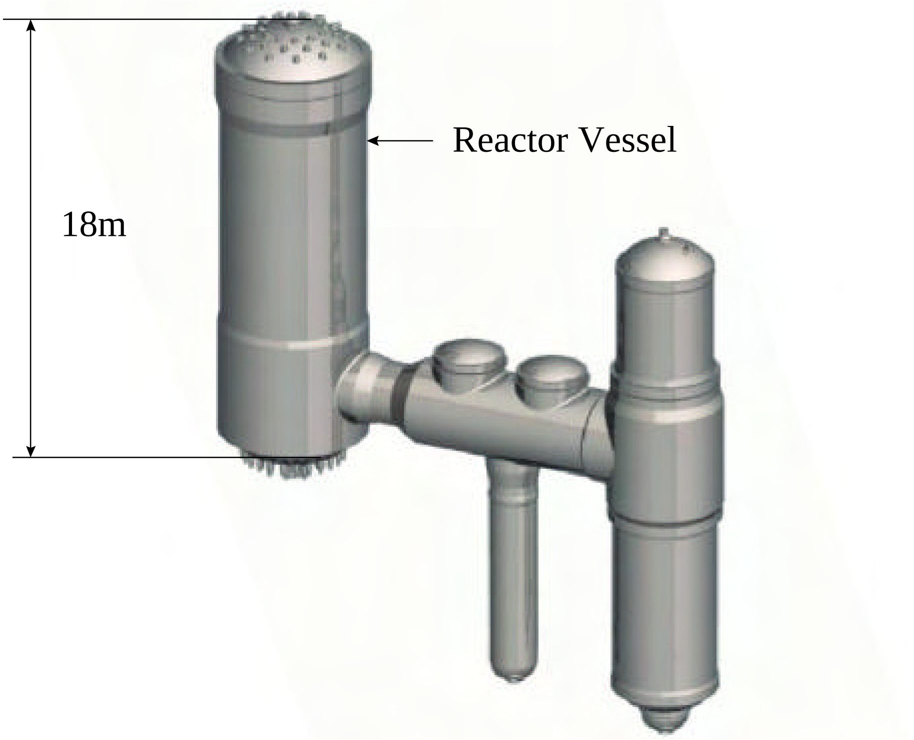


Figure 3. Gas circuit diagram.

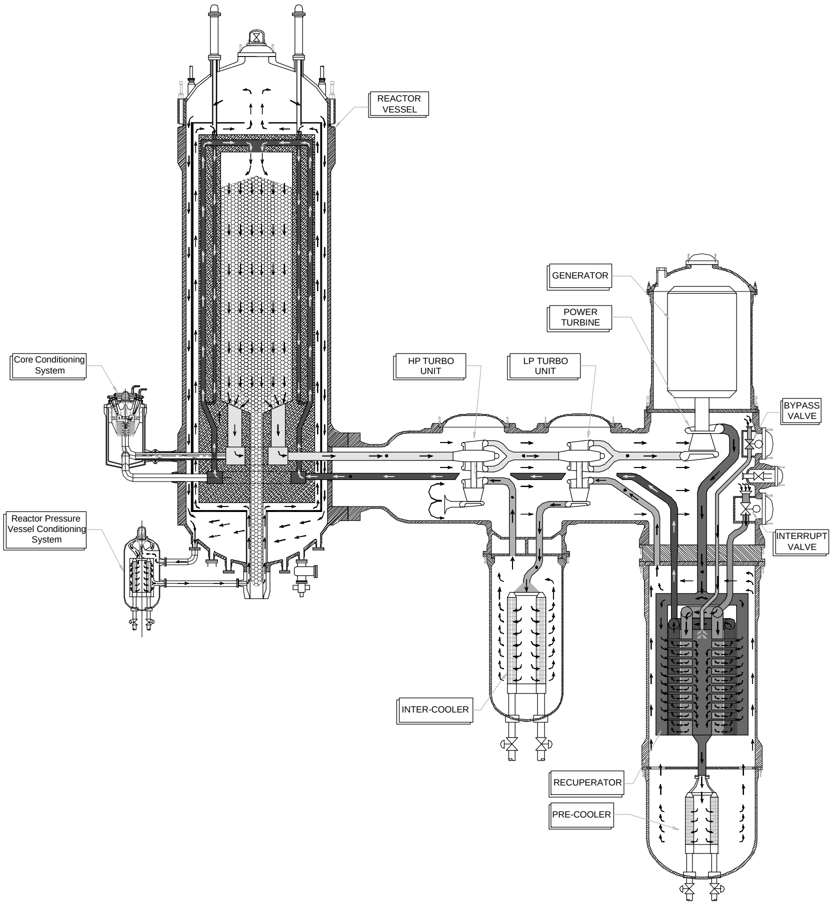
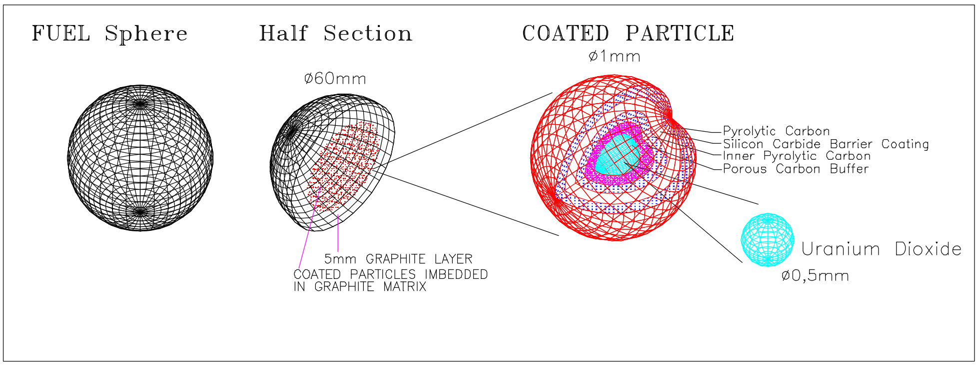


Figure 4. Construction of fuel particle.



Annex: The Cost of Electricity from the PBMR

John H Gittus

A detailed study has been made of all financial aspects influencing generating costs assuming a series built PBMR of 100 MWe capacity.

Derived fuel costs include German and US experience of the manufacturing cost of each pebble. A figure of US$9 for the cost of manufacturing a single pebble has in this way been computed. The base estimate of the generating costs are then as follows:

- fuel cost — 0.38 US cents/kWh,
- non-fuel cost — 1.06 US cents/kWh.

Even if the fabrication costs have been grossly underestimated by Eskom and turn out to be US$18 per pebble and not US$9 per pebble as was the case for the figures above, the cost of the fuel pebble is only increased by 20.8%. This raises the fuel cost including interest charges from 0.38 US cents/kWh to 0.436 US cents/kWh. As the non-fuel cost element is 1.06 US cents/kWh, with fuel at 0.436 US cents/kWh, the total generation cost rises to 1.06 + 0.436 =1.496 US cents/kWh.

Non-fuel costs include capital charges which have been comprehensively computed for a variety of likely discount rates and expressed in terms of net present value. If the capital cost of the plant is 10% in error, then at the worst the non-fuel cost per kWh will rise from 1.06 to 1.166 US cents/kWh. This with a worst-estimate of 0.436 cents/kWh for fuel would give a total generating cost of 1.166 + 0.436 = 1.602 US cents/kWh.

This is cheaper than electricity from new power stations relying on other sources of electricity in South Africa and in most other countries.

Figures A1, A2, A3 and A4 show the sensitivity of the cost of electricity to the price of uranium, the cost of disposing of spent fuel and other variables. Only in the case of the size of the reactor is there a significant effect on costs.

Figure A5 shows the relative cost of electricity from a PBMR, a PWR and a LMFBR, calculated on the same basis. The PBMR is the lowest cost option, and indeed it produces electricity more cheaply than coal or gas. The higher efficiency of the PBMR accounts, in part, for its lower costs, and this is illustrated in Figure A6.

Figure A1. Effect of plant size on electricity cost.

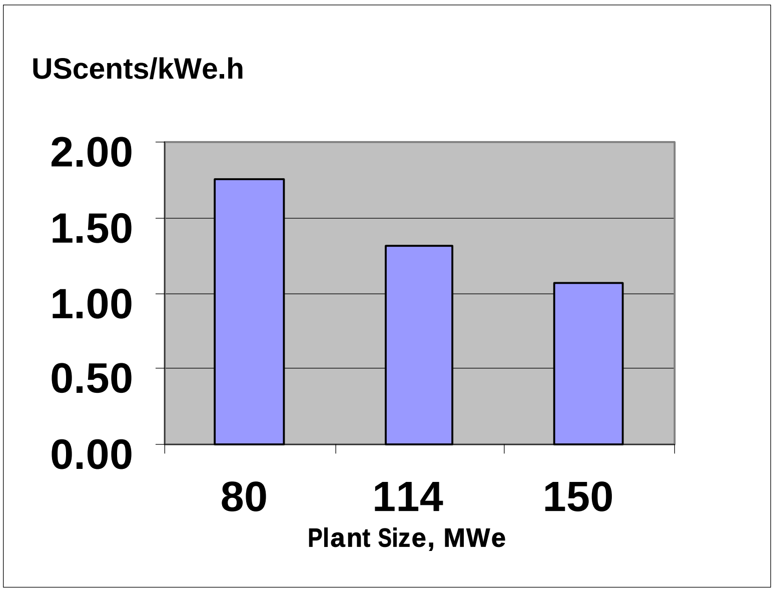


Figure A2. Effect of uranium price on electricity cost.

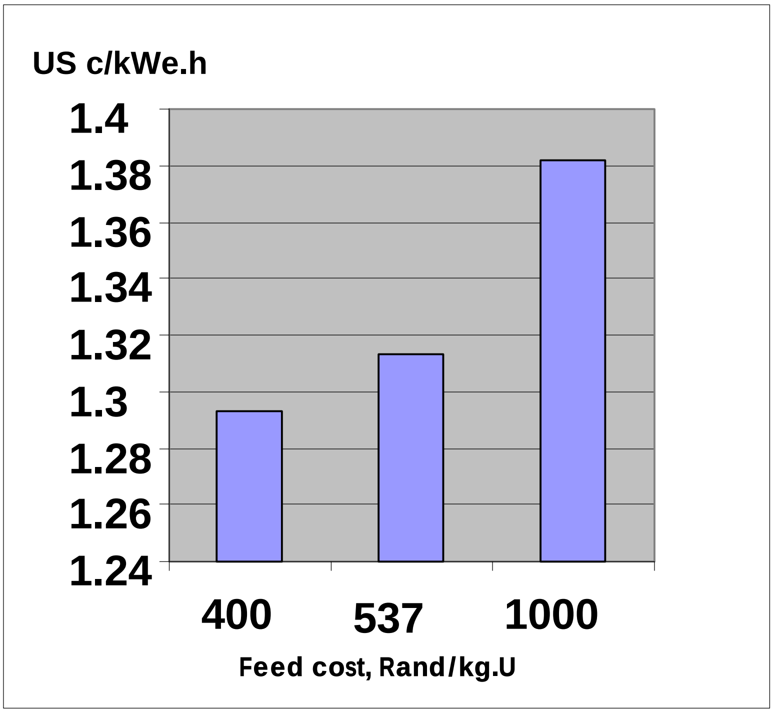


Figure A3. Effect of disposal cost on electricity cost.

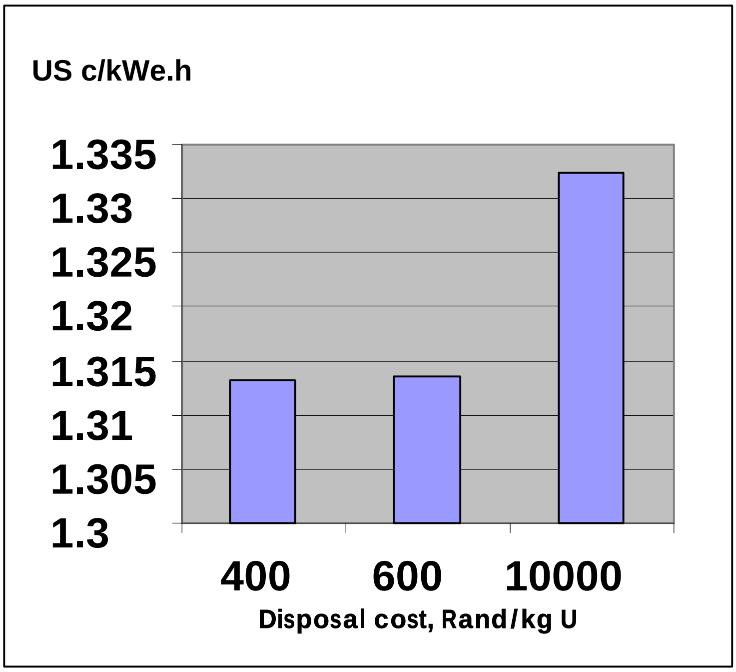


Figure A4. Effect of decontamination cost on electricity cost.

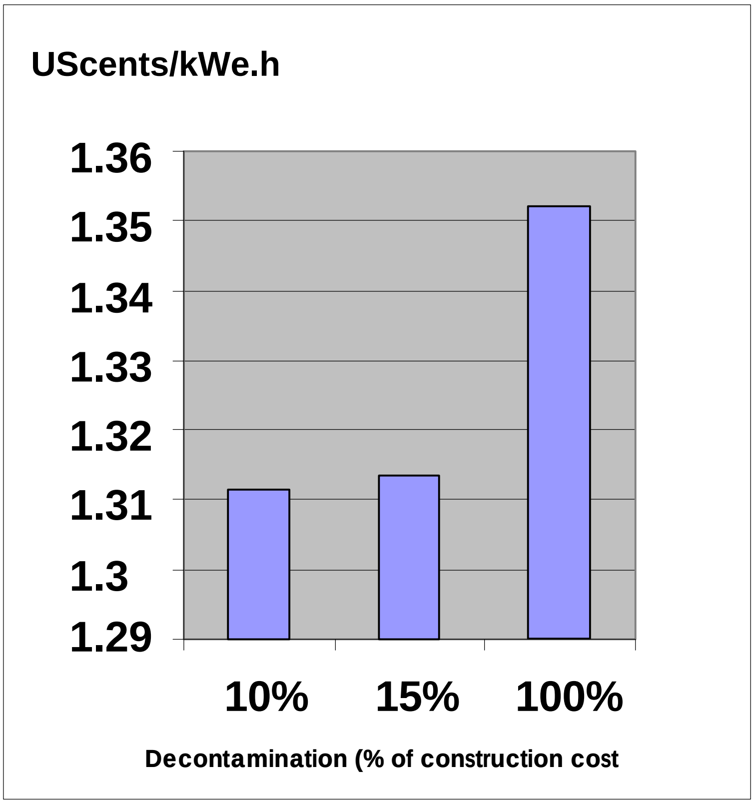


Figure A5. Relative cost of electricity from PBMR, PWR and LMFBR.

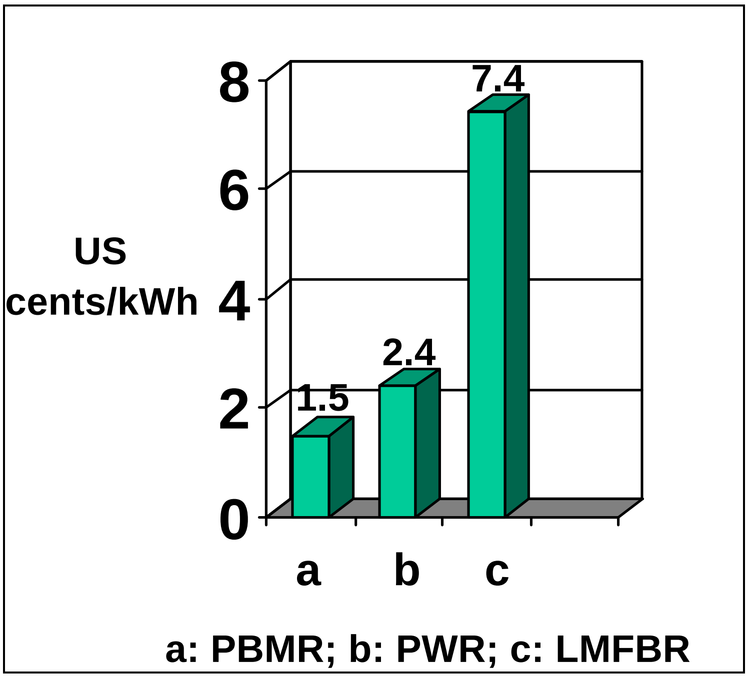


Figure A6. Efficiency of PWR, AGR and PBMR power stations.