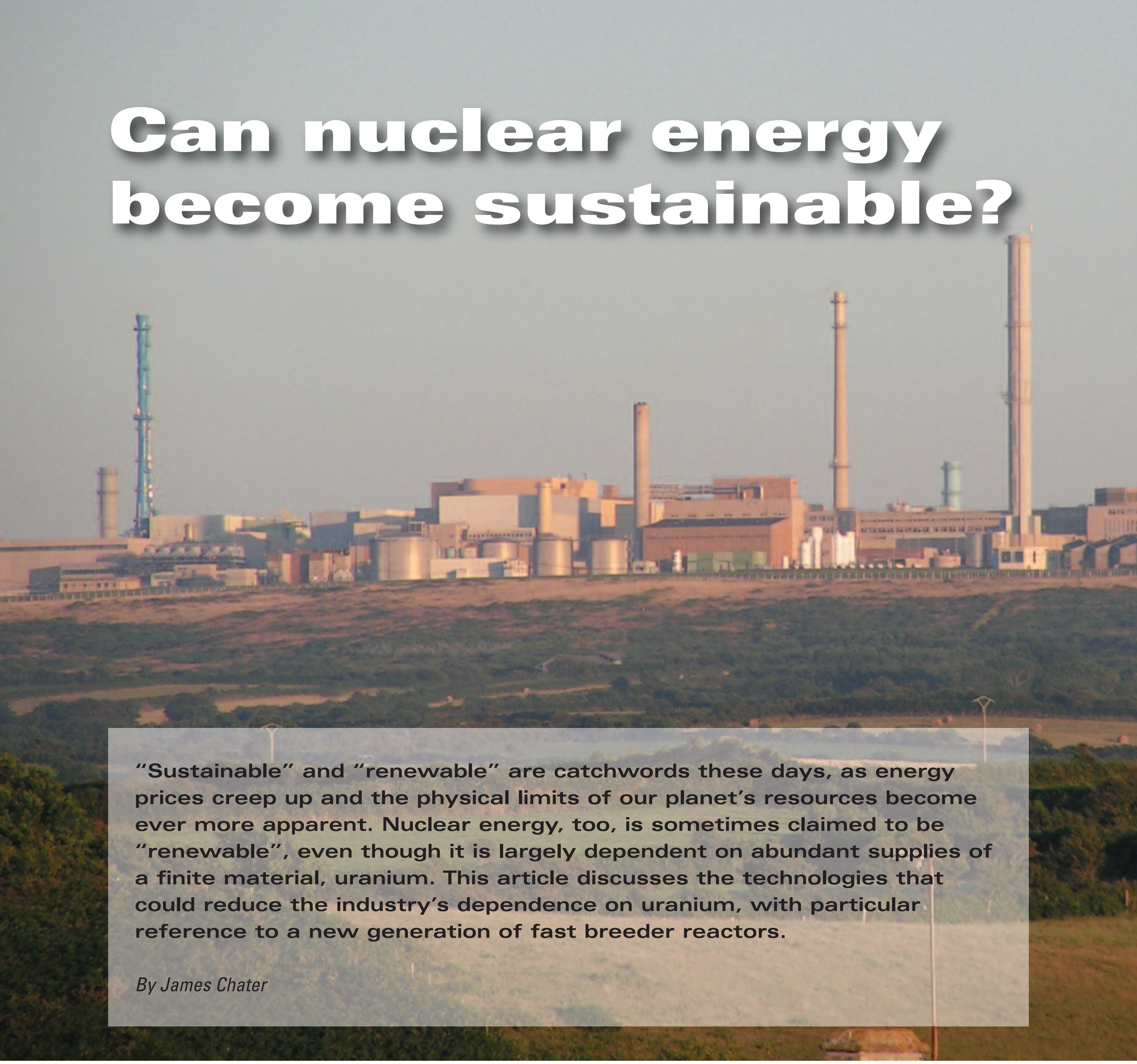
Can nuclear energy become sustainable?



"Sustainable" and "renewable" are catchwords these days, as energy prices creep up and the physical limits of our planet's resources become ever more apparent. Nuclear energy, too, is sometimes claimed to be "renewable", even though it is largely dependent on abundant supplies of a finite material, uranium. This article discusses the technologies that could reduce the industry's dependence on uranium, with particular reference to a new generation of fast breeder reactors.

By James Chater

Uranium prices

Oil prices have been much in the news recently. Through a combination of tight supply, increasing demand (especially from the booming Asian countries), perceived political risk and the bandwagon effect, the price of an oil barrel rose to nearly 150 USD a few months ago, before subsiding as a result of economic downturn and the unwinding of speculative positions.

What is less well known is that something similar has been happening to the price of uranium. Like oil and several metals, the price of uranium has soared then collapsed, and will in all probability stabilise at something near its current level (the spot price of U308 was USD/lb as of 29 September 2008), which is still higher than its recent historical level of below 20 USD/lb (see diagram). The rise in price was due to a number of factors, including mining accidents, floods, and above all increased demand as a direct result of the "nuclear renaissance", whereby in short succession several countries announced plans (or at least their intention) to build a new generation of reactors.

Supply concerns

As the uranium price ran up, warnings of possible shortages came from several quarters: on 21 March 2007 an MIT expert said that past under-investment may hamper the future growth of the nuclear industry[1]; similar warnings have come from elsewhere in the USA[2], Britain,[3] Russia[4] and especially India, where a shortage has threatened new capacity and reduced output of existing plants.[5]

Recently, however, the supply situation has eased somewhat: India has signed an agreement with the USA allowing it to import nuclear fuel, and the IAEA recently revised upwards its estimation of "identified conventional uranium resources", to 5.5 million tonnes compared to 4.7 million tonnes in 2005. The increase is credited to new discoveries in

Australia, Russia, South Africa and Ukraine, and an increase in E&D.[6]

However, there are no grounds for complacency. Estimates of how long uranium supplies will last vary wildly, but generally fail to take into account future anticipated growth in the number of reactors. In other words, there is plenty of uranium in the ground, but can it be extracted quickly enough to meet increasing demand – especially if all the countries that have announced their intention to develop a nuclear programme actually go ahead and do so?

Uranium is abundantly present in the earth's crust and in seawater, but the process of extracting it from its ore and refining it into uranium 235 (U235) for use in nuclear reactors is protracted, polluting and energy-intensive. In 2007, annual demand for uranium was expected to grow by an average of 3.8 per cent for the next 25 years, higher than the earlier forecast of 2.2 per cent growth.[7] In 2007 the IAEA revised its projections for growth in nuclear power upwards: it forecasts global nuclear power capacity of at least 447GW in 2030, compared to 370GW at the end of 2006. But the same report points out that in 2006 only 60 per cent of reactor requirements for uranium were met by production, the remainder coming from stockpiles.[8] In particular, the USA currently meets around half its uranium needs from Russian nuclear weapon stockpiles, an agreement dating from 1991 that will expire in 2013. Some countries with nuclear power programmes, such as Canada and China, have abundant supplies of uranium for the time being, while other countries, notably France (which has used up its indigenous uranium reserves), depend entirely on imports.

Thorium, a successor to uranium?

Discovered in Norway, the metal was named by Swedish chemist Jöns Jakob Berzelius in 1828 after Thor, the Norse god of thunder.

World reserves of thorium exceed those of uranium by a factor of about three. One third of these reserves are found in India, hence this country's interest in thorium-powered reactors.

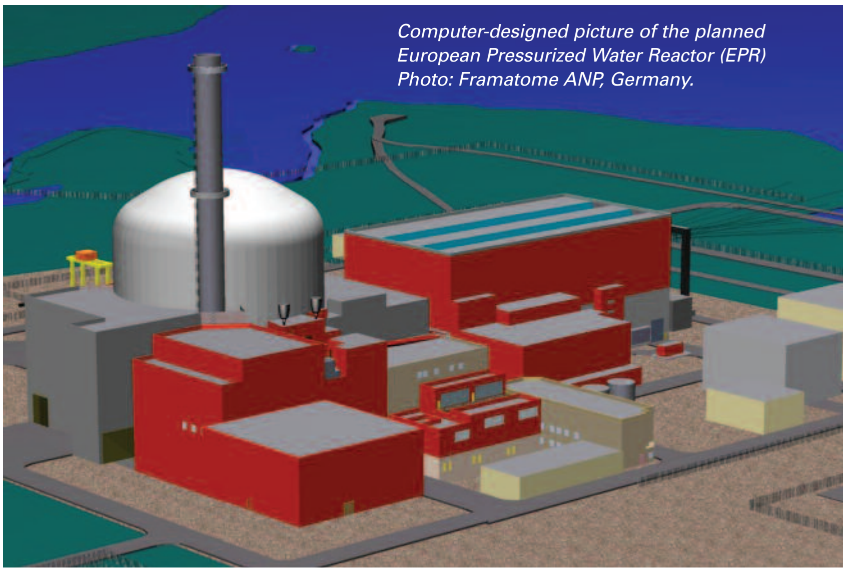
Among its many applications, thorium is used as a feedstock in breeder reactors. The thorium isotope Th232 absorbs a neutron of U233, plutonium or MOX to become U233.

Advantages:

- More abundant and produces less waste than uranium.
- More efficient: all thorium mined can be used in the nuclear process, compared to about 0.7 per cent uranium.

Disadvantages:

- Some risk of weapons proliferation, though less than in the case of uranium.
- High radioactivity during fabrication and recycling increases costs.
- Use of thorium as a fuel is still at the demonstration stage, so widespread commercial use is a long way off.



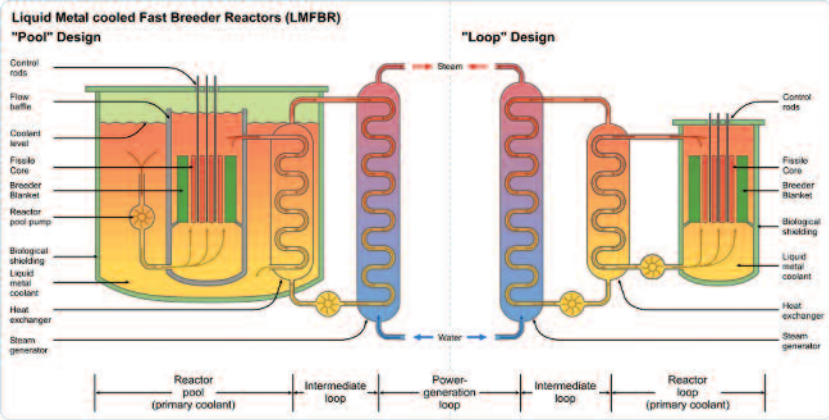
Computer-designed picture of the planned European Pressurized Water Reactor (EPR) Photo: Framatome ANP, Germany.

"Breeding" fuel

These supply constraints have not gone unnoticed by the nuclear industry, which is attempting to enhance the efficiency with which uranium is consumed and thereby lessen its dependence on ever-new supplies of uranium. The generation of reactors currently being built – the EPR, AP1000 and pebble bed reactor – are designed to achieve a higher burn-up, which means they can "breed" (see box) a higher percentage of the fuel than they consume – roughly 70-80 per cent, compared to 55 per cent for the current generation.[9]

An even more efficient breeding ratio can be achieved with breeder reactors. In this type of reactor new fissionable material is generated at a greater rate than it is consumed. The breeding rate so far achieved is 20 per cent more fuel produced than consumed, but designs exist that could increase this ratio to 40 or 80 per cent.[10]

The problem with conventional reactors is that they run on U235, an isotope that makes up less than 1 per cent of naturally occurring uranium, whereas most uranium comes in the form of U238, an isotope that cannot be used in conventional reactors as it is non-fissionable. Breeder reactors allow the exploitation of U238, which would otherwise go to waste. They are of two types, thermal breeder reactors or fast breeder reactors (FBRs). In thermal breeder reactors thorium (see insert) is added to uranium, plutonium or MOX, the output being U233, which is capable of much higher neutron capture than U235. In FBRs a fission reaction produces heat to drive the turbines while at the same time breeding plutonium fuel for the reactor. In the reactor core plutonium 239 (Pu239) undergoes spontaneous fission, releasing neutrons. These neutrons bombard a surrounding layer of U238, converting it into Pu239 that can then be used as fuel. In FBRs liquid sodium is the preferred heat transfer medium rather than water, which would slow down the neutrons too much. Three of the proposed generation IV reactor types are FBRs, the Gas-Cooled Fast Reactor (cooled by helium), the Sodium-Cooled Fast Reactor (SFR) and the Lead-Cooled Fast Reactor (LFR).



The "pool" and "loop" designs of a fast breeder reactor. In the loop design, all the components are contained in separate systems for ease of maintenance (as with PWRs). In the more compact pool design, all the primary reactor components are submerged in the reactor's sodium pool, so that less radiation is released. From upload.wikimedia.org/wikipedia/commons/8/85/LMFBR_schematics.pngDesigns.

Renewed interest in breeders

Breeder reactors have been around since the dawn of civil nuclear energy, but most of the early attempts have been discontinued because of a combination of political opposition, technical problems and high costs. The most ambitious projects were developed in France and Japan. France's Superphénix FBR was closed in 1997 after a fierce political campaign and huge financial losses. Japan's FBR at Monju was closed in 1995 after a sodium leak and fire but is expected to re-open in 2008. Recently, however, there has been a revival of interest, stimulated by concerns about the price and availability of uranium. This revival is being led by Asian countries.

After building a number of heavy water reactors using uranium, India is moving to a second phase in its nuclear programme, in which it will build FBRs using thorium 232 to breed fissile U233. Currently, a 500MW FBR is being built at Kalpakkam that is scheduled to go critical in September 2010. However, commercial application is a further decade down the road. The third phase of India's nuclear programme consists of the Advanced

Breeding

"Breeding" in nuclear reactors means the creation of a fissile material in such a way that more fissile material is produced than is consumed for the production of energy. During the fission process, high-energy (fast) neutrons are released. When these fast neutrons hit a "fertile" atom such as 238U, a new fissile material is created, in this case 239Pu.

The Superphénix fast breeder reactor at Creys-Malville, Isère, France. Photo: Yann Forget. After a fierce opposition campaign, the reactor was closed in 1997, purportedly because of "excessive costs".

Heavy Water Reactor, which will convert thorium into U233 with the fissile material gained from phases 1 and 2. A reactor of this kind has been in development at the Bhabha Atomic Research Centre in Mumbai since 2006. Other breeder reactors are planned. India has about 360,000 tonnes of thorium, enough to fuel nuclear projects for about 2,500 years. In China, the 25MW sodium-cooled, Chinese Experimental Fast Reactor (CEFR) is under construction, with first criticality scheduled for 2009 and grid connection for 2010. This is to be followed by the construction of a 600MW prototype fast reactor (CPFR) and a 1000-1500MW demonstration fast reactor (CDFR). Two other Asian countries interested in FBRs are Japan and South Korea. In April 2007 Mitsubishi Heavy Industries was selected to lead the development of a Japanese FBR industry, and shortly afterwards Mitsubishi FBR Systems (MFBR) was set up. A demo reactor is scheduled to be built by 2015, the KALIMER-600, a sodium-cooled fast reactor. In Russia, the BN-600 FBR at Beyolarsk, operational since 1980, will reach the end of its life in 2010. A second reactor, BN-800, is scheduled to be constructed before 2015. France is also planning to develop sodium- or gas-cooled fast reactors. The United Arab Emirates has just signed an agreement with Thorium Power Inc. to develop a nuclear programme.

Conclusion

Much work still needs to be done to make FBRs affordable, safe and commercially viable. This will take at least a decade, and most probably the efforts of India, China, Japan, South Korea, Russia and eventually France to develop a closed nuclear cycle will bear fruit in the Generation IV reactors that will be available for commercial use around 2030. This will come too late to avoid a uranium supply crunch in the near term, if not enough uranium can be made available to supply both the light water reactors that are currently operating and those that will come on-line in the near future. Perhaps the current economic slowdown will reduce the demand for energy in the short term, thus buying time for the industry to come up with solutions.

Focus on India's PFBR

Reactor name: Prototype Fast Breeder Reactor (PFBR).
Location: Indira Gandhi Centre for Atomic Research, Kalpakkam, Tamil Nadu, India.
Criticality date: September 2010.
Capacity: 500MW.
Technology: plutonium-uranium oxide fuel with liquid sodium coolant.
Components: safety vessel weighing 160 tonnes designed by Larsen & Toubro, made of austenitic stainless steel 316LN, to cover the main vessel.
Materials used: 316LN for hot leg components of reactor assembly except for the core (>673K); 304LN for cold leg components (<673K); alloy D9 20% cold-worked (modified from 316: 15Ni, 14Cr, 2 Mo, Si, Ti) for initial core cladding and wrapping, optimised to D9I; modified 9Cr-1Mo steel for steam generators. 2000 tonnes of SS 316LN and 304 LN plates were used in the steam supply system. For welding of 316LN and 304LN components, 16-8-2 filler wire for TIG welding and 18-12-2 electrodes for MMA welding were selected.[11]

Focus on Japan's MONJU

Reactor name: Prototype Power Reactor (MONJU).
Location: Tsuruga, Fukui Prefecture, Japan.
Criticality date: 1994.
Subsequent history: closed in 1995 following a serious sodium leak and fire. Expected to re-open in 2008.
Capacity: 280MW.
Technology: sodium-cooled, MOX-fuelled loop type reactor.
Materials used: 304 stainless steel (reactor vessel and internals, coolant systems); 2¼Cr-1Mo (steam generators).[12]

Focus on Japan's DFBR

Reactor name: Japanese Demonstration Fast Breeder Reactor (DFBR).
Location: unknown.
Constructed by: Mitsubishi FBR Systems.
Criticality date: around 2025.
Materials used: 316FR (fast reactor grade type 316 stainless steel, low-carbon, with more closely specified nitrogen content, modified to improve strength and creep resistance at high temperatures; for reactor vessel and internals); modified 9Cr-1Mo (for coolant systems). FBR-grade high-Cr steel (Nb, V, W, Mo) also to be developed for use in commercialized reactor around 2050.[13]

References

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13 See above, note 12.