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**The dream  
that failed**



## The dream that failed

**Nuclear power will not go away, but its role may never be more than marginal, says Oliver Morton**

THE LIGHTS ARE not going off all over Japan, but the nuclear power plants are. Of the 54 reactors in those plants, with a combined capacity of 47.5 gigawatts (GW, a thousand megawatts), only two are operating today. A good dozen are unlikely ever to reopen: six at Fukushima Dai-ichi, which suffered a calamitous triple meltdown after an earthquake and tsunami on March 11th 2011 (pictured above), and others either too close to those reactors or now considered to be at risk of similar disaster. The rest, bar two, have shut down for maintenance or “stress tests” since the Fukushima accident and not yet been cleared to start up again. It is quite possible that none of them will get that permission before the two still running shut for scheduled maintenance by the end of April.

Japan has been using nuclear power since the 1960s. In 2010 it got 30% of its electricity from nuclear plants. This spring it may well join the ranks of the 150 nations currently muddling through with all their atoms unsplit. If the shutdown happens, it will not be permanent; a good number of the reactors now closed are likely to be reopened. But it could still have symbolic importance. To do without something hitherto seen as a necessity opens the mind to new possibilities. Japan had previously expected its use of nuclear energy to increase somewhat. Now the share of nuclear power in Japan’s energy mix is more likely to shrink, and it could just vanish altogether.

In most places any foretaste of that newly plausible future will barely be noticed. Bullet trains will flash on; flat panels will continue to shine; toilet seats will still warm up; factories will hum as they hummed before. Almost everywhere, when people reach for the light switches in their homes, the lights will come on. But not quite everywhere. In Futaba, Namie and Naraha the lights will stay off, and no factories will hum: not for want of power but for want of people. The 100,000 or so people that once lived in those and other towns close to the Fukushima Dai-ichi nuclear power plant have been evacuated. Some 30,000 may never return.

The triple meltdown at Fukushima a year ago was the world’s

### CONTENTS

- 4 A brief history**  
From squash court to submarine
- 7 Safety**  
Blow-ups happen
- 9 Nuclear waste**  
Leave well alone
- 10 Costs**  
Bandwagons and busts
- 12 Prospects**  
Over the rainbow

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A list of sources is at  
[Economist.com/specialreports](http://Economist.com/specialreports)  
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► worst nuclear accident since the disaster at Chernobyl in the Ukraine in 1986. The damage extends far beyond a lost power station, a stricken operator (the Tokyo Electric Power Company, or Tepco) and an intense debate about the future of the nation's nuclear power plants. It goes beyond the trillions of yen that will be needed for a decade-long effort to decommission the reactors and remove their wrecked cores, if indeed that proves possible, and the even greater sums that may be required for decontamination (which one expert, Tatsuhiko Kodama of Tokyo University, thinks could cost as much as ¥50 trillion, or \$623 billion). It reaches deep into the lives of the displaced, and of those further afield who know they have been exposed to the fallout from the disaster. If it leads to a breakdown of the near-monopolies enjoyed by the country's power companies, it will strike at some of the strongest complicities within the business-and-bureaucracy establishment.

For parallels that do justice to the disaster, the Japanese find themselves reaching back to the second world war, otherwise seldom discussed: to the battle of Iwo Jima to describe the heroism of everyday workers abandoned by the officer class of company and government; to the imperial navy's ill-judged infatuation with battleships, being likened to the establishment's eagerness for ever more reactors; to the war as a whole as a measure of the sheer scale of the event. And, of course, to Hiroshima. Kiyoshi Kurokawa, an academic who is heading a commission investigating the disaster on behalf of the Japanese parliament, thinks that Fukushima has opened the way to a new scepticism about an ageing, dysfunctional status quo which could bring

about a "third opening" of Japan comparable to the Meiji restoration and the American occupation after 1945.

To the public at large, the history of nuclear power is mostly a history of accidents: Three Mile Island, the 1979 partial meltdown of a nuclear reactor in Pennsylvania caused by a faulty valve, which led to a small release of radioactivity and the temporary evacuation of the area; Chernobyl, the 1986 disaster in the Ukraine in which a chain reaction got out of control and a reactor blew up, spreading radioactive material far and wide; and now Fukushima. But the field has been shaped more by broad economic and strategic trends than sudden shocks.

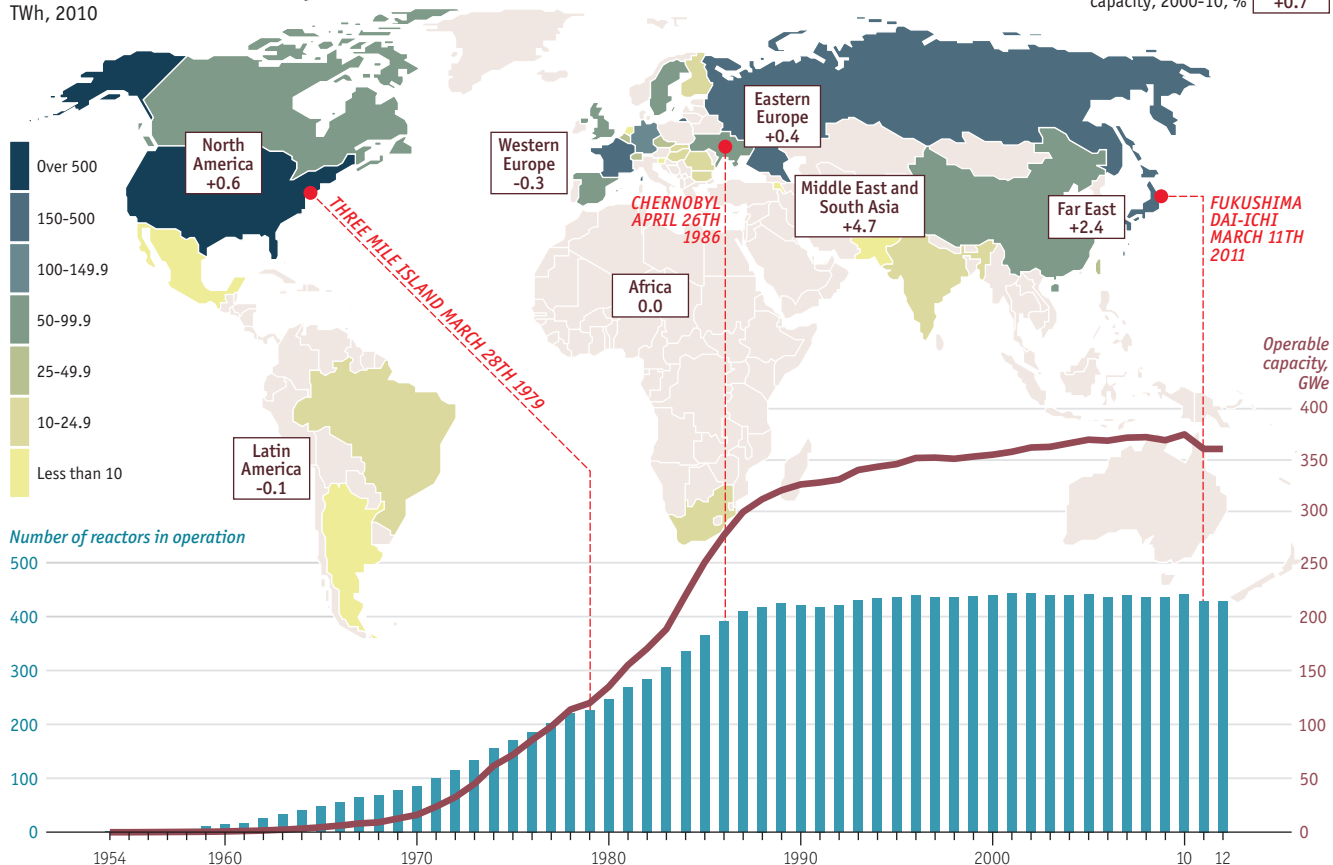
### The renaissance that wasn't

America's nuclear bubble burst not after the accident at Three Mile Island but five years before it. The French nuclear-power programme, the most ambitious by far of the 1980s, continued largely undisturbed after Chernobyl, though other countries did pull back. The West's "nuclear renaissance" much bruited over the past decade, in part as a response to climate change, fizzled out well before the roofs blew off Fukushima's first, third and fourth reactor buildings. Today's most dramatic nuclear expansion, in China, may be tempered by Fukushima, but it will not be halted.

For all that, Fukushima is a heavier blow than the previous two. Three Mile Island, disturbing as it was, released relatively little radioactivity and killed nobody. By causing nuclear safety to be tightened and buttressed with new institutions, it improved the industry's reliability and profitability in America. Chernobyl ►►

## Generation of nuclear power

TWh, 2010



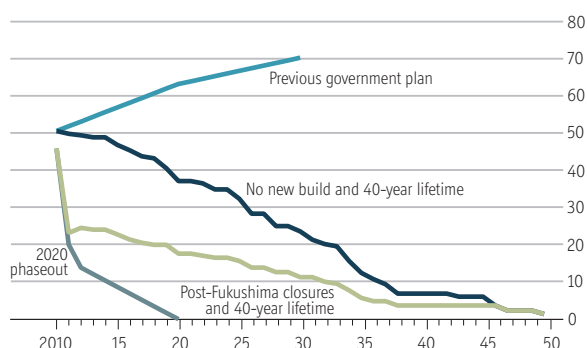
**Interactive:** Explore our guide to nuclear power around the world at [Economist.com/reactors2012](http://Economist.com/reactors2012)

Sources: "Nuclear Power in a Post-Fukushima World", Mycle Schneider et al; IAEA



**Decline and fall**

Scenarios for Japan's nuclear capacity, GW



Source: Institute for Sustainable Energy Policies, Tokyo

► was far worse, but it was caused by egregious operator error in a totalitarian regime incapable of the sort of transparency and accountability needed to ensure nuclear safety. It put paid to nuclear power in Italy and, for a while, Sweden, but in general it could be treated as an aberration of little direct relevance to the free world's nuclear programmes. Poor regulation, an insufficient safety culture and human error (without which the Japanese tsunami's effects might have been very different) are much more worrying when they strike in a technologically advanced democracy working with long-established reactor designs.

And if the blow is harder than the previous one, the recipient is less robust than it once was. In liberalised energy markets, building nuclear power plants is no longer a commercially feasible option: they are simply too expensive. Existing reactors can be run very profitably; their capacity can be upgraded and their lives extended. But forecast reductions in the capital costs of new reactors in America and Europe have failed to materialise and construction periods have lengthened. Nobody will now build one without some form of subsidy to finance it or a promise of a favourable deal for selling the electricity. And at the same time as the cost of new nuclear plants has become prohibitive in much of the world, worries about the dark side of nuclear power are resurgent, thanks to what is happening in Iran.

Nuclear proliferation has not gone as far or as fast as was feared in the 1960s. But it has proceeded, and it has done so hand in hand with nuclear power. There is only one state with nuclear weapons, Israel, that does not also have nuclear reactors to generate electricity. Only two non-European states with nuclear power stations, Japan and Mexico, have not at some point taken steps towards developing nuclear weapons, though most have pulled back before getting there.

If proliferation is one reason for treating the spread of nuclear power with caution, renewable energy is another. In 2010 the world's installed renewable electricity capacity outstripped its nuclear capacity for the first time. That does not mean that the world got as much energy from renewables as from nuclear; reactors run at up to 93% of their stated capacity whereas wind and solar tend to be closer to 20%. Renewables are intermittent and

take up a lot of space: generating a gigawatt of electricity with wind takes hundreds of square kilometres, whereas a nuclear reactor with the same capacity will fit into a large industrial building. That may limit the contribution renewables can ultimately make to energy supply. Unsubsidised renewables can currently displace fossil fuels only in special circumstances. But nuclear energy, which has received large subsidies in the past, has not displaced much in the way of fossil fuels either. And nuclear is getting more expensive whereas renewables are getting cheaper.

**Ultior motives**

Nuclear power is not going to disappear. Germany, which in 2011 produced 5% of the world's nuclear electricity, is abandoning it, as are some smaller countries. In Japan, and perhaps also in France, it looks likely to lose ground. But there will always be countries that find the technology attractive enough to make them willing to rearrange energy markets in its favour. If they have few indigenous energy resources, they may value, as Japan has done, the security offered by plants running on fuel that is cheap and easily stockpiled. Countries with existing nuclear capacity that do not share Germany's deep nuclear unease or its enthusiasm for renewables may choose to buy new reactors to replace old ones, as Britain is seeking to do, to help with carbon emissions. Countries committed to proliferation, or at least interested in keeping that option open, will invest in nuclear, as may countries that find themselves with cash to spare and a wish to join what still looks like a technological premier league.

*Barring major technological developments, nuclear power will continue to be a creature of politics not economics. This will limit the overall size of the industry*



Besides, nuclear plants are long-lived things. Today's reactors were mostly designed for a 40-year life, but many of them are being allowed to increase it to 60. New reactor designs aim for a span of 60 years that might be extended to 80. Given that it takes a decade or so to go from deciding to build a reactor to feeding the resulting electricity into a grid, reactors being planned now may still be working in the early 22nd century.

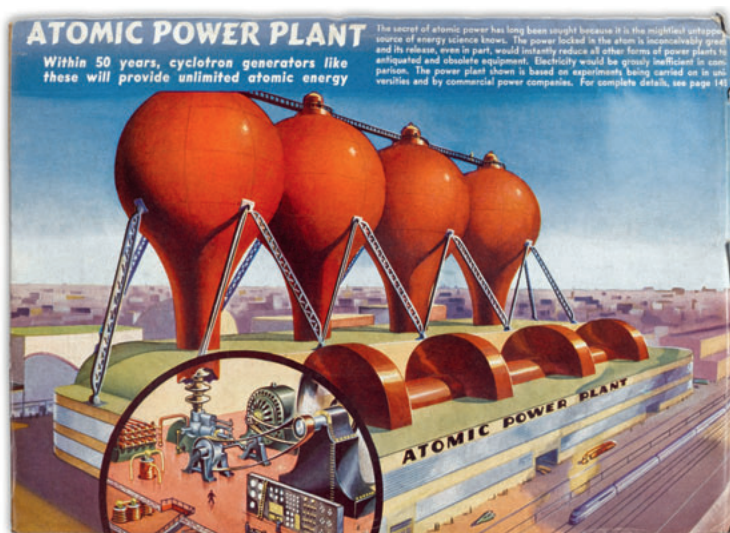
Barring major technological developments, though, nuclear power will continue to be a creature of politics not economics, with any growth a function of political will or a side-effect of protecting electrical utilities from open competition. This will limit the overall size of the industry. In 2010 nuclear power provided 13% of the world's electricity, down from 18% in 1996. A pre-Fukushima scenario from the International Energy Agency that allowed for a little more action on carbon dioxide than has yet been taken predicted a rise of about 70% in nuclear capacity between 2010 and 2035; since other generating capacity will be growing too, that would keep nuclear's 13% share roughly constant. A more guarded IEA scenario has rich countries building no new reactors other than those already under construction, other countries achieving only half their currently stated targets (which in nuclear matters are hardly ever met) and regulators being less generous in extending the life of existing plants. On that basis the installed capacity goes down a little, and the share of the electricity market drops to 7%.

Developing nuclear plants only at the behest of government will also make it harder for the industry to improve its safety culture. Where a government is convinced of the need for nuclear power, it may well be less likely to regulate it in the stringent, independent way the technology demands. Governments fa- ►►

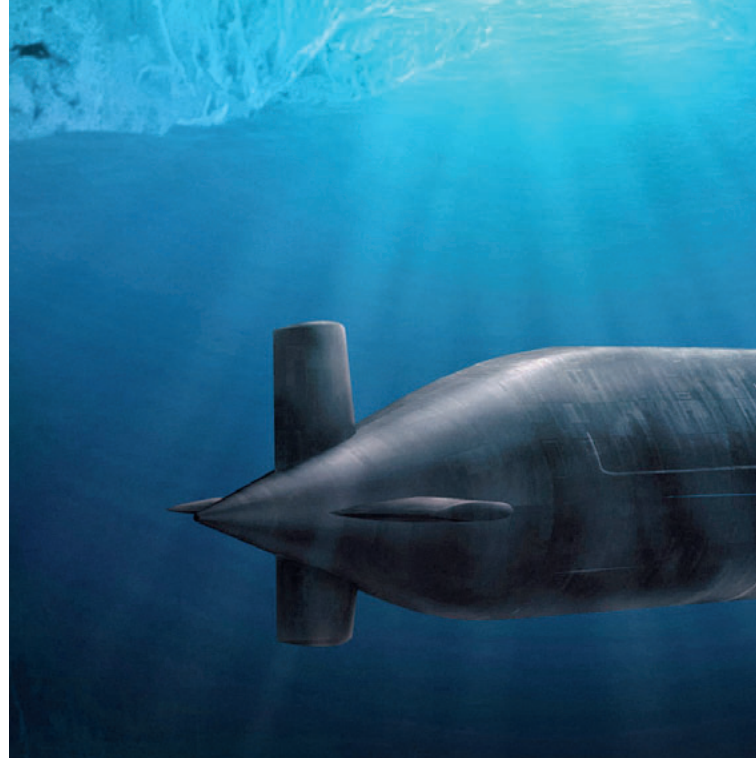
► your nuclear power by limiting the liability of its operators. If they did not, the industry would surely founder. But a different risk arises from the fact that governments can change their minds. Germany's plants are being shut down in response to an accident its industry had nothing to do with. Being hostage to distant events thus adds a hard-to-calculate systemic risk to nuclear development.

The ability to split atoms and extract energy from them was one of the more remarkable scientific achievements of the 20th century, widely seen as world-changing. Intuitively one might expect such a scientific wonder either to sweep all before it or be renounced, rather than end up in a modest niche, at best stable, at worst dwindling. But if nuclear power teaches one lesson, it is to doubt all stories of technological determinism. It is not the essential nature of a technology that matters but its capacity to fit into the social, political and economic conditions of the day. If a technology fits into the human world in a way that gives it ever more scope for growth it can succeed beyond the dreams of its pioneers. The diesel engines that power the world's shipping are an example; so are the artificial fertilisers that have allowed ever more people to be supplied by ever more productive farms, and the computers that make the world ever more hungry for yet more computing power.

There has been no such expansive setting for nuclear technologies. Their history has for the most part been one of concentration not expansion, of options being closed rather than opened. The history of nuclear weapons has been defined by avoiding their use and constraining the number of their possessors. Within countries they have concentrated power. As the American political commentator Gary Wills argues in his book, "Bomb Power", the increased strategic role of the American presidency since 1945 stems in significant part from the way that nuclear weapons have redefined the role and power of the "commander-in-chief" (a term previously applied only in the context of the armed forces, not the nation as a whole) who has his finger on the button. In the energy world, nuclear has found its place nourishing technophile establishments like the "nuclear village" of vendors, bureaucrats, regulators and utilities in Japan whose lack of transparency and accountability did much to pave the way for Fukushima and the distrust that has followed in its wake. These political settings govern and limit what nuclear power can achieve. ■



The way the future was



## A brief history

# From squash court to submarine

## Nuclear reactors and their uses have not changed much over seven decades

THE NUCLEAR AGE began 70 years ago on a squash court in Chicago, under the watchful eye of a man with an axe. A team led by Enrico Fermi, Italy's greatest physicist since Galileo, had been building a nuclear "pile" for weeks, slotting pellets of uranium and bricks of graphite into a carefully planned geometry through which ran various "control rods" of cadmium. The squash court was the only convenient large space available on the university campus. On December 2nd 1942 the pile had grown large enough to allow a nuclear reaction to take off when the control rods were drawn back from its heart.

The axeman was there in case the reaction went out of control. If it did he would chop through a rope, sending the main control rod crashing back into place, absorbing the neutrons driving the reaction and restoring stability. Like many of Fermi's ideas, it had the charm of simplicity. Today every commercial power reactor has control rods poised to shut it down at a moment's notice, a procedure called a scram—in honour, so it is said, of Chicago's "safety control rod axeman".

On that first occasion, nothing went wrong. As the pile's other control rods were mechanically withdrawn, radiation counters ticked up. Once Fermi was satisfied that they were showing a true chain reaction, he had the rods reinserted. A celebratory bottle of Chianti was opened. A coded phone call informed the head of the National Defence Research Committee that "the Italian navigator has landed in the new world." The axeman put down his axe.

The energy output of that first reactor was tiny: just half a watt. Today's most powerful reactors produce ten billion times as much energy in the form of heat, about a third of which can be converted into electricity. Five gigawatts is an amount beyond easy comprehension, the daily equivalent of the energy given ►►





done. It blossomed fast, then held strangely steady.

Using reactors to generate electricity was not an early priority. The reactors of the Manhattan Project—the wartime nuclear programme begun in earnest shortly after Fermi’s success—were designed to further the project’s only goal: making bombs. A nuclear chain reaction, whether in a reactor or an exploding bomb, comes about when the splitting of a “fissile” nucleus by a neutron produces neutrons that will go on to split further fissile nuclei. The fissile nuclei in Fermi’s reactor were of a particular type or “isotope” of uranium, U-235. In natural uranium, only seven nuclei in every 1,000 are of this fissile sort. That was not a problem for Fermi’s reactor. The addition of graphite—a “moderator”—slowed down the neutrons that were being given off, which made them better at splitting other nuclei and enabled a chain reaction to take place even when fissile nuclei were scarce. Bombs are not the place for moderation: to make a uranium bomb you need a core that is almost entirely U-235. As separating out U-235 is extremely difficult, the Manhattan Project’s physicists were not sure they could provide it on the scale that bomb-makers would require.

That created a need for an alternative source of fissile material, and reactors provided it. When a neutron hits one of the non-fissile uranium nuclei—the vast majority—it can turn it into a new element: plutonium. Plutonium nuclei are fissile, and getting a bit of plutonium out of uranium that has been sitting in a reactor is far easier than separating uranium isotopes. Reactors could thus serve as plutonium factories, and the early ones were used exclusively for that purpose. By the mid-1950s some reactors in Britain and France were generating electricity as well; they needed to be cooled anyway, and using the gas that cooled them to drive steam turbines was good public relations. But their main purpose was still to provide fuel for bombs.

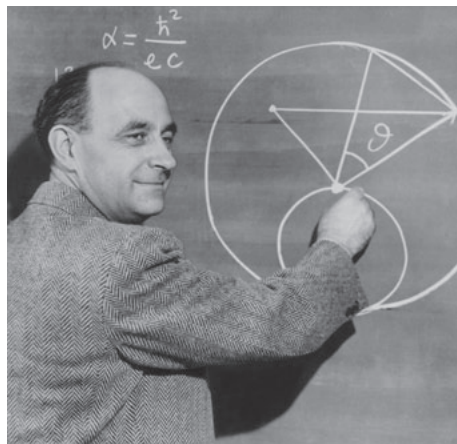
### Rickover’s killer app

Almost all of today’s nuclear power plants have a different lineage. Hyman Rickover, a redoubtable American submariner, saw a niche for nuclear power plants in submarines. The diesel-powered sort needed to take on air through a snorkel; nuclear-powered ones would be able to stay submerged indefinitely. But a graphite-moderated reactor would never be compact enough for submarines. Rickover eventually settled on a reactor design that economised on space by using water as both moderator and coolant—a pressurised water reactor, or PWR. In many ways this is a poor compromise. Water cannot be heated much above 350°C, even under pressure, and still stay liquid. That limits the

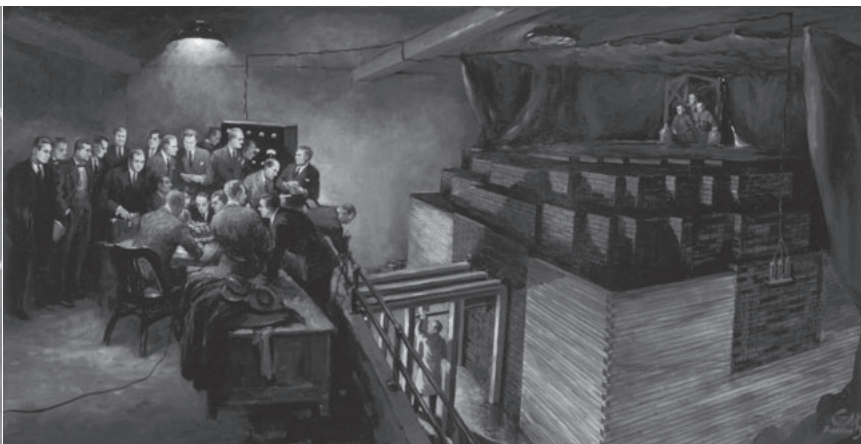
off by six bombs like the one that destroyed Hiroshima. Imagine that energy coursing through a few swimming pools-worth of water at three times the normal boiling point, trapped in a steel cylinder under pressures found a mile below the sea, and you have a sense of the hellish miracle that is a modern reactor.

If flights had lasted a billion times longer 70 years after the Wright brothers’ first one took off, they would have gone a thousand times round the world and taken centuries; a billion times faster, and they would have run up against the speed of light. Even at the heady rates of progress that Moore’s law ascribes to the computer industry (stating that the number of transistors on a chip doubles roughly every two years), things take 60 years to get a billion times better.

But such comparisons flatter nuclear technology. The Wright brothers wanted their first aircraft to fly as far and as fast as it could; the first reactor was designed to do things in as small and safe a way as possible. At the time Fermi demonstrated the first controlled chain reaction, the uncontrolled ones that would devastate Hiroshima and Nagasaki were already being planned. Reactors capable of generating hundreds of megawatts of heat were on his colleagues’ drawing boards. Nuclear power did not grow steadily over decades the way aircraft and computers have



Fermi and his nuclear family



► efficiency of energy conversion (the hotter the better in such matters). And normal water is not a very good moderator. So-called “heavy water”, which contains a different hydrogen isotope, is better, but a lot harder to come by than the “light” type.

To make up for poor moderation, a light-water reactor needs fuel enriched in U-235. It does not have to be enriched as much as uranium for bomb-making does, but the enrichment systems used to make fuel for such reactors can almost as easily be used to make the weapons-grade uranium that bomb-makers need. This is the technological basis of the stand-off with Iran, which has claimed unconvincingly that its enrichment facilities are just for reactor fuel. Other combinations of fuel and moderator would have allowed the use of non-enriched uranium, and could indeed have got by without producing plutonium as a waste product, thus establishing a much clearer dividing line between nuclear power and nuclear weapons. But they would not have powered the submarines of the 1960s.

In the early 1950s nuclear physicists were for the most part unexcited by the light-water reactor’s potential. By the time the nuclear age was just ten years old they already knew of many kinds of fuel, various moderators (as well as designs that needed no moderation) and many ways of getting heat out of reactors. They were excited by “breeder” reactors that both burned and created plutonium. America’s first was built in 1951, and the assumption was that any nuclear-energy economy worth the name would make use of the technology’s miraculous ability to produce its



### *Developing a nuclear reactor has never been a matter for barnstorming experimentation*

own fuel. The fascination continued for decades. Breeder reactors have been built in Russia, Britain, Germany, India, China, France and Japan as well as America. But they have not proved remotely attractive enough for commercial development in a world which seemed to have plenty of uranium.

By 1952 bomb-makers had also massively multiplied the power of their wares by adding nuclear fusion, in which energy is liberated by adding together small nuclei rather than splitting apart large ones. Schemes to make reactors on the same principle sprang up immediately. Sixty years on, this line of research continues, at great expense, without any prospect of commercial plausibility.

#### **Make mine a PWR**

The navy did not need exciting ideas; it needed submarine power plants that used available technologies. In Rickover it had an organisational genius capable of creating the industrial base needed to provide them, choosing and training the naval engineers needed to operate them, and instilling in that cadre the meticulous safety culture needed to stop the reactors from going haywire. Under Rickover’s tutelage American industry learned



**Admirable admiral**

to make PWRs, which it went on to offer to electrical utilities. So PWRs became the mainstay of America’s nuclear-power industry as it grew up in the 1960s, with the boiling-water reactor (BWR)—a similar light-water design, less efficient and unseaworthy but in some ways simpler and possibly safer—providing an alternative. BWRs currently make up 21% of the world’s nuclear capacity, but that figure is set to diminish, not so much because the Fukushima reactors were of that kind (old PWRs in a similar setting would not necessarily have fared better) but because the few countries that ever went for the technology on any scale have little appetite for new plants (America) or none at all (Germany and Japan). The 68% of the world’s nuclear electricity from

PWRs is thus set to increase, with other technologies trailing way behind.

Such homogeneity in a 70-year-old high-technology enterprise is remarkable. Seven decades after the Wright brothers’ first flight there were warplanes that could travel at three times the speed

of sound, rockets that could send men to the moon, airliner fleets that carried hundreds of thousands of passengers a day, helicopters that could land on top of skyscrapers. Include unmanned spacecraft, and there really were flights a billion times as long as the Wright brothers’ first and lasting for years. But aircraft were capable of diversity and evolution and could be developed cheaply by small teams of engineers. It is estimated that during the 1920s and 1930s some 100,000 types of aircraft were tried out.

Developing a nuclear reactor, on the other hand, has never been a matter for barnstorming experimentation, partly because of the risks and partly because of the links to the technologies of the bomb. And whereas there are lots of things you can do with aircraft, more or less the only practical things you can do with a reactor are to make plutonium for bombs, power submarines, produce isotopes used in medicine and generate heat and electricity. Only the last is big business, and it can easily be done by other means. So options have been closed down and eggs have been piled into single baskets. The world went with pretty much the first sort of reactor it saw deployed at scale, contenting itself with increasing its size and trying, over the years, to render it ever less in need of the attentions of the axeman. ■



## Safety

## Blow-ups happen

## Nuclear plants can be kept safe only by constantly worrying about their dangers

FOR THE SURFERS offshore the wall will be almost invisible, hidden behind the existing sand dunes and pine trees. From the land it will tower 10-12 metres above the Hamaoka nuclear power plant's perimeter road. It will be 1.6 kilometres long and two metres thick; its foundations will be deeper than the wall itself is tall. It will weigh the best part of 1m tonnes. This is what Japan's Chubu Electric Power thinks it will take to stop a tsunami a touch bigger than the one that hit Fukushima, which is slightly farther from Tokyo to the north-east than Hamaoka is to the south-west. Chubu expects to have the wall finished by the end of this year. Until then Hamaoka's three reactors—two of them similar to those at Fukushima—remain shut down.

At Fukushima the 14-metre tsunami easily topped the inadequate defences. It flooded all but one of the plant's back-up diesel generators and trashed the pumps meant to dump the reactors' waste heat into the sea. The plant's reactors had been scrambled 40 minutes before the wave hit, but although shutting down a reactor's chain reaction lowers its heat output by about 97% almost instantaneously, the other 3% takes some time to drop to negligible levels, and that still amounts to a lot of heat. With no electricity either from the grid or from diesel generators to pump the heat away, all that was available were back-up systems powered by steam from the reactors themselves.

In part because of human error, they failed. The fuel in the reactors' cores got hot enough to melt. The cladding on the fuel rods reacted with steam to produce hydrogen. Systems that should have flushed the potentially explosive hydrogen out of the containment vessels around the reactors also failed, so the gas started to accumulate in the buildings housing the reactors. One after the other, three of the buildings blew up, releasing ra-

dioactive material and contaminating an area that in some directions went well beyond the 20-kilometre evacuation zone.

The reactors at Fukushima were of an old design. The risks they faced had not been well analysed. The operating company was poorly regulated and did not know what was going on. The operators made mistakes. The representatives of the safety inspectorate fled. Some of the equipment failed. The establishment repeatedly played down the risks and suppressed information about the movement of the radioactive plume, so some people were evacuated from more lightly to more heavily contaminated places.

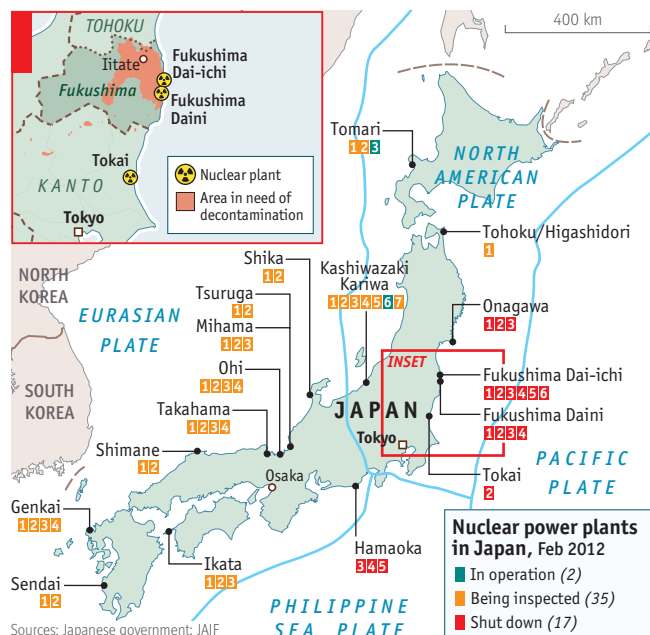
The outcome could quite easily have been even worse. Fukushima had a lot of used fuel in spent-fuel ponds, which keep it cool and absorb its radiation. The explosion in building 4, which had no fuel in its reactor but whose spent-fuel pool was full, led some to believe that the water in the pool had drained away and the spent fuel was melting, though in fact the explosion seems to have been caused by hydrogen from building 3. A worst-case analysis by Japan's Atomic Energy Commission, not published at the time, suggested that if the hot fuel was indeed left high and dry, people as far away as parts of Tokyo would need to be evacuated and everyone in the capital would have to stay indoors. And there are a number of big cities—London, New York, Hong Kong, Los Angeles—that are closer to ageing nuclear plants than Tokyo is to Fukushima.

## Just in case

The governing principle of nuclear safety is "defence in depth". Seek first to prevent failure, then to correct failures not prevented, then to control the consequences of failure, then to deal with emergencies beyond normal control. The mighty wall at Hamaoka provides a good example. It should, in itself, protect the plant from the worst that the sea can throw at it. But if the wall should fail, new pumps installed in watertight buildings will make sure the plant can still dump heat in the sea. The three reactor units are being reinforced to keep the sea from ever reaching the locomotive-sized diesel generators on their ground floors. More diesel generators are mounted on the roofs, well above any conceivable tsunami; on the bluff behind the reactor buildings there is a gas turbine to provide further back-up, not to mention a fleet of small trucks with their own little pumps, ready to go where they are needed.

This is not the first revamping of Hamaoka. The plant sits on top of the Nankai Trough, where two tectonic plates grind together. This action can produce powerful earthquakes such as that of March 11th last year or the one that caused the Boxing Day tsunami in 2004. In the past decade Chubu has revamped the Hamaoka plant to make sure that it could ride out a big earthquake, reinforcing various parts of the plant and closing the two oldest reactors. On paper, at least, there is no plant in the world more earthquake-proof than Hamaoka.

There are, though, plants with greater claims to a safe design overall. Two of the reactors at Hamaoka, commissioned in 1987 and 1993, are what is known as "generation II" designs, dating from the period after the industry settled on certain standards in the late 1960s but before Chernobyl. The third, switched on in 1999, is one of Toshiba's Advanced Boiling Water Reactors, the first of the post-Chernobyl "generation III" designs. Modelling based on experience with previous plants suggests that the risk of a significant radiation leak from generation I reactors was between one in 1,000 and one in 10,000 per reactor year. For generation II it is between one in 10,000 and one in 1m. For generation III it should be between one in 1m and one in 100m. These calculations do not reflect the absolute risks as experienced in the real world; there have been five major releases of radioactiv-







**Hamaoka defended in depth**

ity (Three Mile Island, Chernobyl and the three reactors at Fukushima) in only 14,000 reactor years of operation. But the trend towards safety seems to be real.

Two generation III designs thought to be particularly advanced are currently under construction. The AP1000 from Westinghouse (now owned by Toshiba) is being built in China and America, and the EPR from Areva, a French company resulting from a merger between French and German nuclear-plant-builders, in China, Finland and France. The EPR is the biggest plant ever designed and has safety systems galore, which means more pipes, more wiring, more concrete and higher capital costs. The AP1000 aims instead for simplicity, with fewer valves, pumps and wires and a greater reliance on “passive” safety systems that use basic physics to provide emergency cooling and other safety functions. A French insider, unwilling to be named, considers the AP1000 to be a far more creative piece of engineering. The Union of Concerned Scientists, an American ginger group critical of most real-world nuclear programmes (though not of the technology per se), prefers the safety concept of the EPR, with its multiple back-ups.

Proponents of generation III reactors, which is to say pretty much the entire nuclear establishment, think—with some reason—that they would have fared much better at Fukushima. Indeed some feel that the circumstances at Fukushima—a freakishly large wave, an old set of reactors with insufficient safety equipment and a poor operator, poorly regulated—limit its relevance elsewhere. Those operating reactors with lower risks of flooding or earthquake, better emergency cooling systems and

*When the reactor was opened for maintenance in 2002, it was discovered that boric acid had eaten a head-sized hole pretty much all the way through its top*

more robust power supplies might see themselves as having little to learn from it.

Philippe Jamet, of France’s nuclear regulator, the ASN, insists on a broader view; that Fukushima demonstrates a shortfall in imagination, not just in Japanese regulators but also in people like himself. “If you had asked me a year ago about an accident in which multiple units were left without power and cooling,” he says, “I would have said it was not credible.” The ASN has introduced new requirements for nuclear plants based on the Fukushima accident that go beyond safeguards against earth-

quakes and flooding. A report from America’s Nuclear Regulatory Commission reflects similar concerns. As well as suggesting new rules, it calls for a new coherence in the regulatory “patchwork” that has grown up to deal with highly unlikely events.

### **Never be satisfied**

The need to keep questioning things—from the details of maintenance procedures to one’s sense of the worst that could go wrong—is at the heart of a successful safety culture. Mr Jamet gives the example of a worker noticing that a diesel generator has been switched off. It is not enough to switch it back on. You also have to ask how and why it got switched off, and what other consequences that may

have had. When you have got to the root of it, you not only have to change procedure but also to make sure that all other similar plants know about the problem and how to solve it.

It was to help with this kind of effort that, after Three Mile Island, the American nuclear industry set up its Institute of Nuclear Power Operations. INPO, headquartered in Atlanta, regularly inspects power plants, using its own staff as well as engineers from other operators, and offers lessons learned from mistakes throughout the industry so that all plants benefit from what happens at any one of them. INPO brings fresh eyes and high standards, and its reports can be scathing. Phil Sharp, a former congressman who now heads a think-tank,

Resources for the Future, and sits on the board of a power company, Duke Energy, says that INPO meetings at which the bosses of nuclear operating companies are called to account for their plants’ failings in front of their peers are unlike anything he knows of in the private sector.

But despite the attentions of the NRC and INPO, things can still go wrong at American plants. In the late 1990s Davis-Besse, a nuclear plant in Ohio, had less downtime than almost any other plant in America. Various signs of incipient trouble—air filters clogging up too frequently, borate salts of unusual consistency and rusty colour building up—were not fully investigated. When the reactor was opened for maintenance in 2002, it was discovered that boric acid had eaten a head-sized hole pretty much all the way through the top of the reactor vessel. Only a thin layer of stainless steel was holding things together. As the plant’s operator, FirstEnergy, later reported, “there was a focus on production, established by management, combined with taking minimum actions to meet regulatory requirements, that resulted in the acceptance of degraded conditions.” Disaster was only narrowly avoided.

George Felgate, a veteran of Rickover’s nuclear navy who spent almost three decades at INPO before joining the World Association of Nuclear Operators, points to a seeming paradox at the heart of nuclear safety: if, having made every provision for safety, you think for a minute that an accident is not possible, you put yourself at risk of being proved disastrously wrong. This ►►



- stress on constant vigilance means that nuclear safety can never be a technological given, only an operational achievement.

In many places, and particularly in Japan, the industry has felt a need to tell the public that nuclear power is safe in some absolute way. This belief is clearly no longer sustainable. The only plausible replacement is to move from saying “it is safe” to saying “trust us to make it as safe as it can be,” and accepting that in some situations and some communities that trust will not always be given.

Japan’s government is trying to restore the trust its people are now unwilling to give. It is moving nuclear regulation from the industry ministry, where civil servants were devoted to building up the industry, to the environment ministry. But the response to Fukushima has, so far, been inadequate. Many ques-

tion marks remain. One of the more worrying is how much damage the earthquake did to the reactors. It is claimed that they weathered the quake, but some experts, such as Masashi Goto, a retired nuclear engineer, argue that there is evidence of significant damage that speeded up the subsequent meltdown. Analysis of the spread of fallout suggests that the first releases came very soon after the tsunami hit, if not before. With quakes a more constant threat than monster tsunamis, these are the sort of lessons that Japan’s “nuclear village” needs to learn.

If the Japanese nuclear establishment—industry and regulators alike—wants to earn trust, it must be seen to be learning every lesson it can. It must admit how little it previously deserved trust and explain clearly how it will do better in future. Even then, such trust will not always be given. ►►

## Leave well alone

The best thing to do with nuclear waste is to stash it away, not reprocess it

OF ALL THE difficulties nuclear power is heir to, that of waste has most fired the public imagination. Building power plants that last a century is one thing; creating waste that will be dangerous for 100 times as long is another. For decades America has failed to create a long-term repository for the waste from its civilian reactors at its chosen site, Yucca Mountain in Nevada. Most other countries have similarly failed, so the waste from today’s reactors piles up.

As it happens, long-term waste disposal is among the more tractable nuclear problems. Temporary storage is a good start. Once fuel has cooled down in spent-fuel pools for a while, it can be moved to “dry cask” storage. Such storage appears robust (dry casks at Fukushima, hit by the tsunami, show no sign of having leaked) and can be maintained indefinitely. It takes space and needs to be guarded, but it can provide an adequate solution for a century or more.

That is if you do not want to reprocess the fuel to recover the plutonium inside it. If you are a nuclear engineer you may find reprocessing rather appealing, partly to show that your nuclear programme is as sophisticated as any and partly because it gets around the offensive inefficiency of light-water reactors. If all the uranium in reactor fuel was either split or turned into plutonium which itself was then split, you would get 170 times more energy than you get from just using the fuel once, and would have opened the way to technically intriguing breeder systems.

You will not, though, be attracted to reprocessing if you are an accountant. It costs a great deal, and the plutonium produced is for the most part more of a liability than an asset. If you are a plant operator you will also have your doubts. Burning fuel to which plutonium has been added has various



In a cavern, in a canyon

drawbacks, one of which is that it is much hotter when it comes out of the reactor, straining the capacity of your spent-fuel pools. Nor will you be that eager if you are concerned about the local environment; reprocessing plants have a bad contamination record. And if you are sceptical about the merits of nuclear proliferation, you will want to keep reprocessing to a minimum.

Having avoided reprocessing, in the long term you will want to find a safe deep underground repository for the waste in your dry casks. This need not be too hard. Find a community that may be willing to take on the challenge (one that already has ties to the nuclear industry might be thus predisposed) and that has access to a suitable

geological setting. Then have an open discussion of the issues, look at people’s concerns and offer ways to lessen them while recompensing the community for its trouble. Set up arrangements by which local people can reassure themselves about any threats to their health, perhaps with free medical treatment and tests. Don’t scrimp on investment in the community. Then let them choose. The chances are that they will say yes. This kind of approach seems to be working in Sweden and Finland, and Britain is trying something similar.

This is more or less the opposite of what was done at Yucca Mountain. What some now refer to as the Screw Nevada act of 1987 imposed the choice of site and schedule. Nevada politicians objected. Geological surveys threw up some problems. Nevada’s caucuses moved up the electoral calendar, meaning that presidential candidates were greatly helped by an anti-Yucca stance. Moreover, the state’s senior senator, Harry Reid, became Senate majority leader. President Obama drew a line under the episode by finally abandoning the project in 2010, 12 years after the facility was meant to have entered service.

But as well as providing a textbook example of how not to handle long-term storage, America also boasts a success. The Waste Isolation Pilot Plant in the salt caverns of Carlsbad, New Mexico, started taking shipments of waste from the country’s military programme in 1999. Throughout the life of the project the local community has been consulted and, on occasion, recompensed. WIPP is not entirely trouble-free, but it has achieved enough social and political stability to make the best of its geological gifts.



That is why Hamaoka, for all the tsunami protection and earthquake-proofing it has undertaken, is unlikely to reopen. It is too close to Tokyo, and too close to the expected epicentre of a very big earthquake that might happen one day, for people ever to think it truly safe. Oddly, this may be the world's only nuclear power station that could benefit from a quake. Only if the big one comes and goes, and Hamaoka rides it out unscathed, might it be able to build some trust.

Meanwhile, its engineers are trying to work out why, when the plant was being shut down last summer, a pipe in a heat exchanger in the most advanced of the reactors burst in a peculiar way, damaging other plumbing so that a few tonnes of seawater got into the reactor proper. The damage it may have done has yet to be assessed. It was something that nobody had expected. ■

### Costs

## Bandwagons and busts

### Nuclear plants are getting ever more expensive. But Asian countries may build them more cheaply

IN HAIYANG, ON the northern Chinese coast, and at Sanmen, farther south, an international consortium led by Westinghouse is well into building two AP1000s, with two more in the works; China plans eventually to have 12 split between the two sites. If the plans go ahead, each site will have as much capacity connected to the grid as the whole of Nigeria has today. Yet the two plants represent only a small fraction of China's nuclear ambitions. Its pre-Fukushima plans to increase its nuclear capacity from 10GW to 80GW by 2020 may fall behind schedule, but China still looks certain to build more new nuclear plants than any other country over the decade to come—and possibly more than all others combined.

By nuclear standards, this is a big deal; China will add more nuclear capacity in those ten years than France has in total. But for China itself it is less big; nuclear will go from generating less than 2% of the country's electricity to less than 5%. Ming Sung, who works for the Clean Air Task Force, an American think-tank in Beijing, points out that China is not betting on nuclear; it is betting on everything that offers an alternative to coal. China consumes half the world's annual coal output, and has the supply problems, dirty air and huge death toll (hundreds of thousands a year from respiratory diseases) that go with it. Junda Lin of the China Greentech Initiative points out that the 2020 target for nuclear has to be seen in the context of a 200GW target for wind and an extra 100GW of hydropower. The idea is to try everything and see what works best.

Most of the plants China is currently building are generation IIs derived from a French design it bought in the 1980s and now built by Chinese companies, but there are also Russian PWRs in Tianwan and Canadian Candus in Qinshan. In Taishan two EPRs are being built by Areva and the China Guangdong Nuclear Group, which has a long-standing relationship with the French industrial base from which its domestic designs ultimately derive. And then there are the AP1000s. Westinghouse won that contract in large part by promising to transfer the technology in full to local companies, but it hopes that its expertise will allow it to keep a prominent role in the Chinese industry.

After Fukushima the state council stopped approving new power stations and called for re-evaluations of the seismic and

flooding risks faced by those already built and under construction. A new law expected later this year will take nuclear regulation away from the National Development and Reform Commission, the state's industrial planners, and hand it over to the environment ministry, thus splitting the role of cheerleading from that of invigilation. Part of what passes for the Chinese government's legitimacy comes from the perception that it can manage large-scale technology well. The backlash against China's high-speed train programme after last year's accident at Wenzhou, which provoked criticism and anger of a sort that Chinese leaders fear, would be dwarfed by what could be expected from a nuclear accident.

A sincerely self-interested desire to avoid accidents, though, will not necessarily translate into a model regulatory infrastructure. A safety culture of constant questioning will not be easy to instil. And China's nuclear regulatory workforce is already more stretched than that of other big economies in terms of employees per gigawatt under regulation.

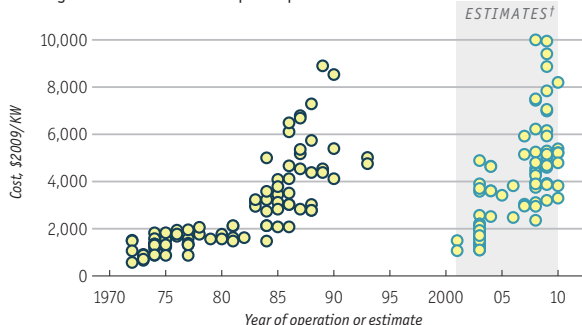
### Beside the seaside

Another new law will outline future plans for the industry. Some expect China's nuclear boom to slow down in the wake of Fukushima, with new capacity perhaps reaching only 40GW by 2020. And China could get proportionally more AP1000s and fewer of its own home-made designs, the safety of which may be less assured. All China's current plants are by the sea, both because it is convenient for cooling and because that is where the demand is. There have been plans for nuclear plants inland, cooled by rivers, but concerns about the availability of water in drier years to come and the risk of contaminating it may cause these plans to be shelved.

China's expansion into nuclear power is hardly a market-driven development, but it helps that the plants involved look comparatively cheap. There are two ways of measuring the cost of a nuclear power plant: the "overnight" cost, which counts up the material and labour that goes into a new plant as if it had all been purchased simultaneously, and the "levelled" cost, which is a measure of the total amount of energy a plant provides over its life divided by the total expenditure—construction, operation, maintenance, fuel and, eventually, decommissioning. One is the cost of the capacity to produce electricity, the other the cost of the electricity produced. The 2010 edition of the IEA/NEA Costs of Generating Electricity study puts overnight costs for Chinese generation II plants at \$1,700 for every kilowatt of capacity, giving a gigawatt plant a price tag of less than \$2 billion. For the AP1000s the estimated costs are higher (\$2,300/kw), and by the

### Exploding

Overnight costs\* of US nuclear power plants



Source: "The Economics of Nuclear Reactors: Renaissance or Relapse?", Mark Cooper (updated)

\*Construction cost if all material and labour were purchased simultaneously. †By a range of analysts, utilities and academics

► time the projects are finished they may be higher still; these are the first AP1000s being built anywhere, so its wise to expect surprises. Schedules are being stretched, and the Chinese contractors for key parts of the third and fourth AP1000s are falling behind a bit, according to Westinghouse.

Still, almost anywhere else in the world, these figures would today be a source of envy—or incredulity. When companies were beginning to pitch generation III reactors ten years ago, they claimed that better, standardised designs and improved construction techniques would make them both safer and cheaper. In Western countries that second claim has gone by the board. British studies in 2004, 2006 and 2008 put the overnight cost of new PWRs at \$2,233/kw, then \$2,644, then \$3,000. Estimates from the Massachusetts Institute of Technology (MIT) rose from \$2,208/kw to \$4,000 over roughly the same time. The NEA quotes costs for an EPR in Belgium (now cancelled) at \$5,400 per kw. Capacity fired by gas turbines, for comparison, can cost less than a fifth of that.

Real construction costs, which include the cost of borrowing the money needed, are even higher than overnight costs. Construction costs for the two AP1000s that Progress Energy has planned for its Levy site in Florida have recently been reported at about \$20 billion, which works out at about \$9,000 per kw and strongly suggests that the reactors will not be built.

Cost escalation has been the rule throughout the industry's history. In the late 1960s what is now called the "great bandwagon market" took off in America. Companies selling plants they had no real experience of building offered fixed prices to make them attractive. Utilities keen to reduce their reliance on coal in an age of clean-air standards took the bait. As orders flooded in, costs started to climb. Projects meant to be completed in years dragged on for more than a decade, in part because of new environmental concerns, in part because designs were revised as lessons were learned. At the Vogtle plant, in Georgia, a pair of reactors originally priced at \$660m in 1971 came in at \$8.87 billion 16 years later. Half the projects ended up cancelled.

The French experience is often quoted as a positive counter-history to the American mess. France had long been keen on energy security. When it made PWRs based on a Westinghouse design a national priority in the early 1970s, it brought a thorough-minded discipline to the matter, building its capacity region by region, improving the designs as it went along and increasing the size of its plants to reap economies of scale. Having the same contractor and customer for so many plants allowed the system to learn from mistakes and to refit older plants to newer standards. Even so, according to calculations by Arnulf Grübler of IASA, a think-tank near Vienna, each of the six designs France has fielded has cost more per kilowatt than the previous one had. He estimates that the four reactors built in the 1990s cost between \$2,267 and \$3,252/kw in 2010 dollars, more than twice the real cost of capacity built in the 1970s and early 1980s. The first two EPRs to be built in Europe, in France and Finland, have both gone extravagantly over schedule and budget.

A decade ago the nuclear industry hoped that the combina-

tion of safe, low-cost generation III reactors and governments eager to encourage lower carbon-dioxide emissions would lead to a "nuclear renaissance". In the West those low costs have failed to materialise, so the renaissance is largely stalled. Whereas a few years ago Britain was talking of building eight new reactors to replace its ageing fleet, only two are likely to make it in the near term. Steve Thomas, an economist at the University of Greenwich, argues that even with a fixed carbon price of €36/tonne and a guaranteed price for the electricity (both features of a currently planned re-regulation of Britain's energy market; today's EU carbon price is under €10), those plans remain vulnerable.

In a capital-intensive industry such as the nuclear one, the



A clear argument for nuclear power

cost of capital is always crucial, and higher overnight costs magnify the problem. Calculations of the levelled costs of energy by UBS, a bank, show clearly that the cost of capital dominates the picture. For a plant costing \$5,500 per kw, capital makes up 75% of total costs in Europe and America. UBS reckons the levelled cost of such a plant in Europe is 11% higher than the cost of a gas plant. It would take a quintupling of the carbon price to wipe out that differential. And those calculations assume that it is as easy to borrow to finance a nuclear plant, with all its uncertainties and regulatory risk, as it is to finance a gas plant, which is probably unrealistic.

### Step on the gas

In eastern Europe, where Russian dominance of gas markets is a political issue and electricity markets are still quite regulated, governments may consider such a differential acceptable. The Czech Republic is about to tender for new generation III PWRs, and Poland has plans along those lines too. But in America things look very different. Asked if Fukushima put America's nuclear renaissance on ice, Ernest Moniz of MIT replies succinctly: "No. Shale gas did." For all the production incentives, loan guarantees and indemnity for costs due to regulatory change offered by government, the sharp drop in gas prices caused by new ►►



► sources of supply ruled out new nuclear plants in any market where the two energy sources compete freely. According to UBS, the advantage of gas over nuclear in America is roughly twice what it is in Europe.

John Rowe, CEO of Exelon, an energy company that has ten nuclear power plants in its portfolio, says that companies like his no longer have any reason to build nuclear plants. All plans to build nuclear plants in parts of America where the electricity market has been deregulated are coming to naught. Some American plants will still be built, but only in the south-east, where regulators allow the cost of increasing a utility's asset base to be passed on directly—indeed pre-emptively—to its captive customers. Thus electricity consumers in Georgia are already paying for two new AP1000s which in February got clearance from the NRC to complement the two reactors at Vogtle. In Sumner, South Carolina, two more AP1000s are under contract. Those four will probably be all the renaissance America sees for some time.

If the West could build new reactors as cheaply as China can, things would look different. That it cannot is in part due to labour costs. But the Chinese must have other advantages too. The levelled costs of modern Chinese coal-fired power stations are lower than the competition's even when the power stations are not built in China. The same is true for cement works; Chinese companies operating outside China cannot build them as cheaply as they do at home, but they still easily beat the international competition.

Further evidence that a different industrial approach can cut costs comes from South Korea. Like Japan, the country has little by way of indigenous energy supplies, and it too decided on nuclear power to solve that problem and bring new technological skills to its industrial base. It gets some 30% of its electricity from nuclear plants, much the same as Japan did before Fukushima, and more than any large economy other than France. In 2010 KEPCO, the South Korean power company, sold its reactors overseas for the first time, beating the French to a contract in the United Arab Emirates; at home its overnight costs for such generation II reactors are calculated at just over \$1,500/kw.

The true costs in South Korean business can be hard to make out. It would not be at all surprising if, working abroad for the first time and having been keenly competitive in its bidding, KEPCO failed to deliver the UAE reactors on budget. And given that nuclear prices have gone up everywhere else, it is fair to expect that they will do so to some extent in Asia, too. But if China and South Korea can build reactors abroad at prices not much higher than those at home, nuclear may see its fortunes tick up elsewhere, argues David Victor, of the University of California. Both Westinghouse and EDF have plans for new reactors in the export market that would be designed and sold in collaboration with Chinese partners. Russia is keen to export PWRs too, but its costs are not clear.

Inviting the Chinese to come in and build a nuclear plant is an unlikely step for a Western government (though the South Koreans are bidding on a Finnish contract). Some developing countries, though, may be interested. This is a matter of concern for backers of the American nuclear industry with an eye to national security issues, such as Pete Domenici, a former senator. If America is not engaged in the market, how can it use its influence to deter proliferation?

And it will indeed have less scope for such influence. But even at Chinese prices, nuclear energy is expensive compared with coal, and if other countries gain easier access to gas, as America did, that will reduce demand too. Vietnam is enthusiastic about nuclear reactors; other Asian countries, especially those in tectonically active places—such as the Philippines and Indonesia—may be less keen than they were before the great tsu-

nami. South Africa is talking of buying nuclear reactors. India has big plans on paper, but a law that makes the designers (rather than the operators) of power stations liable in case of accidents gets in the way (and buying Chinese reactors might be anathema anyway). There is interest in the Middle East, but as Charles Ebinger of the Brookings Institution, a think-tank, points out, the countries talking about buying nuclear power in response to runaway electricity demand might do better to curb their handsome consumer subsidies. They might also do well to invest in alternative energy. The sun's nuclear reactor has been going for 4.5 billion years, and extracting power from it is getting cheaper every year. ■

## The prospects

# Over the rainbow

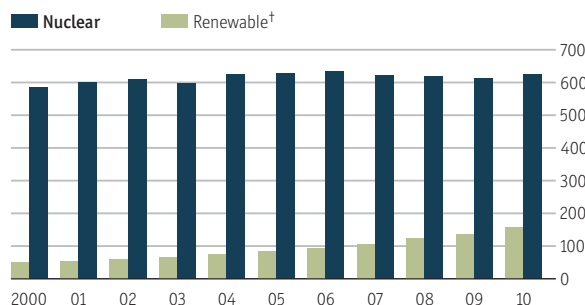
## If there are better ways to split atoms, they will be a long time coming

"THERE IS ONLY one reason for America to subsidise nuclear," says Ernest Moniz, of MIT, "and that is the climate." He has a point. By 2020, carbon emissions since the start of the 21st century will have surpassed those of the entire 20th. There is a real risk that emissions on such a scale will bring disaster to humans, or to the natural world, or both. Nuclear power, which produces no direct carbon-dioxide emissions, should be able to make things better.

Robert Socolow, of Princeton University, and his colleagues calculate that if the world were to replace 700GW of coal-fired plant with nuclear reactors over 50 years—which would more or less triple its current nuclear capacity—it could reduce its annual emissions of carbon dioxide by 3.7 billion tonnes. Allowing for the need to replace most of the current fleet over the same period, that would mean deploying nuclear reactors at three times the speed of China's planned record-breaking deployment between now and 2020, and doing it for five decades straight. But even that would make only a minor dent in the problem. In 2010 the amount of carbon dioxide emitted by industry was about 30 billion tonnes, and was growing at 3% a year. At that rate, the savings from such a beefed-up nuclear-power programme would compensate for just four years of emissions growth. ►►

## Spot the potential

World energy consumption\*, million tonnes of oil equivalent



\*Based on gross generation and not accounting for cross-border electricity supply.

†Converted on the basis of thermal equivalence assuming 38% conversion efficiency in a modern thermal power station.

Source: BP Statistical Review of World Energy, 2011

†Wind, geothermal, solar, biomass and waste

▶ No technology can solve the climate problem on its own. Even in combination, today's remedies—renewables, nuclear and energy efficiency—hardly seem up to the job. To have a reasonable chance of keeping down the rise in temperature to less than 2°C, industrial economies need to reduce emissions by 80% by 2050. The true scale of this challenge is not widely understood. A thorough study of options for such cuts in California, long a leader in energy efficiency, concluded that with today's technology and plausible extrapolations of it, 60% was the best that could be done. If California can't do better than that, says Jane Long, of Lawrence Livermore National Laboratory, who led the study, "neither can anyone else".

Even getting close to such goals, though, is easier with more technologies than fewer. Even if nuclear can make only a small contribution, it could be worth having. The IEA's 2011 World Energy Outlook calculates that, between now and 2035, an emissions path that keeps the 2°C limit plausible would cost \$1.5 trillion more if OECD countries were to stop building nuclear plants and other countries halved their nuclear ambition, largely because much more would have to be spent on renewables.

Germany, long keen on renewables and squeamish about nuclear, provides an example. Its decision after Fukushima to phase out nuclear power entirely will mean that most of the lost capacity will need to be made up with even more renewables, though it will also build new fossil-fuel plants and import electricity from nuclear plants in France. As the new fossil-fuel plants will probably run on gas, emitting less carbon dioxide than do coal plants which are also due for retirement, this may keep the carbon in check. But electricity prices for industrial customers, according to an analysis by UBS, will rise by more than 60% in real terms by 2020. Ottmar Edenhofer of Berlin's Technical University says this is a pretty middle-of-the-road projection.

The market, too, will probably need some re-engineering. Systems with a lot of renewables make life hard for fossil-fuel generators, which have to shut down when it is sunny and windy and take up the slack when it is not. To get the fossil-fuel investment it needs, Germany may well have to pay for the capacity built even if it stands idle, or guarantee rates of return.

## *In a low-emissions world, the role for nuclear will be limited to whatever level of electricity demand remains when renewables are deployed as far as possible*

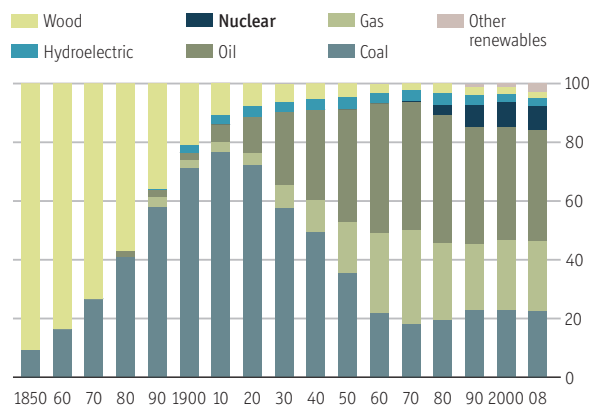
But though renewables are expensive, so is building new nuclear plants; the bills Britain will face as it tries to meet carbon goals with new nuclear should keep any *Schadenfreude* in check. The cheap new supply-side route to lower carbon-dioxide emissions is to replace old coal-fired stations with new gas-fired ones, which emit half as much carbon dioxide per megawatt hour. Plumping for renewables or nuclear will cost a lot more.

Still, renewables are getting cheaper, through technological change and through the benefits of mass production and market competition. In the long run, technologies that get cheaper can be expected to edge out a technology that has only ever got more expensive. In a low-emissions world, the role for nuclear will be limited to whatever level of electricity demand remains when renewables are deployed as far as possible.

That is a large enough role for some Greens to have become nuclear converts. For the most part, though, they are thinking about a nuclear programme more exciting than the slow, expensive and only marginally helpful deployment of PWRs. There

### Long waves

US energy supply, %



Sources: "From Energy Innovation to Energy Transformation", Steven Koonin and Avi Gopstein; EIA

are many alternative reactor designs, and each has its champions. An international body called the Generation IV International Forum (GIF), co-ordinated by the NEA, is drawing up plans for prototypes using such ideas, all claiming to offer improvements over the current crop.

Yet the problems these new reactors solve are for the most part those that the industry wishes it had, rather than those it actually faces. The GIF designs, and others, are mostly "fast" reactors that use highly fissile fuel and unmoderated neutrons; they can both burn plutonium and create it in copious amounts. If fissile material were in short supply that might be an advantage. But uranium is not currently in short supply, and it makes up only a small part of nuclear energy's costs. The ability to make new nuclear fuel solves a problem that reactors will run into only if their use becomes massively more widespread. What new reactors need is an advantage that will make them popular in the first place.

Indeed, at present the ability to make plutonium is a disadvantage. Detering countries with nuclear programmes, or that want nuclear programmes, from reprocessing their fuel to produce plutonium is one of the core priorities in anti-proliferation work (the other is trying to keep newly nuclear countries from developing their own enrichment systems). If established nuclear powers were to stop reprocessing (as Britain is doing), it might help to persuade others, such as South Korea, that it is better not to start. A new generation of plutonium breeders would completely undermine that effort.

Admittedly, other kinds of breeders are available. Molten-salt reactors, which keep their fuel in liquid form, could be used to turn thorium, of which the world has an abundant supply, into a type of fissile uranium not found in nature, U-233. This would be rather unsuitable for bomb-making and gets round the continuing use of U-235 or plutonium, so thorium molten-salt reactors offer the possibility of breeding fuel in a way that does not facilitate proliferation.

Like some of the other GIF designs, molten-salt reactors also have novel safety features; but although safety is a condition of getting into the game, it is hardly a means of winning it. If generation III reactors, well operated, prove safe, why upgrade? If they are not safe, who would trust generation IV? The way to ▶▶



► win will be on price.

At the moment, those who want to bring down the cost of nuclear power are not, for the most part, looking at big generation IV reactors that will not be built for 20 years, if ever. Instead, they are thinking small. Particularly in America, small modular reactors (SMRs) of up to 300MW are all the rage. Some, such as the 100MW mPower reactor offered by Babcock and Wilcox, are scaled-down PWRs. Others are more exotic.

### Think small

Such reactors can reach markets which today's big reactors cannot. Many utilities—and smaller countries—have little interest in gigawatt-scale plants: they prefer to build around 100MW of capacity at a time. Small reactors might also open up new applications, perhaps in desalination, district heating or even transport. He Zuoxiu, a Chinese physicist critical of his government's rush to build lots of big PWRs, has suggested that SMRs for ships, both military and merchant, would be a good way to train up a cadre of engineers and designers.

SMRs can also be slotted into underground silos, which cuts down on civil engineering costs. Perhaps most promising of all, they would be built in factories, not on site. That should make them less subject to delay than manufacture in the field. And a factory building ten such reactors a year for years on end might be able to make significant cost reductions through incremental improvements—economies of number as opposed to economies of scale.

But these advantages do not add up to a conclusive case for a small modular future. Babcock and Wilcox claim overnight costs per kilowatt of capacity for the mPower roughly on a par with those of big PWRs like the AP1000. But in an industry that has long pursued economies of scale, many are unconvinced that smaller reactors can deliver the same costs per kilowatt. Atam Rao, who led the design of an advanced generation III reactor, GE's ESBWR, describes such claims as "complete BS". Things like control systems are needed for all reactors, big or small. Providing them for each small reactor is bound to push up costs. Will any utility really think it makes sense to field ten SMRs with ten control systems and ten safety systems rather than one big PWR? Only if it has seen it done economically elsewhere.

In the end, that is the biggest problem for proponents of new approaches to nuclear energy. If a radically new technology, as opposed to an incremental one, is to take off, it needs not only to be researched and developed; it needs to be deployed, and industry will not do this until it has seen the technology work. It was the American navy's deployment of nuclear reactors that convinced the world that they could be used as power generators. And it was the experience of deploying them that allowed Admiral Rickover, in the 1950s, to sum up the gap between ideas that might work and those that are in fact working, in a way that still seems spot on 60 years later:

An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose. (7) Very little development will be required. It will use off-the-shelf components. (8) The reactor is in the study phase. It is not being built now.

On the other hand a practical reactor can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It requires an immense amount of development on apparently trivial items. (4) It is very expensive. (5) It takes a long time to build because of its engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated.

Innovators need to be able to take risks, to try variations on their ideas and to be able to learn. They flourish in unregulated markets. They frequently depend on venture-capital funds which are dwarfed by the cost of even a single utility-scale power plant. They also need rewards. Yet makers of nuclear reactors cannot take risks that might compromise safety, and they cannot try lots of different things because it would be too expensive. And even if they succeed, all they will be making is commoditised electricity. Power stations are not conducive to radical innovation.

Nuclear reactors, as Philippe Jamet notes, last for centuries; the technology is, by its own standards, still young. Longevity and inertia ensure that even a disaster like Fukushima cannot wipe it from the world. But they also ensure that it cannot grow fast. In energy in general, technologies mature and succeed each other over decades. Nuclear seems likely to lag behind even in this slow field. That does not mean it will not, eventually, play a larger role, but that it will get there slowly. Inside a reactor, things can change in milliseconds. Outside, it takes lifetimes. ■

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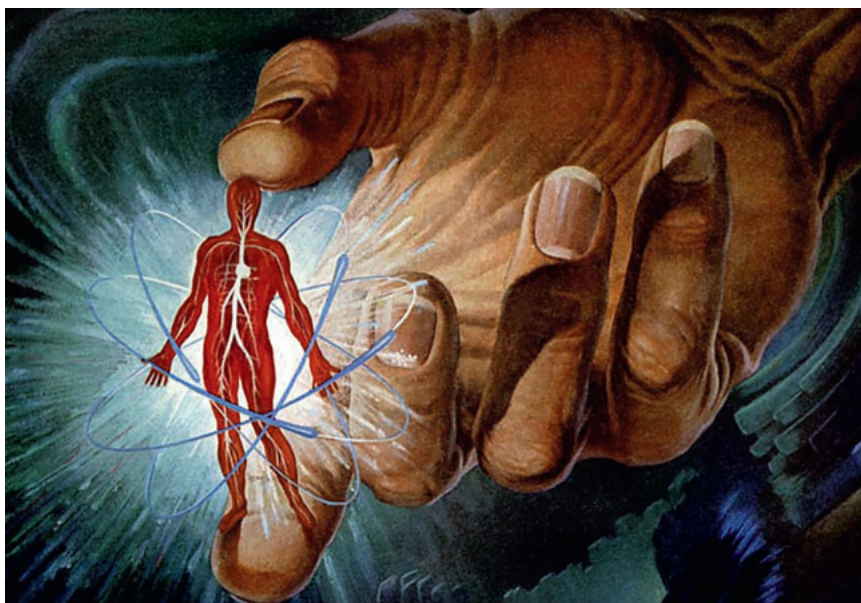
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