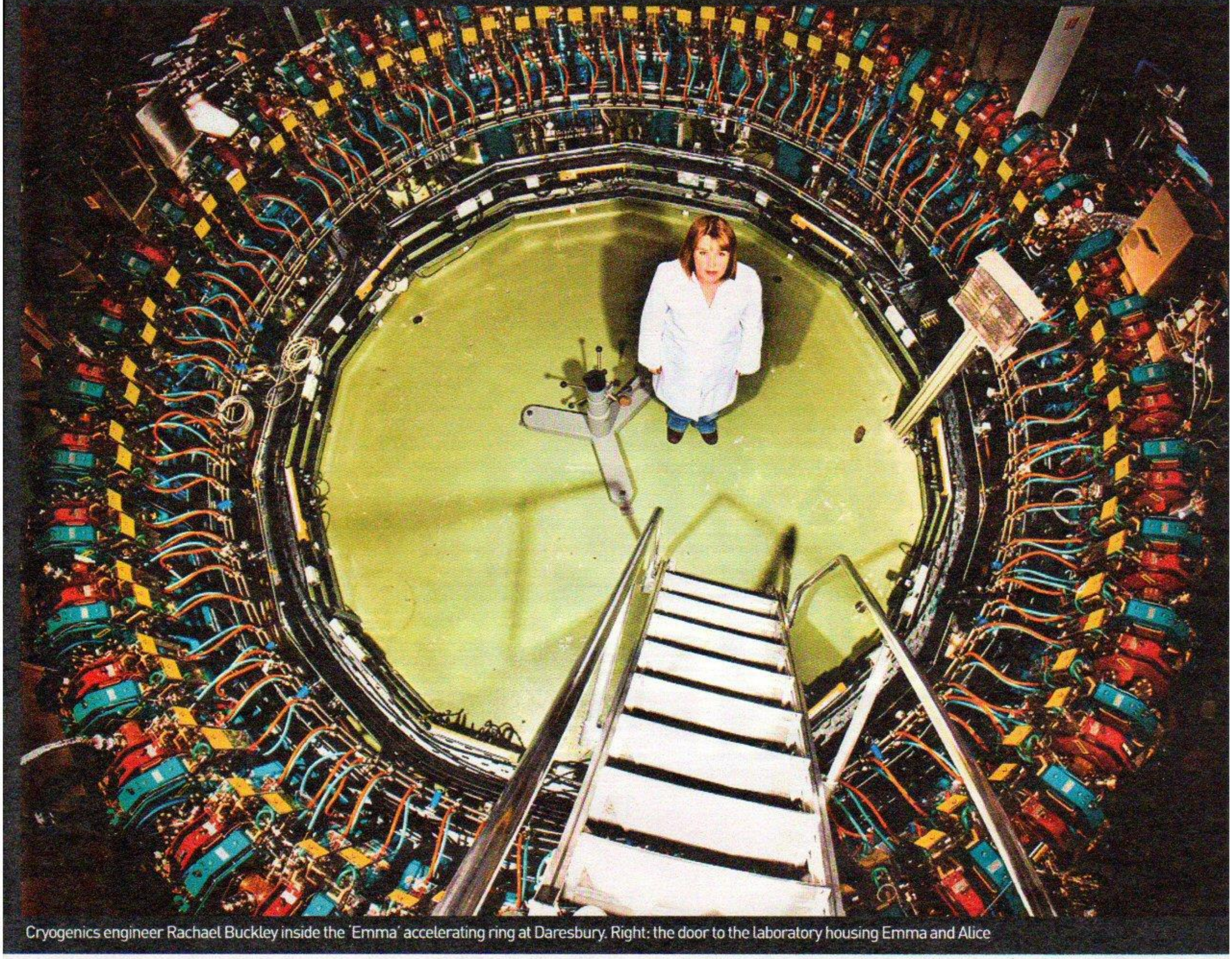

Cryogenics engineer Rachael Buckley inside the 'Emma' accelerating ring at Daresbury. Right: the door to the laboratory housing Emma and Alice

Imagine a safe, clean nuclear reactor that used a fuel that was hugely abundant, produced only minute quantities of radioactive waste and was almost impossible to adapt to make weapons. It sounds too good to be true, but this isn't science fiction. This is what lies in store if we harness the power of a silvery metal found in river sands, soil and granite rock the world over: thorium.

One ton of thorium can produce as much energy as 200 tons of uranium, or 3.5 million tons of coal, and the thorium deposits that have already been identified would meet the entire world's energy needs for at least 10,000 years. Unlike uranium, it's easy and cheap to refine, and it's far less toxic. Happily, it produces energy without producing any carbon dioxide: so an economy that ran on thorium power would have virtually no carbon footprint.

Better still, a thorium reactor would be incapable of having a meltdown, and would generate only 0.6 per cent of the radioactive waste of a conventional nuclear plant. It could even be adapted to 'burn' existing, stockpiled uranium waste in its core, thus enormously reducing its radioactive half-life and toxicity.

Since the Japanese earthquake and tsunami, and the consequent meltdowns and radiation leaks from the Fukushima I power plant, the future for nuclear energy worldwide has been cast into doubt: Germany has announced that all its plants are to be closed. Thorium offers the potential to revive a moribund industry – along far less dangerous lines.

'If we're given the resources to do the research and development, we can make this happen,' says Professor Bob Cywinski of Huddersfield University. 'What's more, we can do it here in Britain, where right now we're at the leading edge of this technology. If we're prepared to make the necessary investment, we'll not only reinvigorate our own nuclear industry, but exploit a lucrative export market which could be worth many billions of pounds, creating thousands of jobs.'

The good news is that, thanks to funding from the Research Councils UK Basic Technology Programme, we've taken the first, critical step to making this dream a reality – constructing an incredibly hi-tech, cutting-edge machine with a surprisingly ordinary name: Emma.

Daresbury, the science park where Emma lives in a big, bare building with solid concrete walls more than two feet thick, isn't especially scenic – it's overlooked by a power station and stands on the boggy Cheshire flatland between Runcorn and Warrington, at the head of the Mersey estuary. Inside, it's hard to talk, as the cryogenic vacuum pumps that keep the innards of Emma's friend Alice cooled to -271°C are extremely noisy. Yet Emma – the Electron Model of Many Applications – is an object of scientific beauty, a shiny blue-and-red metallic ring bristling with cables and flat, octagonal quadrupole magnets (magnets arranged in groups of four).

To one side of her ring, sticking out at an angle of 65 degrees, is a pipe to a special magnet that allows particles to be injected – what scientists call a 'septum'. It's connected to Alice, a separate machine that generates a beam of electrons: think of her as the spring-loaded trigger you pull to start a pinball game. Once injected through the septum into Emma, the electrons travel around the ring in a stainless-steel beam tube, 4cm wide and 18m in circumference. Thanks to radio-frequency cavities, which accelerate the beam, and the quadrupole magnets, which focus it, the electrons' energy swiftly increases, until they approach the speed of light.

Attached to Emma are numerous electronic monitoring systems and remote-controlled motors to fix the magnets' exact position. Ultimately, everything is hooked up to computer consoles in the control room next door. Above them is a rough wooden shelf. On it is a long line of champagne bottles – each opened to toast one of the many technological milestones in Emma's four-year history from drawing board to functionality.

THIS IS EMMA. SHE'S GOING TO SAVE THE WORLD (AND CURE CANCER)

No, not the engineer in the lab coat. Rather, the Electron Model of Many Applications in which she's standing – a remarkable new technology which could change everything about the way we live. And which, splendidly, is based not a mile beneath Switzerland… but on boggy flatland somewhere in Cheshire

'The most welcome one was the last, at the end of last year,' says Neil Bliss, the project's manager and Emma's lead engineer. 'We had everything connected up, and at last the moment had arrived: it was time to switch her on. We were expecting it to take weeks. But after only four days all the systems were operating properly: the beam injector, the diagnostics, the power.

'That was when we knew Emma worked. We've known in theory that you could build something like this for years. But it's taken the world-class skills here in this lab to make it happen.'

Emma is a particle accelerator, the first of an entirely new type. Since the first such machines were built nearly 80 years ago, accelerators – devices that propel beams of electrons, protons or other particles to high speeds – have played a vital role in experimental physics, opening up fresh insights into the origins of the universe and the nature of matter. But most are big and expensive. The best known and biggest of all is the Large Hadron Collider operated by CERN in Switzerland, an underground ring 17 miles in circumference, which cost billions to construct.

Emma is different. She is the world's first 'non-scaling, fixed-field, alternating-gradient' (NS-FFAG) accelerator. In layman's terms, says Bliss, this means she is a 'pocket-sized' machine, the prototype of a new generation that will be significantly smaller and cheaper than its predecessors.

And this is Emma's special significance. Making particle accelerators affordable means they could be built and used in practical, everyday settings – such as thorium power stations. The key to thorium energy is likely to be the further development of 'pocket-sized' machines – precisely the kind of accelerator that looks and behaves like Emma.

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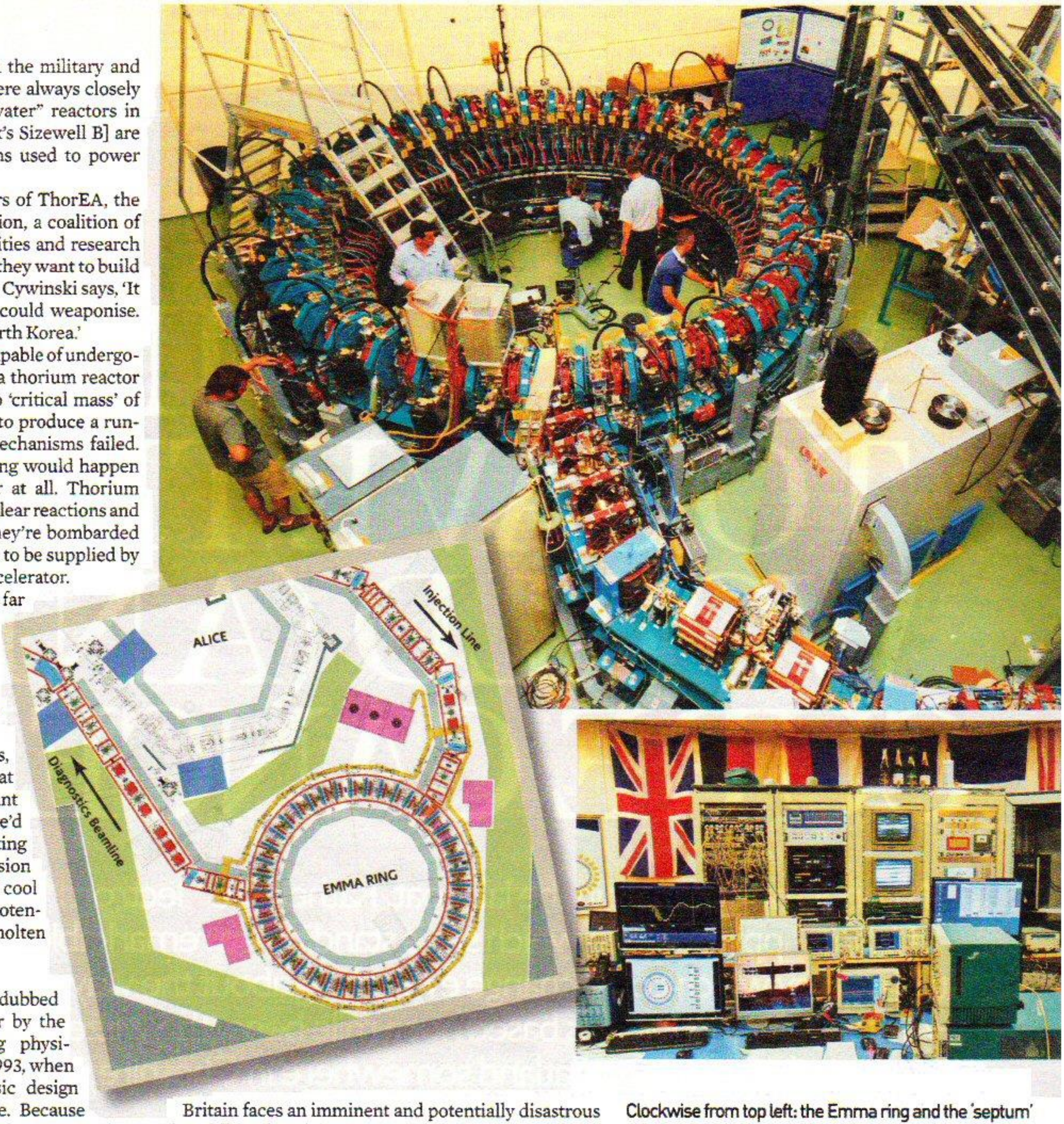
Although nuclear power plants have always derived electricity from enriched uranium or plutonium, the potential of thorium as a nuclear fuel has long been known. A small prototype reactor – built on very different lines to what is now envisaged – was actually constructed in the United States in the Sixties. Back then, though, at the height of the Cold War, there was little official appetite for pursuing the technology. The reason was that a thorium reactor is effectively useless at producing material for weapons.

'Thorium has so many apparent advantages that you have to ask why the world ever went with uranium,' says Dr Bill Nuttall, an energy-technology expert at Cambridge University's Judge Business School. ▶

WORDS BY **DAVID ROSE** PICTURES BY **NEALE HAYNES**



Clockwise from top left: the Emma ring and the 'septum' pipe feeding electrons from Alice; fine-tuning the machine's magnets; the control room; diagram showing how electrons are fed from Alice to Emma, which speeds them up and then discharges them down a diagnostic tube for analysis

▶ 'The answer is that investment in the military and investment in civil nuclear power were always closely linked. In fact, the mature, "light water" reactors in common use now [such as at Suffolk's Sizewell B] are directly descended from the systems used to power naval submarines.'

Cywinski and Nuttall are members of ThorEA, the Thorium Energy Amplifier Association, a coalition of experts from several British universities and research institutes. The type of thorium plant they want to build is effectively 'proliferation-resistant'. Cywinski says, 'It just wouldn't produce material you could weaponise. You could happily sell it to Iran or North Korea.'

It would also, as mentioned, be incapable of undergoing a Chernobyl-style meltdown, as a thorium reactor would be 'subcritical'. There'd be no 'critical mass' of unstable, radioactive material liable to produce a runaway chain reaction if its control mechanisms failed. In fact, left to its own devices, nothing would happen spontaneously in a thorium reactor at all. Thorium atoms only start to undergo fissile nuclear reactions and thus to release their energy when they're bombarded with neutrons, and these would have to be supplied by an external source – ultimately, an accelerator.

'This means the margin of safety is far greater than with a conventional plant,' says Cywinski. 'If the accelerator fails, all that will happen is that the reaction will subside. To stop the reactor, all you would have to do is switch off the accelerator.'

And if hit by an earthquake, he adds, even one as powerful as the one that wrecked Fukushima, a thorium plant would be 'intrinsically safer'. 'There'd be some residual radioactivity heating the core, but sustained nuclear fission would simply stop. Everything would cool much faster. You'd be left not with potential catastrophe, but just a heap of molten metal and metal oxides.'

This type of plant – dubbed the Energy Amplifier by the Nobel Prize-winning physicist Carlo Rubbia in 1993, when he patented the basic design – wouldn't be simple. Because neutrons carry no electrical charge, the magnets in a particle accelerator have no effect on them. Hence, the way to generate the neutrons necessary to trigger nuclear reactions in thorium would be to build a 'spallation source' in the middle of the reactor core. This is a substance – molten lead, for example – which produces neutrons when you fire a beam of protons at it. That beam, in turn, would come from a particle accelerator.

'In fact,' says Cywinski, 'you'd probably need two or preferably three accelerators for each plant.' One reason is that each accelerator would need regular maintenance. 'You can't just switch them on and expect them to work continuously for ten years.' Moreover, if one failed, you'd need a back-up; otherwise, the reactor would undergo potentially damaging cycles of cooling and heating, which would greatly shorten its life.

In theory, you could generate your beams of protons using a well-established accelerator type, perhaps a synchrotron like the giant collider at CERN. But the cost of three synchrotrons capable of firing beams big and energetic enough to use in a power station would be measured in the billions. Hence Emma's significance.

Last year, ThorEA published a report, Towards An Alternative Nuclear Future, which concluded it should be possible to build the first 600MW power plant fuelled by thorium with three attached 'pocket-sized' NS-FFAG accelerators within 15 years, at a cost of about £2 billion – making it highly competitive in relation to fossil-fuel or conventional nuclear alternatives.

Britain faces an imminent and potentially disastrous shortfall in electricity generation, as power stations of all types reach the end of their lives. With gas, coal and oil prices continuing to rise, you don't have to be a climate-change zealot to see the advantages of making electricity without fossil fuels. Lord Drayson, who was science minister in the last Government, embraced the thorium concept with enthusiasm, and it was his interest that triggered the ThorEA report.

But although the Coalition Government continues to pour subsidies worth many millions of pounds into wind power, which, as *Live* revealed earlier this year, produces at best intermittent energy with potential environmental costs, it has so far decided to do nothing about thorium except to maintain a 'watching brief'. The reason is that a review last year by the Government's Chief Scientific Adviser, Sir John Beddington, concluded that thorium research shouldn't be a priority, as 'development of the appropriate technology would appear to be some way into the future'.

That could be described as a depressingly circular argument: if the scientists aren't funded to pursue the research and development, the technology will indeed remain in the future. Meanwhile, the reasons for Sir John's pessimistic assessment seem baffling. In a letter to Cywinski, he admitted the science behind thorium reactors was 'well based', and said the main reason he couldn't recommend government support was because there had never been research on how to reprocess thorium fuel 'on an industrial scale'.

But this, says Cywinski, totally missed the point: not only would thorium plants produce far less waste, but their fuel – which would only need to be refreshed every ten years, as opposed to 18 months in a conventional nuclear reactor – wouldn't need to be reprocessed at all. 'This is a one-time fuel cycle,' Cywinski says. 'It's yet another of thorium's attractions.'

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Its construction hasn't yet been funded, but the next crucial milestone on the road to thorium power, a powerful proton NS-FFAG accelerator, isn't merely some remote theoretical possibility. The same group of scientists that designed and built Emma have already come up with detailed plans for her successor, Pamela, the Particle Accelerator for Medical Applications. As her name suggests, Pamela would have an immediate practical use in a field far removed from that of power generation: cancer treatment.

In a handful of private hospitals around the world, proton radiotherapy – using a beam of protons instead of X-rays – is already taking place. Its value is widely recognised: proton beams can be far more accurately

targeted on diseased parts of organs, and cause far less damage to surrounding tissue. But in Britain, there's only one proton therapy centre, at Clatterbridge in Merseyside, and the beam from its small, relatively weak accelerator can't penetrate far inside the body, and so can only be used for treating tumours of the eye.

Pamela would be much more versatile. The unit used to measure the energy produced in an accelerator is the electronvolt, or eV. Emma operates at around 20 MeV (20 million electronvolts); the Clatterbridge machine at 62 MeV. Pamela, on the other hand, would fire protons at 400 MeV. At that level, it could be used to treat a wide range of tumours that either aren't susceptible to X-ray radiotherapy at all, such as cancers deep in the brain, or are notoriously hard to treat, such as prostate and lung cancer. The NS-FFAG design also means that its beam would be delivered continuously, rather than in the brief pulses emitted by the much more expensive accelerators currently used. Not only the cost, but the length of a patient's treatment would thus be reduced.

Meanwhile, a 400 MeV accelerator would take scientists a large part of the distance towards the 1 GeV (one billion electronvolts) beam needed to power a thorium reactor. 'If we can build Pamela, we'll have done the heavy lifting,' says Cywinski. 'In terms of further research and development, we'd be almost there.'

So is Pamela a pipe dream, an expensive gamble that can't be justified at a time of austerity? Not according to Professor Ken Peach, of Oxford University's Particle Therapy Cancer Research Institute. 'I'm optimistic we can build a machine that overcomes the technical challenges and would be applicable for cancer therapy straight away,' he says. 'I think Pamela can be built for an overall cost of £10-15 million, and would take about five years. And that would be a crucial stepping stone towards a thorium power station. It wouldn't be cheap. But it would be highly competitive.'

The ThorEA report suggests that once Pamela and later proton NS-FFAGs are up and running, most of the further costs of developing thorium energy can be met from the private sector. The Norwegian engineering firm Aker Solutions is already working with Carlo Rubbia on developing possible reactor designs.

Meanwhile, as Peach says, the British scientists responsible for building Emma, designing Pamela and writing the ThorEA report have published their ideas. 'It's all out there now, in the public domain. Now that Emma has proved we can make an NS-FFAG accelerator and get a beam, I think there's a genuine opportunity here for the UK to gain a vital technological lead. But if we don't put the money in, someone else will.'

'MATERIAL FROM A THORIUM PLANT COULDN'T BE WEAPONISED. YOU COULD HAPPILY SELL IT TO IRAN OR NORTH KOREA'

Already, Belgian scientists, backed by more than £300 million of government funding, are developing a thorium reactor aimed primarily at deactivating old nuclear waste. Their colleagues in China and India – which has copious thorium deposits – are taking a strong interest.

Possibly because there remains a powerful vested interest in the 'old' uranium nuclear industry, this commitment hasn't yet been matched by the UK Government. But according to Cywinski, 'we shouldn't be asking whether we can afford to invest in this technology. We should be asking whether we can afford not to.' Like oil and gas, uranium is a finite resource, and its cost is already rising. Some economists estimate that by the middle of the century, it will be prohibitive.

Back in Daresbury, Neil Bliss stands proudly next to Emma. 'For the UK, the important thing for me is that we use the skills we have to stay at the cutting edge. I just don't want to have spent the past four years of my life in this building and not seen the next stage happen. It wouldn't just be a waste – it would be a tragedy that could end up costing this country billions.' ■