We have the technology

The global spread of nuclear weapons is once again a major headache for world leaders. Geoff Brumfiel reports on efforts to put the genie back in the bottle.

"Here's my bomb design," quips Joe Cirincione, unrolling a blueprint on his office table. The paper shows a cutaway view of a teardrop-shaped device with a flattened cylinder of uranium-235 at one end, and a small plug of the same highly enriched metal at the other. When the two pieces are brought together at the right speed, they begin a chain reaction with the explosive power of several thousand tonnes of TNT.

Cirincione, who directs the Carnegie Endowment for International Peace's non-proliferation programme in Washington, bought the simplified design a few years ago from the gift shop at Los Alamos National Laboratory in New Mexico, where the world's first nuclear-bomb programme began 60 years ago.

Picking up a real, detailed bomb blueprint is not yet quite as simple as visiting a shop — but it seems to be much easier than experts thought just a few months ago. In January, Abdul Qadeer Khan, the father of Pakistan's nuclear bomb, confessed to heading an extensive network of scientists, engineers and businessmen who were selling nuclear secrets on the black market. The group's bill-of-fare included complete design data for at least one tested nuclear warhead.

The revelation that a private network was selling such a blueprint was a wake-up call for many politicians and arms-control experts, says Corey Gay Hinderstein, deputy

M. CAVANAUGH

Joe Cirincione shows off his souvenir bomb plan.

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US	Russia	China	France	UK	Israel	India	Pakistan	N. Korea
100	150	5	5	8	0.5	0.5	0.04	0.02
700	800-1,400	20	30	20	?	?	1	?
10,000	17,000	400	350	200	100	70	45	0-5

All figures are approximate and rounded

SOURCE: INSTITUTE FOR SCIENCE AND INTERNATIONAL SECURITY/CARNEGIE ENDOWMENT FOR INTERNATIONAL PEACE/INTERNATIONAL ATOMIC ENERGY AGENCY

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S. CRISE/CORBIS

Time bomb: the United States' nuclear arsenal is envied by a clutch of aspirant nuclear powers.

director at the Institute for Science and International Security, a Washington-based think-tank. "We're used to states putting together these efforts," she says. "But this was pretty amazing."

The Khan network is just part of a rapidly changing nuclear landscape. The end of the cold war has left a glut of fissile materials in Russia that could potentially be fashioned into a crude bomb by terrorists or sold on the black market to states with nuclear ambitions (see 'Russia: under lock and key', page 436). Countries such as South Korea and Brazil, which once might have struggled to develop nuclear weapons on their own, now have the technical ability to do so if they wish. And Iran and North Korea, two nations that signed an international treaty meant stop the spread of nuclear weapons, either have bombs of their own or are very close to having them (see 'Nuclear weapons update', previous page).

On the brink

Whether these developments will unravel 60 years of effort to control the nuclear-arms race is open to question. But one thing seems clear — old assumptions about who can get a nuclear weapon no longer hold. "We are at a nuclear tipping point," Cirincione says. "The decisions that we make over the next couple of years will decide whether progress continues or whether we go off on the second great proliferation wave since the Second World War."

Proliferation was a deep concern after 1945. With tensions between the Soviet Union and the United States rapidly on the rise, many nations began to develop nuclear programmes as a safeguard against an uncertain future. The threat was all too clear to President John F. Kennedy, who narrowly avoided nuclear war when the Soviet Union tried to place nuclear missiles on Cuba in October 1962. "I ask you to stop and think for a moment what it would mean to have nuclear weapons in so many hands. … There would be no rest for anyone then, no stability, no real security, and no chance of effective disarmament," he said in July 1963 in a televised speech that announced the first major US–Soviet treaty, which banned atmospheric testing of nuclear weapons.

> "If fuel-cycle technology continues to spread around the world the non-proliferation treaty will break down."
> — John Wolf

By the end of the 1960s, the United States and the Soviet Union had signed the Nuclear Non-Proliferation Treaty (NPT), a landmark agreement that defined the next 30 years of nuclear-arms control. The treaty pledged that states with nuclear weapons would prevent the spread of weapons technology to non-nuclear nations — and that they themselves would work towards complete nuclear disarmament. Non-nuclear nations agreed not to develop weapons as long as all countries would have access to peaceful nuclear technology, including nuclear power. The treaty also specified that states without nuclear weapons must comply with rules set up by the International Atomic Energy Agency (IAEA).

In addition to the diplomatic barrier formed by the NPT, would-be nuclear-weapons states faced formidable technical hurdles. Like all forms of nuclear energy, bombs get their power from the massive amounts of energy released when trillions of atomic nuclei are split apart. The bombs that are easiest to build — such as the design in Cirincione's office — rely on uranium-235, a relatively rare isotope of the metal found in small quantities in ore deposits.

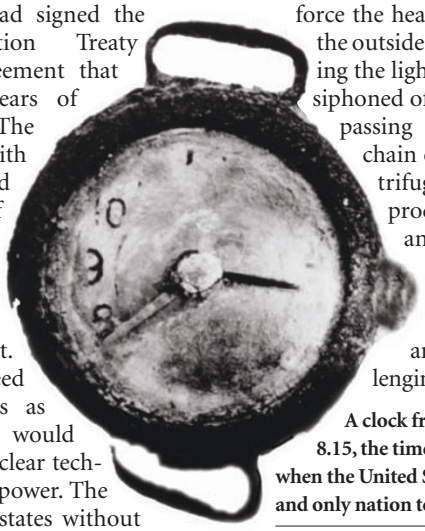
Enriched pickings

The bulk of natural uranium is the heavier uranium-238 isotope, so to produce fuel for a nuclear reactor or a bomb the 235 isotope must be separated from the 238. When the proportion of uranium-235 in the metal reaches about 5%, it can sustain a controlled fission reaction in a nuclear-power plant. A much higher level of uranium enrichment — 90% or more uranium-235 — will produce a nuclear explosion when the metal is brought together in a 'critical mass' of just a few kilograms.

The two uranium isotopes are chemically identical, and can only be separated using techniques that exploit the difference in their atomic masses. Until the 1960s, this meant using gas-diffusion facilities, which separate the atoms by taking advantage of the slightly different rate at which they pass through a maze of chambers and membranes. These immense facilities were difficult for aspiring weapons states to build and easy for inspectors to spot, says Ernest Moniz, a theoretical physicist at the Massachusetts Institute of Technology and former under-secretary of the US Department of Energy, which runs the US nuclear-weapons programme. But in the 1970s Urenco, a European consortium for making nuclear fuel, developed another concept that would prove far easier to hide.

Urenco used centrifuges, which spin gaseous uranium fluoride at high speeds to force the heavier uranium-238 to the outside of the chamber, leaving the lighter 235 isotope to be siphoned off from the inside. By passing the gas through a chain of thousands of centrifuges, it is possible to produce nuclear fuel and, with a little more effort, bomb-grade material.

The centrifuges are technically challenging to build. They need



B. BRAKE/SCIENCE SOURCE/SPL

A clock from Hiroshima still says 8.15, the time on 6 August 1945 when the United States became the first and only nation to use nuclear weapons.

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Middle East: politics and power plays

Simple phrases can have far-reaching power. When the US foreign-policy establishment coined the term 'rogue state' in the mid-1990s, its members were well aware of this. The phrase, which is often used as an epithet for nations that seek nuclear weapons, triggers images of maverick, unstable governments whose leaders want the bomb at any cost, and don't care about the consequences.

Yet when nations choose to pursue nuclear-weapons programmes, the decision usually reflects the cold demands of local politics. This is the case even in regions where the spread of nuclear weapons is sometimes characterized as scary and unpredictable, such as the Middle East, where Israel and Iran have each fostered undeclared nuclear-weapons research programmes.

The history of Israel's clandestine programme, which began shortly after the establishment of the Jewish state in 1948, reads like a Tom Clancy novel. Parts of the country's fledgling nuclear facilities at Dimona, in the Negev Desert of southern Israel, were probably hidden from inspectors by bricking up elevators and installing false control panels. Weapons may have been secretly tested underwater in the Indian Ocean, when cloud cover was shielding the bright explosions from watching satellites.

Calculated risk

The country is now believed to have about 100 warheads. Details are impossible to confirm as the programme does not officially exist, but Avner Cohen, a nuclear-proliferation expert at the University of Maryland in College Park, says that Israel could probably launch warheads from submarines, planes and by using missiles.

Initially, the programme risked angering Israel's closest ally, the United States, especially because it was US inspectors who were deceived when visiting Dimona. But Israel thinks the gamble was worthwhile. Nuclear weapons may have played a role in dissuading Israel's neighbours, in particular Egypt, from pursuing the path of war, says Cohen. In the case of the 1973 Yom Kippur war with Syria and Egypt, he says, Israel may even have secured US military aid more rapidly because it threatened to use its nuclear capability.

Analogous calculations may now be going on in the minds of Iran's rulers. Officially, the country's nuclear programme is a civilian one. But since the 2002 announcement that Iran would build six nuclear power stations, the International Atomic Energy Agency (IAEA) has accused the nation of misreporting the amount of uranium it has imported, and what it is doing with it. Iran is entitled to own the uranium as part of its power plans, but most Western analysts think that it provided misinformation in a bid to hide a weapons programme.

The programme, which is dispersed around at least five locations, is thought to include efforts to produce both plutonium and highly enriched uranium.

According to the Carnegie Endowment for International Peace, a Washington-based think-tank, one of the most advanced facilities is at Natanz, some 300 kilometres south of Tehran. Iran says that the site, which has been visited by the IAEA, will produce reactor fuel. But when running at full capacity, it could make 400–500 kilograms of weapons-grade uranium, enough for 15–20 weapons, per year.

> "Over time, Iran will create the impression that it is close to developing the bomb. That could have a deterrent effect."
> — Avner Cohen

In the dock

The United States, which already imposes sanctions against Iran for its alleged links to terrorism, wants the country referred to the United Nations Security Council over the IAEA's assessment of its uranium imports. Any weapons programme would breach the Nuclear Non-Proliferation Treaty, which Iran signed in 1968. By violating the treaty, Iran could alienate nations with which it has less fraught relations, such as France and Germany.

Yet from a national-security perspective, Iran might still decide that a nuclear-weapons programme is worthwhile. Two of Iran's immediate neighbours, Iraq and Afghanistan, are now occupied by the United States. Israel's nuclear weapons can probably reach Iranian territory. And Iran must also consider whether a revitalized, independent Iraq — should one emerge — would resume old hostilities.

"Over time, Iran will create the impression that it is close to developing the bomb," predicts Cohen. "That could have a deterrent effect."

Internal Iranian politics certainly point in this direction. The country has looked set for change since reformists won elections in 1997, but they have lost some popular support after struggling to overcome resistance from conservative religious groups. The idea that Iran has the right to nuclear energy and nuclear weapons unites supporters of both factions. "The public-pride issue is huge," says Michael Levi, an arms-control expert at the Brookings Institution in Washington.

If Iran continues to defy the West and develops nuclear weapons, drastic action seems unlikely, at least in the short term. Israel ended Iraq's nuclear programme in 1981 by bombing the country's reactors, but Iran's facilities are farther away and more dispersed. And even hawks in the United States are reluctant to confront Iran — which is nearly three times more populous than Iraq — militarily.

European nations have had some success in holding back Iran's nuclear ambitions by offering trade and aid packages. But Iran has so far said only that it will suspend, not halt, its programme. And if it continues to accrue nuclear technology, experts fear yet more proliferation in the region, with Saudi Arabia, Syria or Egypt next in line.

Jim Giles

Clandestine operations: civilian nuclear sites in both Iran (top) and Israel are believed to harbour production of weapons-grade material.

EPA/PA PHOTOS

GETTY IMAGES

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Russia: under lock and key

Top Russian officials no longer pull their punches when describing the prospect of nuclear proliferation on their doorstep.

"We cannot fully rule out the probability of Russian fissile materials, as well as technologies lending themselves to the creation of nuclear weapons, falling into the hands of terrorists," Alexander Rumyantsev, Russia's minister of atomic energy, told a September meeting of the Global Threat Reduction Initiative in Vienna.

On the ground in Moscow, researchers at the birthplace of the Russian atomic bomb take a more sanguine view of security at their own facility.

"Efforts to improve the physical protection of weapons material originated here ten years ago," says Nikolai Ponomarev-Stepnoi, vice-president of the Kurchatov Institute, Russia's premier institute for basic research into weapons physics and fission technology. "Our own activities have become the impetus for security upgrades at many locations throughout Russia."

The ageing, but well-maintained 100-hectare complex in Moscow houses the world's oldest nuclear reactor outside the United States. The reactor first attained fission in 1946 and still serves as a neutron source. To this day, all kinds of fissile material, including substantial amounts of weapons-grade enriched uranium and small amounts of plutonium, are stored here behind brick and corrugated iron.

Under control

Some 5,000 staff still work at the institute, located only twelve kilometres from the Kremlin, and now surrounded by restless Moscow traffic and overlooked by dreary concrete apartment blocks.

Ponomarev-Stepnoi greets visitors in a chilly, low-ceilinged conference room on the edge of the site, and reassures them that here, at least, fissile materials are under careful control.

"We understand very well that we must continuously work on risk reduction," he says. "We also know that we can't solve the problem alone. But thanks to US Department of Energy support, the Kurchatov Institute has become one of the best-protected nuclear sites in Russia."

AP

KURCHATOV INST.

The remnants of Russia's nuclear programme (top) are kept behind bars at places such as the Kurchatov Institute.

From 1949, when it carried out its first test, until the mid-1980s, the Soviet Union built about 45,000 nuclear weapons. This cold war arsenal has been heavily reduced since. In the past 15 years, Russia has dismantled thousands of tactical weapons, and in 2002 it agreed to cut its number of strategic warheads to between 1,700 and 2,200 by the end of 2012.

But despite substantial disarmament, the nuclear legacy of the Soviet Union remains the most severe headache for non-proliferation experts worldwide. Russia still has a massive nuclear-weapons production complex, including some 3,500 weapons scientists, roughly 100 of whom are believed to have comprehensive knowledge of bomb design. Weapons-grade material is stored at about 250 sites of variable vulnerability, stretching from Murmansk to Vladivostok.

Shut in

Perhaps the greatest risk is that insiders might try to sell valuable material to criminal groups. But nuclear-watchdog groups think that genuine progress has been made in improving the protection of the former Soviet nuclear facilities.

Since 1994, roughly half of the 250 sites have received some kind of security upgrade under the US-funded Material Protection, Control, and Accounting programme. These range in scope from rapid measures, such as bricking up windows, to high-tech security systems such as those installed at the Kurchatov Institute.

But *Securing the Bomb*, a recent analysis commissioned by the Nuclear Threat Initiative (NTI), a US watchdog group, concluded that truly 'comprehensive' upgrades have been completed at only one-fifth of all Russian sites storing weapons material, and at merely 5% of about 150 military sites believed to house actual warheads.

These upgrades have slowed lately, as the administration of President Vladimir Putin has become more reluctant to allow foreigners into sensitive Russian facilities.

At the ten-year anniversary meeting last month of the International Science and Technology Center (ISTC) — a multilateral agency that redirects activities formerly related to weapons research into civilian projects — experts stressed the urgency of reinforcing joint non-proliferation efforts.

"At the current rate, it will take at least another decade to sufficiently secure all nuclear material in Russia," says Charles Curtis, president of the NTI. "We must do a lot more, a lot faster."

Since 1992, ISTC grants have helped thousands of Soviet weapons scientists survive in the market economy. Although not all Russian officials were enthusiastic about the programme in the first place — there were widespread concerns about national knowledge being sold off on the cheap — the success of ISTC-funded projects, from environmental research to software development, has convinced many sceptics.

Ex-Soviet weapons scientists are not now thought to be particularly susceptible to illicit offers to buy their knowledge. Extra grants, such as those from the ISTC, allow most of them to maintain a decent standard of living. But badly paid guards, technicians and machinists working at Russian nuclear sites don't get similar aid, and fears remain that some of them could be tempted by financial offers.

> **"At the current rate, it will take at least another decade to sufficiently secure all nuclear material in Russia. We must do a lot more, a lot faster."**
> **— Charles Curtis**

In the age of terrorist warfare, the Soviet Union's nuclear arsenal has become a national security threat to Russia itself, and non-proliferation efforts have become a military necessity. "Our task is to always be one step ahead of terrorists," says Ponomarev-Stepnoi. "I don't believe that they will ever be able to get hold of a Russian weapon. But if somebody says there is no risk, everyone will go to sleep."

Quirin Schiermeier

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powerful motors, strong and lightweight materials to withstand the stresses of the spinning, and special bearings to house the chambers. But they require significantly less space and power than a gas-diffusion plant, making them more efficient and easier to conceal. These traits make centrifuges "the proliferation technology *du jour*", Moniz says.

Since its debut, centrifuge technology has gradually spread across the globe. Some non-weapons states, including Japan and Germany, use it for their nuclear-power industries, as the NPT permits. In other cases, centrifuge technology has percolated through illicit channels. From 1972 to 1975, Khan, for example, worked for a firm collaborating with Urenco, where, according to arms-control experts, he stole centrifuge designs that provided the basis for the nuclear weapon that Pakistan successfully tested in 1998.

"Many consider Japan to be little more than a screwdriver away from a nuclear weapon."
— Paul Leventhal

Secrets for sale

Later, Khan offered the centrifuge designs to Iran, Iraq, Libya and North Korea, among others. He turned the international network he had built for Pakistan's bomb programme into a one-stop-shop for nuclear technology, according to Hinderstein. It manufactured components that weren't readily available on the open market and even offered whole centrifuges for sale. Among the items the network sold were plans for an outdated but functional Chinese warhead that could deliver tens of kilotonnes of explosive energy and was small enough to fit on a missile.

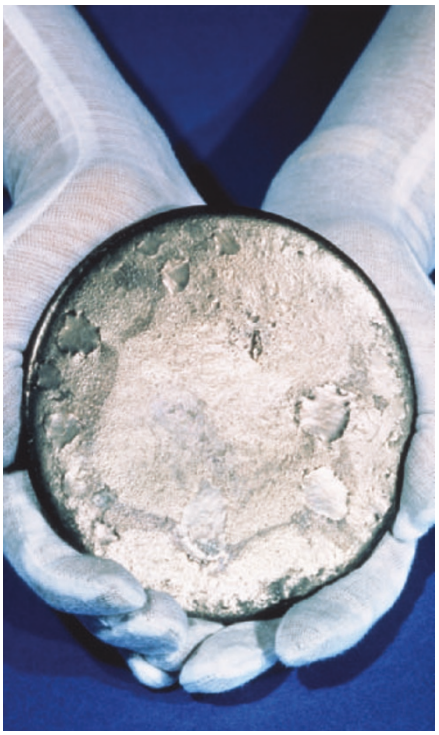
The assistance Khan offered, together with the availability of modern computers, precision machining equipment and advanced alloys, brought countries that a generation ago would have been considered too primitive to build their own bombs to the brink of nuclear statehood.

For US analysts, the most troubling of Khan's clients is Iran. Iran has ample reason to develop a nuclear bomb (see 'Middle East: politics and power plays', page 435), but the government says that it obtained the centrifuge technology to further its domestic nuclear-power programme — something that is perfectly legal under the NPT.

Paul Leventhal, head of the Nuclear Control Institute, a non-profit watchdog in Washington, says that Iran is taking the path followed by one of the United States' most steadfast allies: Japan. Since its first nuclear-power plant became operational in 1966, Japan has developed a large civilian nuclear programme that has produced several tonnes of plutonium-239, the other metal commonly used for nuclear bombs. Leventhal says that many consider Japan to be little more than "a screwdriver away" from a nuclear weapon. "Most think it could get a bomb in a matter of weeks to months, if not days," Leventhal says.

It's a strategy that Hinderstein describes as "virtual proliferation", and it seems to be catching on. Earlier this year, Brazil began operating a centrifuge-based uranium-enrichment plant that it says will provide fuel for civilian and naval reactors, but which could just as easily lay the foundation for a bomb programme. The nation has also limited IAEA inspectors' visits to the facility. And in South Korea, a country long alarmed by the nuclear ambitions of its northern neighbour, a group of scientists recently admitted to enriching a small amount uranium using lasers — a technique that they had been developing for commercial purposes such as medicine and industrial testing. Laser separation of the different kinds of uranium would never be profitable for producing fuel, says Moniz — but it could be scaled up to make enough material for a handful of bombs.

Arms-control specialists say that virtual proliferation isn't really constrained by the NPT. The treaty was written at a time when nuclear power seemed to be the solution to the world's energy problems, and it was considered important that all nations had access to it. The main problem with treaty, according to John Wolf, president of the Eisenhower Fellowships programme in Philadelphia and former assistant secretary for non-proliferation at the US Department of State, is that it allows all countries access to all nuclear technology — including fuel-cycle technology that could be used for making bombs. If these technologies continue to spread, Wolf predicts, "the treaty will break down".



US DOE/SPL

Raw material: this lump of highly enriched uranium could be used to make a bomb.

An international conference to review the NPT is set for next spring, but there is no consensus on what it ought to achieve. Mohamed ElBaradei, director-general of the IAEA, has called for an international treaty that would place fresh restrictions on the export of sensitive nuclear technologies. "We must universalize the export control system, remove these loopholes, and enact binding, treaty-based controls — while preserving the rights of all states to peaceful nuclear technology," he wrote in *The New York Times* earlier this year.

Going it alone

But the US administration is at loggerheads with ElBaradei and seems to set little stock by reinvigorating the NPT. Treaties are not the most attractive strategy at the moment, says Linton Brooks, head of the National Nuclear Security Administration, the arm of the US Department of Energy responsible for the nation's nuclear stockpile and many of its non-proliferation programmes. Instead, Brooks says that the United States advocates unilateral action, such as a moratorium on the sale of uranium-enrichment technologies abroad. The United States has also launched a Proliferation Security Initiative, under which it works with its allies to block trafficking of sensitive technologies.

A lively debate is unfolding in the broader arms-control community on how to proceed. Ted Carpenter, vice-president for defence and foreign-policy studies at the libertarian Cato Institute in Washington, argues that allowing nuclear weapons to spread will ultimately lead to stability.

Others seek to strengthen the NPT through new efforts to combat trafficking. At its annual meeting in June, the Carnegie Endowment, for example, unveiled a plan to reinforce the principles of the NPT by securing all nuclear materials, stopping illegal transfers, and committing nuclear states to regional conflict resolution (see *Nature* **430,** 6; 2004).

Paul Robinson, director of Sandia National Laboratories in Albuquerque, New Mexico, thinks that a network of regional security alliances similar to NATO could watch over the world's nuclear weapons (see page 441).

Whatever the solution, Cirincione remains resolutely upbeat about the future. Twenty-five years ago, the world sat on the perpetual brink of nuclear annihilation at the hands of two superpowers, he says. Now it need only worry about regional nuclear war and the destruction of individual cities at the hands of nuclear terrorists. That's cause for some optimism, he contends: "The good news is that we're down to a few hard cases. The bad news is that they're really hard." ■

Geoff Brumfiel is *Nature*'s Washington physical sciences correspondent.

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