water consumption, mandatory restrictions improved total water savings by up to 23%, whereas voluntary water restrictions resulted in only 6% water savings (*11*).

Data from water meters can also help to inform water conservation measures. Progress is being made in dual metering (indoor/outdoor billing segregation), smart metering (real-time monitoring that transmits to the utility), and intelligent metering (real-time monitoring that can also include informational feedback and control options) (*12*, *13*). The extensive, detailed data provide valuable information on consumer use to utilities and resource managers. However, smart and intelligent metering systems are expensive and not yet widely used (*14*). The data are typically not in a user-friendly format, requiring sophisticated data processing for analysis. Further work is also needed to better understand how information from advanced metering technologies can help to influence consumer water use (*15*).

If detailed observational data are combined with other databases and advanced models, they can inform targeted water conservation efforts. However, many water agencies do not have technical capacity to mine data over time and analyze change. For example, the current drought in California has led to calls to develop and report water use analysis, because agencies lack the ability to differentiate indoor and outdoor water use to evaluate the effectiveness of water conservation measures. Applying water use models that acknowledge sociodemographic characteristics and local characteristics, such as size of residence, outdoor water use, and vegetation, will be crucial for meeting water conservation goals and targets. ■

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Foreign ministers discuss Iran's nuclear program in Lausanne, April 2015.

PHOTO: GLEN JOHNSON/US STATE DEPARTMENT

NUCLEAR SECURITY

After the Iran deal: Multinational enrichment

World powers should buy a stake in Iran's enrichment capacity and accept the same rules

By **Alexander Glaser**, **Zia Mian**,* **Frank von Hippel**

In April 2015, Iran and the E3+3 nations (France, Germany, and the United Kingdom, plus China, Russia, and the United States) negotiated a framework for a "comprehensive solution that will ensure the exclusively peaceful nature of the Iranian nuclear program" (*1*, *2*). The final settlement, expected by July 2015 or soon after, would constrain Iran's activities for various extended periods in return for the lifting of sanctions and affirm Iran's right to pursue its nuclear program free of the limits on its uranium enrichment capacity a decade or more from now. What happens when these restrictions begin to phase out? We outline one approach to limit the long-term risk by using the next 10 years to convert Iran's national enrichment plant into a multinational one, possibly including as partners some of Iran's neighbors and one or more of the E3+3 countries.

POLICY

After Iran's enrichment efforts were made public in 2003, the United States organized a broad alliance to pressure Iran to end this program, fearing that it was seeking nuclear weapons. Despite ever more punishing international sanctions, Iran built up its enrichment capacity, insisting that this program was peaceful and permitted under the 1968 nonproliferation treaty (NPT), which recognizes an "inalienable right of all the Parties to the Treaty to develop research, production and use of nuclear energy for peaceful purposes without discrimination" (*3*).

As part of its efforts to address concerns about the proliferation risks from its nuclear program, in November 2013 Iran agreed with the E3+3 on a Joint Plan of Action involving temporary limitations on its nuclear activities in exchange for limited sanctions relief (*4*). The April 2015 framework for a final settlement builds on the joint plan and includes limiting Iran to one operating enrichment plant (at Natanz); placing limits on its capacity, enrichment level, and stockpile of enriched uranium for "specified durations"; and an agreed-upon plan for Iran's centrifuge research and development. It also includes constraints on the plutonium production capacity of research reactors and an agreement by Iran not to separate plutonium from spent fuel or other irradiated uranium. The final element is increased transparency, including of centrifuge fabrication, and enhanced access for International Atomic Energy Agency (IAEA) inspectors to assure compliance. These transparency measures encompass and go beyond the reporting and access obligations of normal IAEA safeguards on NPT nonweapon states, including an additional protocol to the IAEA safeguards agreement, which Iran has signed and agreed to implement.

Program on Science and Global Security, Princeton University, Princeton, NJ, USA.
**Corresponding author. E-mail: zia@princeton.edu*

When restrictions expire, Iran will continue to be bound by the NPT and subject to IAEA inspection of its nuclear program, including the extra transparency measures and access provided by the additional protocol. Despite this transparency, there will remain concerns in the West and among Iran's major competitors for influence in the Middle East about the nuclear-weapon option implicit in Iran's enrichment program. Prince Turki bin Faisal, the former Saudi intelligence chief, recently stated, "Whatever the Iranians have, we will have, too" (*5*).

ENRICHMENT AND BREAKOUT. The proliferation threat inherent in national uranium enrichment plants was recognized at the beginning of the nuclear era. In 1946, the Acheson-Lilienthal report—drafted in large part by J. Robert Oppenheimer, the scientific director of the U.S. World War II nuclear-weapon-design effort—described uranium enrichment and technology for plutonium separation from irradiated uranium (reprocessing) as "dangerous" and proposed that they be put under international control as part of a global ban on nuclear weapons (*6*). This idea was revived in the 1970s and again in the early 2000s, but without success (*7*).

Natural uranium is 0.7% uranium-235 (U-235), the chain-reacting isotope used for nuclear power plant fuel. Modern commercial gas-centrifuge enrichment plants typically contain tens of thousands of machines connected in series and in parallel into cascades to enrich uranium hexafluoride (UF_6), the chemical form in which uranium is enriched in centrifuges, to 3 to 5% U-235. However, these cascades could quickly be reconnected to produce "weapon-grade" uranium enriched to 90% U-235 or more.

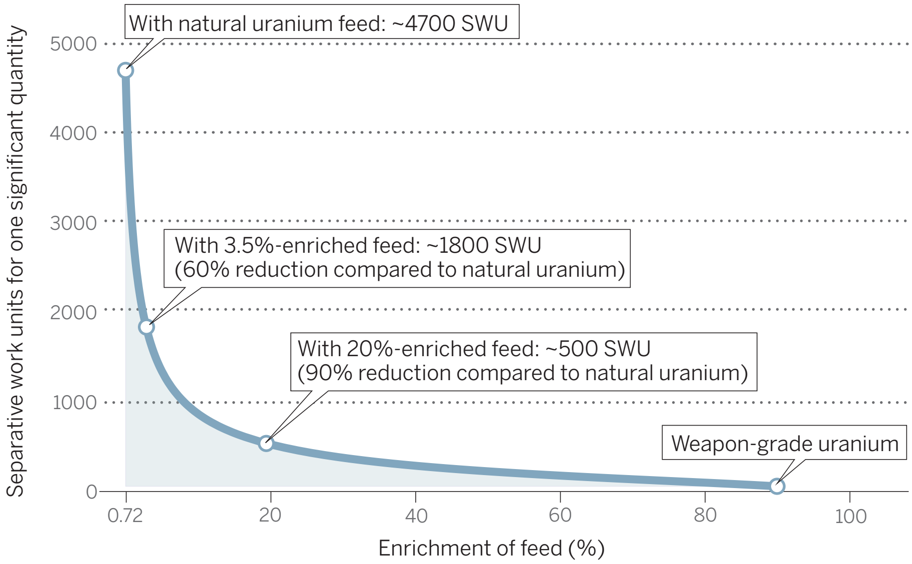
Iran demonstrated this flexibility in 2010 when it interconnected pairs of cascades designed to produce 3.5% enriched uranium for eventual use to fuel its Bushehr power reactor and began to produce uranium enriched up to 19.75% for the Tehran Research Reactor (*8*). Uranium enriched to 20% and above is defined as highly enriched uranium (HEU) and considered weapon-usable by the IAEA.

A primary U.S. objective in international negotiations with Iran has been to limit Iran's enrichment capacity to a level from which it would take at least a year to "break out" and produce enough weapon-grade uranium for a first nuclear explosive. On advice from the weapon states, for purposes of establishing safeguards criteria, the IAEA has defined HEU containing 25 kg of U-235 as a "significant quantity" (SQ), the approximate amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded (*9*).

Enrichment capacity is measured in separative work units (SWU), reflecting the effort expended in separating feedstock into enriched and waste products. From IAEA reports on the quantity and enrichment of the product from Iran's first-generation IR-1 centrifuges since 2010, the average IR-1 has been producing 0.7 to 1 SWU per year (*10*). According to the 2 April 2015 White House fact sheet on the framework agreement (*2*), Iran has accepted a limit of 5060 operating IR-1 centrifuges for 10 years and has agreed not to deploy more advanced centrifuges during that period.

AFTER 10 YEARS. Looking a decade ahead when limitations begin to loosen, Iran has made clear its intention to produce enough enriched uranium to fuel its Bushehr-1 power reactor rather than continue to rely on importing Russian fuel. To produce the 27 tons a year of 3.5% enriched uranium for reactor fuel would require more than 100,000 SWU per year (*11*, *12*). If this enrichment capacity were converted to the production of weapon-grade uranium, Iran would be able to produce 20 SQ a year from natural uranium and 50 SQ a year from 3.5% enriched uranium. Converting Iran's enrichment capacity from a national to a multinational enterprise could help limit long-term risk. Regional and E3+3 partners could, for example, purchase a share of the Natanz plant based on the investment and operating cost per unit capacity of large commercial enrichment plants. This would mean that Iran would have to continue to subsidize its enrichment program until it became competitive. All the potential E3+3 partners have expertise in centrifuge enrichment. They would not be required to provide technology but could be given full access to the Iranian plant without raising new proliferation concerns. Further transparency would follow, when it becomes politically possible, were Middle Eastern countries to form a regional nuclear inspectorate to supplement IAEA safeguards, as Argentina and Brazil did after they both simultaneously gave up their nuclear weapon programs (*13*).

Enriching uranium to weapon-grade



The SWU capacity required for a 1-year breakout time would depend on whether the feed into Iran's enrichment cascades was natural or enriched uranium. According to the U.S. fact sheet (*2*), Iran has agreed to enrich to less than 3.67% and reduce its stock of enriched UF_6, which could quickly be fed into centrifuges, to much less than the amount required to produce one "significant quanitity" (SQ). Feeding enriched uranium into centrifuges dramatically reduces the capacity required to produce an SQ of 90% enriched weapon-grade uranium within a given period of time (*11*). See the supplementary materials for details on this estimate.

A multinational approach to uranium enrichment could be an important step toward a long-hoped-for nuclear weapon–free zone in the Middle East. Iran and Egypt proposed such a zone to the United Nations General Assembly in 1974, and the proposal was broadened by Egypt in 1990 to include all weapons of mass destruction (WMD). The 1995 NPT Review and Extension Conference supported this goal. In 2014, a group of 22 Middle East states (all but Syria and Israel) sent letters to the United Nations

Secretary General confirming support for declaring the Middle East a region free from WMDs (*14*). Achieving a Middle East nuclear weapon–free zone, as part of a Middle East WMD-free zone, would benefit from all its members accepting the enrichment and reprocessing restrictions and enhanced transparency obligations agreed to by Iran and eventually will require Israel to verifiably give up its nuclear weapons (*15*).

MULTINATIONAL ENRICHMENT. Multinationalizing Iran's uranium enrichment program could become a step toward phasing out or multinationalizing national enrichment programs worldwide as part of a regime in which nuclear power rules apply equally to all states.

Uranium enrichment is required by the "light" (ordinary) water-cooled reactors that dominate the current global nuclear power reactor fleet. National enrichment programs currently exist in China, France, and Russia. None of these states has enriched uranium for weapon purposes since the end of the Cold War. India, Pakistan, and North Korea enrich uranium on a much smaller scale, including for military purposes. Three nonweapon states also have national enrichment plants: Japan, Brazil, and Iran.

An alternative to national enrichment plants emerged in the 1970s in the form of Urenco, a company jointly controlled by Germany, the Netherlands, and the United Kingdom, which operates one enrichment plant in each of these countries. Urenco currently operates 60% of the enrichment capacity outside Russia and owns the only commercial enrichment facility currently operating in the United States. This plant supplies about 40% of U.S. requirements, with the remainder imported. Most countries with nuclear power plants purchase uranium enrichment services from Urenco and Russia.

Since 1983, the United States has argued with countries interested in launching spent-fuel reprocessing (plutonium-separation) programs, in effect, "We don't reprocess. You don't need to either." This argument, reinforced by the poor economics of plutonium recycling, helped discourage additional countries from launching reprocessing programs. The United States is now in a position to argue similarly with countries like Iran, "We have the largest nuclear power program in the world, but we currently don't have a national enrichment program. You don't need one either."

By committing, as part of the forthcoming deal on Iran's nuclear program, to working on multinational enrichment arrangements for the Middle East, and ultimately around the world, Iran and the E3+3 could chart a path to reduce the proliferation risks from national control of civilian enrichment plants, regardless of location. In parallel, a Fissile Material Cutoff Treaty would end unsafeguarded uranium enrichment in the weapon states. ■

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ACKNOWLEDGMENTS

We thank anonymous reviewers for comments.

SUPPLEMENTARY MATERIALS

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10.1126/science.aac5989

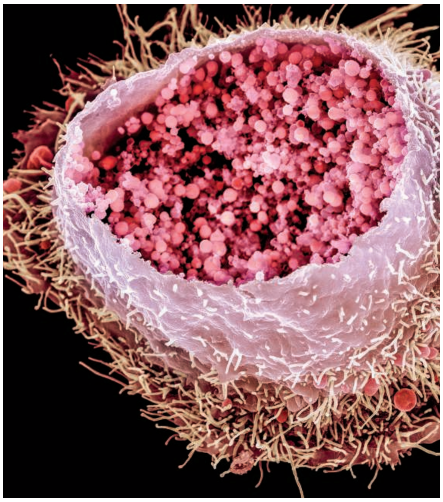
IMMUNOLOGY

A *Chlamydia* vaccine on the horizon

Results of a new *Chlamydia* vaccine in mice should spur human clinical trials

By **Robert C. Brunham**

Chlamydia trachomatis is the most common reported sexually transmitted bacterial infection in the United States, with more than 1.4 million cases of infection reported to the U.S. Centers for Disease Control and Prevention in 2012 (*1*). Worldwide, it is likely the most common infectious cause of infertility in women. An estimated 106 million cases of *C. trachomatis* occur globally among both women and men each year, so the worldwide burden of disease is substantial. Current public health efforts to prevent sexually transmitted disease caused by *C. trachomatis* or *Neisseria gonorrhoeae* emphasize prevention, but screening and treatment programs in medium- and low-income countries are rarely implemented because of financial and logistical difficulties. The findings reported by Stary *et al.* on page 1331 of this issue (*2*) constitute a major step forward in understanding *C. tracho-*



Ready to spread. A colored scanning electron micrograph of a human cervix cancer cell infected with *C. trachomatis* is shown. At the center is an inclusion body (ripped open) containing hundreds of *Chlamydia* particles.

PHOTO: SPL/SCIENCE SOURCE