For a number of other countries, the fundamental restructuring of their armed forces is also urgently required. Some of the truths of a changed security policy in a changed world will be difficult to accept: countries such as Russia or Ukraine, but even more so several developing countries which spend a substantial part of their GNP on the military, will have to accept that they cannot afford to maintain the type of armed forces they have had previously if they want to free the resources required for economic and social development. Their present course is a ruinously expensive effort.

Alternatives do exist. For disarmament to be viable there must be a long-term approach rather than a few stopgap measures. The first reason for this is to prevent war. But there is another important reason: the allocation of world resources is still seriously distorted; official development assistance continues to be a fraction of the amount spent on global military efforts. Similarly, in many countries development expenditure is below the level of investments in the armed forces. Although money is not the solution to all problems of human development, promoting expenditures for conflict prevention, peace and development and reducing the funding for war must be given a more prominent place on the international agenda. More fundamentally, the question must be raised as to which long-term security threats can be dealt with by military means. A lasting, viable disarmament process is required to free resources for development and to diminish the options for using the military in trying to solve political problems.

Conversion deals with the economic and social consequences of military downsizing and disarmament. The benefits achieved from conversion might also have an impact on the willingness to disarm. 'Proactive conversion', a term signalling that conversion is more than simply reacting to a military draw-down, could provide a means for preparing for disarmament. Conversion goes beyond the identification of opportunities. Conversion facilitates the productive use of scarce resources and — if well managed — reduces the risk of violent conflict. Well-managed conversion activities provide opportunities and can serve as catalysts for this type of transformation, making lasting human and economic development, and thereby peace and security, possible.

# Building confidence in a fissile materials production moratorium using commercial satellite imagery

*Hui Zhang and Frank von Hippel*

One key building block in a comprehensive strategy to contain and eliminate nuclear weapons is the Fissile Material Cutoff Treaty (FMCT), which would ban the production of plutonium and highly enriched uranium (HEU) for nuclear weapons. However, negotiations on this treaty have been at an impasse in Geneva since 1993. Since realistically a FMCT will probably not come into force for some years, a moratorium on the production of fissile material for weapons should be encouraged in order to capture as many of the benefits of an FMCT in the interim.[1]

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Four nuclear-weapon states (the United States, Russia, Britain and France) have announced that they have ended their production of plutonium and HEU for weapons and China has privately communicated that it has not been producing these materials for weapons since approximately 1991. A moratorium would therefore impact principally Israel, India and Pakistan, the only nations currently believed to be still producing fissile material for weapons.[2] Confidence-building measures, especially in these tense areas, would enhance regional security and stability. Satellite monitoring of a voluntary moratorium could prove to be extremely useful as a confidence-building measure to verify whether or not a facility is operating.

## *Monitoring a moratorium*

The shutdown of many plutonium-production reactors has been announced in connection with the declared American and Russian production moratoria. This includes all fourteen American plutonium-production reactors and ten of thirteen Russian plutonium-production reactors. Russia continues to operate three plutonium-production reactors to produce heat for regional populations. However, under a bilateral agreement, the plutonium that they produce is to be subject to American monitoring to verify that it is not used for weapons.

China is reported to have shut down its two plutonium-production reactors, although there has been no public announcement to this effect. France reportedly continues to operate the two Célestin heavy-water reactors to produce tritium for weapons and the Phénix breeder reactor as a civilian research reactor, and Britain continues to operate the 8 Calder Hall and Chapel Cross reactors to produce power. However, all of the operating British and French reactors except for the Célestin reactors are subject Euratom monitoring.

As a result of its production moratorium, France has also shut down its gaseous diffusion uranium-enrichment plants (GDPs) at Pierrelatte. Other GDPs and centrifuge enrichment plants (CEPs) in Europe are under Euratom safeguards. The United States had previously shut down its Oak Ridge GDP, is currently operating its Paducah and Portsmouth GDPs in tandem to produce low-enriched uranium (LEU) and has offered to subject them to IAEA safeguards. Russia had converted its GDPs to more energy-efficient CEPs by 1992 and is believed to be using them primarily to produce LEU for power-reactor fuel. It would be inconsistent with the American-Russian agreement, under which the United States purchases excess Russian weapons uranium after it has been blended to LEU, for Russia to be producing additional weapon-grade — or even weapons-useable — HEU (less than 20% U-235). It would increase confidence in the effectiveness of this agreement in achieving its objective of reducing the proliferation threat from Russia's stocks of excess HEU, however, if the United States and Russia were to enter into a bilateral arrangement to verify that their enrichment plants are producing only LEU.

Pakistan has reportedly been operating gas-centrifuges to produce HEU for weapons for more than a decade. The IKONOS image recently put on the web site of the Federation of American Scientists[3] reveals that the new production reactor at Khushab, Pakistan is producing unsafeguarded plutonium. India is believed to be continuing to produce weapons plutonium with its two plutonium-production reactors at the Bhabba Atomic Research Center. And Israel is believed to be continuing to produce weapons plutonium with its reactor at Dimona.

In some cases, confidence in the declared moratoria is being or could be provided by international monitoring arrangements (by Euratom in Western Europe) or a bilateral monitoring arrangement (the not yet in-force American-Russian bilateral cut-off on the production of weapon-grade plutonium and the bilateral monitoring of the enrichment of the product from their uranium-enrichment plants proposed above). In cases where such arrangements are not in force, however, satellite monitoring could provide additional confidence in a nation's moratorium declaration. After describing the capabilities of the most recent generation of commercial imaging satellites, we present examples using recently declassified images of an equivalent resolution.

## *New, more capable commercial imaging satellites*

Since the early 1960s, the use of telescopic cameras in space to verify arms-control agreements has been primarily the preserve of the United States and the USSR/Russia. The capabilities of these systems have recently been revealed through the Hubble telescope which, if flown just above the atmosphere and pointed downwards, could detect objects about 10 centimetres (4 inches) in size. However, prohibitively expensive, high resolution satellites have meant that most governments and NGOs were limited to much cheaper (and therefore lower resolution) images.

Starting in 1999, a new generation of commercial imaging satellites is being launched with 1m spatial resolution at visible wavelengths. Although still an order of magnitude less capable than military imaging satellites, the resolutions of these new satellites are an order of magnitude better than the 10–30m resolution of previous generation of commercial observation satellites, such as France's SPOT and the American Landsat 4 and 5 whose capabilities for treaty verification have already been examined in previous studies.[4]

Although we have not as yet had the opportunity to carefully analyze images of nuclear facilities taken by the new high-resolution commercial satellites, a large number of older images of such facilities with comparable resolution have become available as a result of the declassification of "Corona" panchromatic satellite images taken by American KH-4B intelligence satellites during the period 1967–72.[5] The spatial resolutions of these images are comparable to those of the new high-resolution commercial satellites.[6]

The capabilities of thermal infrared (TIR) images of civilian satellites are also improving. In April 1999, Landsat 7, with a 60m spatial resolution, i.e. half of that of Landsat 5, was launched. In December 1999, ASTER, with a 90m spatial resolution but better temperature accuracy, was launched. This new generation of civilian satellites opens up the possibility that all interested governments and NGOs may participate in monitoring a fissile materials production moratorium. The following sections explain how the new commercial satellite imagery could be used for this purpose.

## *The Corona images*

In 1995, anticipating the imminent public availability of images from new commercial imaging satellites, the United States declassified comparable images obtained in the late 1960s and early 1970s by the "Corona" KH-4B and earlier intelligence satellites. These satellites took numerous photographs of Soviet and Chinese nuclear facilities. John Pike and Charles Vick of the Federation of American Scientists have put some of these images on the FAS web site (http://www.fas.org).

We have examined these historical images to see how useful the new commercial satellite images could be in building international confidence in production moratorium declarations. We conclude that the images will be useful, at least for confirming that plutonium-production reactors and gaseous-diffusion uranium-enrichment plants have been shut down.

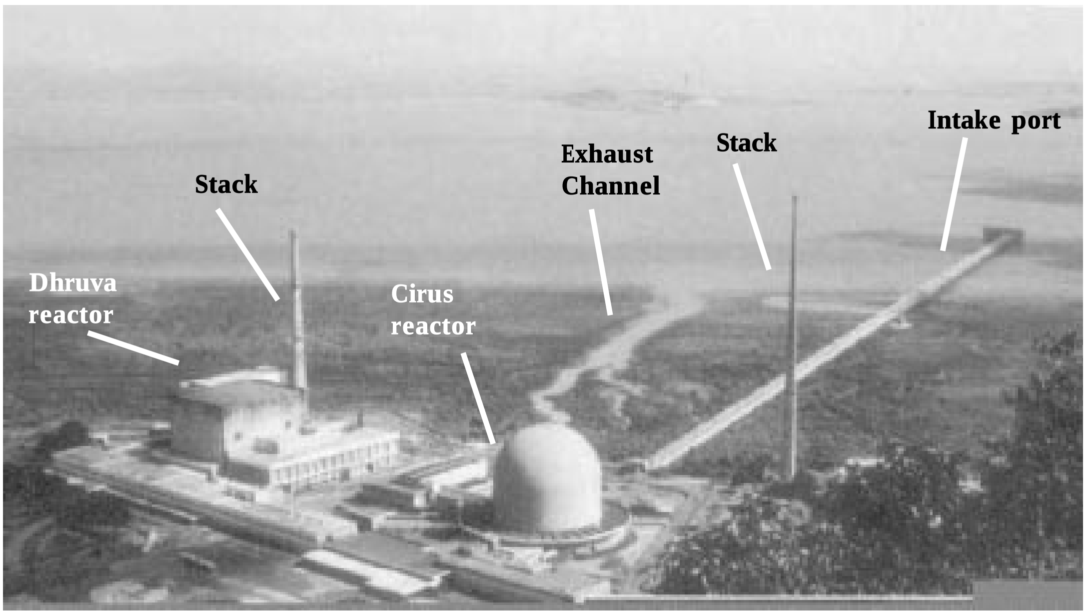
Figure 1. Corona image of a Siberian plutonium-production-reactor site (Tomsk-7, 15 September 1971).


Figure 1 shows a Corona image of an area containing the three oldest Soviet/Russia plutonium-production reactors at Seversk (Tomsk-7). One can see clearly down inside some of the cooling towers in this image while others have white clouds of condensed water vapour coming out of them.

These are standard, natural-draft, evaporative cooling towers that operate by the "chimney effect". The hot water from the reactors heats the air in the bottom of the cooling tower, which then rises, sucking cool replacement air into the bottom of the towers. The cooling capacity of the towers is increased by using evaporative cooling. Water is dripped through the warmed air in the base of the tower, absorbing the additional heat by evaporation.

A vapour cloud develops at the top of the tower because the saturated air cools as it rises. Furthermore, since the amount of water vapour that air can carry decreases rapidly with decreasing temperature, dilution of the plume can increase the degree of its super-saturation if the ambient air is not too dry. The excess water vapour condenses out in visible droplets — the same mechanism by which clouds form in the atmosphere. The cooling towers in Figure 1 with white vapour coming out of their tops were evidently in use, while the others were not. When the humidity is high, visible plumes can extend far downwind.

Figure 2. India's two plutonium-production reactors dump their heated cooling water into the upper Bombay bay. *Source*: Research Reactors at Trombay (Bhabba Atomic Research Center, 1987).



The Russian government has stated that the reactors associated with the cooling towers in Figure 1 were shut down in 1990 and 1992. Today, therefore, there should be no condensation plumes coming out of the cooling towers. The same technique could be used to verify the shutdown of China's first plutonium-production reactor near Jiuquan which, Corona photographs show, has six large cooling towers.[7]

Since these natural-draft cooling towers are usually very large (several tens of meters in height and more than 10m in diameter at the top) it is easy to identify them and their vapour plumes using 1m resolution images. Moreover, since it requires at least several weeks irradiation to produce a practical concentration of plutonium in reactor fuel, the several-day revisit time of current commercial satellites should be adequate for detection of operation.

For reactors with mechanical-draft cooling towers that drive airflow primarily by large fans instead of by the buoyancy of the heated air in the tall natural draft cooling towers, the visible plumes inside or over the towers could also be visible in the satellite images once the towers are operating. The February 2000 IKONOS image of the Pakistan Khushab reactor clearly shows the reactor's mechanical-draft cooling tower. Vapour plumes are barely visible over some vents, indicating that the reactor was operating at the time. The power of this reactor has been estimated at about 40–70 MW, much less than the estimated 2,000 MW of the later Russian plutonium-production reactors. Israel's plutonium-production reactor at Dimona, also estimated to be in the 40–70 MW range, is cooled with small mechanical-draft cooling towers that can be identified in Corona satellite photos. However, the dry desert air at the production site minimizes the presence of a condensation plume. Verifying the shutdown of this reactor using commercial imaging satellites may therefore be difficult.

## *Imaging in the thermal infrared*

What about reactors that are cooled by water from a pond or river? Here, in most cases, commercial infrared imaging can be used to detect the warmed water.

Because the wavelengths of thermal infrared radiation are about twenty times longer than those of visible light, the resolution for any given optical system in the infrared is degraded by a similar factor. However, even such lower-resolution images can provide useful information. This was demonstrated in 1986 after the Chernobyl accident when Landsat 5 thermal images showed that all four reactors had been shut down. The flow of warm water into their common cooling pond had stopped. When the reactors were operating, the warm water was easily visible, even with Landsat 5's 120m resolution, because the warm water flowed over a pond area of more than 10km$^2$ before cooling.[8]

Although India's two plutonium production reactors at the Bhabba Atomic Research Center (see Figure 2) have a combined waste-heat output of only about 2% of that of the four Chernobyl reactors, it is quite likely that the hot-water plume that they release could be detected using Landsat 7 or ASTER.

The operating status of large GDP can also be determined using thermal infrared images. Figure 3 shows a Landsat 5 thermal image of the three huge process buildings of the American GDP at Portsmouth, Ohio. The buildings are arranged in an "L" configuration. The two in the long arm of the "L" are about 670m long and 200m wide. The building that makes up the short arm of the L is 300m wide.

At full capacity, the Portsmouth GDP consumes more than 2,000 MW of electric power — the output of two large nuclear-power reactors. Virtually all of this electrical energy is converted into heat in the process of pumping $UF_6$ gas through thousands of porous nickel barriers to enrich the gas in the lighter molecules containing the isotope U-235. Most of the waste heat is removed to cooling towers and some of it is vented with hot air through the roofs of the buildings. The temperatures in the process rooms under the roofs are still high enough, however (around 80ºC or 175ºF), to make the roofs of the buildings unusually hot. As seen in this image, this elevated temperature can be readily detected by existing satellite TIR imagery.

Figure 3. Landsat 5 thermal image of the American GDP near Portsmouth, Ohio (12 March 1994).

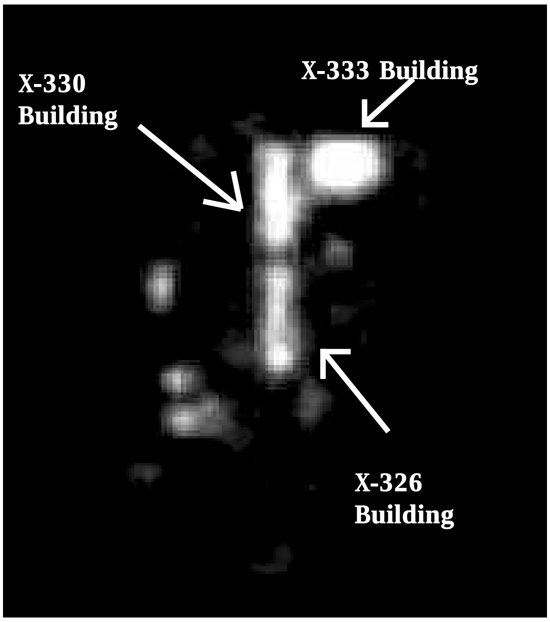
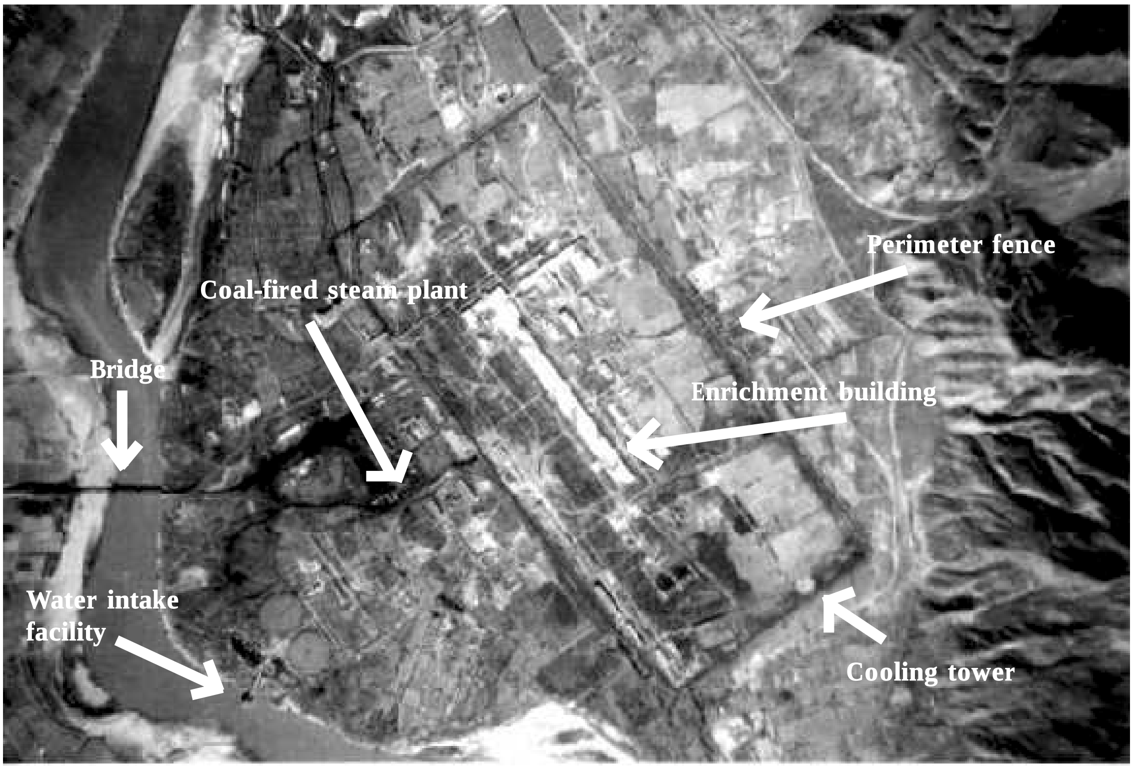



Figure 4 shows a Corona KH-4B image of China's GDP at Lanzhou.[9] This facility is about one-tenth the size of the Portsmouth plant and has a reported enrichment capacity 1/25th as large. It is cooled by mechanical-draft cooling towers. Chinese officials have stated that HEU production at Lanzhou and a second GDP near Heping ended around 1987. More recently, they have stated that the Lanzhou plant is to be shut down. The Heping GDP may also be shut down as much more energy-

Figure 4. Declassified American Corona satellite image of China's first uranium-enrichment plant (Lanzhou, 31 March 1971).



efficient centrifuge plants provided by Russia come online. Since Russia requires that the centrifuge plants be under international safeguards to assure that they are not used to make HEU for weapons, the shutdown of the Lanzhou and Heping plants would build confidence that China has indeed ended HEU production.

We have obtained a Landsat 4 thermal image of the Lanzhou plant area, taken on 3 February 1989. However, the plant is not visible at thermal wavelengths against the background. It is possible that it was not operating but, more likely, the resolution of the Landsat 4 thermal imager was not good enough. The Lanzhou building is only 60m wide, half the 120m resolution of the Landsat 4 thermal imager. If the plant is still operating, however, its warmth may be detectable by Landsat 7 or ASTER.

Under a moratorium, small, uneconomic CEPs, such as that operated by Pakistan at Kahuta, ought to be shut down. However, because of their small size and relatively low energy intensity, these plants do not require special cooling systems such as cooling towers. Also, the TIR imaging systems on current generation commercial satellites could not measure the roof temperature increase associated with their operation. Verification of their shutdown would most likely require on-site monitoring — although it might be possible to do this non-intrusively.

Of course, civilian imaging satellites are not a substitute for on-site verification of a future FMCT. In most of the cases that we have discussed, it would be possible to institute countermeasures to conceal the signatures. Cooling towers could be modified so that they did not produce a saturated plume; hot roofs could be cooled. Nevertheless, when a country announces that it has shut down a plutonium-production reactor or a gaseous diffusion plant, it will be worth checking the evidence provided by commercial-satellite images.

## Notes

1 Steven Fetter and Frank von Hippel, A Step-by-Step Approach to a Global Fissile Materials Cutoff, *Arms Control Today*, vol. 25, no. 8, October 1995, pp. 3–8.

2 David Albright, Frans Berkhout and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories and Capabilities*, SIPRI/Oxford University Press, 1997. Except when otherwise indicated, this has served as our primary reference concerning the status of fissile-material production facilities worldwide.

3 www.fas.org/nuke/guide/pakistan/facility/khushab.htm

4 M. Krepon et al., *Commercial Observation Satellites and International Security*, St. Martin's Press, New York, 1990; M. Slack and H. Chestnutt, *Open Skies—Technical, Organizational Operational, Legal and Political Aspects*, York University, Canada, 1990; M. Krepon et al., *Open Skies, Arms Control, and Cooperative Security,* St. Martin's Press, New York, 1992.

5 See www.fas.org/nuke/guide/russia/facility/nuke/index

6 The KH-4B cameras took images on photographic film. For such a system, the most common definition of spatial resolution is based on its ability to resolve parallel dark bars. The spatial resolution definition used in this paper is that used for electro-optical sensors, the "instantaneous field of view" (IFOV) on the ground of a single system "pixel" detector element. This depends not only on the characteristics of the detector and of the optical system, but also the orbit height and the wavelength of the radiation to be detected. Approximately two pixels are required to present the same amount of ground information as one line pair at "normal" film contrast. Therefore, the 1m (3ft) IFOV images produced by the new commercial satellites are comparable to the 1.8m (6ft) resolution photographic images produced by the KH-4B. However, using digital image processing techniques, the 1m resolution images of the new commercial satellites can be made to appear clearer than those from the KH-4B satellites.

7 www.fas.org/nuke/guide/china/facility/nuke

8 *United States Army Multispectral Imagery Product Guide, 2nd edition*, ATC-IA-2681-030-94, May 1994.

9 www.fas.org/nuke/guide/china/facility/nuke/