Report

Uses of Commercial Satellite Imagery in FMCT Verification

HUI ZHANG

Hui Zhang is a Research Fellow at the Belfer Center for Science and International Affairs at Harvard University's Kennedy School of Government. From 1997 to 1999, he was a Post-Doctoral Fellow at the Center for Energy and Environmental Studies at Princeton University. The views and opinions expressed here are the author's alone.

Negotiations on a fissile material cut-off treaty (FMCT) were agreed to in 1998 at the Conference on Disarmament (CD) in Geneva after several years' delay caused by debates over its scope and linkage to nuclear disarmament measures.[1] However, the negotiations have yet to get underway, as they have not been reauthorized by the CD in subsequent years. Should the negotiations move forward, it is expected that the proposed treaty would ban the production of plutonium, highly enriched uranium (HEU), and uranium-233 for explosives and perhaps would require that any fissile materials declared excess to military needs be placed under irreversible International Atomic Energy Agency (IAEA) safeguards. Fissile material, in practice plutonium or HEU, is the fundamental ingredient in all nuclear weapons.[2] It is also the most difficult and expensive part to produce. An FMCT would make irreversible the reduction in nuclear weapon material in the United States and Russia. It would cap the size of all potential nuclear arsenals. A universal FMCT would also draw the three de facto nuclear weapon states (India, Pakistan, and Israel)[3] into the nuclear nonproliferation regime. A global, verified ban on the production of fissile materials for nuclear explosives would, therefore, be a key building block in a comprehensive strategy to contain and eliminate nuclear weapons.

The principal focus in negotiating the FMCT will be the verification provisions. Verification measures must be seen as efficient and effective, but must also be politically acceptable. The scope of verification will depend on the facilities and activities subject to an FMCT. In principle, all facilities and activities that could be used to produce or divert weapon-usable fissile material for weapons would be subject to FMCT verification. Facilities dedicated to plutonium or HEU production must obviously be included in a cut-off treaty. Plutonium production facilities include uranium-fueled reactors in which plutonium-239 is produced through the capture of fission neutrons by uranium-238, and also reprocessing facilities in which the plutonium is separated from the uranium and fission products present in the spent fuel discharged from the reactors. HEU production involves uranium enrichment facilities such as gaseous diffusion facilities and centrifuge enrichment facilities. Some other facilities might also be covered by a treaty.

For example, tritium production reactors can be used to produce plutonium when the target material lithium-6 is replaced by uranium-238, or these reactors can use HEU as fresh fuel, which could be diverted for weapon production. A naval power reactor could also use HEU as its fuel. Other related facilities, such as uranium and plutonium storage facilities and fuel fabrication facilities, could also be included in FMCT verification.

However, the scope of verification is open to negotiation, and many options have been proposed.[4] The proposed scope ranges from focused verification to wide verification. Focused verification would concentrate on only sensitive fissile material production facilities, i.e., reprocessing and enrichment facilities, and fissile materials produced after an FMCT enters into force along with the facilities where these materials are present. A wide-scope approach would also cover a variety of less sensitive civil facilities such as fuel fabrication plants and civilian power reactors.

Whether the chosen verification system is focused or wide, however, FMCT verification will have to cover the following three classes of facility: declared shutdown production facilities; declared operating fissile material production facilities; and undeclared production facilities. The verification objective for a cut-off treaty—to assure that no fissile material is being produced for weapons—is similar to the objective of existing IAEA nuclear safeguards in non-nuclear weapon states (NNWS) that have ratified the nuclear Non-Proliferation Treaty (NPT). The basic FMCT verification measures will include: safeguards at declared facilities similar to those administered by the IAEA, including a state's establishment of a material accounting system and on-site inspections to determine the accuracy and veracity of the accounting system; challenge inspections involving managed access; environmental monitoring; and remote sensing involving satellite imagery.

Appropriate verification measures for each class of facility are described briefly here. In this report, I will focus on the most sensitive facilities: reprocessing and enrichment facilities and also plutonium production reactors. Once the most likely basic verification measures have been outlined, the rest of this report assesses how commercial observation satellites could be used as part of a verification system.

VERIFICATION OPTIONS FOR EACH CLASS OF FACILITY

Declared Shutdown Production Facilities

A primary goal of an FMCT will be to attain the signatures of the five declared nuclear weapon states (the United States, Russia, the United Kingdom, France, China) and three de facto nuclear weapon states, because almost all other countries will already be subject to its requirements by virtue of their ratification of the NPT as NNWS. Under an FMCT, these eight nations would end production of nuclear-weapon-usable fissile material except under international safeguards. FMCT verification would focus in the first instance on these states' past military nuclear production facilities. After the FMCT enters into force, many production facilities would be declared and shut down. Therefore, the verification system's primary task will be to affirm the status of these shutdown facilities.

The FMCT verification system for facilities in the eight nuclear-armed nations would have to be different from the IAEA safeguards system for NNWS. For IAEA safeguards, the main target nations are NNWS, and these states have confirmed that their nuclear facilities will not produce fissile material for weapons. However, for the eight nuclear nations, an FMCT is likely to permit their holding of undeclared stockpiles (from past production) and their using or processing of already produced fissile material for sensitive military activities (such as the assembly of nuclear weapons). These allowed sensitive production facilities and activities could be collocated with facilities (such as reprocessing and enrichment plants) requiring verification. Some states subject to inspections would worry about potential loss of sensitive information at these defense-related nuclear processing sites. Eventually, some on-site safeguards and environmental sampling might be seen as too intrusive and might not be permitted. Less intrusive verification measures, such as satellite remote sensing, therefore would be preferable. Commercial observation satellites with high resolution could be used effectively to monitor shutdown facilities. Such satellite monitoring will reduce the frequency of on-site inspection.

Declared Operating Fissile Material Production Facilities

Satellite imagery would be less useful for declared operating fissile material production facilities because it could be difficult to distinguish between different operating modes (whether for weapons or non-weapons production) of operating facilities. The verification measures used for these facilities would be primarily the IAEA safeguards (based on the INFCIRC/153 guidelines) applied to NNWS under the NPT.[5] The IAEA has accumulated extensive experience in safeguarding fissile material and has established a set of relatively complete safeguards systems and techniques for declared civil nuclear power facilities.[6] However, the IAEA safeguards cannot be applied directly to the eight nuclear weapon states because of the possibility that they might uncover sensitive information.

Undeclared Production Facilities

After an FMCT enters into force, a state could produce fissile materials for weapons from undeclared nuclear production facilities. Therefore, like IAEA safeguards, an FMCT verification system must also detect any such undeclared production activities. After the discovery of Iraq's clandestine nuclear weapon program and North Korea's noncompliance with its safeguards obligations, the IAEA determined that the traditional safeguards system under INFCIRC/153 was ineffective for detecting undeclared nuclear facilities and activities. In May 1997, the IAEA Board of Governors adopted the Additional Safeguards Protocol (based on INFCIRC/540) to expand existing safeguards agreements and improve the IAEA's ability to detect the undeclared production of fissile material.[7] This new strengthened safeguards system gave the IAEA access to more information, greater inspection rights, and the ability to use new technologies to improve safeguards. This new system has opened the door for the IAEA to use of all types of information, including the potential use of commercial satellite imagery. The IAEA is now studying the use of such satellite imagery to strengthen safeguards.

As a potential FMCT verification tool, commercial satellite imagery could provide the targets for on-site inspections and environmental sampling; this would be especially useful for identifying undeclared sites. The satellite imagery could also be used to confirm information acquired by the agency from other sources. Before conducting a challenge inspection, it is necessary to investigate and confirm suspicious information, especially when the suspect facilities are within or near a sensitive site. Conversely, to assist in identifying suspect facilities, other sources could be used to narrow the targets for satellite observation. Although satellite imaging could detect undeclared facilities, it cannot make the final determination about the activities of the facilities. However, it could trigger a special inspection involving on-site sampling and visual observation. In short, the commercial satellite imagery could play a significant role in the verification of an FMCT; however, all verification measures would be synergistic in an effective and efficient FMCT verification system.

In the following sections, I will discuss in detail the potential use of commercial observation satellite imagery to verify an FMCT. First, I review the capabilities of present and planned commercial observation satellites. Then, in separate sections, I explore how commercial observation satellites could be useful in verifying the status of reprocessing plants, plutonium production reactors, and uranium enrichment plants. Within each section, I discuss first the possible value of satellites in verifying that nuclear facilities formerly used to produce weapons fissile materials stay shutdown under the FMCT, and second, their possible contribution to the detection of undeclared nuclear facilities and sites.

CAPABILITIES OF PRESENT AND PLANNED COMMERCIAL OBSERVATION SATELLITES

Observation satellites can apply different types of imaging sensors designed to detect electromagnetic radiation reflected or emitted from the surface of the earth. Here I will focus on sensors for visible and near-infrared wavelengths (about 0.4 to 1.0 micrometers), which produce traditional photographic images, and for thermal infrared wavelengths (about 8 to 14 micrometers), which reveal heat signatures by representing relatively hotter objects in lighter shades.

Satellites with Visible and Near-Infrared (VNIR) Capabilities

Soon after the Soviet Union and the United States launched their first satellites (Sputnik-1 in October 1957 and Discoverer-1 in February 1959, respectively), they developed military reconnaissance satellites. Starting in 1972, these satellites as well as other national technical means were used to verify strategic arms control agreements, including SALT I and the Anti-Ballistic Missile Treaty. At the same time, lower resolution observation satellites were made available for civilian purposes, starting with the launch of the US Landsat-1 in 1972; this satellite's spatial resolution in the visible spectrum is 80 meters.[8] Thus, the smallest feature that the sensor can detect is 80 meters in diameter in photographs and 80 square meters in digital data.

In 1986, international competition in satellite imaging began with France's launch of SPOT-1, with a resolution of 10 meters. In 1987, the Soviet Union began marketing imagery from its KVR-1000, with a resolution down to five meters. In the meantime, India's IRS-1C and IRS-1D were successfully launched into orbit, in December 1995 and September 1997 respectively, each with a resolution of 5.8 meters.[9] Recently, Russia's SPIN-2 (Space Information—two meters) began to provide two-meter resolution images dating back to 1980.[10]

On March 9, 1994, the US government decided to allow US companies to build and launch private observation satellites that can obtain imagery with a one-meter or better resolution.[11] On September 24, 1999, the US firm, Space Imaging, launched the first such satellite—IKONOS—with a one-meter-resolution panchromatic sensor and a four-meter resolution multispectral sensor.[12] Recently, one-meter resolution satellite images became available to the public. Also other companies, such as the US companies EarthWatch and Orbimage, and the Israeli firm West Indian Space (WIS), plan to launch their high-resolution commercial imaging satellites soon.[13] All these new-generation commercial observation satellites have one-meter resolution; relatively short revisit intervals (one to five days); fore-and-aft and side-to-side pointing capability, as well as stereo imaging; huge on-board data storage capacity; and the ability to deliver images to customers in hours or days.

It is clear that the capabilities of commercial observation satellites are improving greatly. Although still an order of magnitude less capable than military imaging satellites,[14] the resolutions of these new satellites will be an order of magnitude better than the 10- to 30-meter resolution of previous generation commercial observation satellites such as France's SPOT satellite and the United States' Landsat-4 and -5 satellites.[15]

Although there has not yet been an opportunity to carefully analyze high-resolution commercial satellite images of nuclear facilities, a large number of older images of such facilities with comparable resolution have recently become available as a result of the declassification of CORONA panchromatic satellite images taken by the US KH-4B intelligence satellites from 1967 to 1972.[16] The spatial resolutions of these images—especially towards the end of this period—are comparable to those expected from the new high-resolution commercial satellites.[17]

Satellites with Thermal Infrared (TIR) Capabilities

High-resolution images of one meter in the VNIR are very useful for identifying nuclear sites and facilities and can provide indirect evidence, such as plumes of vapor rising from cooling towers, of their operation. However, TIR imaging is directly sensitive to temperature differences, which means it could detect certain operations that do not create external, visible evidence. TIR has another advantage over VNIR: TIR images can be taken during the night as well as the day. It also has a disadvantage: TIR generally has a much lower spatial resolution because of the longer wavelengths involved. Objects with temperatures below 100 degrees centigrade (^{0}C) emit dominantly at wavelengths above eight microns. Therefore, TIR measurements are taken within the 8- to-4-micron atmospheric transmission "window"; they thus involve wavelengths 20 times longer than visible wavelengths, which center around 0.5 microns. To achieve the same resolution from a given altitude would correspondingly require an aperture 20 times larger.

Measuring absolute temperatures accurately with TIR requires difficult corrections for atmospheric transmission. However, the most useful information for verification purposes is usually the difference between the temperature of an object of interest and its surroundings. The thermal sensitivity of TIR instruments for relative temperature measurement is referred to as the temperature "accuracy."

The only existing commercial satellites with TIR are Landsat-5, Landsat-7, and ASTER. Landsat-5, which was launched in 1984, carries two imaging sensors, the Multispectral Scanner (MSS) and the Thematic Mapper (TM). The Thematic Mapper, which operates in the thermal infrared region in the spectral range of 10.4 to 12.5 microns, has a spatial resolution of 120 meters. Based on its TIR images, its relative temperature accuracy is probably about 0.5 to one degree Kelvin (^{o}K).[18] Landsat-7, which was launched on April 15, 1999, carries the Enhanced Thematic Mapper Plus (ETM+), which has an improved spatial resolution of 60 meters.[19] I assume that it has the same temperature accuracy as Landsat-5.

A second new satellite with TIR, the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), was launched on December 18, 1999.[20] The US National Aeronautics and Space Administration (NASA) and Japan's Ministry of International Trade and Industry, as part of the Earth Observing System constellation of satellites, jointly fund ASTER. It has five TIR bands covering the spectral range from 8.125 microns to 11.65 microns at a spatial resolution of 90 meters. Its relative temperature accuracy around 300^0K is 0.2^oK. It can be expected that TIRs with higher resolution will be in orbit in the near future. For example, the United States is planning to launch a research satellite, Multispectral Thermal Imager (MTI), soon.[21] This system will have a TIR capability of 40-meters spatial resolution and 1^oK temperature sensitivity.

Commercial satellite imagery in the VNIR band could be used to monitor the declared shutdown status of production facilities, such as reprocessing plants, plutonium production reactors, and enrichment plants. TIR satellite images could also be used to detect the operation of these nuclear facilities.

Satellite images could also detect undeclared nuclear facilities by their infrastructure signatures. To produce fissile material for weapons, production reactors and reprocessing and/or uranium enrichment facilities need to be built. These plants would have some infrastructure signatures, which can be detected and identified by fine resolution satellite images. In the following sections, the use of satellite images in the VNIR and TIR for each type of facility will be discussed.

REPROCESSING PLANTS

Monitoring the Shutdown Status of Reprocessing Plants

Under an FMCT, some military reprocessing plants will be shut down. It will be very important to monitor the status of these sensitive plants. For satellite monitoring of the status of a reprocessing plant, the most important characteristic would be the activity level at the plant. When a reprocessing plant is operating, there could be many shipments of various forms of nuclear material. During a routine operation of the US Hanford PUREX plant, for example, the number of shipments for one year was over 1,000 to transport irradiated fuel from N-Reactor to the PUREX plant by railcar.[22] If a reprocessing plant is closed, the activity level should be very low or non-existent. For example, there should be no shipments moving at the railroad cask portals (the point for railcar-mounted shipping of casks from the reactor), no activity at the shipping dock (the loading point for plutonium products), and no activity at the cold feed loading point (the point for periodic addition of fresh chemicals to the reprocessing process). For these activities, transport vehicles, such as trucks, would be big enough to be detected by one-meter resolution images from a satellite. However it would be difficult to use satellite imagery to monitor a very small-scale reprocessing plant. Consequently, satellite imagery should be complemented with other verification measures, such as on-site inspections, environmental monitoring, and remote monitoring, at shutdown reprocessing plants. Finally, a reprocessing plant would have no evident thermal signatures for commercial satellite TIR imaging.

Detection of Undeclared Reprocessing Plants

Figure 1 shows an image taken by a CORONA satellite on September 15, 1971, of the reprocessing plant at Seversk (Tomsk-7), Russia. The facility was probably first used to separate plutonium shortly after the first reactor at the site became operational in 1956. Besides manufacturing plutonium from the spent fuel of the reactors at Seversk, the reprocessing plant in 1978 also started reprocessing plutonium from the spent fuel of the five military production reactors at Mayak. Irradiated fuel was therefore transported by train to Seversk for reprocessing until the last military reactor at Mayak was shut down in 1990. Now, the plant reprocesses only the fuel from Seversk's remaining two production reactors, which produce heat and electricity for nearby populations.[23] From the image, the long (more than 800-meter long) "canyon-like" building (typical of large reprocessing plants) can be seen clearly. Also clearly visible is the very high stack, which creates negative air pressures inside the work environment designed to contain any leaks of radioactive gases, and permits their dispersal high in the atmosphere in the event such gases are not trapped inside the building.

Thus, the declassified CORONA satellite images reveals identifiable features of a reprocessing plant: a long "canyon-like" building, and a very high stack[24] (readily distinguished by its long shadow). Also around the site there appear to be some holding ponds or reservoirs for waste or sludge, and railroads. These distinguishing features would make it possible to use a commercial satellite image to identify an undeclared site as a reprocessing facility.

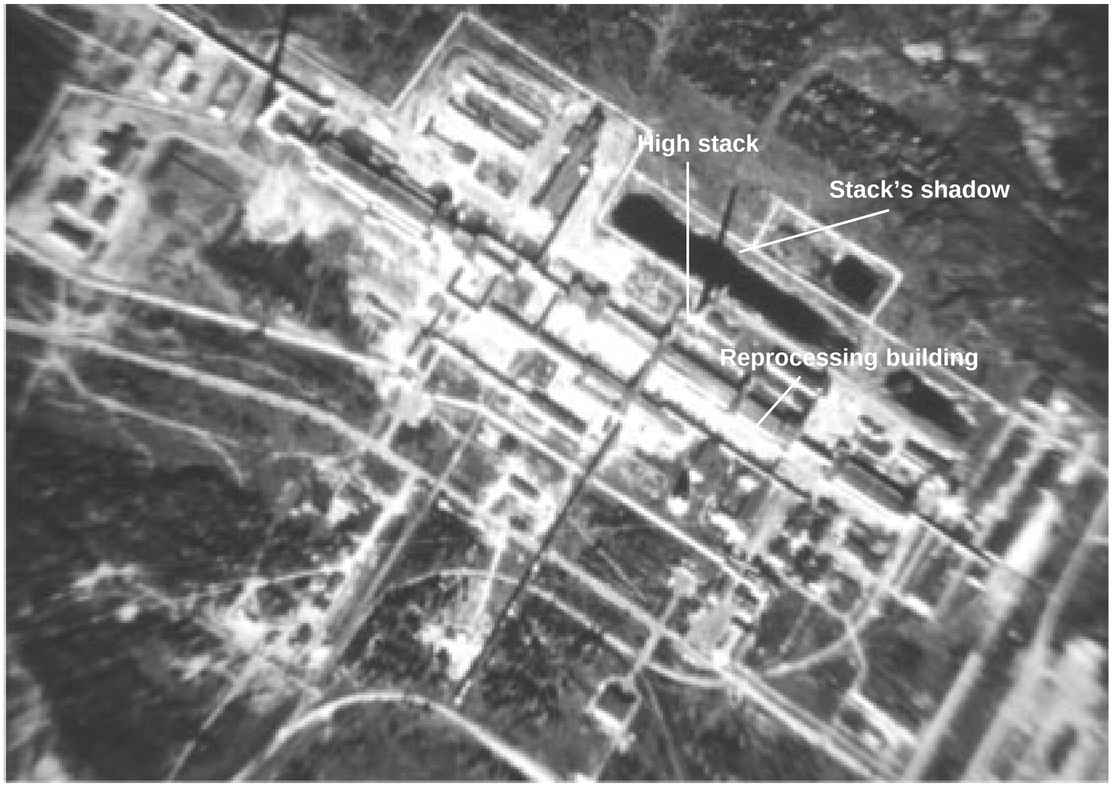

Figure 1: *Declassified US CORONA satellite image of the reprocessing plant at Tomsk-7, Russia.(CORONA mission 1115-1 on September 15, 1971, KH-4B system, six-foot spatial resolution). The long reprocessing building and the high stack (through its shadow) are clearly visible. Source: US Geological Survey, EROS Data Center, Sioux Falls, SD.*

PLUTONIUM PRODUCTION REACTORS

Monitoring the Shutdown Status of Plutonium Production Reactors

Satellite images in the VNIR: Once an FMCT enters into force, most plutonium production reactors will be shut down. It is therefore necessary to determine whether the new-generation commercial satellite images in the visible band can non-intrusively verify that these reactors have really ceased operation.

During operation and for a time after shutdown, removal of heat from the reactor core is essential to prevent a meltdown of the reactor fuel. A variety of cooling systems exist for dissipating the waste heat in the environment; these include the use of cooling towers, cooling ponds, and once-through condenser cooling with river or seawater.[25] The operation of different types of cooling systems can be monitored by satellite images in the visible band.

For reactors using cooling towers, most of these towers are of the "wet" type, which means that their primary heat-removal mechanism is the vaporization of externally supplied water on heat-exchange surfaces. The water requirement for wet-type cooling towers is much smaller than for once-through cooling systems.[26] For this reason, reactors with wet-type cooling towers can be located at a distance from large bodies of water. However, a significantly larger cooling tower is required for a given cooling capacity.[27] Production reactors with wet-type cooling towers generally use natural-draft hyperbolic cooling towers,[28] such as those at the sites of Russia's Tomsk-7, China's Jiuquan, and the United Kingdom's Sellafield and Chapelcross. The natural-draft hyperbolic cooling towers are typically very large: several tens of meters in height and more than 10 meters in diameter at the top. It would be very easy to identify such a large structure using one-meter resolution satellite images.[29]

When a cooling tower is operating, a water-vapor plume will be seen emerging from the top (see Figure

2). Since the air is saturated after it passes through wet packing at the base of the tower and the water cools as it rises through the tower, the vapor plume is supersaturated when it emerges. Downwind from the tower the air mixes with cooler ambient air. How far downwind the mix remains supersaturated depends upon the saturation of this ambient air. In any case, a plume should always be visible from above where it exits the tower.[30] Since the diameter of the tower exit is on the order of 10 meters, the plume should be easy to detect with a one-meter resolution satellite image. Since it requires at least several weeks irradiation to produce a useful concentration of plutonium in reactor fuel,[31] the current commercial satellites' revisit time of several days should be adequate to detect an operating plant.

Figure 3 shows an image taken by a CORONA satellite on September 15, 1971,[32] of two of the five production reactors then operating at the Siberian Chemical Combine (Tomsk-7). All except the first of these reactors (I-1) were equipped with natural-draft hyperbolic cooling towers. The diameter of the tower tops is about 30 meters.[33] The ground resolution in this panchromatic image is about 1.8 meters.[34] The six towers at the upper left and the eight towers at the bottom right are, in all likelihood, allocated to the EI-2 and ADE-3 reactors respectively. EI-2 operated from September 1958 to December 1990 at an average power output of approximately 1,200 megawatts thermal (MWt) and produced about 10 tons of weapons-grade plutonium (WgPu). ADE-3 operated from July 1961 to August 1992 at an average power output of approximately 1,900 MWt and produced about 14 tons of WgPu.[35] The physical structures of the cooling towers and the vapor plumes at their tops can be clearly seen.

The clarity of a commercial satellite image with a one-meter pixel resolution would be comparable. Therefore, I conclude that a one-meter resolution commercial satellite could monitor the shutdown status of reactors with cooling towers. It might also be possible to monitor the frequency of shutdowns of power reactors equipped with cooling towers. Since the fuel is irradiated to much higher burnups in power reactors than in production reactors producing weapons-grade plutonium,[36] continuous operation is important for power production. Hence, frequent shutdowns would raise suspicions that plutonium was being removed from the reactor for weapons purposes.

Some production reactors have a cooling pond or once-through cooling supplied by a river;[37] the P and R reactors at the Savannah River Plant use cooling ponds as their cooling systems. Also reactors with a once-through cooling system supplied by rivers often have a holding pond where the cooling water is pumped before being treated and pumped through the reactor. These holding ponds can also be used for emergency cooling water if the pumps from the river fail. If such a holding or cooling pond were to dry up, that would be a good indication that the reactor remained shutdown. A dried up pond would be easily detected by one-meter resolution VNIR images from the change in the reflectivity of pond.[38]

Satellite images in the TIR: If a reactor has a cooling pond, the pond usually requires a large surface area because cooling ponds have a low heat transfer rate. Estimates suggest that to dissipate 1,000 MWt requires about two to eight square kilometers (km^2) of surface area. Such large areas are easily imaged, even with the poor spatial resolutions of the TIR instruments described above.[39] This capability was demonstrated in 1986 when Landsat-5 thermal images of Chernobyl after the accident showed that all four reactors had been shut down.[40] 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 120-meter resolution, because the warm water flowed over a pond area of more than 10 km^2 before cooling.

Some production reactors have once-through cooling in which water from a river, large lake, or the ocean is used for cooling and then discharged back into to the river downstream of the intake or into the lake or ocean where it will not be taken back into the intake before it has cooled to near equilibrium temperatures. If the body of water is near a steady-state and steady-flow condition, the thermal pattern of the discharged hot water around the outlet is similar to that of the cooling pond. Based on the estimate for the cooling pond, it can be expected that the discharged hot water would cover a large area, large enough for modern TIR commercial satellites to detect. For example, India's Dhruva and Cirus research reactors at Trombay[41] discharge their hot water into the upper Bombay bay. It is quite likely that the hot water plume they release could be detected using Landsat-7 and ASTER, with thermal imagers having resolutions of 60 meters and 90 meters respectively. In fact, even with the relatively poor resolution TIR images of Landsat-5 TM, hot effluents discharged by reac-

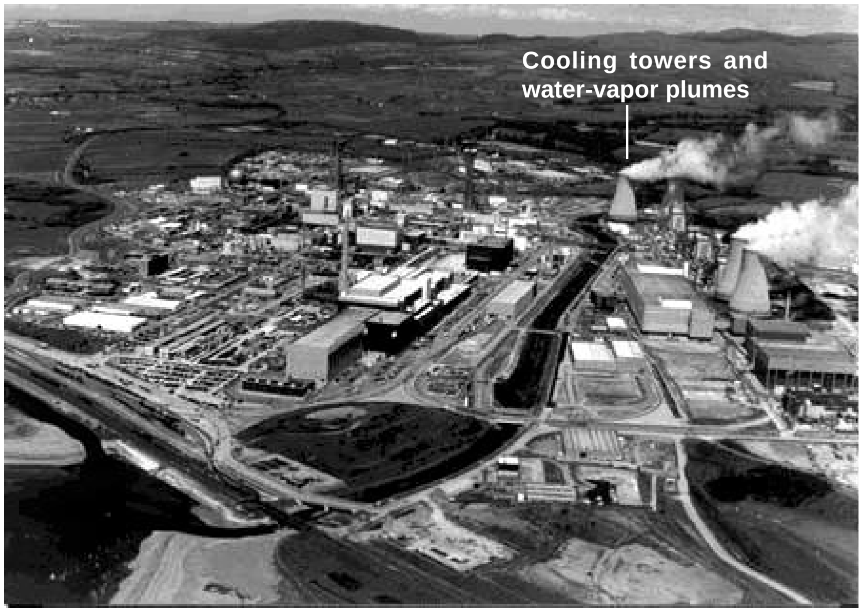

Figure 2: *The four Calderhall Magnox reactors at Sellafield, United Kingdom. These four reactors made a significant contribution to the UK's plutonium for weapons. Now they have stopped producing plutonium for weapons and are producing electricity. The photograph shows the four huge natural-draft hyperbolic cooling towers of the reactors and their water-vapor plumes. Source: http://www.fas.org/nuke/guide/uk/facilit/.*

Figure 3: *Declassified US CORONA satellite image of two Russian plutonium production reactors at Tomsk-7. (CORONA mission 1115-1, September 15, 1971, KH-4B with 1.8-meter resolution). The water-vapor plumes over the operating cooling towers are clearly visible.*

tors into lakes and rivers have been detected. This has been shown by several Landsat-5 TIR images.[42]

As long as the warm water from a reactor is discharged into surface waters, an area of elevated temperatures around the discharge point should be detectable using satellite-borne TIR sensors.[43] Finally, in the case of reactors with cooling towers, existing TIR on Landsat-5 and -7 might detect the warm plume from the towers, though probably not in all cases.[44] However, probability of detection would be high with high-resolution TIR satellites such as ASTER.

Detection of Undeclared Plutonium Production Reactors

To produce plutonium for weapons, a country could operate a dedicated, undeclared production reactor and associated facilities. In the absence of elaborate concealment measures, such a reactor site could be detected and identified using one-meter resolution VNIR satellites. This can be illustrated with CORONA images of China's plutonium production reactor site at Jiuquan Atomic Energy Complex (often referred to as Plant 404). This site, reportedly the first of China's two plutonium production complexes, is located in Subei county in Gansu province.[45] Construction of the reactor started around 1960. By the end of 1966, the reactor had begun to operate. It is a graphite-moderated water-cooled reactor, fueled with natural uranium. The Union of Concerned Scientists, using published information, estimated that the Jiuquan reactor initially had a power of 250 MWt and that this capacity was doubled by the early 1980s.[46] According to a recent report, the Jiuquan plutonium production center was shut down in 1984. It has also been reported that China is preparing to systematically decommission other major military nuclear material facilities, including facilities at the Guangyuan plutonium production complex.[47]

Recently declassified intelligence imagery, collected between 1960 and 1972, shows that US CORONA photoreconnaissance satellites began to target the Jiuquan complex at least as early as December 7, 1960, and thereafter took photos of this area frequently. Figure 4a shows a declassified CORONA satellite image of the Jiuquan nuclear complex taken by a CORONA satellite on May 30, 1972.[48] The physical structure of the six cooling towers can be seen clearly. Even their size can be estimated. Based on KH-4B system parameters, it is estimated that the inside diameter of the tower top is about 20 meters.[49]

Figure 4b shows a KH-4B CORONA satellite image of the Jiuquan reactor taken on December 9, 1969, when the sun was relatively low. The security perimeter fence and the high stack at the site can be identified clearly from their shadows, even though they are too narrow to be visible themselves. The sun angle in combination with

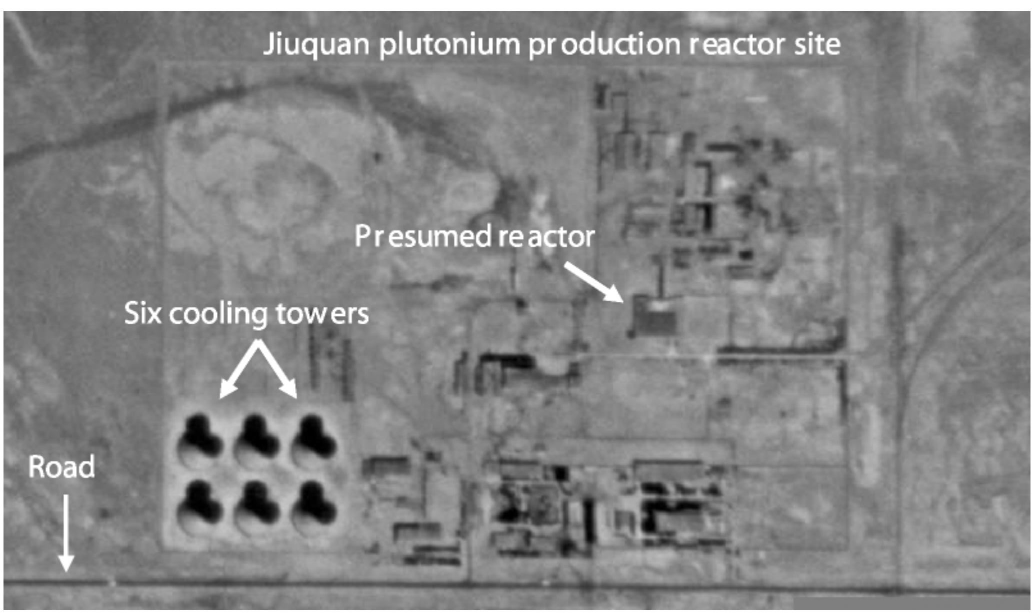

Figure 4a: *Declassified US CORONA satellite image of plutonium production reactor at Jiuquan Atomic Energy Complex, China. (CORONA Mission 1117 on May 30, 1972, KH-4B system, 1.8-meter spatial resolution). The six natural-draft hyperbolic cooling towers are readily visible.*

Figure 4b: *Declassified US CORONA satellite imagery of Jiuquan plutonium production reactor. (CORONA mission 1108-1, December 9, 1969). From this photo, the perimeter fence and high stack are made visible through their shadows.*

the length of the shadow can be used to obtain good estimates of the heights of the stack, cooling towers, and fences. The roads and railway at the site can also be seen in these images.

From an initial study of these declassified CORONA satellite images, it is quite straightforward to identify characteristic features of a military plutonium production reactor site: a cooling system of cooling towers or other water source; a high, narrow stack for safe disposal of leaks of radioactive gases from failed fuel elements; a railroad track reflecting the presence of heavy equipment; and the absence of facilities for storage of coal, gas, or oil, and of high-tension power lines that would be present if the site were a commercial power plant.

URANIUM ENRICHMENT PLANTS

Monitoring the Shutdown Status of Gaseous Diffusion Plants

Satellite images in the VNIR: To acquire weapons-usable HEU, it is necessary to operate a uranium enrichment facility. All known uranium enrichment plants in target states are either gaseous diffusion or gas centrifuge plants. However, research and development (R&D) on laser enrichment is well advanced in a number of countries. Under an FMCT, it can be expected that most military gaseous diffusion plants (GDPs) would be shut down.[50]

Because the degree of enrichment that can be achieved in a single diffusion stage is very small, to achieve a useful amount of enrichment, a gaseous diffusion cascade must have many stages.[51] A typical GDP covers many hectares of floor space and requires large amounts of electrical power—generally between 2.3 and three megawatt hours for every kilogram-Separative Work Unit (kg-SWU) produced.[52] Each stage in the cascade has at least one compressor to force the uranium hexafluoride (UF_6) through the diffusion barriers. More than 90 percent of the electrical energy is converted into compression heat that is dissipated by the plant cooling towers or by the discharge of cooling water into a local body of water. A GDP cannot operate without one of these heat sinks.

Most GDPs, other than those in Russia, have wet cooling towers.[53] If a GDP, such as the United Kingdom's Capenhurst, has natural-draft cooling towers, it will be very easy to identify such large structures using one-meter resolution satellite images. When a natural-draft cooling tower is operating, a white water-vapor plume will ordinarily be seen emerging from its top.

Air discharged by mechanical-draft cooling towers is also usually saturated. Thus, a visible plume is ordinarily formed when the warm, humid air leaving the tower mixes with colder atmospheric air, leading to super saturation and condensation of small water droplets. The plume can be quite long when the ambient air is near saturation.

Figure 5 shows a Landsat-5 visible band thermal image of the US uranium GDP at Portsmouth, Ohio, taken on February 16, 1991. The enrichment "cascade" is contained in three large, two-story buildings identified as X-333, X-330, and X-326. In all three buildings, the equipment used to separate the gases, and associated valves and piping, are located on the upper floors. Building X-333, which contains 640 stages, is 25 meters high, and has an area of 0.1 km^2 (440 meters by 300 meters). Building X-330, housing 1,100 stages of intermediate size, is 20 meters high and has an area of 0.13 km^2 (660 meters by 200 meters). Finally, building X-326, which houses 2,280 small stages, including the high-enrichment end of the cascade, is 19 meters high and has an area of 0.12 km^2 (680 meters by 170 meters). Each process building has its own cooling system that dissipates the waste heat into the environment through mechanical cooling towers. Even though the spatial resolution of the image is only 30 meters, the plumes from the towers can be seen clearly. The plume images would be much clearer in a one-meter resolution satellite image.

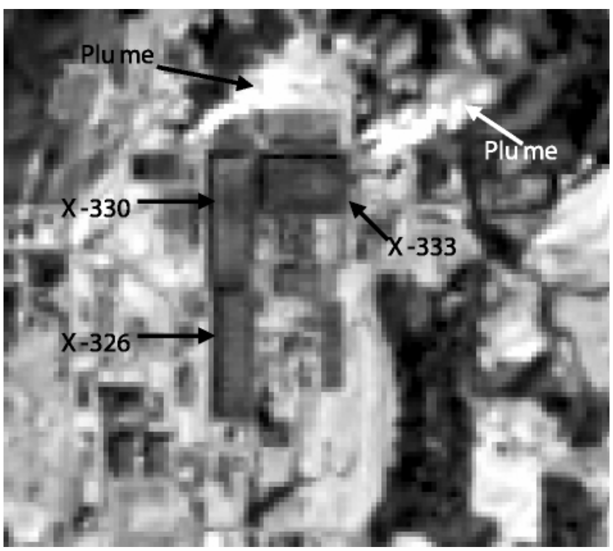

Figure 5: *Landsat-5 TM visible image of Portsmouth GDP taken on February 16, 1991. The plumes from the mechanical cooling towers at the northwest and northeast corners of the processing buildings can be easily detected. Source: US Geological Survey.*

Because of their large inventory of in-process UF_6, the time required for GDPs producing 90-percent enriched uranium-235 to reach equilibrium is about two to three months.[54] A satellite revisit time of several days should therefore be adequate for detection of GDP operation.

TIR imaging of cooling tower vapor plumes: The visible plume from a cooling tower is usually at least a few degrees centigrade warmer than the ambient air. The size of the area it covers depends upon the humidity of the ambient air and other factors.[55] If the plume is warmer than the ground below and has an area comparable to the instantaneous field of view (IFOV) of a pixel in the TIR sensor, the temperature difference should easily be detectable by the sensors on Landsat-5 and -7. These sensors have relative temperature resolutions of better than one degree Celsius.[56] If the size of the plume is smaller than the IFOV of a pixel, then it will be detectable if its relative temperature is high enough to drive the average effective relative temperature detected by the pixel above its detection threshold.[57] For example, in the case of the natural-draft cooling towers of the Capenhurst GDP in the United Kingdom, it can be expected that the existing TIR of Landsat-5 and -7 might detect the plume from the towers, and the TIR of ASTER could more easily detect it.[58]

The area of the top of each tower vent of a mechanical-draft cooling tower is smaller than that of a single natural-draft tower. However, each tower building usually contains an array of tower cells. So the detection of

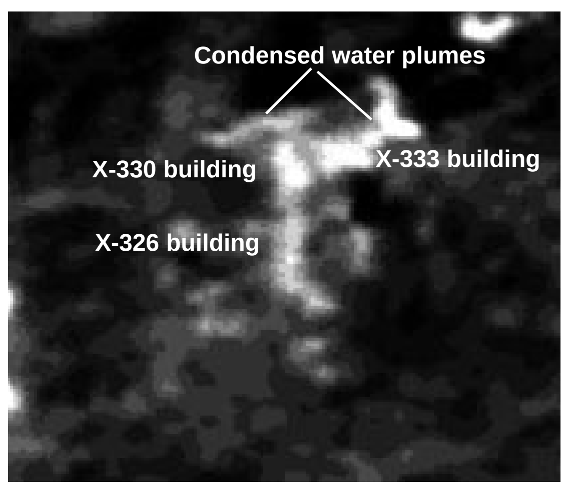

Figure 6: *Landsat-5 TIR image of Portsmouth GDP taken on February 16, 1991, showing the condensed water plumes observed to the northeast and northwest of the process buildings in the counterpart visible image (Figure 5).*

the warm plume will depend on the effective area (the total area of the tower cells within one pixel) and the size of the visible plume.

Figure 6 shows a TIR image of Portsmouth GDP taken by Landsat-5 on February 16, 1991. This image shows the condensed water plumes observed to the northeast and northwest of the processing building in the counterpart visible image (see Figure 5). Consequently, it can be expected that the existing TIR on board satellite LandsatTM could detect the plume from the cooling towers. The probability of detection will be high with a high-resolution TIR satellite such as ASTER.

TIR imaging of the hot roof of a GDP processing building: Most of the waste heat from a GDP is discharged from its cooling towers. However, since the temperature in the spaces housing the cascades must be kept much higher than that of ambient air,[59] the roof above can be expected to be much hotter than ambient air when the GDP is operating. Because of the large area of GDP processing buildings, this elevated temperature might be detectable using the TIR images of a commercial satellite.

Figure 7 shows a Landsat-5 thermal image of the three processing buildings of the Portsmouth GDP taken on March 12, 1994. The GDP consumes about 2,260 MWe when operating at its full separative capacity of about 8.3 million SWU/yr.[60] This corresponds to a power consumption per unit area in the processing buildings of about six kW/m^2. The Portsmouth GDP processing buildings are so huge that each can cover the IFOV of several Landsat-5 pixels, and they are so hot that there is no question that their temperature elevation is detectable when the compressors inside are operating.[61] As shown in Figure 7, the roofs of the process buildings are clearly visible. Based on these images, I expect that the TIR images obtained with ASTER will clearly show the warmth of the processing buildings under virtually all conditions when the GDP is operating.

I would also expect that the hot roof of a medium GDP, such as China's GDP at Lanzhou, would be detectable by TIR images. China's Lanzhou GDP (Plant 504) in Gansu Province provided that country's first source of weapons-grade uranium, starting in mid-January 1964. It is located on the bank of the Yellow River near Lanzhou. Published estimates put its initial capacity at 10,000 to 50,000 (later increased to about 300,000) kg-SWU per year.[62]

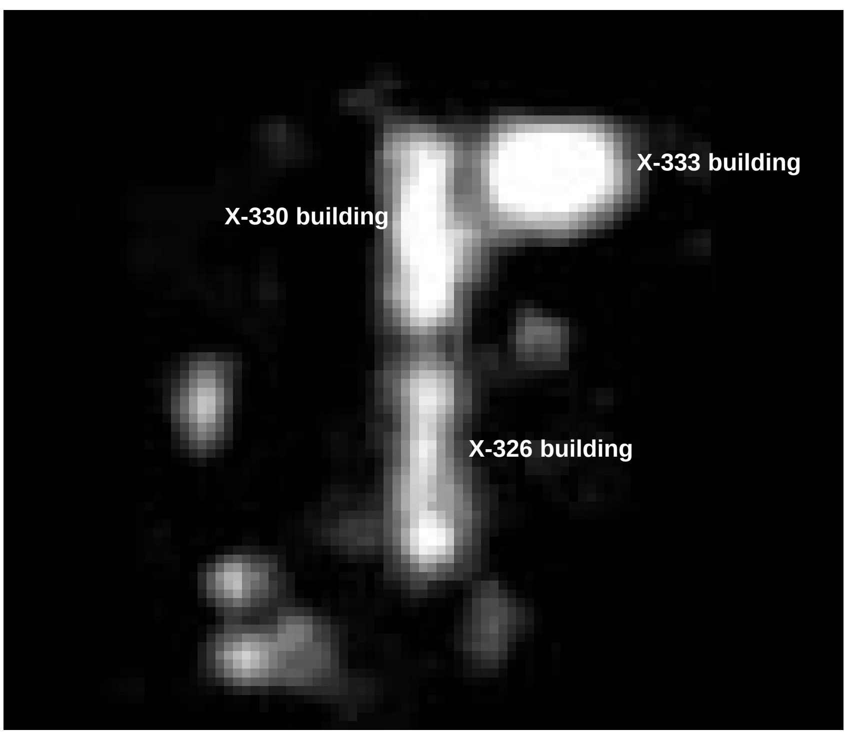

Figure 7: *Landsat-5 TIR image of Portsmouth GDP taken March 12, 1994. The hot roofs of buildings X-333, X-330, and X-326 are clearly visible.*

From a recently declassified CORONA satellite image of the Lanzhou GDP taken on March 31, 1971, it is estimated that the enrichment building is about 600-meters long and 60-meters wide.[63] At its maximum capacity, for a specific energy consumption of 2.5 MWh/kg-SWU, the power consumption of the plant would be 86 MWe (which would produce excess heat of 77 MW), or about 2.4 kWt/m^2.

The 60-meter width of the Lanzhou plant means that it cannot completely fill the IFOV of Landsat-5 or ASTER pixels (120 and 90 meters wide respectively). This will require more heat flux from the roof to be detected by the TIR sensor. If the energy consumption per unit area of the process buildings of the Portsmouth GDP is just above the threshold sensitivity of the Landsat-5 TIR detector, the TIR of Landsat-5 could have difficulty in detecting the heated roof of the process building of the Lanzhou GDP.[64] However, the TIR detectors of Landsat-7 and ASTER should be able to detect it. Similar analyses could be carried out for the United Kingdom's Capenhurst and France's Pierrelatte GDPs.

It should also be noted that, just as with nuclear reactors, the hot-water plumes from the once-through cooling of GDPs should be detectable by TIR imaging of the rivers or other bodies of water into which the hot water is discharged.

Detectability of Centrifuge Enrichment Plants (CEPs) in the TIR: Under an FMCT, nations can be expected to continue to operate large CEPs to produce low-enriched uranium for nuclear power plants. As at operating GDPs, on-site verification measures will be required to verify that HEU is not being produced in these plants. Small uneconomic CEPs, such as that operated by Pakistan at Kahuta, might 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. To detect such a thermal signature, 20-meter spatial resolution and 0.1^{0}K temperature accuracy would be required.[65] This could be accomplished by using the same optics as satellites with one-meter resolution at visible wavelengths.

Detection of Undeclared GDPs

An analysis of the declassified CORONA images of China's Lanzhou GDP and Russia's GDPs[66] suggests common characteristics of a GDP. An undeclared GDP's structural integrity and layout would include multiple large-area processing buildings (the roofs of most buildings have ventilation shafts); cooling towers or a nearby river or lake (with intake and discharge ports); a nearby fossil-fuel power plant to supply the enrichment complex with hot water and electricity; high-voltage power lines to transmit this electric power; a large electric switchyard (substation); waste management and disposal facilities, such as a liquid-waste discharge area; and holding ponds at some enrichment sites. Finally, all these sites are usually located in an isolated area away from cities and with a security perimeter. All these characteristic features could provide targets for satellites' searching areas. In addition to these characteristic features visible on satellite images in the visible band, when these nuclear facilities operate, discharged heat effluents could be detected by thermal infrared imaging as discussed above.

Undeclared nuclear facilities and sites could also be detected by commercial satellite imagery during their construction. A CORONA image of China's Jiuquan reactor site taken by the KH-4A system on October 7, 1965, clearly shows that four cooling towers had been finished, and two were under construction. Another CORONA image taken by a KH-4B satellite on September 18, 1967, shows that all six cooling towers had been finished. This is consistent with the report that the Jiuquan reactor began its operation at the end of 1966.[67] Of course, reactor construction includes a great many activities, such as the shipment of heavy components. Large trucks should be big enough to be identified in one-meter resolution VNIR images. Such activities would take place for a considerable period of time. It has been estimated that even a small, simple, graphite-moderated, air-cooled, 30-MWt production reactor able to produce about nine kilograms—or about one bomb's worth of plutonium—per year would take about three years to construct.[68]

Similarly, the construction of a reprocessing plant or a GDP also involves a great many activities (such as the shipment of various materials), and also takes a long period of time. So commercial satellites with several days' revisit time and one-meter resolution could detect these facilities and activities.

Moreover, the information provided by satellite images could be used to trigger on-site special inspections. For example, US satellite photos taken around the declared nuclear sites at Yongbyon, North Korea, triggered the IAEA's request to inspect two suspected waste sites and one building suspected of being used for reprocessing activities near the Radiochemical Laboratory at Yongbyon.[69]

CONCLUSION

I conclude that the shutdown status of a reprocessing plant could be monitored by high-spatial-resolution VNIR images. Whether or not a production reactor or a GDP is operating can be monitored effectively using a commercial observation satellite with one-meter resolution VNIR images and/or by the new satellites, such as Landsat-7 and ASTER, taking TIR images. These satellites can also be useful for the detection of undeclared nuclear production facilities and suspicious construction activities. Therefore, the new generation of commercial observation satellites could play a valuable role in the verification of an FMCT. According to the legal regime of the Outer Space Treaty of 1967, satellites for verification are protected by the understanding that outer space is open to all nations or groups to be used for peaceful purposes.[70] Consequently, the use of observation satellites to verify multilateral agreements would be politically acceptable and technically feasible. However, satellite imagery is only one tool of many for FMCT verification, and its use should be considered in combination with other verification means.

There is a potential concern that a nation could enter into an exclusive arrangement with the operator of a commercial satellite to buy all images of sensitive sites and thus to deny these images to other organizations. To promote equality and minimize political disputes, an international verification agency could own one or more dedicated observation satellites.[71] In fact, since 1978, France has proposed an International Satellite Monitoring Agency. Canada and Sweden have since also proposed similar concepts.[72] One of the greatest obstacles to using satellite imagery could be the financial cost of acquiring large volumes of images and training analysts to interpret them; to be effective, the monitoring process will have to involve large numbers of people and large amounts of equipment. As more and more commercial satellite companies enter the market, however, the competition could reduce these costs. Furthermore, the financial cost of satellite imagery would probably be outweighed by the potential benefits of its use for FMCT verification.

---

[1] George Bunn, "Making Progress on a Fissile Material Cut-Off Treaty After the South Asian Tests," *The Nonproliferation Review* 5 (Spring-Summer 1998), p. 81. For background information on the FMCT, see The Acronym Institute, "The Fissile Material Treaty," <http://www.acronym.org.uk./fmctdesc.htm>.

[2] The plutonium could be any isotopic composition (except that containing 80 percent or more of the isotope plutonium-238). HEU is defined as uranium enriched to over 20 percent in the isotope uranium-235. I know of no deployed nuclear weapon that uses uranium-233; I do not discuss this fissile material further.

[3] Although India and Pakistan conducted nuclear tests in May 1998, they were not chartered as nuclear weapon states by the NPT. Here I will call them de facto nuclear weapon states.

[4] "Fissile Materials: Scope, Stocks and Verification," UNIDIR *Disarmament Forum* 2 (1999), <http://www.unog.ch/UNIDIR/E-DF2.htm>.

[5] International Atomic Energy Agency, "The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons," IAEA Information Circular (INFCIRC)/153 corrected, Vienna, June 1972, <http://www.iaea.org/worldatom/infcircs/inf101-200.html>.

[6] US Congress, Office of Technology Assessment, "Nuclear Proliferation and Safeguards," (Washington, DC, 1995).

[7] International Atomic Energy Agency, "INFCIRC/540: Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards," Vienna, 1997, <http://www.iaea.org/worldatom/infcircs/inf501-600.html>.

[8] That is, the "pixel" size is 80 meters. The spatial resolution definition used in this paper is the same as that used for electro-optical sensors: the size of the smallest area on the ground that is sampled by one picture element in the system's detector array. This is referred to as the "instantaneous field of view" (IFOV). Thomas M. Lillesand and Ralph W. Kiefer, *Remote Sensing and Image Interpretation* (New York: John Wiley & Sons, Inc., 1994).

[9] For commercial information on IRS-1C and IRS-1D satellites, see <http://www.euromap.de/doc_004.htm> and <http://www.euromap.de/doc_005.htm>.

[10] For commercial information on the Spin-2 satellite imagery, see <http://www.spin-2.com/pan.html>.

[11] US White House, "Fact Sheet on US Policy on Foreign Access to Remote Sensing Space Capabilities," March 10, 1994, p. 1.

[12] A panchromatic sensor takes a single image of an observed object by collecting light over a wide wavelength band. It is usually referred to as "black and white" mode. A multispectral sensor takes a separate image of an observed object for each narrow wavelength band of light it is designed to detect.

For commercial information on the IKONOS satellite, see <http://www.spaceimaging.com/aboutus/satellites/IKONOS/ikonos.html>. In recently released IKONOS imagery of Beijing, China, one could readily discriminate between trucks, buses, and automobiles, and pedestrians were easily detectable as well.

[13] See the West Indian Space website, <http://www.westindianspace.com/>.

[14] US KH-12 satellites, first launched in November 1992, can reportedly achieve 10-cm resolution images in the visible spectrum. They also carry TIR imaging systems. If the TIR system uses the same optical system, its resolution could be as good as two meters. For further information, see the Federation of American Scientists website, <http://www.fas.org/spp/military/program/imint/kh-12.htm>.

[15] The use of these satellites for treaty verification has been examined in previous studies. See Michael Krepon et al., *Commercial Observation Sat-*

ellites and International Security (New York: St. Martin's Press, Inc., 1990); Michael Slack et al., *Open Skies-Technical Organizational, Operational, Legal and Political Aspects* (Toronto: York University, 1990); Michael Krepon et. al., *Open Skies, Arms Control, and Cooperative Security* (New York: St. Martin's Press, Inc., 1992); Vipin Gupta and Frank Pabian, "Commercial Satellite Imagery and the CTBT Verification Process," *The Nonproliferation Review* 5 (Spring-Summer 1998).

[16] John Diamond, "Declassified Spy Photos Studied," Associated Press, February 17, 1999, <http://www.fas.org/nuke/guide/russia/facility/nuke/index.html>.

[17] The KH-4B cameras took images on photographic film. For such a system, the most common definition is based on the number of equidistant dark bars, in a standard resolution target, which can be resolved per millimeter of film. Approximately one line-pair is necessary to detect an object. For a digital imaging system, the spatial resolution definition is referred to as the IFOV (see note 8), or one pixel size. This depends on not only 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 one-meter (three-foot) resolution images (one pixel) of the commercial satellites are comparable to the 1.8-meter (six-foot) resolution images of the KH-4B. However, using digital image processing techniques, the one-meter resolution images of the new commercial satellites can be made to appear clearer than those from the KH-4B satellites.

[18] Lillesand and Kiefer, *Remote Sensing and Image Interpretation*; G. E. Wukelic et al., "Radiometric Calibration of Landsat Thematic Mapper Thermal Band," *Remote Sensing of Environment* 28 (1989), p. 339.

[19] For information on the ETM+, see <http://ls7pm3.gsfc.nasa.gov/science.html>.

[20] See <http://asterweb.jpl.nasa.gov/>.

[21] For more information on the MTI, see <http://nis-www.lanl.gov/nis-projects/mti>.

[22] Gordon Thompson**,** "Verification of a Cut-off in the Production of Fissile Material," in Frank Barnaby, ed., *A Handbook of Verification Procedures* (New York: Macmillan, 1990).

[23] Nils Bøhmer and Thomas Nilsen, "Reprocessing Plants in Siberia," Bellona Working Paper 4 (1995).

[24] For example, for the PUREX plant, the stack is 61 meters (200 feet) tall, with a 2.1-meter (seven-foot) inner diameter. See R. A. Libby, W. D. Stanbro, J. E. Segal, and C. Davis, *Hanford PUREX Exercise-March 29 to 31,1994, Special Nuclear Material Cutoff Exercise: Issues and Lessons Learned*, Vol. 2 (Richmond, WA: Pacific Northwest Laboratory, August 1995), PNL-10705, UC-515.

[25] Kam W. Li and A. Priddy, *Power Plant System Design* (New York: John Wiley & Sons, 1985).

[26] The evaporation of a kilogram of water at 25°C absorbs about 2.4 megajoules (Mj). The warming of a kilogram of water by 10 °C absorbs only two percent as much heat: 42 kilojoules (Kj).

[27] Heating a kilogram of dry air at 20°C by 10°C absorbs 10 kJ. Adding water to keep it saturated requires the evaporation of 12 grams of water, absorbing an additional 28 kJ.

[28] Israel's Dimona reactor and Pakistan's Khushab reactor use mechanical-draft cooling towers. In both cases, air circulation through the tower results at least in part from the buoyancy of the heated air, which creates a chimney effect. Towers that rely solely on this buoyancy effect are classified as natural-draft towers. When large fans are used to increase the airflow through the tower, the tower is classified as a mechanical-draft tower

[29] It is generally agreed that three to five resolution elements of pixel are required to recognize a detected feature and up to 10 elements are required to describe a feature or object. See also R. Ondrejka**,** " Imaging Technology," in Kosta Tsipis et al., eds., *Arms Control Verification: The Technologies That Make it Possible* (Washington, DC: Pergamon-Brassey's International Defense Publishers, 1986).

[30] Hui Zhang and Frank von Hippel, "Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Uranium-Enrichment Gaseous Diffusion Plants," *Science and Global Security* 8 (June 2000).

[31] For a commercial light-water power reactor, the typical specific power is about 30 MWt per metric ton (Mt) of fuel. Production reactors usually have much lower specific powers. Achieving a typical burnup of 1,000 MWt-days/ton to produce weapon-grade plutonium would therefore require more than 33 days.

[32] Federation of American Scientists website, <http://www.fas.org/nuke/guide/russia/facility/nuke/tomsk-7/index.html>.

[33] Private communication with Oleg Bukharin, Center for Energy and Environmental Studies, Princeton University, 1999.

[34] From the recent declassified collection of KH-1 to KH-6 photos for the period 1960 to 1972. This photo was taken by the KH-4B satellite. A directory to these photos was shown on the US Geological Survey website, <http://edcwww.cr.usgs.gov/glis/hyper/guide/disp>.

[35] Bohmer and Nilsen, "Reprocessing Plants in Siberia;" David Albright et al., *Plutonium and Highly Enriched Uranium 1996-World Inventories, Capabilities and Policies* (Oxford: Oxford University Press, 1997).

[36] The burnup required to produce weapon-grade uranium in natural-uranium fueled production reactors is about 1,000 MWt-days/ton. Power reactors are designed to fission most of the uranium-235 in their fuel. This corresponds to burnups of about 7,000 MWt-days/ton for natural-uranium-fueled power reactors and 30,000-60,000 MWt-days/ton for reactors fueled with three to six percent enriched uranium.

[37] Some production reactors have used cooling ponds in which the water that cools the reactor directly or indirectly is cycled through a pond from whose surface the heat is dissipated via evaporation, convection and radiation (see Li and Priddy, *Power Plant System Design*). In other cases, a "once-through" system is used in which water is withdrawn from a river and discharged downstream or is drawn from a lake or estuary so large that the temperature of the intake water is not significantly affected by the hot water discharged by the reactor.

[38] For details, see Zhang and von Hippel, "Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Uranium-Enrichment Gaseous Diffusion Plants."

[39] Ibid.

[40] *United States Army Multispectral Imagery Product Guide,* Second Edition, ATC-IA-2681-030-94, May 1994.

[41] The Cirus and Dhruva reactors use natural uranium fuel and a heavy water moderator. The 40 MWt Cirus reactor began operation in 1960; the 100 MWt Dhruva reactors started in August 1985. Both reactors produce plutonium for India's nuclear weapons. They are still in operation without IAEA safeguards. Bhabha Atomic Research Center, "Research Reactors at Trombay," Bombay-400 085 (July 1987).

[42] For example, two Landsat-5 TM images of the "Mayak" plutonium production complex at Ozersk (Chelyabinsk-65) in the Urals, acquired on August 1, 1987 and May 13, 1993 were analyzed by Bhupendra Jasani and Alan Blackburn. Water from Lake Kyzyltash was used to cool the reactors. In the 1987 thermal image, a plume of warm water can be clearly seen extending north for a considerable distance along the eastern fringes of Lake Kyzyltash. The surface temperature of the water within this plume is a maximum of 10°C warmer than that of the bulk of water in the lake. In the 1993 thermal image of Lake Kyzyltash, the warm plume of effluent water is still evident, and is in fact larger in spatial extent and thermal magnitude, being a maximum of 15°C warmer than the bulk of water. Bhupendra Jasani and Alan Blackburn, " Piercing into Secret Nuclear Establishment Using Imagery from Civil Satellites," in Paul Curran and Colette Robertson, eds., *Proceedings of the 21st Annual Conference of the Remote Sensing Society*, September 11-14, 1995.

[43] It is should be noted that in theory at least a discharge might be concealed by releasing it through a long pipe with many holes along its length laid in deep water so that a mix results with a temperature which is not detectably warmer than that of the surface waters above.

[44] The LandsatTM detectors do not detect plumes from some towers. A test was done by the Carnegie Endowment's Nonproliferation Project in which they requested an operating history for a 60 MW research reactor operated at Brookhaven National Lab near New York City along with Landsat images taken of the reactor on two days, one when the reactor was operating,

and one when it was shut down. This reactor uses closed cooling towers (presumably wet-type cooling towers) to dissipate heat. The Landsat-5 TIR did not find convincing evidence of the thermal signature when the reactor was operation. See Leonard Sandy Spector, "Monitoring Nuclear Proliferation," in Michael Krepon et al., eds., *Commercial Observation Satellites and International Security* (Carnegie Endowment for International Peace, 1990).

[45] The second site where weapons plutonium has been produced is in Guangyuan county in Sichuan province and reportedly began operation in early the 1970s. See Robert S. Norris et al., *Nuclear Weapons Databook Volume V: British, French, and Chinese Nuclear Weapons* (Boulder: Westview Press, 1994).

[46] David Wright, Lisbeth Gronlund, and Ying Liu, "Estimating China's Stockpile of Fissile Materials for Weapons," Draft, Union of Concerned Scientists Technical Working Paper (Washington, DC, April 1996).

[47] Mark Hibbs, "China Said to be Preparing for Decommissioning Defense Plants," *Nuclear Fuel*, May 17, 1999.

[48] See Federation of American Scientists website, <http://www.fas.org/nuke/guide/china/facility/jiuquan.htm>.

[49] The reported best ground resolution is 1.8 meters in the panchromatic mode; the frame format of the film is approximately 2.18 inches by 29.8 inches; the normal photo scale on film is 1:24,500; and normal ground coverage in an image frame is therefore about 14x190 km.

[50] See Hui Zhang and Frank von Hippel, "Using Commercial Observation Satellites to Verify that Uranium-Enrichment Gaseous Diffusion Plants Are Not Operating," CEES Report, No. 323, Princeton University.

[51] For example, the enrichment of natural uranium to "weapon-grade" (94 percent U-235) with 0.25 percent U-235 being left in the depleted uranium requires about 4,000 stages.

[52] S. Villani, "Uranium Enrichment" in *Topics in Applied Physics* Vol. 35 (New York: Springer-Verlag, 1979), pp. 167-170. The separative work D, in kg-separative-work units (SWUs) is given by D = WV(ew) +PV(ep) – F(ef) where P is the mass of product in kg, W of waste depleted uranium and F of feed – all in kg. V(e) = (2e – 1)ln[e/(1-e)] and ep, ew, and ef are the fractional enrichments of the product, waste and feed streams.

[53] Zhang and von Hippel, "Using Commercial Observation Satellites to Verify that Uranium-Enrichment Gaseous Diffusion Plants are Not Operating."

[54] The equilibrium time for a uranium enrichment cascade is the time required to reach the first production of uranium at the design product assay, starting with the cascade initially filled with inventory at the feed assay.

[55] Zhang and von Hippel, "Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Uranium-Enrichment Gaseous Diffusion Plants."

[56] Only the visible plume would be detected, even though the invisible unsaturated plume beyond it would be warm for some distance as well. The reason is that water droplets radiate with a continuous spectrum, some of which falls in the atmospheric transmission "window," while water molecules radiate at discrete wavelengths that are absorbed by cooler water molecules in the air layer above.

[57] The detection threshold Dth = Ap*Tth where Ap is the instantaneous field of view (IFOV) of a pixel on the sensor and Tth is the threshold temperature accuracy of the sensor. The Dth for the TIR detectors on Landsat-5, -7, and ASTER is: 7-14,000, 2-4,000, and 1,600 m^2-^{0}C respectively. See details in Zhang and von Hippel, "Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Uranium-Enrichment Gaseous Diffusion Plants."

[58] Considering the natural-draft cooling towers of the Capenhurst GDP: The temperature difference between the plume and the ambient air, Tp - Ta, is on the order of 10^0C and the area (A) of each cooling tower top is about 80 m^2. The product A*(Tp - Ta) is therefore on the order of 800m^2-^{o}C. The IFOV of one pixel of Landsat-5 could contain five operating towers. If the areas of their visible plumes were four times larger than the areas of the towers' tops, the heat of the combined plumes would be at or above the detection threshold of the Lansat-5 TIR imager. The IFOVs of one pixel of Landsat-7 and ASTER could contain three and two towers respectively.

[59] The lowest UF_6 temperature for a GDP must be safely above the UF_6 condensation or freezing temperature. Consequently, the operating temperature for the process gas is typical above 70^0C (158^0F). For example, for the GDP at France's Tricastin site, the air temperature in sections of the building containing the cascades must be kept at 80^0C (176^0F). See M. Molbert, "The Eurodif Program," in J. Robert Merriman et al. eds., *Recent Developments in Uranium Enrichment*, Vol. 78 (New York: American Institute of Chemical Engineers, 1982), p. 221.

[60] Brookhaven National Laboratory, *Transparency Measures for DOE SNM Production Facilities*, SSN 93-7, December 1993.

[61] For a thermal emissivity of one, the threshold sensitivities of the TIR detectors are 0.5-1 ^{0}C for Landsat-5, and -7, and 0.2 ^{0}C for ASTER–corresponding to radiation flux increases of 3-6 and 1Watt/m^2 respectively–less than one thousandth of the power consumption of the plant. See Zhang and von Hippel, "Using Commercial Observation Satellites to Verify that Uranium-Enrichment Gaseous Diffusion Plants are Not Operating.")

Note that during the day, the temperature of the roof of the GDP might be different from that of the surrounding area due to its differing solar absorption, and during the night it might cool down at a different rate because of its different rate of emission, thermal conductivity, and wind exposure. Therefore, to assure detection of a GDP's operation would likely require a greater increase in the roof's temperature than the threshold value estimated above.

[62] Albright, *Plutonium and Highly Enriched Uranium 1996*, p.127.

[63] Zhang and von Hippel, "Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Uranium-Enrichment Gaseous Diffusion Plants."

[64] A Landsat-5 TM thermal image of Lanzhou GDP was acquired by the author on February 3, 1989. However, I did not find evident thermal signatures from the roof. It is possible that the plant was not operating. It is also possible, however, that it was operating and the pixel average radiated power was below the discrimination threshold of the Landsat-5 TIR detector.

[65] Zhang and von Hippel, "Using Commercial Observation Satellites to Verify that Uranium-Enrichment Gaseous Diffusion Plants are Not Operating."

[66] Ibid.; also, see Federation of American Scientists website, <http://www.fas.org/nuke/guide/russia/facility/nuke/index.html>.

[67] Zhang and von Hippel, "Using Commercial Imaging Satellites to Detect the Operation of Plutonium-Production Reactors and Uranium-Enrichment Gaseous Diffusion Plants."

[68] United State Congress, Office of Technology Assessment, *Nuclear Proliferation and Safeguards* (New York, 1977), pp. 94-98.

[69] David Albright, "North Korean Plutonium Production," *Science & Global Security* 5 (1994).

[70] US Arms Control and Disarmament Agency, *Arms Control and Disarmament Agreements: Texts and Histories of the Negotiations* (Washington, DC: Government Printing Office, 1996).

[71] Hui Zhang, "A View on the Application of Overhead Imagery to Strengthen the IAEA Safeguards Regime," in J. Marshall Beier and Steven. Mataija, eds., *Arms Control and The Rule of Law: A Framework for Peace and Security in Outer Space* (Toronto: York University, 1998).

[72] Johan Swahn, "Open Skies for All: the Prospects for International Satellite Surveillance," *Report of the Technical Peace Research Unit*, Chalmers University of Technology, Goteborg, Sweden (1989).