Guidance for
High Temperature Gas Reactors (HTGRs) with Prismatic Fuel
Safeguards-by-Design: Guidance for High Temperature Gas Reactors (HTGRs) With Prismatic Fuel

Philip Casey Durst (INL Consultant)

August 2012
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With Prismatic Fuel

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August 2012

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<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3DLR</td>
<td>(IAEA) 3-Dimensional Laser Range Finder</td>
</tr>
<tr>
<td>AFR</td>
<td>(IAEA) Away-From-Reactor Storage Facility for spent fuel, also known as an ISFSI</td>
</tr>
<tr>
<td>ALARA</td>
<td>As Low as Reasonably Achievable (radiation exposure guidelines)</td>
</tr>
<tr>
<td>Amp</td>
<td>Amperes (electrical current)</td>
</tr>
<tr>
<td>AP</td>
<td>(IAEA) Additional Protocol (see also INFCIRC/540)</td>
</tr>
<tr>
<td>AWCC</td>
<td>(IAEA) Active Well Coincidence Counter</td>
</tr>
<tr>
<td>BARC</td>
<td>Bhabha Atomic Research Centre (India)</td>
</tr>
<tr>
<td>BISO</td>
<td>Bi-layer coating for fuel particles used in high temperature reactors</td>
</tr>
<tr>
<td>BOG</td>
<td>IAEA Board of Governors</td>
</tr>
<tr>
<td>CA</td>
<td>(IAEA) Complementary Access (under the Additional Protocol)</td>
</tr>
<tr>
<td>CAPS</td>
<td>(IAEA) Metal cap and wire seal</td>
</tr>
<tr>
<td>CNEC</td>
<td>China Nuclear Energy and Construction Group (CNEC)</td>
</tr>
<tr>
<td>cm</td>
<td>Centimeters</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DCVD</td>
<td>Digital Cerenkov Viewing Device</td>
</tr>
<tr>
<td>DIE</td>
<td>(IAEA) Design Information Examination</td>
</tr>
<tr>
<td>DIQ</td>
<td>(IAEA) Design Information Questionnaire</td>
</tr>
<tr>
<td>DIV</td>
<td>(IAEA) Design Information Verification</td>
</tr>
<tr>
<td>DOE</td>
<td>U. S. Department of Energy</td>
</tr>
<tr>
<td>EOSS</td>
<td>(IAEA) Next Generation Electro-Optical Sealing System</td>
</tr>
<tr>
<td>ES</td>
<td>(IAEA) Environmental (Swipe) Sampling</td>
</tr>
<tr>
<td>HEU</td>
<td>Highly Enriched Uranium (U-235 ≥ 20%)</td>
</tr>
<tr>
<td>HM-5</td>
<td>(IAEA) Hand-held Radiation Meter Model #5</td>
</tr>
<tr>
<td>HRGS</td>
<td>(IAEA) High Resolution Gamma Spectrometer</td>
</tr>
<tr>
<td>HTGR</td>
<td>High Temperature Gas Reactor (generic)</td>
</tr>
<tr>
<td>HTR</td>
<td>High Temperature Reactor (includes gas and liquid metal cooled)</td>
</tr>
<tr>
<td>HTTR</td>
<td>(JAERI) High Temperature Test Reactor</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz (cycles per second)</td>
</tr>
<tr>
<td>IAEA</td>
<td>International Atomic Energy Agency</td>
</tr>
<tr>
<td>ICVD</td>
<td>Improved Cerenkov Viewing Device</td>
</tr>
<tr>
<td>ID</td>
<td>Identification</td>
</tr>
<tr>
<td>INFCIRC/66</td>
<td>(IAEA) Early Safeguards Agreement (now limited to India, Israel, and Pakistan)</td>
</tr>
<tr>
<td>INFCIRC/153</td>
<td>(IAEA) Model Comprehensive Safeguards Agreement</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>INFCIRC/540</td>
<td>(IAEA) Model Additional Protocol</td>
</tr>
<tr>
<td>ISFSI</td>
<td>(U.S. DOE/NRC) Independent Spent Fuel Storage Installation, also known as AFR Storage Facility</td>
</tr>
<tr>
<td>JAERI/JAEA</td>
<td>Japan Atomic Energy Research Institute/Japan Atomic Energy Agency</td>
</tr>
<tr>
<td>KMP</td>
<td>Key Measurement Point (nuclear material flow or inventory)</td>
</tr>
<tr>
<td>LCBS</td>
<td>(IAEA) Load Cell Balance System</td>
</tr>
<tr>
<td>LEU</td>
<td>Low Enriched Uranium (0.7% &lt; U-235 &lt; 20%)</td>
</tr>
<tr>
<td>LOF</td>
<td>(IAEA) Location Outside Facilities</td>
</tr>
<tr>
<td>LWR</td>
<td>Light Water Reactor</td>
</tr>
<tr>
<td>m</td>
<td>Meter</td>
</tr>
<tr>
<td>MBA</td>
<td>Nuclear Material Balance Area</td>
</tr>
<tr>
<td>MMCC</td>
<td>(IAEA) Mini Multi-Channel Analyzer with CdTe probe</td>
</tr>
<tr>
<td>MOX</td>
<td>Mixed Plutonium/Uranium Oxide</td>
</tr>
<tr>
<td>MWe</td>
<td>Megawatts, Electrical Output</td>
</tr>
<tr>
<td>MWth</td>
<td>Megawatts, Thermal Power Output</td>
</tr>
<tr>
<td>NDA</td>
<td>Non-Destructive Assay</td>
</tr>
<tr>
<td>NGAM</td>
<td>(IAEA) Next Generation ADAM (radiation detector data collection module)</td>
</tr>
<tr>
<td>NGNP</td>
<td>(U.S. DOE) Next Generation Nuclear Plant</td>
</tr>
<tr>
<td>NGSI</td>
<td>(U.S. DOE/NNSA) Next Generation Safeguards Initiative</td>
</tr>
<tr>
<td>NGSS</td>
<td>(IAEA) Next Generation Surveillance System</td>
</tr>
<tr>
<td>NNSA</td>
<td>(U.S. DOE) National Nuclear Security Administration</td>
</tr>
<tr>
<td>NPT</td>
<td>Treaty on the Non-Proliferation of Nuclear Weapons</td>
</tr>
<tr>
<td>NRC</td>
<td>U.S. Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>ORIGEN</td>
<td>Oak Ridge spent fuel burn-up code</td>
</tr>
<tr>
<td>PBMR</td>
<td>Pebble Bed Modular Reactor (a pebble fuel HTGR)</td>
</tr>
<tr>
<td>PIE</td>
<td>Post Irradiation Examination</td>
</tr>
<tr>
<td>PNCL</td>
<td>(IAEA) Plutonium Neutron Coincidence Collar</td>
</tr>
<tr>
<td>Pu</td>
<td>Plutonium, chemical symbol</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RMSA</td>
<td>(Canberra/AREVA) Remotely Monitored Sealing Array</td>
</tr>
<tr>
<td>RRC</td>
<td>Russian Research Center (formerly Kurchatov Institute, Russia)</td>
</tr>
<tr>
<td>SBD</td>
<td>(NNSA) Safeguards-by-Design</td>
</tr>
<tr>
<td>SNRI</td>
<td>(IAEA) Short-Notice Random Inspection</td>
</tr>
<tr>
<td>SQ</td>
<td>(IAEA) Significant Quantity of Fissile Material</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>SSAC</td>
<td>State System of Accounting for and Control of Nuclear Material, (a function performed by the State Regulatory Authority)</td>
</tr>
<tr>
<td>Th</td>
<td>Thorium, chemical symbol</td>
</tr>
<tr>
<td>TRISO</td>
<td>Tri-layer coating for fuel particles used in high temperature reactors</td>
</tr>
<tr>
<td>U</td>
<td>Uranium, chemical symbol</td>
</tr>
<tr>
<td>U-233</td>
<td>Uranium Fissile Isotope, produced from irradiating thorium</td>
</tr>
<tr>
<td>U-235</td>
<td>Uranium Fissile Isotope, naturally occurring but can be enriched to produce LEU and HEU</td>
</tr>
<tr>
<td>UPS</td>
<td>Uninterruptible Power Supply</td>
</tr>
<tr>
<td>VAC</td>
<td>Volts, Alternating Current</td>
</tr>
<tr>
<td>VACOS</td>
<td>(IAEA) Variable-Coded Sealing System</td>
</tr>
</tbody>
</table>
Introduction and Purpose

This document is part of a series of guidance documents developed by the National Nuclear Security Administration’s Next Generation Safeguards Initiative to assist facility designers and operators in implementing international Safeguards-by-Design (SBD). SBD has two main objectives: (1) to avoid costly and time consuming redesign work or retrofits of new nuclear fuel cycle facilities and (2) to make the implementation of international safeguards more effective and efficient at such facilities. In the long term, the attainment of these goals would save both industry and the International Atomic Energy Agency (IAEA) time, money, and resources – a mutually beneficial win-win endeavor. This particular safeguards guidance document focuses on prismatic fuel high temperature gas reactors (HTGRs).

The purpose of the IAEA safeguards system is to provide credible assurance to the international community that nuclear material and other specified items are not diverted from peaceful nuclear uses. The safeguards system consists of the IAEA’s statutory authority to establish safeguards, safeguards rights and obligations in safeguards agreements and additional protocols, and technical measures implemented pursuant to those agreements. Of foremost importance as a basis for IAEA safeguards is the international safeguards agreement between the country and the IAEA, concluded pursuant to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT).

According to a 1992 IAEA Board of Governors decision, countries must: notify the IAEA of a decision to construct a new nuclear facility as soon as such decision is taken; provide design information on such facilities as the designs develop; and provide detailed design information (called a “Design Information Questionnaire” in IAEA parlance) based on construction plans at least 180 days prior to the start of construction, and on "as-built" designs at least 180 days before the first receipt of nuclear material. Since the main interlocutor with the IAEA in each country is a State Regulatory Authority or Regional Regulatory Authority (e.g. EURATOM), the responsibility for transferring this design information falls to the State Regulatory Authority.

For the nuclear industry to reap the benefits of SBD (i.e., avoided costs and averted schedule slippages), designers/operators should work closely with the State Regulatory Authority and IAEA as soon as a decision is taken to build a new nuclear facility. Ideally, this interaction should begin during the conceptual design phase and continue throughout construction and start-up of a nuclear facility. Such early coordination and planning could influence decisions on, for example, the chemical processing flowsheet and design, the material storage and handling arrangements, and the facility layout. Communication among the designer, facility operator, State Regulatory Authority, and IAEA should be frequent and iterative throughout facility design, construction, and start-up. This dialog will help to more effectively and efficiently incorporate IAEA safeguards into the design of nuclear facilities and to minimize misunderstandings that could arise from misinterpretation of the safeguards input and guidance.

Background

Nuclear facility designers, operators, electrical utilities, and government nuclear R&D organizations have looked to the promise of HTGRs since the early days of nuclear power development in the 1950s. Major global high temperature reactor projects are listed in Table-I, showing historic milestones, as well
as countries pursuing this reactor type for possible deployment in the future. \textsuperscript{3, 4, 5, 6, 7} The majority of these designs are helium gas-cooled reactors, and a significant percentage are prismatic fuel HTGRs.

The fuel for the HTGR is of two fundamental types. The nuclear fuel seeds or kernels in both cases are very small, approximately 0.5mm in diameter. The kernels typically consist of uranium dioxide enriched in U-235 (between 3\% and 19\%), but may also contain plutonium and/or thorium, which are coated with high temperature silicon carbide and pyrolytic graphite. In one case, these kernels are embedded in a tennis-ball sized pyrolytic graphite matrix, which is termed a fuel “pebble.” In the other case, the coated fuel kernels are pressed and sintered into cylindrical fuel compacts (like fuel pellets), which are loaded into graphite sleeves, and then into larger hexagonal (prismatic shaped) assemblies. \textsuperscript{8, 9} Consequently, the two fundamental HTGR types are those using pebble-fuel and those using prismatic-shaped assemblies. This safeguards design guidance document addresses the prismatic fuel HTGR in particular. A companion document in this series provides safeguards design guidance for the pebble fuel HTGR.

Apart from the higher operating temperature, the prismatic fuel HTGR is similar in many ways to a conventional LWR. Similarities with the LWR include the following: \textsuperscript{11}

- Fresh fuel is stored as large integral assemblies in shipping containers or nearby storage pits
- The core is periodically refueled in the same manner, with the fuel kept in a fixed array
- Spent fuel is transferred as large integral assemblies to a spent fuel storage pool or gas-cooled dry storage pits.

Because of these similarities, the basic IAEA safeguards approach for the LWR can be applied to the prismatic fuel HTGR, with some modification. How this would be done will be discussed later in more detail. The main safeguards difference between the two deals with the potential direct transfer of spent fuel to dry-storage. Another aspect is that most prismatic fuel HTGR designs are modular. Consequently, groups of reactor core modules may be collocated in a facility to meet a variety of customer power and process heat needs, from medium to large-scale (i.e. 400 to 3000 MWth). The safeguards impact of these various issues will be discussed later in more detail.

In this discussion, the reader should be mindful that IAEA nuclear safeguards measures and equipment evolve over time. Best practices are also continuously being improved by the IAEA and facility operator to be more efficient and cost effective. Consequently, the IAEA should be consulted regarding specific design details and issues.
Table-I: Major High Temperature Reactor Projects Worldwide
(Source: Durst Nuclear Engineering and Consulting Inc., 2012)

<table>
<thead>
<tr>
<th>Item</th>
<th>Reactor &amp; Developers</th>
<th>Country</th>
<th>Type &amp; Power Output</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Next Generation Nuclear Plant (NGNP); U.S. DOE &amp; NGNP Industry Alliance</td>
<td>USA &amp; International Partners</td>
<td>Prismatic fuel HTGR, 3000 MWth (1025 MWe)</td>
<td>Design Phase, start-up planned for ca. 2025</td>
</tr>
<tr>
<td>2</td>
<td>Pebble Bed Modular Reactor (PBMR); PBMR (Pty) Ltd. &amp; Toshiba/Westinghouse Partners</td>
<td>South Africa &amp; International Partners</td>
<td>Pebble fuel HTGR, 180 MWe per module</td>
<td>Design Phase; ongoing</td>
</tr>
<tr>
<td>3</td>
<td>Anatres; AREVA</td>
<td>France</td>
<td>Prismatic fuel HTGR, 625 MWth per module</td>
<td>Design Phase; ongoing (Selected for NGNP)</td>
</tr>
<tr>
<td>4</td>
<td>High Temperature Reactor Production Model (HTR-PM); China Nuclear Energy &amp; Construction Group (CNEC)</td>
<td>China</td>
<td>Pebble fuel HTGR, 200 MWe per module</td>
<td>Design Phase; start-up planned for ca. 2015</td>
</tr>
<tr>
<td>5</td>
<td>High Temperature Test Reactor (HTTR); Japan Atomic Energy Agency (JAERI/ JAEA)</td>
<td>Japan</td>
<td>Prismatic fuel HTGR, 30 MWth</td>
<td>Initial criticality in 1998; in standby shutdown</td>
</tr>
<tr>
<td>6</td>
<td>Gas-Turbine Modular Helium Reactor (GT-MHR); Rosatom, OKBM, RRC (Kurchatov), General Atomics</td>
<td>Russia &amp; International Partners</td>
<td>Prismatic fuel HTGR, 287 MWe per module</td>
<td>Design Phase (began in 1995); ongoing</td>
</tr>
<tr>
<td>7</td>
<td>Modular Helium Reactor, High Temperature (MHR-T); Rosatom, OKBM, RRC (Kurchatov), et al.</td>
<td>Russia &amp; International Partners</td>
<td>Prismatic fuel HTGR, 600 MWth per module</td>
<td>Design Phase (began in 2004); ongoing</td>
</tr>
<tr>
<td>8</td>
<td>Compact High Temperature Reactor Demonstration (CHTR); Bhabha Atomic Research Centre (BARC), India</td>
<td>India</td>
<td>Pebble fuel, PbBi Cooled HTR, 100 kWth</td>
<td>Design Phase; ongoing</td>
</tr>
<tr>
<td>9</td>
<td>High Temperature Reactor, 10 MW (HTR-10); Tsinghua University, China</td>
<td>China</td>
<td>Pebble fuel HTGR, 10 MWth</td>
<td>Initial criticality in 2000; operating in research mode</td>
</tr>
<tr>
<td>10</td>
<td>THTR-300; HTRB GmbH, KFA-Juelich, Germany</td>
<td>Germany</td>
<td>Pebble fuel HTGR, 300 MWe</td>
<td>Initial criticality in 1983; shutdown and decommissioned</td>
</tr>
<tr>
<td>11</td>
<td>Fort St. Vrain; General Atomics and PSC Colorado</td>
<td>USA</td>
<td>Prismatic fuel HTGR, 330 MWe</td>
<td>Initial criticality ca. 1972; shutdown and converted to natural gas power plant</td>
</tr>
</tbody>
</table>
2. IAEA SAFEGUARDS

The legal basis for implementing IAEA safeguards is the international safeguards agreement between the country and the IAEA concluded pursuant to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). The NPT requires each Non-Nuclear-Weapon State party to the NPT to conclude a comprehensive safeguards agreement (CSA) with the IAEA, modeled on IAEA document INFCIRC/153 (corrected), The Structure and Content of Agreements between the Agency and States Required in Connection with the Treaty on the Non-Proliferation of Nuclear Weapons. A State may also conclude an additional protocol (AP) to its safeguards agreement, which requires the State to provide broader information and IAEA access to locations related to its nuclear fuel cycle beyond that provided by the CSA.

The objective of international (IAEA) nuclear safeguards is the timely detection of the diversion of significant quantities of nuclear material from peaceful to non-peaceful uses, and the deterrence of such by the risk of early detection. In addition the IAEA must detect any potential misuse of the facility for undeclared purposes (e.g. undeclared receipt, transfer, irradiation, or removal of nuclear fuel). To summarize, the overarching IAEA safeguards objectives common to all states with a CSA and AP are to detect:

- Diversion of declared nuclear material at facilities and locations outside facilities (LOFs)
- Undeclared production or processing of nuclear material at facilities and LOFs
- Undeclared nuclear material and activities anywhere in the State.

The IAEA is currently in transition moving towards a state-level safeguards approach and will rely less on facility-centric safeguards criteria in the future. In the interim, the safeguards goals summarized below continue to define key elements of the approach and the safeguards tools and measures the IAEA may apply. Relevant safeguards goals are cited from the IAEA Safeguards Criteria for inspecting “Other Types of Reactors,” found in the IAEA Safeguards Manual and associated annexes, which have been incorporated into the IAEA Quality Management System (QMS).

Safeguards Detection Goals

The specific IAEA detection goals relevant to safeguarding a prismatic fuel HTGR are:

- Detect the diversion of 8 kg of plutonium in the form of unirradiated fresh fuel within one month of possible diversion, or in the form of irradiated core or spent fuel within three months of possible diversion.
- Detect the diversion of 25 kg of U-235 in the form of unirradiated highly enriched fuel (HEU; U-235 ≥ 20%) within one month of possible diversion, or in the form of irradiated core or spent fuel within three months of possible diversion.
- Detect the diversion of 8 kg of U-233 in the form of unirradiated fuel within one month of possible diversion, or in the form of core or spent fuel within three months of possible diversion.
- Detect the diversion of 75 kg of U-235 in the form of depleted, natural, or low enriched uranium fuel (LEU; U-235 < 20%) within one year of possible diversion.
- Detect the diversion of 20 tonnes of thorium in the form of fuel within one year of possible diversion.
- Detect possible misuse of the facility for undeclared nuclear activities (e.g. undeclared fuel irradiation, production of plutonium or U-233, and subsequent removal of the fuel).
Traditional vs. Integrated Safeguards

The detection goals of traditional (facility-level) nuclear safeguards are as noted above. In general, these same goals apply under integrated safeguards. The IAEA defines integrated safeguards as the “optimum combination of all safeguards measures available to the IAEA under comprehensive safeguards agreements and additional protocols to achieve maximum effectiveness and efficiency in meeting the IAEA’s safeguards obligations within available resources.” More will be said about the typical safeguards strategy for a prismatic fuel HTGR in the following sections.

A key distinction regarding integrated safeguards is that it is applied to the country as a whole. Traditional IAEA safeguards were applied at the level of the facility. However, the objectives of detecting the diversion of significant quantities of nuclear material or misuse of the facility remain relevant, as well as the material goal quantities. If a prismatic fuel HTGR were under integrated safeguards, additional measures such as the use of remotely monitored safeguards equipment, satellite imagery, and/or short-notice random inspections (SNRI) could enable a reduction in the frequency and number of on-site inspections. This is an example of achieving maximum effectiveness, as well as efficiency.

In terms of design, the facility must accommodate IAEA safeguards equipment (e.g. seal, surveillance, and radiation detection systems), regardless of whether the prismatic fuel HTGR is under traditional (facility-level) or integrated safeguards. As the prismatic fuel HTGR is being designed and constructed, the facility operator, State Regulatory Authority, and IAEA should also discuss whether the reactor will need to accommodate other measures, such as the remote monitoring of safeguards equipment.

Safeguards Responsibilities

Engagement and dialog between the facility operator, designer, State Regulatory Authority, and IAEA should begin early in the design process to ensure that IAEA safeguards goals can be efficiently and effectively met. The proposed timing for the engagement of the stakeholders in the case of a model design and construction project is described in more detail in the reference noted.

In the context of SBD, the safeguards related responsibilities can be summarized as follows:

- **Facility Designer:** Design the facility, per the requirements of the facility owner and operator (customer) to meet the specified operational objectives, and to be compliant with relevant national and international regulations, requirements, and guidelines. These include, but are not limited to: nuclear safety, security, and safeguards regulations, requirements, and guidelines. The designer should design the facility in a manner that accommodates IAEA safeguards equipment and systems, facilitates design verification for safeguards purposes, and facilitates IAEA inspection activities during construction, operation, and decommissioning of the facility.

- **Facility Operator:** Operate the nuclear facility, for the purposes as declared to the State Regulatory Authority, in accordance with relevant national and international regulations, requirements, and guidelines. The facility operator prepares the construction specifications for the facility, which include specifications for implementing effective nuclear safeguards and providing space and utilities for nuclear safeguards equipment and measures. The facility operator hosts IAEA inspections and must operate the facility in the manner declared to the IAEA.

- **State Regulatory Authority:** Oversee the implementation of national (domestic) nuclear regulations within the country, particularly those pertaining to nuclear safety, security, and safeguards. The State Regulatory Authority ensures effective accounting, control, and regulated use of nuclear material within the country and liaises with the IAEA to ensure the effective implementation of international nuclear safeguards as per the safeguards agreement. Dialog and engagement with the IAEA is coordinated through the State Regulatory Authority/SSAC.
• **IAEA:** Verify that the country is upholding its international safeguards agreement with the IAEA, concluded pursuant to the NPT. The IAEA Department of Safeguards uses the safeguards measures available to ensure that significant quantities of nuclear material have not been diverted from peaceful to non-peaceful uses within the defined timeliness goal for detection, and uses the risk of early detection to minimize the threat of diversion.

### 3. ELEMENTS OF DESIGN RELEVANT TO SAFEGUARDS

**Nuclear Material Balance Areas and Key Measurement Points**

In international safeguards, nuclear material accountancy is the safeguards measure of fundamental importance with containment and surveillance (seal, surveillance, and radiation detection systems) used as important complementary measures. Simply stated, nuclear material accountancy is the accounting and control of the nuclear material inventory and related inventory changes with independent verification by the IAEA.

To account for the nuclear material inventory and associated changes, the facility operator defines a nuclear material balance area (MBA), in consultation with the IAEA. Each separate HTGR would typically be defined as a separate and distinct facility and MBA. The facility owner/operator and designer propose the MBA layout and structure to the State Regulatory Authority. To facilitate this discussion, an MBA layout diagram should be prepared by the facility designer at the earliest design stage, because it allows the stakeholders to visualize the overarching issues regarding the safeguarding of the nuclear material (i.e. where the nuclear material is stored and where the inventory and associated changes can be verified). It is advisable to involve the IAEA in these discussions at an early stage, because the layout of the MBA and associated key measurement points (KMPs) impacts the implementation of nuclear safeguards. An example of a typical MBA layout diagram for a prismatic fuel HTGR is shown in the figure below. Note that this is for the simplest case of a single fresh fuel storage area, spent fuel storage area, and reactor core.

Inventory KMPs (lettered and depicted as dark blue circles) are where the nuclear material would be stored and made accessible for inventorying and verification by the facility operator, State Regulatory Authority, and IAEA. Inventory flow KMPs (numbered and depicted as light blue diamonds) are located to verify the inventory changes or transfers.

The example below shows the most basic MBA layout diagram for a typical prismatic fuel HTGR. The nuclear material is in the form of integral and serialized prismatic-shaped fuel assemblies and is stored in three KMPs, where the nuclear material can be inventoried and verified:

- **KMP-A:** Fresh Fuel Storage
- **KMP-B:** Reactor Core Fuel
- **KMP-C:** Spent Fuel Storage

If the facility is a modular design that has multiple reactor cores and/or fresh fuel and spent fuel storage areas, each would typically have a unique inventory KMP designation.

To verify the nuclear fuel as it is received, transferred, and shipped from the HTGR, the following flow KMPs would normally be established:

- **KMP-1:** Fresh Fuel Receipts
- **KMP-2:** Fuel Transfers from Fresh Fuel Storage to the Reactor Core
- **KMP-3:** Irradiated Fuel Transfer from the Reactor Core to Spent Fuel Storage (and back again)
KMP-4: Spent Fuel Transfer/Shipment from the MBA/Facility

In this discussion, it is important to note that nuclear production and “loss” (i.e. radionuclides created or consumed by nuclear reactions) would be accounted for in flow KMP-3 at the time irradiated nuclear fuel is transferred from the reactor core to spent fuel storage. From an accounting standpoint, it is important to recognize that irradiated fuel can also be moved from spent fuel storage back into the reactor core in some cases (e.g. to maximize fuel burn-up). In these cases, the accounting for the associated nuclear loss and production would be reversed, until the fuel is finally removed from the core and transferred to spent fuel storage for good.

Figure-1: Typical Material Balance Area (MBA) Layout and Key Measurement Points (KMPs) for a Prismatic Fuel HTGR
(Source – DNE/INL, 2010)

Safeguards Strategy and Possible Diversion Scenarios

The development of the “Safeguards Approach” for a particular facility (in the official sense) is the strict purview of the IAEA. However, to implement SBD, the facility designer must anticipate where the nuclear material could be removed and diverted. This analysis should not be viewed as doing the work of the IAEA. It merely helps prepare the facility designer and operator for subsequent discussions with the IAEA on this subject. It also helps the facility designer and operator address domestic nuclear safeguards issues as well.
In the current example, fresh fuel is delivered to the reactor and stored in a local fresh fuel storage area. Every one to three years, irradiated fuel is removed from the reactor core and transferred to the nearby spent fuel storage. The core is rearranged for optimal burn-up and fresh fuel is transferred from storage to the reactor core. The local spent fuel storage may be a spent fuel storage pool (wet) or gas-cooled storage pits (dry). As the local spent fuel storage becomes filled near capacity, the cooled spent fuel may be transferred from the HTGR to a nearby independent spent fuel storage installation (ISFSI) or to a long-term spent fuel repository. In either case, this would be a shipment of spent fuel from the HTGR to another nuclear facility.

Based on the example, the diversion scenarios that would need to be addressed by the safeguards strategy are:

1. Diversion of fresh fuel during shipment, upon receipt, or from inventory (KMP-A)
2. Diversion of fresh fuel during transfer to the reactor core (KMP-A & B)
3. Diversion of irradiated core fuel during refueling (KMP-B)
4. Diversion of spent fuel during transfer from the core or from spent fuel inventory (KMP-B & C)
5. Diversion of spent fuel during shipment from spent fuel storage to an offsite location (KMP-C)

In this discussion, the nuclear fuel may be in the form of complete and integral fuel assemblies or fuel pin sized “compacts.”

A quick sketch of the typical safeguards strategy is presented to discuss the safeguards relevant design elements or features. The safeguards strategy and approach will be discussed in more detail in the next section. The following discussion is not meant to describe exactly how the IAEA will safeguard the prismatic fuel HTGR. It is merely an aid to the facility designer to help them understand the kind of safeguards measures and equipment that the facility design would need to accommodate.

To address Diversion Scenario-1, the IAEA would typically verify the fresh fuel after the fuel has been received at the HTGR. The particular safeguards measures employed will be discussed in more detail in Section-4. Alternatively, the fresh fuel may be verified by the IAEA at the fuel fabrication facility and the fresh fuel shipped under IAEA seal. In this case, the IAEA would verify the seals upon receipt at the HTGR. To address Diversion Scenario-2, the IAEA would normally be present during the refueling to simultaneously verify the fresh fuel in nearby storage and the fuel in the reactor core. To address Diversion Scenario-3 and 4, the IAEA would simultaneously verify the reactor core and spent fuel storage inventory. After the inventory of fresh fuel, core fuel and spent fuel had been verified, the IAEA would use containment and surveillance measures (seal, surveillance, and radiation detection systems) to verify that undeclared nuclear fuel removals do not occur. To address Diversion Scenario-5, the IAEA would re-verify the spent fuel as it is being loaded into transfer casks. The IAEA would likely seal the spent fuel transfer/shipping casks, since re-verification of the spent fuel would be challenging at the ISFSI or long-term repository.

Regarding potential facility misuse, the primary misuse scenario is:

1. Undeclared use of the HTGR to irradiate target fuel for subsequent removal and undeclared separation of plutonium or U-233.

To address this misuse scenario, the IAEA would simultaneously verify the fresh fuel, core fuel, and spent fuel, and use the foregoing containment and surveillance measures to detect the undeclared removal of nuclear fuel from inventory (potentially containing target material). More will be said about the particular safeguards measures in Section-4. The IAEA would also verify the declared operating history of the HTGR during the inspection period, using the facility’s instruments and records, to verify that undeclared or unexplained shutdowns and refueling did not occur for potential target removal.
Design Features Relevant to Safeguards

From the foregoing discussion, the HTGR fresh fuel, core fuel, and spent fuel locations, and the associated nuclear fuel transfer paths, should be designed to accommodate the following:

- IAEA seal systems
- IAEA surveillance systems
- IAEA radiation-based fuel flow monitors
- Safe engineered access for verification (by direct or indirect means)
- Possible remote monitoring and transmission of data from IAEA seal, surveillance, and radiation detection systems
- Emerging safeguards measures.

At an HTGR, the IAEA would typically apply seals to the fresh fuel storage positions and the reactor cover to prevent undeclared access to the fresh fuel and core fuel inventory. Consequently, the fresh fuel storage positions and reactor core cover bolts and fasteners would need to accommodate IAEA seals. If the spent fuel is stored in dry storage pits, the lids of the storage pits would need to accommodate IAEA seals. The requirements for the common IAEA sealing systems are noted in Section-5. Surveillance systems would typically be used, in addition to the seal systems, to detect undeclared removal of nuclear fuel, especially from the core and spent fuel storage areas. The arrangement and location of the IAEA surveillance systems would need to be discussed in advance between the facility operator, designer, State Regulatory Authority, and the IAEA. This would ensure that when the IAEA surveillance systems are installed they will have the requisite space and utilities. In locating the surveillance cameras, the IAEA will design the systems to have overlapping coverage. The space and utility requirements for the most common IAEA surveillance systems are noted in Section-5. If the fuel transfers are not directly observable, or if the spent fuel is stored in covered dry storage, the IAEA may additionally use radiation-based fuel flow monitors to verify the declared nuclear fuel movements. The same concerns regarding the placement and installation of the surveillance cameras applies to the installation of the radiation detectors and fuel flow monitors as well. The most common radiation detectors and fuel flow monitors, and the associated requirements, are noted in Section-5. Keeping these points in mind, it is important that the designer provide space and utilities to accommodate the foregoing safeguards equipment. The facility design should not be so densely packed with equipment to preclude effective surveillance and monitoring of the nuclear fuel inventory locations and fuel transfer paths. Similarly, surveillance and monitoring of the HTGR fuel transfer cask entry and exit locations should not be obstructed.

As large prismatic fuel HTGRs are deployed worldwide, the approach for safeguarding these facilities will need to evolve from the traditional approach applied to LWRs - because of increasing facility size, complexity, and complications that arise from HTGR fuel containing direct-use nuclear material (i.e. plutonium, HEU, and U-233). It is in the interest of the facility designer to be aware of these trends. See the Appendix for more details regarding emerging technologies relevant to safeguarding current and future prismatic fuel HTGRs.

4. KEY ELEMENTS OF SAFEGUARDS STRATEGY/APPROACH

The typical safeguards strategy implemented at a prismatic fuel HTGR has been outlined, but is described now in more detail. The strategy focuses on accounting for the receipts, inventory, and shipments of HTGR nuclear fuel, to detect nuclear material diversion and facility misuse (i.e. removal of undeclared target fuel). Seal, surveillance, and fuel flow monitor systems are used to maintain continuity of knowledge of the nuclear fuel in the reactor core and fresh and spent fuel storage areas. Because re-
verification of irradiated fuel in the reactor core and in spent fuel storage is disruptive, the IAEA uses redundant containment and surveillance measures that do not share a common mode of failure. To date, the IAEA has relied heavily on seal and surveillance systems, because these are easy to install, service, and evaluate. In cases where the transfer of irradiated fuel from the core to spent fuel storage may not be observable (e.g. to gas-cooled dry storage), the IAEA may also use radiation-based fuel flow monitors. If the prismatic fuel HTGR has multiple reactor cores and fresh and spent fuel storage areas, the IAEA would install multiple containment and surveillance systems with overlapping coverage.

**Nuclear Material Accountancy**

The IAEA examines the facility operating/accounting records, source documents, and reports submitted by the State Regulatory Authority for consistency, regarding the nuclear fuel inventory and changes in the reactor core(s), fresh fuel storage area(s), and spent fuel storage area(s). The inspector verifies that the nuclear fuel receipts, inventory, and shipments are as declared by the facility operator. The inspector also examines the facility instrument records for the declared period of operation and irradiation of the core, to verify that the period of operation is consistent and as declared. This activity typically takes place in an available office at the HTGR. Associated field inspection activities are described below.

**Verification of HTGR Fresh Fuel Inventory and Receipts**

Fresh prismatic HTGR fuel may be verified at the fuel fabrication facility. In this case, the fuel may be shipped under IAEA seal to the HTGR. At the HTGR, the IAEA inspector verifies the seals, checks for tampering, and observes storage of the sealed fuel containers. The number and ID of the fresh fuel containers, and final fresh fuel storage locations, are confirmed by the inspector to be as declared by the facility operator. If the fuel is to be placed in storage pits, the inspector detaches the seals, observes the loading of the fuel into the pits, and seals the fuel in place. Alternatively, the fresh HTGR fuel may not be sealed during transit. In this case, the nuclear material content of the fuel (i.e. uranium, thorium, plutonium, U-235, and U-233) is verified at the HTGR by the IAEA inspector using NDA instruments. The particular instruments currently used by the IAEA for this purpose, and the associated space and utility requirements, are described in Section-5. In addition to verifying the nuclear material content and length of the active fuel zone, the inspector may also verify the mass of the HTGR fuel using an IAEA Load Cell Balance System (LCBS) or the facility operator’s scale, which has been calibrated and verified by the inspector. Regarding the frequency of verification, if the prismatic HTGR fuel contains LEU (U-235 < 20%) or thorium, the IAEA typically verifies the fresh fuel once per year at the time of the physical inventory verification (PIV). If, however, the fresh HTGR fuel contains direct-use material (i.e. plutonium, HEU, or U-233), then the IAEA verifies the fresh fuel every one to three months, because of the more stringent timeliness goal for detecting a diversion. After the fresh fuel has been verified by the IAEA and placed in storage, containment and surveillance measures (seals and/or video surveillance systems) are used to detect the undeclared removal or movement of fresh HTGR fuel, especially if it contains direct-use material.

**Verification of HTGR Core Fuel and Associated Transfers**

Seal, surveillance, and fuel flow monitoring systems are used to detect the undeclared removal or movement of HTGR fuel to and from the core. Seals are replaced by the inspector to detect potential tampering. Video surveillance systems are reviewed to verify that the transfers of HTGR fuel assemblies are as declared by the facility operator and consistent with the declared operation. The reactor core is considered “difficult to access” during irradiation. Consequently, the core fuel is typically verified during the periodic refueling, which historically has been every one to three years. At this time, the IAEA simultaneously verifies the fresh and spent HTGR fuel storage, together with the fuel in the reactor core. Since the prismatic fuel HTGR core is sealed and gas-cooled as opposed to a water cooled (LWR) core that can be opened, the IAEA is in the process of developing methods to verify the fuel in the HTGR core. These are discussed in more detail in Section-5. The IAEA counts the transfers of HTGR assemblies from
the fresh fuel storage to the core; and from the core to spent HTGR fuel storage. To the extent possible, they also check and confirm the ID of the assemblies transferred, and verify whether they are dummy, fresh, partially irradiated, or spent HTGR fuel. It is expected that fuel flow monitors, such as have been used by the IAEA in safeguarding other inaccessible cores, will be used for this purpose. The IAEA examines the operating and accounting records pertaining to irradiation of the core, and compares this to the relevant installed instruments to verify that there were no undeclared reactor shutdowns or outages. The IAEA also independently verifies the radionuclide content of the core and spent fuel, using a suitable fuel burn-up code (e.g. ORIGEN) based on the declared location of the fuel in the core and irradiation history.

Verification of HTGR Spent Fuel Inventory and Shipments

Seal, surveillance, and fuel flow monitoring systems are used to detect the undeclared removal or shipment of spent fuel at the HTGR. If a spent fuel shipment from the HTGR occurs, the shipment would typically be verified by the IAEA at the receiving location. If the shipment is sealed by the IAEA at the HTGR, the seals are verified and randomly replaced by the inspector at the receiving location to detect potential tampering of the spent HTGR fuel during transit. Video surveillance systems at the HTGR are reviewed to verify that the shipments of spent HTGR assemblies and movements of spent fuel transfer casks are as declared by the facility operator. The spent HTGR fuel inventory is verified by the IAEA every 3 months or less frequently, depending on the state-level safeguards approach. If the spent HTGR fuel is stored in a pool, the IAEA will use instruments typically used for verifying spent LWR fuel in wet storage, which are described in more detail in Section-5. If the spent HTGR fuel is stored in sealed gas-cooled dry storage, IAEA NDA instruments may need to be developed or optimized to verify the spent HTGR fuel in this environment. Based on IAEA experience to date, it would be possible to use fuel flow monitors, in combination with seal and surveillance systems, to provide assurance that there have been no undeclared removals of spent HTGR fuel from “difficult to access” dry storage. If the seal, surveillance, and fuel flow monitoring systems covering the spent HTGR fuel storage fail, or indicate potential tampering, the spent fuel would need to be re-verified. How this should be done should be discussed between the facility operator, designer, State Regulatory Authority, and the IAEA. This is also discussed in more detail in the Appendix, regarding emerging technologies.

Detection of Potential Facility Misuse (Including Undeclared Activities)

The primary misuse scenario involving an HTGR is the undeclared irradiation of specially designed HTGR target fuel, removal of the irradiated fuel, and subsequent separation of the plutonium or U-233. The IAEA uses seal, surveillance, and fuel flow monitoring systems to detect undeclared removals of nuclear fuel, including undeclared irradiated target fuel. Additionally, the IAEA examines the declared operating and accounting records against the facility’s instruments to verify that no undeclared shutdowns or outages occurred, which could permit the undeclared removal of irradiated target fuel. The IAEA also verifies the declared nuclear material content of the spent fuel, using the appropriate fuel burn-up code, based on data provided by the facility operator.

Detection of Nuclear Material Borrowing

“Nuclear material borrowing” is the undeclared borrowing or exchange of similar nuclear material between facilities in the country in an effort to misrepresent the available nuclear material inventory and deceive the IAEA. The IAEA uses seal, surveillance, and fuel flow monitoring systems to detect the undeclared removal or “borrowing” of fresh, core, or spent HTGR fuel. They also conduct inspections at the HTGR simultaneously with other facilities in the country that could share or swap fuel, such as the HTGR fuel fabrication plant and ISFSIs where spent HTGR fuel is stored.

Verification of Facility Design Information

Over the life of a nuclear facility the IAEA examines and verifies the facility design information relevant to nuclear safeguards. This activity is called design information examination and verification or
DIE/DIV. The inspector uses information provided by the facility operator in the IAEA Design Information Questionnaire (DIQ), as described in the Introduction, which typically includes the following drawings and design information:

- Facility MBA diagram(s), showing the nuclear material transfer paths and inventory/flow KMPs
- Process description that states how the fuel would be received, stored, transferred, irradiated, and shipped from the HTGR
- Design of the HTGR fresh fuel storage area
- Design of the HTGR spent fuel storage area
- Design of the HTGR reactor core
- Design of the HTGR fresh fuel shipping container with fuel capacity per container and estimated frequency of receipts
- Design of the HTGR fuel handling machine and system for transferring fresh fuel to the core, and core fuel to spent fuel storage
- Design of the spent fuel shipping cask and handling system with spent fuel capacity per shipping cask and estimated frequency of shipments
- Fuel burn-up code that shows how the radionuclide content of the spent HTGR fuel would be calculated
- Equipment layout of the HTGR, showing the dimensions and locations of the reactor core, fresh and spent fuel storage areas, and nuclear fuel transfer paths
- Other drawings and information deemed necessary by the IAEA for safeguarding the facility.

The IAEA performs DIE/DIV at the facility to ensure that it has been designed and constructed as declared, i.e. that there are no concealed locations for the storage, transfer, or irradiation of HTGR fuel. The inspector typically uses hand tools, instruments, and the DIQ to verify the design information. If, however, the nuclear facility is large, complex, or of new design, the IAEA may use the 3D Laser Range Finder (3DLR). This is a modified laser-based survey instrument that allows the inspector to measure and confirm the construction and dimensions of large and complex facilities. More will be said about this instrument in Section-5. The safeguards inspector performs DIE/DIV at the facility as it is being built and periodically during operation, until it is officially shutdown and decommissioned (from the standpoint of safeguards).

5. SAFEGUARDS BEST PRACTICES RELEVANT TO THE DESIGN

There are a number of safeguards related considerations that the designer of a prismatic fuel HTGR should take into account when designing the facility. The following reflects the current safeguards measures, which are continuously evolving. The facility designer and operator should discuss these issues in detail with the State Regulatory Authority and the IAEA during the design of the HTGR to confirm the safeguards measures to be used and relevant trends.

Layout Requirements

An idealized layout of the safeguards equipment for a typical prismatic fuel HTGR is shown in the figure below. This figure is intended merely as an example for illustration. The reader should note that this example shows a single reactor core, fresh storage area, and spent fuel storage area. Because many of the current prismatic fuel HTGR designs are modular, additional reactor cores, fresh fuel storage areas, and spent fuel storage areas could be incorporated to produce an HTGR design with a higher power...
output. If this were the case, the safeguards measures shown for the current layout would be replicated for the additional areas where HTGR fuel would be located. One must also note that the actual IAEA safeguards equipment and associated layout would be determined by the IAEA, in consultation with the facility operator and State Regulatory Authority. If a video surveillance or fuel flow monitoring system is used that requires a data collection cabinet, the cabinet should be installed in an area or room that is protected from extreme temperature, humidity, and dust. The space and utilities required for each system are discussed further below. More detailed specifications regarding the safeguards equipment layout can be provided by the IAEA.

Figure-2: Typical Layout of IAEA Safeguards Equipment for a Prismatic Fuel HTGR
(Source – Durst Nuclear Engineering and Consulting Inc., 2012)
Regarding the equipment layout, it is important for the facility designer to recognize that the aforementioned equipment is for IAEA safeguards. The facility operator will require separate systems for security and physical protection, such as their own dedicated surveillance camera system, motion sensors, etc. The facility operator’s systems are not addressed by this safeguards guidance document, although the final HTGR layout design will need to accommodate both.

The space and layout requirements for typical IAEA safeguards equipment are summarized below. IAEA seals are used to secure points on top of the HTGR core to prevent the removal of prismatic fuel assemblies. How the core access is sealed depends on whether the cover consists of integral sections or individual hatch covers. If the core has individual hatch covers, it may be possible to daisy-chain and route the sealing cable through the various covers. The preferred arrangement would be to have a few large interlocking cover blocks that prevent removal of individual fuel assemblies. One-half square meter should be allowed for servicing the seal. The seals are attached in a manner that would indicate tampering if the reactor cover sections were lifted without removal of the seal. IAEA seals may also be applied to the fuel pit covers in the fresh fuel storage area and in the gas-cooled spent fuel storage pits, if dry storage is used. Similarly, 0.5 m$^2$ should be provided for attaching, replacing, or servicing the seals in these locations as well. If spent HTGR fuel is stored in a pool, seals would normally not be utilized.

Surveillance cameras and systems are typically used to verify that undeclared removals of fuel from the HTGR reactor core and spent fuel storage area do not occur. If the fresh HTGR fuel contains direct-use material (i.e. plutonium, HEU, or U-233), then surveillance cameras would likely be used to cover the fresh fuel storage area as well. Surveillance cameras are installed in a manner that provides redundant and overlapping coverage. Surveillance cameras require 1 m$^2$ of space per camera and a clear field of view of the safeguarded area of interest. If radiation detectors are used, they also require 1 m$^2$ of space per detector. Safe engineered and shielded access must be provided to permit servicing the seal, surveillance, and radiation detection systems. If multiple cameras or a radiation-based fuel flow monitoring system are utilized, a data collection cabinet may be used. Data collection cabinets require 3 m$^2$ per cabinet, with safe engineered and shielded access to the front and back doors of the cabinet.

The use of radiation-based fuel flow monitors normally depends on whether the core and spent fuel can be presented easily for verification, e.g. in a spent fuel storage pool. If the core or spent fuel cannot be presented easily for verification, then a radiation-based fuel flow monitoring system would likely be used to count and verify the irradiated HTGR fuel as it is transferred from the reactor core to the spent fuel storage area, and to detect undeclared reverse transfers of fuel. If the spent fuel storage area is “difficult to access,” (e.g. gas-cooled dry storage pits), the fuel flow monitor would be used to maintain the continuity of knowledge of spent fuel in storage.

Office Space

The IAEA requires use of an office or meeting room at the HTGR for examining facility operating and accounting records, source documents and associated state reports. This room need not be dedicated office space, but may be made temporarily available on the occasion of the inspection. The review of these documents is infrequent and is performed at the time of field inspections by the IAEA inspector. This office space should have convenient electrical power outlets for the inspector’s laptop computer and peripheral equipment and be 16 m$^2$ or greater.

Seal Systems

The IAEA uses seals as tamper indicators on the HTGR reactor core, fresh fuel, and spent fuel dry storage pits. Typically, two different types of seal systems are used in case one system fails. Ideally, the seal systems should not have a common failure mode. The seals most commonly used presently are the metal cap seal and the variable-coded sealing system (VACOS), shown in the top row of the figure below. $^{15}$ Shown in the bottom row is the next generation electro-optical sealing system (EOSS), which is being field tested and will likely become the IAEA’s standard seal system within the next 5 years. $^{16, 17}$
To use these seals, the fresh and (dry) spent fuel storage hatch cover hasps and the reactor core cover nuts and bolts must typically be modified. In the case of the fresh and spent fuel hatch covers the hasps are modified to permit routing of the sealing cable. In the case of the reactor cover, the nuts and bolts that secure the cover may be drilled to accommodate the sealing wire or cable, as shown in the figure below. Specifications for the size of the drilled hole for the seal cable and other particulars can be provided by the IAEA. In the past, facility operators have also designed mechanical protection (e.g., metal covers and sleeves) to protect IAEA seals and cables to minimize the risk of accidentally damaging the seal during routine operation of the facility. The IAEA performs a site inspection and vulnerability assessment of the facility operator’s hardware to confirm that it can be effectively sealed, without permitting undeclared removal of the nuclear material secured by the seal.

Figure-3: IAEA Seal Systems  
(Source – IAEA, 2007)

Surveillance Systems

The IAEA typically uses video surveillance systems to detect undeclared fuel removal from the reactor core, spent fuel storage, and fresh fuel storage areas - (especially if the fresh fuel contains direct-use material). The cameras must have a clear field of view of the areas where HTGR fuel is stored and the paths along which the fuel is transferred. If the transfer path is concealed or shielded, as in the case of transferring irradiated core fuel to gas-cooled spent fuel storage, then radiation-based fuel flow monitors are likely to be used as well. If the HTGR has multiple reactor modules and fresh and spent fuel storage areas, each of these will be covered by surveillance with overlapping and redundant coverage. Camera placement is determined by the IAEA, in consultation with the facility operator and the State Regulatory Authority.

The IAEA currently fields a variety of surveillance systems. However, in the near future the next generation surveillance system (NGSS) will become the IAEA standard. The NGSS and associated camera (in a tamper proof enclosure) are shown in the figure below. If a multiple camera system is used, a data collection cabinet will likely be required as shown. This cabinet contains a computer server for storing the digital surveillance data and associated computer peripherals. Consequently, it should be located in a room or area that is not subject to extreme temperatures, humidity, or dust. The designer should note that the facility operator’s surveillance system for security and physical protection is separate and distinct from the IAEA safeguards surveillance system. Each camera unit requires approximately 1 m² of space with a clear field of view covering the safeguards area of interest. The data collection cabinet requires 3 m² per cabinet and clear access to the front and rear cabinet doors. More detailed specifications for the particular surveillance system can be provided by the IAEA.

IAEA surveillance systems are typically installed on a facility emergency power circuit and/or powered by an IAEA un-interruptible power system (UPS), to minimize the possibility of losing surveillance due to localized power outages. The cabling used for the IAEA seal, surveillance, and
radiation detection systems must be tamper resistant and is typically provided by the IAEA; especially the cabling that interconnects the cameras, seals, and radiation detectors to the data collection cabinet(s). The IAEA can provide more detailed specifications regarding these upon request.

**Figure-4: IAEA Next Generation Surveillance Camera and System (NGSS)**
(Source – IAEA, 2010)

**Radiation-Based Fuel Flow Monitors**

If the transfer of irradiated fuel from the core to the spent fuel dry storage cannot be observed by surveillance cameras, or if the reactor core cannot be easily opened and verified, the IAEA may use a radiation-based fuel flow monitoring system to verify the fuel transfers to and from the core. This system can also be used to detect the undeclared removal of fuel, and may permit indirect verification of the fuel inventory in the core and in the spent fuel storage. The types of radiation detection probes used will depend on the type of fuel being verified (i.e. whether it contains plutonium, HEU, thorium, or U-233). For safeguarding MOX-fueled liquid metal fast breeder reactors, the IAEA has used neutron and gamma detectors. The fuel flow monitor must be able to count, verify, and discriminate dummy fuel, fresh fuel, irradiated core fuel, and fully irradiated spent fuel. An example of a fuel flow monitoring system in tamper proof enclosures is shown in the figure below.

**Figure-5: Radiation-Based Fuel Flow Monitoring System and Components**
(Source – IAEA, 2002 & 2010)
The example consists of three data collection cabinets installed side by side. The space requirements are identical to those noted for the surveillance data collection cabinets. A variety of radiation detectors for gamma and neutron detection are shown in the upper right of the figure, with the longest being approximately 40 cm. The bottom of the figure shows a rack-mounted radiation detector data collection module (NGAM) currently being evaluated by the IAEA.

The IAEA is in the process of upgrading its fuel flow monitoring systems to a standardized configuration. In terms of space and utility requirements, this new system will fit into the current tamper proof cabinets shown. Since the newer systems are also computer-based, they will likely have utility requirements comparable to the system shown below. The electrical requirements are described in more detail further below. More detailed specifications regarding radiation-based fuel flow monitors and associated equipment can be provided by the IAEA.

Remote Monitoring

To make more efficient use of field inspectors, the IAEA may propose remote transmission of the safeguards seal, surveillance, and fuel flow monitoring data to a nearby IAEA regional office or to IAEA HQ in Vienna, Austria. Under such an inspection regime, the IAEA would continue to inspect the facility, but at a reduced frequency, because most of the safeguards data would be continuously transmitted to the IAEA. Remote monitoring requires modification to the safeguards equipment, additional cabling, and a suitable connection for data transmission. The potential use of remote monitoring by the IAEA should be discussed between the facility operator, State Regulatory Authority, and IAEA early in the design of the HTGR, and is subject to the approval of all three stakeholders. The actual mode for the remote data transmission is rapidly evolving and has varied greatly in just the last few years. More detailed specifications regarding the remote monitoring scheme and equipment can be provided by the IAEA.

Equipment for Verifying Fresh Fuel

Equipment that has been used for verifying fresh (unirradiated) prismatic HTGR fuel is similar to the NDA equipment that the IAEA uses to verify LWR fuel containing LEU and MOX. The optimization and selection of this equipment will be dictated by the nuclear material content of the new prismatic HTGR fuel designs (i.e. whether they contain LEU, HEU, plutonium, thorium, and/or U-233). Examples of the equipment that the IAEA currently uses to verify fresh LEU and MOX fuel are shown in the reference noted. The main issue for the designer is providing the space and utilities for using this equipment. Two m$^2$ of space is adequate for using most of these systems and they all can be powered using a local convenience electrical power outlet. It is important for the reader to recognize that the IAEA currently inspects a few prismatic fuel HTGR. As these facilities become more common, the IAEA will likely standardize an NDA verification system for the new HTGR prismatic fuel designs. More detailed specifications regarding the equipment the IAEA will use for verifying fresh prismatic HTGR fuel can be provided by the IAEA.

Equipment for Verifying Spent Fuel

Examples of the equipment that the IAEA currently uses to verify spent prismatic fuel in wet storage are shown in the Reference 21. However, if the spent fuel is stacked to maximize storage volume, the facility designer, operator, State Regulatory Authority, and IAEA would need to discuss other options for verifying the spent fuel. Additionally, if the spent prismatic HTGR fuel is stored in sealed gas-cooled dry storage, other verification measures would be needed. As mentioned, the IAEA has used radiation-based fuel flow monitors in similar circumstances to verify spent fuel transfers to storage in cases where the spent fuel cannot be presented or is “difficult to access.” Equipment is also being developed for verifying spent LWR in dry storage, which could potentially be used for verifying spent HTGR fuel in dry storage. One
such system is the Compton Dry-Cask Imaging System, which has been developed for verifying spent LWR fuel in vertical dry storage casks. The system requires the use of a universal mounting fixture, which the IAEA provides for the verification activity. The Compton Dry-Cask Imaging System is discussed in more detail in the Appendix, regarding relevant emerging technologies. If used for verifying spent HTGR fuel, the system would likely be re-designed to fit atop the spent HTGR fuel storage hatch covers. More detailed specifications regarding the HTGR spent fuel verification systems can be provided by the IAEA.

**Design Impacts of Facilitating Inspection**

1. **DIE/DIV Activities**

   IAEA safeguards inspectors perform DIE/DIV while the nuclear facility is under construction and after the facility begins operation, until the facility is decommissioned (from the standpoint of safeguards). In general, the IAEA verifies that the facility has been designed and constructed, and is being operated, as declared by the facility operator in the IAEA Design Information Questionnaire (DIQ). In the case of an HTGR, the IAEA verifies that the HTGR does not have concealed sub-basements, chambers, storage areas, or transfer passageways for the undeclared receiving, transfer, irradiation, storage, or shipping of HTGR fuel. The IAEA will also verify that the design and capacity of the HTGR reactor core and fresh and spent fuel storage areas are as declared by the facility operator in the DIQ. The IAEA verifies the design and capacity of the HTGR fuel receiving and shipping areas, fresh fuel containers, spent fuel casks, and nuclear fuel transfer paths. Particular attention is paid to the fuel entry and removal routes, to confirm that the planned containment and surveillance measures will be effective in detecting the undeclared removal of HTGR fuel.

   Additionally, the IAEA confirms that the HTGR does not have undeclared shielded laboratory space, glove-boxes, and other facilities which could be used for the clandestine reprocessing of HTGR fuel or fuel compacts. If the HTGR has a declared Post Irradiation Examination (PIE) laboratory area for the shielded examination of HTGR fuel compact specimens, the IAEA will evaluate the capability of this laboratory during DIE/DIV for the potential undeclared separation of plutonium and/or U-233.

   The space requirements for conducting the DIE/DIV are comparable to those required for performing normal facility operations or IAEA safeguards inspection activities, i.e. adequate shielded space to walk around and inspect the HTGR fresh fuel storage area, spent fuel storage area, and reactor cover, etc. The IAEA inspectors also check the field of view of the surveillance cameras and radiation detectors, and verify the vulnerability of the sealing systems - including the facility operator’s hardware (i.e. sealing latches, hasps, nuts and bolts, doors, hatches, etc.).

   The facility designer and operator should clarify how the IAEA intends to verify the design of the facility, since the density of the equipment installation and layout may preclude the use of certain IAEA equipment. However, it is important to keep in mind that the IAEA focus is not on the entire facility, but on the safeguards relevant features of the facility, with a focus on the nuclear material inventory and flow KMPs. IAEA inspectors typically use the design information and drawings provided by the operator in the DIQ and portable tools and instruments to verify the safeguards relevant features of the design. In facilities of new design (such as the HTGR), the IAEA may use the 3DLR. The 3DLR is a laser-based survey instrument that requires a free line-of-sight, if the equipment layout is too dense, it may not be possible to use the instrument. The 3DLR would typically be positioned at the corners of the facility and at key areas in between to collect a suitable survey of the primary areas where nuclear fuel will be stored and handled. Since HTGRs are large structures with multiple operating floors, the IAEA would typically survey all of the areas were nuclear fuel could be stored or transferred, including the access doors and transfer paths. HTGR fuel handling machines, fresh fuel containers, and spent fuel transfer casks are also likely to be surveyed.
The 3DLR requires 4 m² at each survey location and a 1 meter-wide path for moving the instrument. Clear labeling or stenciling of the nuclear fuel storage areas, doors, equipment, and fuel transfer pathways facilitates use of the 3DLR. More detailed specifications regarding the DIE/DIV instruments to be used can be provided by the IAEA.

ii. IAEA Inspections during Facility Operation

The aforementioned IAEA safeguards inspection activities performed at a typical prismatic fuel HTGR, and the requisite safeguards equipment, will be discussed from the standpoint of potential impact to the facility design. During an on-site inspection, the IAEA inspector examines the facility operating and accounting records, source documents, and state reports for consistency against the fuel inventory and inventory changes at the HTGR declared by the facility operator. Typically, the inspectors verify the fresh and spent fuel in storage several times per year, using NDA instruments. The frequency of the verification depends on whether the fuel contains direct-use nuclear material (i.e. plutonium, HEU, or U-233) and the IAEA state-level approach. To verify spent HTGR fuel in wet storage, the facility operator allows the inspector(s) to be on the spent fuel pool bridge crane so they can verify the spent fuel inventory in the pool. This verification is complicated if the fuel is stacked, since the inspectors may not be able to verify or discriminate individual spent fuel assemblies. Consequently, the stacking of spent fuel in wet storage is discouraged by the IAEA. If spent fuel must be stacked, then other arrangements for verifying the spent fuel in wet storage must be discussed in advance with the IAEA.

The inspectors also verify the fuel inventory in the reactor core, which is typically done during the refueling. In the case of an HTGR this may be every one to three years. If the core fuel cannot be presented for verification, the IAEA may use radiation-based fuel flow monitors to count, verify, and discriminate the fuel transfers to and from the reactor core. Used together with the seal and surveillance systems, this provides continuity of knowledge of the fresh fuel, core fuel, and spent fuel KMPs, and allows indirect verification of the fuel in the core. In addition to verifying the HTGR fuel inventories, the inspectors verify the fuel receipts, transfers, and shipments. The timing and frequency of the verification depends on whether the fuel contains direct-use nuclear material. HTGR fresh fuel receipts may be verified at the time of the receipt or during a scheduled inspection. Similarly, HTGR spent fuel shipments may be verified at the HTGR or at the facility receiving the HTGR fuel – depending on the verification method. Regarding impact to the facility design, the IAEA inspector needs the ability to access the fresh fuel and spent fuel storage areas and reactor core cover to verify the fuel inventory. The facility design should also allow the inspector to safely service the installed seal, surveillance, and radiation-based fuel flow monitoring systems, and check the field of view of the surveillance cameras and radiation detectors. Typically, platforms and ladders are required for accessing and servicing the surveillance cameras, since the cameras would usually be placed at an elevated level in the reactor hall to cover the areas of safeguards interest.

If the IAEA is permitted by the facility operator and State Regulatory Authority to remotely monitor encrypted data from the seal, surveillance, and fuel flow monitoring systems, then the frequency of on-site inspections can be dramatically reduced – since the IAEA would be receiving most of the safeguards data continuously. In this case the impact on facility operations is lessened, because of the decrease in field inspections. However even in this case, the IAEA will still require access to verify the fresh, core, and spent HTGR fuel at least once per year. Design provisions for seal, surveillance, and fuel flow monitoring systems are still required.

Design Impacts (by Engineering Design Discipline)

i. Electrical/Instrumentation

The electrical and instrumentation design engineers should provide for the power and associated cabling requirements for the IAEA safeguards equipment as specified by the IAEA. The following is based on IAEA practice to date, with consideration for the construction of larger modular prismatic fuel
HTGRs anticipated in the near future. IAEA seal systems are battery powered and do not require external power. IAEA surveillance systems installed at an HTGR typically require facility mains power. Individual cameras require 5 amps or less @ 90 – 265 VAC (50-60 Hz). If a centralized surveillance data collection cabinet is used, they typically require 30 amps per cabinet @ 90 – 265 VAC (50-60 Hz). The components within the IAEA data collection cabinet have internal circuit breakers. If a radiation-based fuel flow monitoring system is used, its power requirements are comparable to those noted for the surveillance data collection cabinet. In both cases, the data collection system is a computer server and requires a dedicated, isolated, and tested electrical ground suitable for sensitive computing equipment. The power for the IAEA surveillance and fuel flow monitor data collection cabinets should be on a facility emergency power circuit and/or have an IAEA-provided UPS within the cabinet. Cabling to and from the IAEA seal, surveillance, and fuel flow monitoring systems must meet IAEA tamper resistance specifications and is typically provided by the IAEA. If the seal, surveillance, or fuel flow monitoring systems are to be remotely monitored by the IAEA, they will specify other relevant requirements. The electrical power requirements for the typical fresh fuel and spent fuel NDA verification systems are 15 amps or less @ 100 - 230VAC (50 – 60 Hz). This can usually be provided by local convenience electrical power outlets. The electrical requirements for the 3DLR are comparable to those stated for the other NDA systems. Under certain circumstances, these systems may require a 50 m electrical extension cord routed from the convenience electrical power outlet to the actual point of use.

ii. Mechanical

The mechanical design engineer should provide for safe engineered access so the IAEA inspector can service the seal, surveillance, and fuel flow monitoring systems; and access the fresh fuel, core fuel, and spent fuel storage areas. Additional mechanical fixtures and modifications to the facility equipment may be required to permit use of the IAEA seal, surveillance, and fuel flow monitoring systems. These modifications are specified by the IAEA, and may include (but are not limited to) the following:

- Modifications to the fresh fuel, core fuel, and spent fuel dry storage hatch covers to accommodate IAEA seals (e.g. seal/cable nuts and bolts, hasps, and covers)
- Modifications to the core/spent fuel (dry storage) transfer channel, to permit the use of IAEA radiation detectors as part of a fuel flow monitoring system
- Fixed stanchions for mounting surveillance cameras, radiation detectors, and additional lighting
- Fixed platforms and ladders for servicing seals, surveillance cameras, and radiation detectors
- A lifting hoist in the fresh fuel storage area to permit the raising and removal of fresh HTGR fuel for verification
- Adequate space on the spent fuel pool bridge crane to permit IAEA verification of the HTGR spent fuel in wet storage
- A movable mechanical fixture and attach points for mating the Compton Dry-Cask Imaging System to the spent fuel dry storage hatch covers, to permit verification of the HTGR spent fuel in dry storage
- Condensate drain(s) for the air conditioning system in the IAEA surveillance and fuel flow monitoring data collection cabinet(s).

iii. Chemical/Analytical

Not relevant to this facility type.

iv. Industrial Safety

The industrial safety design engineer should provide for safe engineered access so the IAEA inspector can service the seal, surveillance, and fuel flow monitoring systems; and access the fresh fuel, core fuel...
and spent fuel storage areas. Design provisions for accommodating IAEA safeguards activities must not introduce other industrial hazards or risks.

v. Radiation Safety and Health Physics

The radiation safety design engineer should provide for safe engineered access so the IAEA inspector can service the seal, surveillance, and fuel flow monitoring systems; and access the fresh fuel, core fuel and spent fuel storage areas. Radiation dose to the inspector must comply with as-low-as-reasonably-achievable (ALARA) radiation guidelines and practices for comparable work as performed by the facility operator and their staff. The verification of HTGR fuel storage or reactor core positions declared to be empty should be in accordance with the facility operator’s procedures and practices and must not result in excessive radiation exposure. Moveable shielding, respirators, or breathing air systems should be provided as necessary, to augment the designed radiation shielding and other safety features.

APPENDIX - EMERGING TECHNOLOGIES

Fresh HTGR Fuel Verification

1. NDA techniques can be optimized for the verification of fresh (un-irradiated) prismatic HTGR fuel. In the past, the IAEA has used a combination of gamma spectroscopy and active and passive coincident neutron counting systems (e.g. MMCC, HRGS, AWCC, and PNCL, etc.) to verify the nuclear material content of LEU and MOX fuel at LWRs. Since many of these systems depend on the measurement geometry and shape of the fuel, they will need to be optimized for verifying new designs of prismatic HTGR fuel. The technique used will also depend on the radionuclides present in the fresh fuel (i.e. plutonium, U-235, U-233, and thorium). However, the designs of the prismatic HTGR fuel are still evolving and it is important to realize that the verification must be more stringent if the fuel contains direct-use nuclear material (i.e. plutonium, HEU, and U-233).

Containment and Surveillance

2. New containment systems are being developed that could potentially replace current IAEA seal systems. One of the challenges faced in using sealing systems is that they are difficult to apply to large numbers of containers or locations, such as the large number of hatch covers in the HTGR fresh fuel or spent fuel dry storage areas. To address this issue, a Remotely Monitored Sealing Array (RMSA) is being developed, which employs active electronic seals that use radio-frequency to communicate the seal status from multiple sealing points to a data collection system. In principle, this would eliminate the elaborate wire tying and daisy-chain cabling schemes that have been used in the past to seal large arrays of hatch covers and storage pits. The RMSA is currently undergoing testing and evaluation by the IAEA, and is designed to remotely transmit the seal status and disposition to IAEA headquarters in Vienna or the nearest IAEA regional office. The data would be fully encrypted and the remote transmission subject to the approval of the facility operator and State Regulatory Authority.

3. Another system that could be used for monitoring a large array of HTGR fuel storage and reactor core positions is the Laser-Based Item Monitoring System (LBIMS), a rastering system being developed at ORNL. This containment system would use fixed laser transmitter/receivers at the corners of the fuel storage array or reactor core and would rapidly raster and scan the area. The fuel storage or reactor core hatch covers would have laser reflective tags for bouncing the rastered laser beams. If the hatch covers were opened, the system would note the missing bounce and record the date and time of the event. Such a system, used in conjunction with surveillance, would be more efficient and easier to service than hundreds of seals applied to hundreds of HTGR fuel storage casks or reactor core positions.
Spent HTGR Fuel Verification

4. NDA techniques can be optimized for the verification of spent HTGR fuel. In principle, spent HTGR fuel stored in pools can be verified by the IAEA using the Cerenkov Viewing Devices (ICVD and DCVD) and other existing NDA instruments. However, this becomes more challenging if the fuel is stacked, because it is difficult to discriminate and verify individual spent fuel assemblies. In this case, it may be necessary to use a spent fuel verification system that is inserted directly into the spent fuel pool, which can be raised and lowered (e.g. SFAT or SMOPY). The optimized HTGR spent fuel verification system would need to be able to verify stacked spent HTGR fuel and detect the removal of small fuel compacts from the spent fuel (i.e. detect partial defects).

5. If the spent HTGR fuel is stored in gas-cooled dry storage, the fuel is generally considered “difficult to access” and cannot be easily presented for verification. In this case, it may be possible to use a system like the Compton Dry-Cask Imaging System being developed at INL to re-verify nuclear fuel in vertical spent fuel dry storage/transfer casks. This system detects and characterizes the Compton-scattering produced by the fission products in the spent fuel in each storage position, making a Compton map of the spent fuel dry storage area. The system could potentially make a collective image showing the presence of the spent fuel assemblies inside each storage position. If the dual containment and surveillance devices covering the HTGR spent fuel dry storage area ever failed, the IAEA would have a means for re-verifying the contents of the spent fuel dry storage area to determine that spent fuel had not been removed. The primary benefit of this system is that it would be non-intrusive and would not require access into the spent fuel storage pits. How well this system would work with stacked spent HTGR fuel in dry storage would need to be demonstrated.

6. To verify spent HTGR fuel in dry storage, it may also be possible to design and construct interrogation wells adjacent to the spent fuel storage pits, which would allow the IAEA to insert radiation detectors from a number of available gamma and neutron NDA instruments. If the fuel were stacked in dry storage, as is typically done in the reactor core, it would be possible for the IAEA to raise the combination gamma/neutron radiation detector to verify and discriminate stacked fuel assemblies. One drawback in this case, is the additional cost of engineering and constructing interrogation wells adjacent to each spent fuel storage pit position. This underscores the importance of the facility designer, operator, and State Regulatory Authority confirming how the IAEA plans to verify the spent fuel in storage. The use of instrument interrogation wells is a practice seen in safeguarding MOX fuel fabrication and spent fuel reprocessing plants. It is feasible, albeit costly.

HTGR Core Fuel Verification

7. Historically, the IAEA has used the facility operator’s instruments and operating records to confirm the declared period of operation of the reactor and irradiation of the core fuel. They also use the relevant nuclear fuel burn-up code to corroborate the facility operator’s calculation of the radionuclide content of the core fuel upon discharge from the reactor. Presently, however, there are very few prismatic fuel HTGR in operation. Consequently, there is scant data for performing the relevant nuclear fuel burn-up modeling calculations. To address this need, an optimized version of a nuclear fuel burn-up code (such as ORIGEN) could be adapted, supported by irradiation studies with prismatic fuel and compacts of the current design.

8. The use of embedded anti-neutrino detectors has been suggested for independently verifying the duration of reactor operation and nuclear fuel burn-up in LWR cores. The technology also appears to be capable of independently verifying the reactor period of operation and burn-up of reactor fuel in the HTGR core as well. Because the HTGR core fuel would typically be considered “difficult to access,” there may be a more compelling reason for embedding anti-neutrino detectors below the HTGR core(s). The additional cost is an issue, although it is feasible, and would provide completely independent verification of the burn-up of the reactor core fuel and period of irradiation.
9. Overhead satellite thermal imagery could be used to confirm the declared period of operation of the HTGR. Commercially available satellite imagery, including thermal/infrared, is available as a tool to verify the operator’s declared period of reactor operation. This is likely to be more affordable than the proposed anti-neutrino detector method. However, one must also consider that satellite imagery for a specific reactor location may not always be available. Regardless, in cases where there is an important need to confirm the reactor period of operation, the use of overhead thermal imagery remains viable and affordable.

HTGR Fuel Transfer Cask Monitoring and Tracking

10. The containment of fresh and spent HTGR fuel in transfer casks could be dramatically improved if so-called “smart” transfer casks were developed. Such casks would have tamper indicating and monitoring/tracking features integrated directly into the cask design. These features could be an add-on package or be integrated into the cask construction. The data monitored might include the cask serial number and position, status of the cask lid (open or closed), radiation field near the cask lid, GPS coordinates, motion or speed of the cask (due to transfer), etc. The monitoring and tracking data could also potentially be remotely transmitted. If the data were transmitted to the State Regulatory Authority and IAEA, these organizations could know in real-time the status, disposition, and location of the fresh and spent HTGR fuel in transit. Radio-frequency monitoring and tracking systems have been developed for UF₆ cylinders, as sponsored by U.S. DOE NNSA. The results from this research and development could also be adapted to the tracking and monitoring of fresh and spent HTGR fuel in transit, which would be especially useful for fresh HTGR fuel containing direct-use material.
REFERENCES


