LA-UR-- 99-1056

Approved for public release; distribution is unlimited.

Title: Advanced Nuclear Measurements - Sensitivity Analysis Emerging Safeguards Problems and Proliferation Risk

RECEIVED
SEP 01 1999
OSTI

Author(s): Jared S. Dreicer

Submitted to: Laboratory-Directed Research and Development Program

Los Alamos
NATIONAL LABORATORY

DISCLAIMER

Advanced Nuclear Measurements – Sensitivity Analysis
Emerging Safeguards Problems and Proliferation Risk

Jared S. Dreicer
Safeguards Systems Group (NIS-7)
Los Alamos National Laboratory

Abstract

During the past year this component of the Advanced Nuclear Measurements LDRD-DR has focused on emerging safeguards problems and proliferation risk by investigating problems in two domains. The first is related to the analysis, quantification, and characterization of existing inventories of fissile materials, in particular, the minor actinides (MA) formed in the commercial fuel cycle. Understanding material forms and quantities helps identify and define future measurement problems, instrument requirements, and assists in prioritizing safeguards technology development. The second problem (dissertation research) has focused on the development of a theoretical foundation for sensor array anomaly detection. Remote and unattended monitoring or verification of safeguards activities is becoming a necessity due to domestic and international budgetary constraints. However, the ability to assess the trustworthiness of a sensor array has not been investigated. This research is developing an anomaly detection methodology to assess the sensor array.

Fissile Material – Minor Actinides

Weapons fissile materials were the focus of previous efforts. This past year the concentration has been on the existing and growing inventory of fissile materials, residues, and wastes in commercial/civilian programs, specifically minor actinides (237-neptunium, 241-americium, and 243-americium). Both neptunium (Np) and americium (Am) are capable of being fabricated into nuclear explosive devices. They have characteristics similar to highly enriched uranium and their critical masses are on the order of 60 kg for a bare sphere. They are products of nuclear reactor operation and exist in substantial quantities in spent fuel globally. Formation is especially prevalent in commercial reactors using low 235U enriched fuel. Because spent fuel reprocessing is dependent on relatively simple process chemistry rather than isotope separation, it is a shortcut to the fissile material necessary for a nuclear weapon. The materials containing the minor actinides (MAs) are difficult to measure and there are currently only limited technical capabilities to measure MAs, but for nonproliferation goals safeguards are required. The recent International Atomic Energy Agency (IAEA) governing board decision Option (b) GOV/1998/61[1] (International Controls on Neptunium & Americium) associated with INFCIRC/540[2] will likely require the measurement of MAs. Nuclear measurement issues for the fissile materials coming from these sources are associated with homogeneity, purity, and matrix effects. Specifically, these difficult-to-measure fissile materials may be heterogeneous, impure, embedded in highly shielding non-uniform matrices, liquid or solid compositions, or as pure metal or oxide. Each of these characteristics creates problems for radiation-based assay and it is difficult and not yet possible to measure the material that has various combinations of them. The MAs resulting from the commercial nuclear fuel cycle cannot be measured in many of their current forms.

---

[1] The Proliferation Potential of Neptunium and Americium, GOV/1998/61, 30 October 1998, International Atomic Energy Agency, Board of Governors

[2] "Model Protocol Additional to the Agreement(s) Between State(s) and the International Atomic Energy Agency for the Application of Safeguards," September, 1997

The global inventories of MAs previously produced and currently being produced in the commercial nuclear fuel cycle are a serious threat to the advancement and success of nonproliferation. Figure 1 illustrates the estimated fissile material inventories globally at the end of 1994. At that time there were roughly 130,000 MT of commercial spent fuel and this had grown to about 180,000 MT by the end of 1997. More than 35,000 MT of this material no longer met the spent fuel standard (self-protecting) at the end of 1997. It had been cooling for more than two decades, a clear proliferation risk. Although there are large quantities of various forms of weapons plutonium and highly enriched uranium, commercial spent and associated waste streams are clearly an important emerging proliferation problem globally.

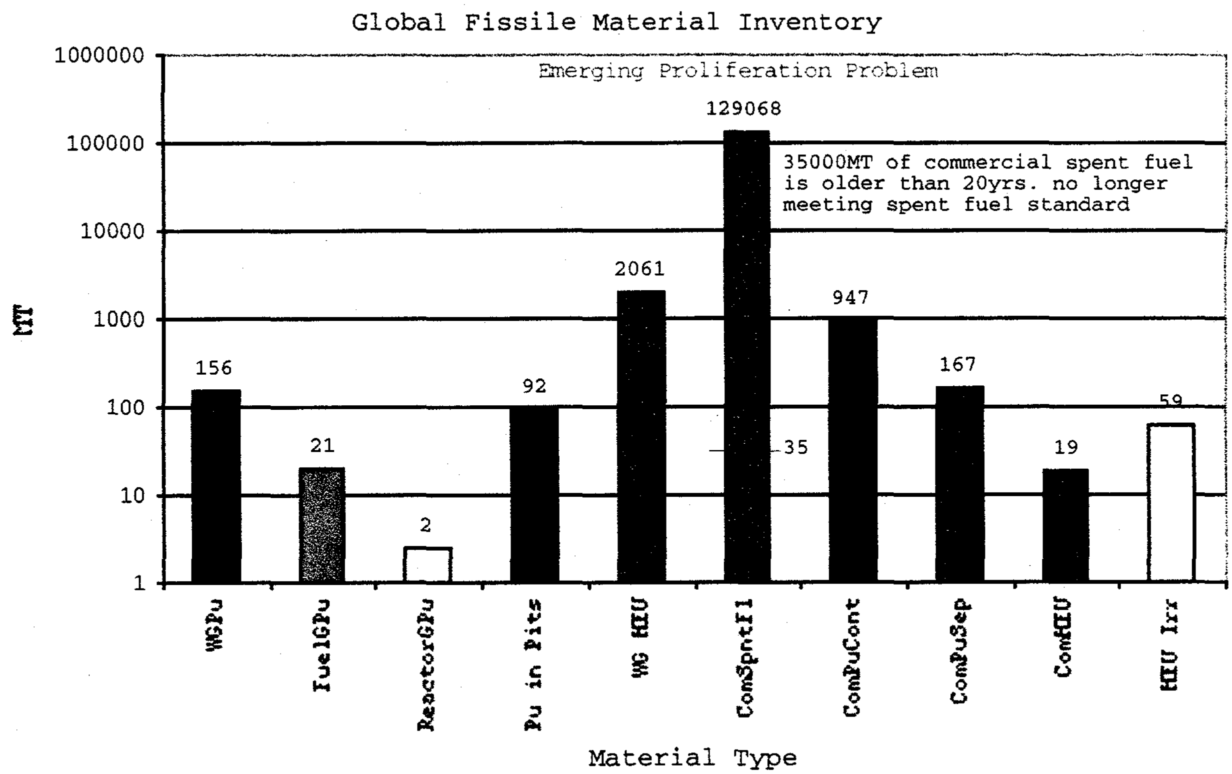

Figure 1. Estimate of Global Fissile Material Inventories (End of 1994).

There are four parameters that impact the isotope formation in reactors: initial 235U fuel enrichment, power level, initial UO2 fuel mass density, and irradiation history. The two dominant parameters are the initial 235U fuel enrichment and power level for reactor operation. The production of 239Pu is higher in fuel with lower initial 235U enrichment. The 239Pu production follows the 238U to 239Pu actinide chain since the 238U complements the low 235U enrichment, given by n + 238U->239U$^{\beta^-}$->239Np$^{\beta^-}$->239Pu. As the 235U is depleted because of neutron absorption and fission, higher fission rates in the 239Pu are required to maintain a constant power level. The lower initial 235U enrichment also results in higher Np and Am formation through the following actinide chains:

1) n+235U->n+236U-> 237U$^{\beta^-}$->237Np
2) n+239Pu->n+240Pu->241Pu$^{\alpha^-}$->237U$^{\beta^-}$->237Np
3) n+239Pu->n+240Pu->241Pu$^{\beta^-}$->241Am
4) n+239Pu->n+240Pu->n+241Pu->n+242Pu ->243 Pu$^{\beta^-}$->243Am

Figure 2 presents the MA formation (g/GW_edtU_{nat}) for the fuel in different types of typical $1000MW_e$ power reactors after having reached target burn-up and the spent fuel having cooled for 150 days[3] based on the energy produced. The rate of minor actinide formation in Magnox graphite moderated reactors (GCR) is a factor of 2.3 to 3.5 times greater than in the other reactor types based on the energy produced by the fuel. This is due

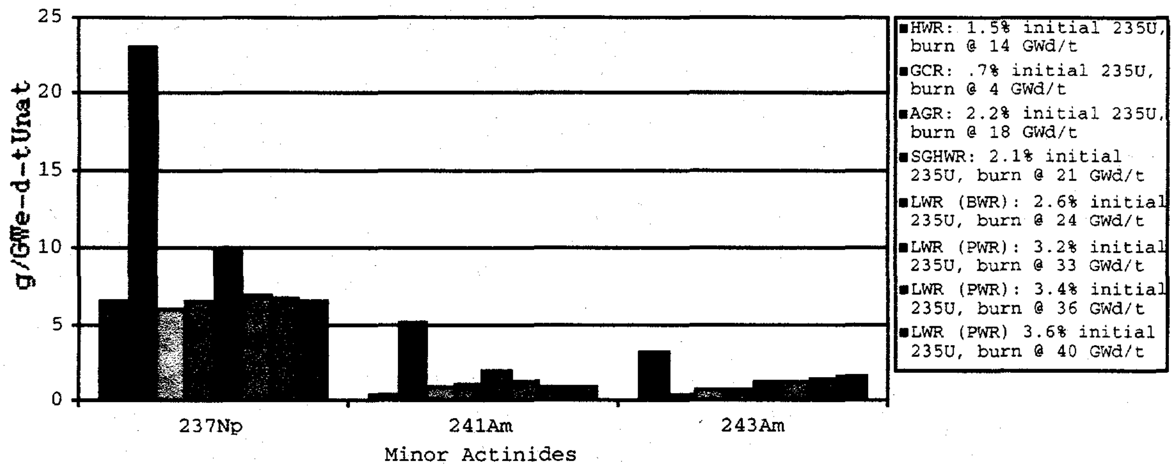

Figure 2. Minor Actinide Formation for Energy Produced by Fuel in Typical 1000MWe Power Reactors.

to the natural uranium, low initial 235U (.7%) enriched fuel. While the HWR also has a low 235U (1.5%) enriched fuel, it forms less 237Np than the LWR using the lowest 235U (2.6%) enriched fuel due to the difference in the burn-up for energy produced. The burn-up in the HWR is such that even though 239Pu is formed, the 235U does not deplete at a rate fast enough to require the 239Pu to fission to maintain constant power and the 237Np is formed following the first actinide chain.

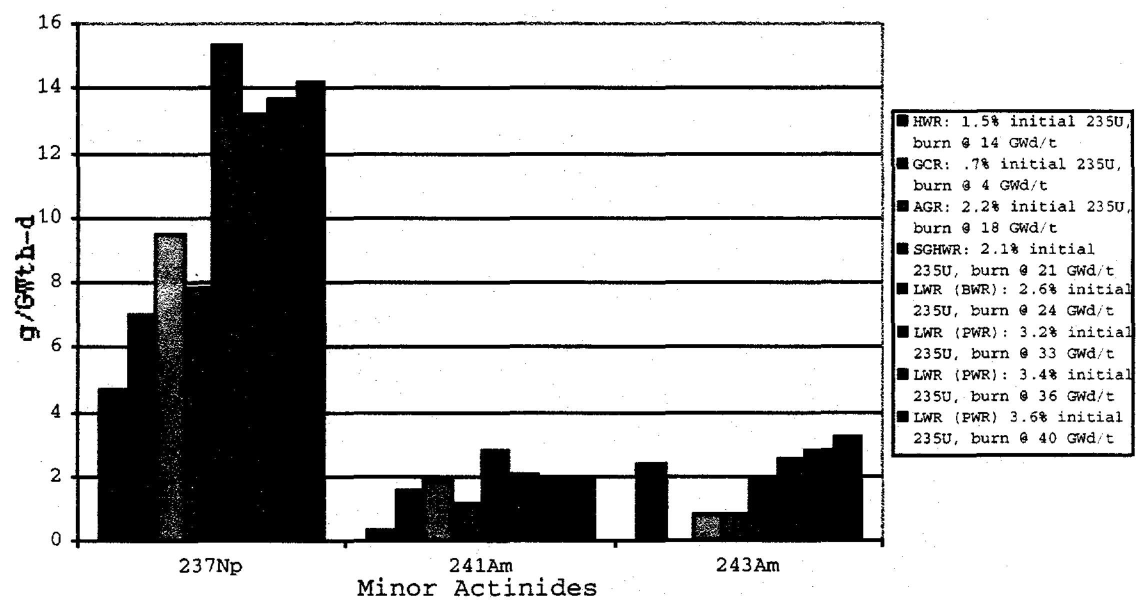

Figure 3. Minor Actinide Formation in Typical 1000MWe Power Reactors.

In contrast to the HWR the depletion rate of the 235U in the LWRs results in the formation of 237Np following the first actinide chain and also from the second actinide

[3] L. Koch, "Formation & Recycling of Minor Actinides in Nuclear Power Stations," Handbook of Physics & Chemistry of the Actinides, pp.459-490, 1986

chain since 239Pu fission is required to maintain constant power. In terms of MA source, Figure 3 presents the MA formation (g/GW_{th}d) in different types of typical 1000MW_e power reactors after having reached target burn-up and the spent fuel having cooled for 150 days[3]. The LWRs are the greatest 237Np source. They produce roughly twice as much 237Np as the other reactor types. This is due to the higher burn-up levels relative to the initial 235U enrichment and the resulting 237Np formation actinide chains followed.

The MA formation rate in spent fuel for LWR power reactors is on the order of 13% to 16%[4] (average of 14.5%) of the plutonium produced, which comprises roughly 1% of the spent fuel. At the end of 1997 there were 437 operating nuclear power reactors in 31 countries producing MAs. In Figure 4 are estimates for the total global spent fuel, plutonium content of the spent fuel, and MA content of the spent fuel broken out by reactor type for the commercial nuclear power fuel cycle.

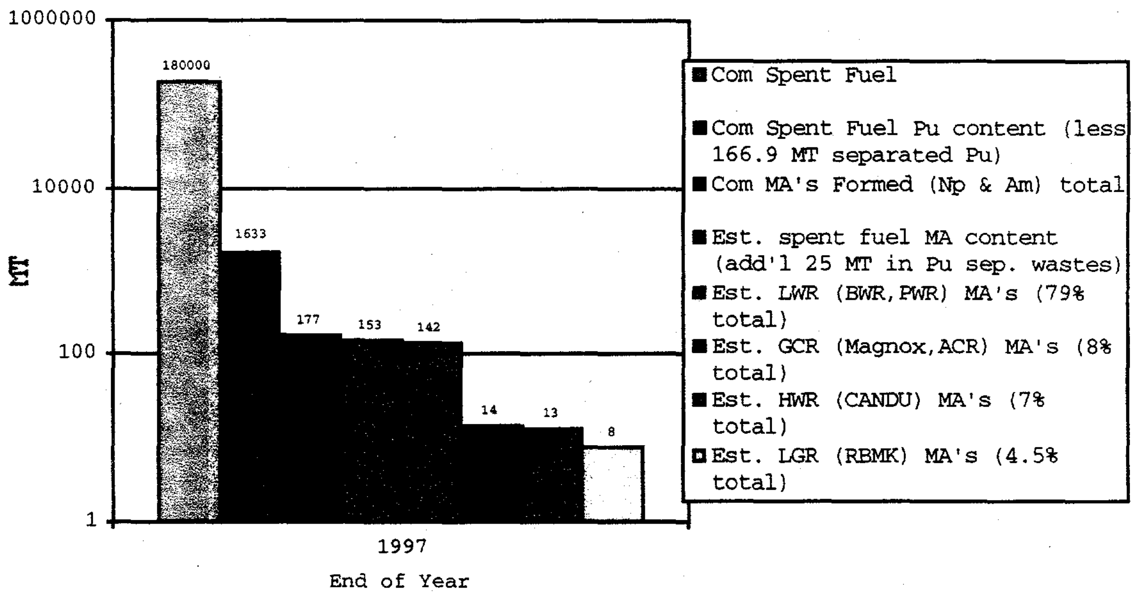

Figure 4. Estimated Spent Fuel, Plutonium and Minor Actinide Content of the Spent Fuel in the Global Nuclear Power Fuel Cycle.

Assuming that the utilization of nuclear energy continues with no additional growth, a constant discharge rate of 12,500 MT/yr., and the reactor type distribution remains the same, calculations indicate that there will be greater than 250,000 MT of commercial spent fuel by 2010. This is important for non-proliferation and measurement requirements, by 2010 all 180,000 MT of existing commercial spent fuel will have been stored and thus cooled for greater than a decade. The roughly 175 MT of MAs in the existing spent fuel will be relatively easy to handle and reprocess. The growth rate of MA formation in commercial spent fuel is illustrated in Figure 5, indicating that by 2010 there will be greater than 300 MT of MAs globally.

There are currently only limited technical capabilities to measure MAs throughout the fuel cycle. There is a need to develop the nondestructive assay (gamma-ray and neutron) analysis instrumentation and methods to meet the current and emerging measurement requirements. MAs exist in many forms in the commercial nuclear fuel cycle. New instrumentation and methods must be developed: to measure or monitor processing streams; to quantify the presence and amount of MAs in wastes (solid and liquid); and to assay MAs in storage, including combinations of metal or oxide and pure or composite. NDA measurement of the MAs is complicated because the presence or absence of MAs in

[4] J. E. Stewart, R. B. Walton, J. R. Phillips, et. al., "Measurement andAccounting of the Minor Actinides Produced in Nuclear Power Reactors," Los Alamos Technical Report, LA-13054-MS, 1996

material are masked by the presence of plutonium or uranium (for example, gamma-ray signatures interfere with current gamma-ray techniques) and the contribution of the uranium or plutonium to the MAs requires analysis.

This effort benefits non-proliferation and strengthens safeguards by specifying the appropriate measurement needs and instrument requirements, based on the material type and adequacy to provide measurement; anticipating and predicting future material measurement problems; and characterizing existing material forms.

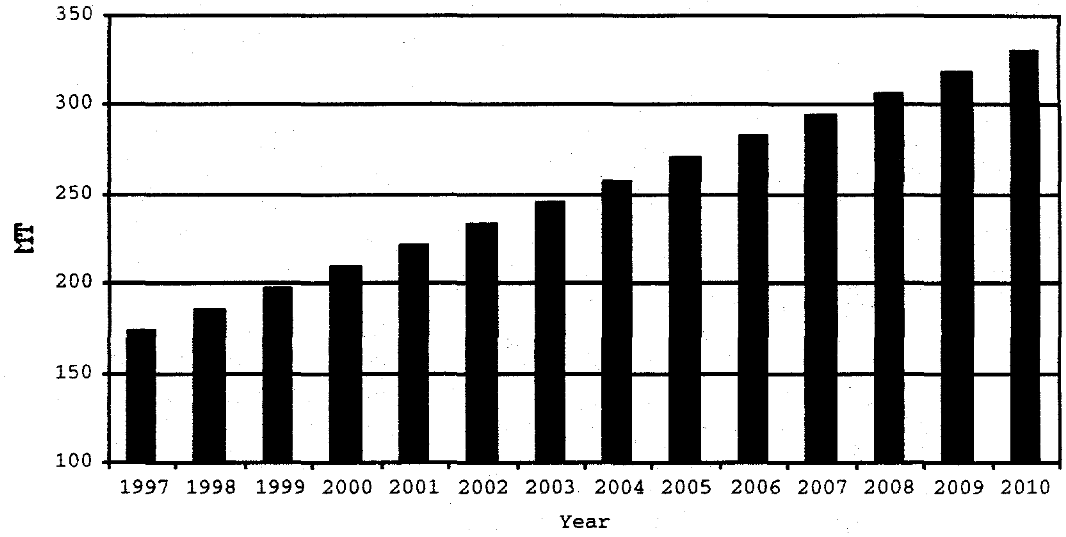

Figure 5. Estimated Growth Rate of Minor Actinide Formation in Commercial Spent Fuel

Sensor Array Anomaly Detection[5]

As required by the Treaty on the Nonproliferation of Nuclear Weapons[6] (NPT) the International Atomic Energy Agency (IAEA) employs a variety of sensors to safeguard civilian nuclear materials and facilities. However, as a result of the revelations concerning the advancement of the attempted Iraqi nuclear weapon development and the international community's experience with North Korea, there is a need for enhanced safeguards to detect undeclared activities and to focus on early detection of proliferation under IAEA safeguards. To achieve enhanced safeguards the IAEA's 93+2 program[7] was developed. The IAEA's 93+2 enhanced safeguards program requires the development and modification of existing sensor capabilities to monitor and detect the production of nuclear material. The IAEA's safeguard responsibilities are increasing while it is constrained by a constant level budget. It is necessary to utilize remote and unattended sensors to cost-effectively satisfy these detection, monitoring, and verification requirements.

---

[5] This component of the Advanced Nuclear Measurement – Sensitivity Analysis is also satisfying the requirements for my dissertation research at the University of New Mexico in Computer Science.

[6] The NPT requires that states accept safeguards for the purpose of verification that the signatory prevents diversion of nuclear energy from peaceful uses to nuclear weapons. Safeguards technology, instruments, and sensors aimed at monitoring nuclear materials are designed to increase international confidence that materials resulting from nuclear power are not being used for military purposes.

[7] The IAEA's 93+2 program will rely on remote and unattended environmental effluent monitoring for detection and confirmation of nuclear activities. Sensor measurement technologies are targeted to air, water, and soil related to any facility environmental releases. The areas that effluent monitoring technologies have focused include a) on-site monitoring, b) regional (1-100 km) and c) long-range (100+ km). Also of interest are continuous monitoring technologies, which analyze non-intrusively and act as a verification mechanism.

Smart, small, low power, and transmission capable sensors can be engineered for application to a broad range of uses. These include proliferation related monitoring, verification and material production detection, and commercial applications (e.g., automation and control). From an engineering perspective, current integrated circuit (IC) technologies provide ample processing power and transmission capabilities to enable the development of such sensors. Determining how to deploy unattended sensors is not well understood and the effectiveness of employing an array (collection) of sensors (from 1 to s) has not been investigated. To effectively employ remote unattended sensors for the detection of nuclear (possibly biological and chemical) material production requires the development of design requirements, utilization strategies, and procedural methodologies.

To accomplish unattended remote monitoring or verification requires a trustworthy, inexpensive, and transmission capable sensor array[8]. A sensor array must provide data that enables the detection of an alarm event. Restrictions for this technology should be analyzed and better understood. Such an analysis would enable a more beneficial and appropriate application of the technology. To ensure effectiveness, the appropriate operational techniques and design restrictions for a sensor array must be determined and developed. If a sensor array is to be used to ensure compliance with treaty requirements it is essential to understand what factors and conditions impact trustworthiness and efficacy.

There are two interrelated objectives for the research:

1. Establish a theoretical model of anomaly detection in a sensor array.
2. Investigate the sensitivity of expected failure rate and sensor covariance on detecting anomalies in a sensor array.

The first objective of this research is to develop a theoretic model of anomaly detection as a basis to conduct analysis of sensor array trustworthiness. The second objective is to develop the statistical methodology to discriminate sensor array anomalies based on failure rate and sensor covariance in the context of spatial distribution. The development of this theory is focused on addressing the open problem concerning sensor arrays: *Can verifying authorities of an unattended sensor array detect anomalies?* It is anticipated that this research will provide the basis for future research toward the challenging and difficult problem of developing tools for sensor array design and configuration.

Model

The sensor system consists of a central processor and an array of s unattended, remotely deployed sensors, S_i, where $i \geq 1$. Relative to the measurement source, the s sensors are configured in a spatial array, not necessarily ordered. The placement environment provides no self-protection and there is a single stationary physical process to be measured. The process does not change state and the refined signal is a real number. Sensors are sufficient and reliable; each sensor is suitable for the placement environment, capable to provide measurement, and are physically and communications secure. A sensor in the array becomes inoperable (shuts down) if there is an attempt at physical tamper. Operable sensors acquire a physical variable (measurand), process the raw signal, and transmit the refined signal following a communication protocol (e.g., periodically transmit). An operable sensor may experience a partial failure and transmit a faulty refined signal or fail completely becoming inoperable. Three types of events influence the measurement of a physical variable: random errors, gross errors, and anomalies. Random errors (e.g., drift) are due to noise (negligible and nonspecific sources); gross errors (e.g., outliers) are due to specific nonrandom sources or a limited number of distinct causes (partial sensor failure); and anomalies (e.g., a heat shield) are due to deliberate or specific activities. Random errors are typical in normal data and assumed to be independent and Guassian. Gross errors result in faulty data. Anomalies create anomalous data. Sensors in the array communicate with the central processor via reliable authenticated synchronous transmissions, which are guaranteed to arrive with negligible delay. There is no sensor-to-

[8] An array of sensors is a collection of sensors that may or may not be deployed in an orderly grid or pattern.

sensor transmission. The central processor is located at a secure facility operated by trusted (monitoring or verifying) authorities.

The model requires the following input: Weibull scale (α) and shape (β) parameters, sensor array spatial distribution (x, y, and z coordinates for each sensor), and scenario definition. Scenarios are defined by postulating an anomalous activity at a subset of the sensors. If the process being monitored will be operated in a manner that increases the value of the physical variable, then the spoofing activity at the subset of S_i sensors employs a method that decreases the value of the sensed physical variable at the time it would be sensed. The refined signal before anomaly correlates well with the refined signal after anomaly for the spoofed sensors. Anomalous activity input includes time of initiation, the specific sensors impacted (how, when, and which), and physical process impact.

Flow of Data in the Sensor System

Figure 6 indicates that for each operable sensor a measurand is acquired, the raw signal is converted to a refined signal through signal processing[9], and the refined signal is transmitted to the central processor. Functionally the central processor assigns accuracy and transforms the refined data, integrates the s transformed data intervals, and then clusters[10] and analyzes the aggregated data. At the central processor the first step is to assign the signal accuracy, ε_i, $(i=1, \ldots\ s)$ associated with each of the s sensors. Accuracy is applied to the corresponding refined signal resulting in refined data, $S_i(x) \pm \varepsilon_i/2$. The refined data represents a measurement by a sensor relative to the measurand. To make the refined data comparable it is transformed according to the sensor array spatial distribution, defined by the distance from the measurement source, d, and material dependent constant, c, resulting in $[S_i(x)\ x\ (cd_i^3)] \pm \varepsilon_i/2$. The sensor accuracy component of the transformed data defines a range. During data integration the range is characterized by an interval, I_i, $(i=1, \ldots\ s)$, the intervals are aggregated and clusters are formed.

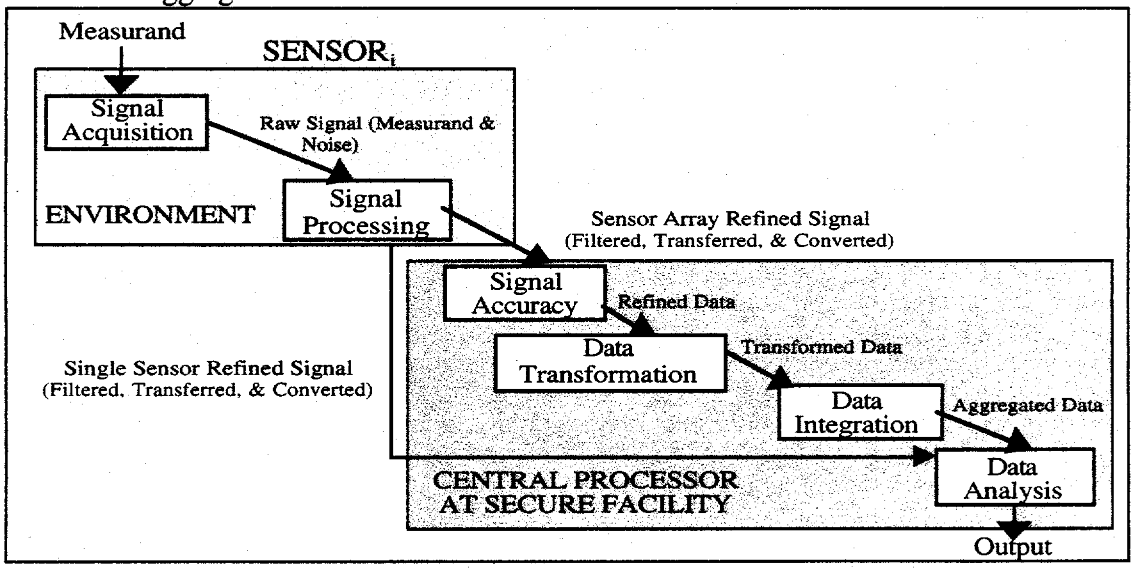

Figure 6: Sensor Array and Central Processor Functionality

Depending on the spatial distribution and types of sensors in the array, the refined data is converted and transformed. Because sensors in the array are spatially configured

---

[9] Signal processing involves filtering, transfer, and conversion. Filtering improves the signal to noise ratio. Transfer employs the transduction principle, transforming a raw signal to a refined signal. During conversion the analog signal is converted to digital and it is also possible (necessary) to convert the measurand to another (e.g., pressure to temperature).

[10] Clustering requires dividing a data set into non-overlapping collections of similar points. Points in a cluster are measured to be nearly similar and a single reference point (usually the mean) characterizes the cluster.

relative to the source being measured, transformation is based on this spatial distribution. If the sensor array utilizes complementary independent sensors, physical conversion is performed during signal processing.

For redundant sensors equidistant from the measurement source spatial transformation is straightforward. For redundant sensors not equidistant from the measurement source, transformation is based on physical principles[11]. If complementary independent sensors are used in the array, different physical variables are measured. Complementary independent sensors can be spatially transformed because conversion during signal processing renders them effectively redundant. For example, if there are temperature and pressure sensors, by reformulating Boyle's law ($PV=nRT$) it is possible to convert the pressure measurement to temperature. Transformed data enables comparison.

Temporal correlation (time-series analysis) will be utilized only to the extent that statistical averages over time are employed during aggregation. Utilizing data from all time instants is necessary when there is only a single sensor. The decision not to utilize time-series analysis is based on the premise that sensor redundancy provides a sufficient quantity of data at each time instant to categorize the sensor array. Rather than correlating the data over time, it is desired to develop a procedure that detects a sensor array anomaly at each time instant based on redundant data.

Approach

This research will be based on the development of analytic equations and computation experimentation. The goal of the computational experimentation is to develop an understanding of the sensitivity of sensor-sensor covariance on the detection of anomalous signals. The experiments will utilize specific scenarios to model the spatial distribution, the expected failure rate, and covariance of the sensors in an array. Anomaly detection has not investigated the impact of sensor covariance in association with failure rate on data discrimination. To answer the question "How important are sensor-sensor covariance and expected failure rates for detecting sensor array signal anomalies?" it is necessary to conduct a sensitivity study.

The research approach will be based on Monte Carlo simulation to determine expected sensor failure rates (EFR) and a first principal simulation model that represents scenarios for an array of sensors that are spatially configured within a placement environment. The Monte Carlo simulation will be used to establish confidence limits (68.3%, 95.4%, and 99.7%) on the number of sensor failures expected for a deployed sensor array. The first principal simulation model will be used to investigate sensor-sensor covariance, define scenarios, generate data, and test the applicability of the statistical methodologies for interval intersection and clustering.

The approach proposed for this methodology is as follows. Pre-process the expected failure rate using Monte Carlo simulation based on specific scale (α) and shape (β) parameters for the Weibull distribution. An expected failure rate curve and associated confidence limits will be produced. The first principal simulation of various scenarios and sensor array spatial distribution relative to measurement source will then be run. The simulation will generate a history of sensor array refined signals over time and includes; spatial correlation, signal interval intersection, intersection aggregation, and clustering algorithms. Central to the simulation is the sensor array spatial configuration and sensor-sensor covariance data. The array spatial distribution data is utilized to transform the sensors by distance, generating comparable sensor signals. The sensor–sensor covariance data represents the degree of agreement or strength of relationship that should exist between refined signal data from similar sensor types. The covariance matrix provides a mechanism to undertake a parameter study of the impact of sensor-sensor correlation on detecting anomalies.

---

[11] Temperature dissipation is relatedto the distance cubed from the source of measurement ($T \alpha cd^3$).

Publications

This research has resulted in a number of publications:

J. S. Dreicer, "Sensor Signal Processing Anomaly Detection Theory Development," Los Alamos National Laboratory report, NIS-7/99-51, LA-UR-99-XX (1999)

J. S. Dreicer, "Graph Theoretic Fault Detection and Isolation," Los Alamos National Laboratory report, NIS-7/99-52, LA-UR-99-XX (1999)

J. S. Dreicer, "START III and Fissile Material Inventory Initialization," Los Alamos National Laboratory report, LA-UR-99-XX (1999)

J. S. Dreicer, "START III - Initialization Impact & Requirements," Los Alamos National Laboratory report, LA-UR-99-544 (1999)

J. S. Dreicer, "Russian Fissile Material Inventory Validation," Los Alamos National Laboratory report, LA-UR-99-545 (1999)

J. S. Dreicer, "Advanced Nuclear Measurements LDRD – Sensitivity Analysis," Los Alamos National Laboratory report, LA-UR-99-64 (1999)

J. S. Dreicer, "Theory Development for Sensor Array Anomaly Analysis," Los Alamos National Laboratory report, LA-UR-98-4331 (1998)

J. S. Dreicer, "Information Analysis and Modeling Research," Los Alamos National Laboratory report, LA-UR-98-3701 (1998)