SAND2011-1769P

Week 10 – Day 1

Nuclear Material Measurement Techniques and Equipment

Lecture 1 – Overview of Safeguards Measurement Techniques
Lecture 2 – Nondestructive Assay Methods: Gamma and Neutron
Lecture 3 – Bulk Measurement Methods
Lecture 4 – Destructive Assay Methods: Chemical Assay

Nuclear Materials Measurement Techniques and Equipment

GNEII Pilot Course

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SAND 2010_____

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Main Teaching Points

1. Understand the main measurement methods used for nuclear materials safeguards
2. Understand the difference between destructive and nondestructive assay methods
3. Become familiar with radiation (gamma and neutron) measurements principles and equipment
4. Become familiar with physical/chemical measurement principles and equipment

Nuclear Material Measurement Techniques and Equipment

- **Key Terms –** nuclear material, measurement technique, measurement equipment, nondestructive analysis (NDA), destructive analysis (DA)
- **Key Concepts:**
  – Main goal of nuclear material measurement techniques
  – Main types of equipment used in measuring quantities of nuclear materials
- **Desired Student Outcomes:**
  – Understand the differences between NDA and DA techniques
  – Understand how nuclear material safeguards use these techniques
  – Understand the terminology used in nuclear material measurement
  – Assess the effectiveness of specific nuclear material measurement techniques

Overview of Safeguards Measurement Techniques

Introduction

- Nuclear material verification relies heavily upon sophisticated measurement techniques
- These include two general categories:
  – **Nondestructive Analysis (NDA):** A measurement of the nuclear material content (or of the element or isotopic concentration) of an item without producing significant physical or chemical changes in the item
    - generally carried out by observing the radiation emission from the item and by comparing that emission with a calibration whose contents have been determined through destructive analysis
  – **Destructive Analysis (DA):** normally involves destruction of the physical form of the sample and could include taking of a representative sample or sample conditioning prior to analysis

Destructive Analysis (DA)

- Used to:
  - verify that *protracted diversion* of safeguarded nuclear materials has not occurred
  - *certify working standards* used for the calibration of NDA and installed verification instruments
  - provide *assurance of the quality* and independence of on-site measurements (e.g. validation of facility specific procedures)
  - carry out *periodic verifications* of the operator's measurement system

DA (continued)

- DA verification measurements involve:
  - taking of independent samples
  - conditioning at the facility to ensure that they are in a chemical form adequate for maintaining their integrity during transport
  - packaging, sealing and shipment to the *IAEA Safeguards Analytical Laboratory (SAL)*
  - analysis by SAL or the *Network of Analytical Laboratories (NWAL)*
  - statistical evaluation of the results of their analysis

Safeguards Analytical Laboratory (SAL)

- IAEA's laboratory, located in Seibersdorf, Austria
- Responsible for *destructive analysis* of nuclear material samples as well as for handling and analysis of *environmental samples* for safeguards purposes
- Provides support to both destructive analysis and environmental sampling programs through
  - the supply of sampling materials, quality assurance and training of IAEA inspectors

Network of Analytical Laboratories (NWAL)

- Group of laboratories in IAEA Member States that have been approved to analyze safeguards samples and to assist the SAL in analysis of nuclear material and environmental samples
- Includes:
  – LANL, LLNL, ORNL, PNL, Savannah River, New Brunswick
  – Karlsruhe
  – V.G. Khlopin Radium Institute
  – NMCC (Japan)
  – CEA Labs (Marcoule, Saclay, Bruyères le Chatel)
  – AEA Technologies (Harwell, UK)
  – AECL (Chalk River Canada)
  – etc…

Comparison of DA and NDA

DA	NDA
slower (includes time to transport and analyze samples)	quicker (sometimes real-time)
requires a fixed laboratory	portable instruments
measures some part of an item (not the whole thing)	usually measures an entire item not just a part of it
generally very expensive	usually less expensive
most accurate	usually less accurate

Comparison of DA and NDA (continued)

- Although DA can produce very accurate results, it is not always practical
  – DA is not practical when
    - *large number* of measurements are needed
    - information on SNM amounts is needed *rapidly*
    - samples are *heterogeneous* (i.e., sampling errors)
    - material composition is *unknown*
    - material is *inaccessible* for sampling (e.g., holdup, sealed product items, etc.)
  – NDA has a useful role where DA is not useful:
    - rapid verification
    - measurements of poorly-characterized items
    - measurement or verification of sealed items
    - measurement of holdup
    - support of audit and inspections

NDA Instrument Examples

http://sti.srs.gov/fulltext/tr2000179/tr2000179.html

Active Well Neutron Coincidence Counter
(He-3 tubes in poly and using AmLi source for counting U-235)

Cerenkov Viewing Device
(for distinguishing spent fuel from voids, etc.)

http://www.sckcen.be/en/Our-Research/Scientific-Institutes-Expert-Groups/Environment-Health-and-Safety/Society-and-Policy-Support/Safeguards/Nuclear-metrology-Measurement-equipment-used-in-safeguards

http://www.sckcen.be/en/Media/Images/Our-Services/Safeguards-nuclear-physics-measurements/Fork-detector/%28gallerymode%29/1

Fork Detector for Measuring Defects in Irradiated Fuel Assemblies
(fission chambers and ion chambers)

NDA Instrument Examples (continued)

mobile FRAM system on a commercial scanner cart

http://www.ortec-online.com/Solutions/in-situ-gamma-spectroscopy.aspx

http://www.ortec-online.com/Solutions/integrated-special-systems.aspx

HPGe spectroscopy system that can run various software programs

Mechanically cooled portable HPGe detector system

https://www.rkb.us/contentdetail.cfm?content_id=208286

Calibrations

- Safeguards measurements have important legal and political ramifications,
  - so physical standards are used extensively to calibrate measurement equipment and provide a basis for determining the accuracy of measurements
- We use these standard reference materials to determine the measurements systems characteristics with respect to:
  - **accuracy**: characterizes the measurement systems ability to provide a result close to the true value when a sample is measured
    - related to systematic error
  - **precision**: characterizes the measurement system's probability of providing the same result every time a sample is measured
    - related to random error

Sampling

- Sampling is an important part of safeguards measurements
  - it is unreasonable to expect all items to be measured
  - instead an appropriate sample plan must be implemented to select a subset of items to be evaluated to gain information about the whole group
    - requires the collection of a **representative sample(s)**
      - sample which is typical in respect of certain characteristics of the population from which it is collected
- Sampling strategies:
  - **Random Sampling**: selecting samples using random number lists or random number generators such that all items in a population have the same probability of being selected
  - **Systematic Sampling**: selecting samples in a repeated pattern
    - such as every 5th item or at fixed time intervals
    - can result in bias

Solutions to Some Common Sampling Errors

- With a mixed population of large and small units
  - selecting only large units would give a sample that is typical of the large units but not representative of the whole population
  - to obtain a representative sample, the population should first be divided into two separate groups (strata) of large and small items
    - and these groups sampled separately
- In sampling from a bulk material,
  - homogenization of the material prior to sampling is likely to be required
    - thus, tanks must be vigorously stirred and powders must be mixed

Matrix Effects

- Any non-homogeneous or non-purely nuclear item may be subject to matrix effects
  - matrix: the non-nuclear part of nuclear material and items
- The matrix materials can in some cases influence the measurement result
  - for example, the presence of hydrogen or fluorine in a matrix can impact on results obtained through the use of a neutron coincidence counting techniques
  - the presence of strong absorbers like steels or lead in scrap could influence gamma-ray measurement techniques
- These matrix effects must be understood and accounted for in the measurement
  - via calibration and calculation

Nondestructive Assay Methods: Gamma and Neutrons

Introduction

- One of the most common ways to analyze safeguarded nuclear materials is by measuring the radiation emitted by the materials
  - *gamma-ray* radiation
  - *neutron* radiation

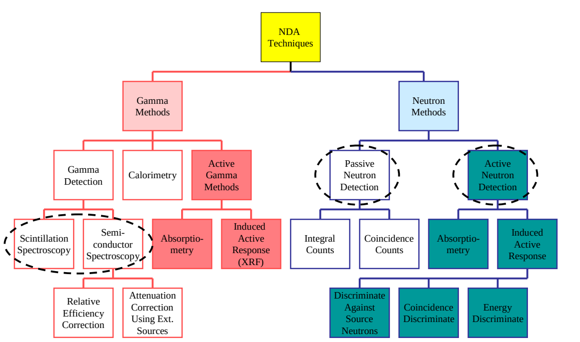
U and Pu Attributes

- Emits *gamma* radiation
- Emits *alpha* radiation
- Emits *infra-red (heat)* radiation
  - from α emission into the matrix
- Emits *single neutrons*
  - from (α,n) matrix interactions and delayed neutrons
- Emits *multiple (coincidence) neutrons*
  - fission neutrons (from 0 to 8 in a burst)
- Is *fissionable*
  - prompt fission, delayed neutrons, delayed gammas

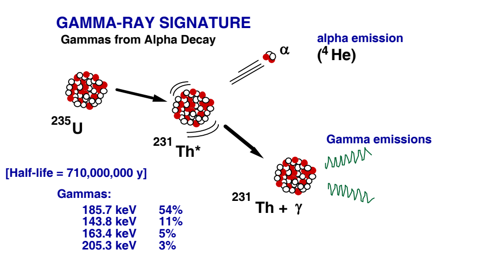
NDA Techniques

- Gamma-ray measurements
  - *detailed* energy information available
  - instruments can be very *portable*
  - measure *isotopic composition* or *grams* of specific isotopes
  - gamma-ray *absorption* is significant (must be corrected for)
  - gamma measurements impractical if sample is *large*, *dense*, or *heterogeneous*
- Neutron Measurements
  - *prompt* (coincidence) or *delayed* neutrons from fissions
  - U assays usually require *active* techniques
  - absorption is a minor problem
  - good for many *large*, *dense*, or *heterogeneous* samples
  - *hydrogenous* (moderating) materials greatly affect response

Classification of NDA Techniques



Origin of γ-rays



U and Pu Gamma-rays

Table 1-2. Major NDA gamma-ray signatures

Isotope	Energy[a] (keV)	Activity[a] (γ/g-s)	Mean Free Path[b] (mm) (High-Z, ρ)	(Low-Z, ρ)
^{234}U	120.9	9.35×10^4	0.23	69
^{235}U	143.8	8.40×10^3	0.36	73
	185.7	4.32×10^4	0.69	80
^{238}U	766.4[c]	2.57×10^1	10.0	139
	1001.0[c]	7.34×10^1	13.3	159
^{238}Pu	152.7	5.90×10^6	0.40	75
	766.4	1.387×10^5	9.5	139
^{239}Pu	129.3	1.436×10^5	0.27	71
	413.7	3.416×10^4	3.7	106
^{240}Pu	45.2	3.80×10^6	0.07	25
	160.3	3.37×10^4	0.45	76
	642.5	1.044×10^3	7.4	127
^{241}Pu	148.6	7.15×10^6	0.37	74
	208.0[d]	2.041×10^7	0.86	83
^{241}Am	59.5	4.54×10^{10}	0.14	38
	125.3	5.16×10^6	0.26	70

Source: Reilly et all "PANDA Manual" Pg 18

X-rays from U and Pu

Table 1-1. Major K x rays of uranium and plutonium[a]

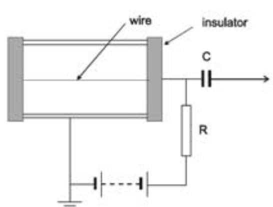
X Ray	Levels (Final - Initial)	Energy (keV) Uranium	Plutonium	Intensity[b] Uranium	Plutonium
$K_{\alpha 2}$	K - L_2	94.67	99.55	61.9	62.5
$K_{\alpha 1}$	K - L_3	98.44	103.76	100	100
$K_{\beta 1}$	K - M_3	111.30	117.26	22.0	22.2
$K_{\beta 2}$	K - N_{2-5}	114.5	120.6	12.3	12.5
$K_{\beta 3}$	K - M_2	110.41	116.27	11.6	11.7

[a] Other x rays in the K series are weaker than those listed here. The energies and intensities are from Ref. 1.
[b] Relative intensity, 100 is maximum.

Source: Reilly et all "PANDA Manual" Pg 11

Radiation Detection

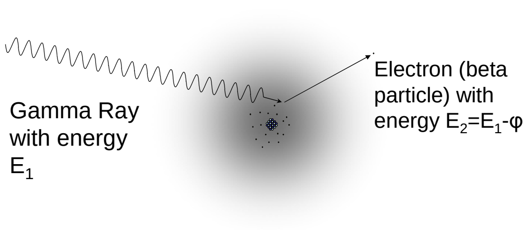
- Radiation detection is based on the *interaction of radiation with the material* of a detector where energy is deposited
- The ultimate goal is the *formation of an electron-ion pair* inside the working volume of the detector
- These electron-ion pairs are then collected on electrodes
  - this creates voltage across the capacitor and causes a *pulse* across the resistor which is recorded as the signal



Properties of Radiation Detection Systems

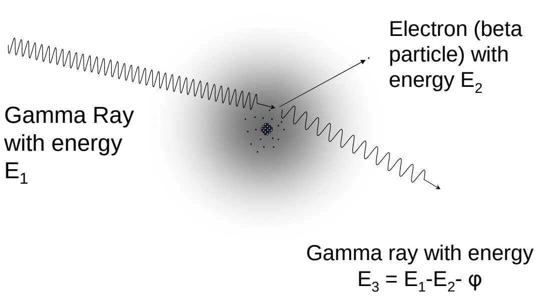
- Sensitivity
  - ability to detect and measure the radiation of interest in the presence of noise and signals caused by other radiation
- Efficiency
  - intrinsic efficiency
    - fraction of particles striking the detector volume that are detected
  - geometric efficiency
    - solid angle that the detector presents to the source
  - absolute efficiency
    - product of geometric and intrinsic efficiencies
- Energy Resolution
  - accuracy with which the system can measure the energy of a radiation and its ability to distinguish radiations of slightly different energy
- Time Resolution
  - accuracy with which the system can determine the time of arrival of a radiation
- Pulse-Pair Resolution
  - ability of system to detect radiations closely spaced in time
  - dead time

The Photoelectric Effect

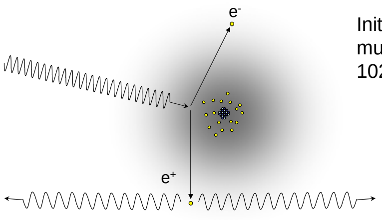


All of the gamma energy is absorbed in the interaction

The Compton Effect



Pair Production and Annihilation

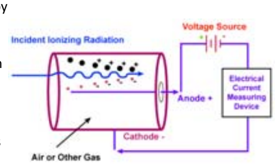


Initial gamma energy must be greater than 1022 keV

Positron annihilates in contact with an electron, producing two 511 keV gamma rays

Gas-Filled Detector

- Operates using the ionization produced by radiation as it passes through a gas
  - consists of two electrodes with an electrical potential applied and gas in between
- Charges move under the influence of the electric field
- Current Chamber: charge motion induces a current on the electrodes
- Pulse Chamber: charge produced is transformed into a pulse
  - particles are then counted individually
  - through appropriate electronics

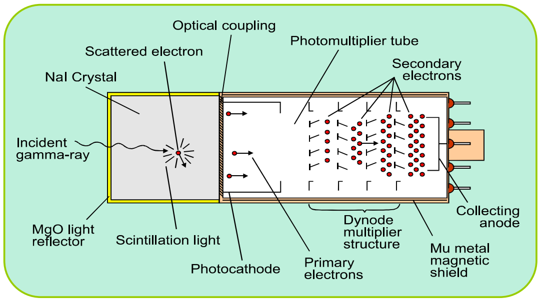


http://www.equipcoservices.com/support/tutorials/introduction-to-radiation-monitors/

Scintillation Detectors

- Scintillators are materials that produce light when ionizing radiation passes through them
  - can be solids, liquids, or gases
- Operation:
  - absorption of incident radiation raising *electrons to excited states*
  - after subsequent *de-excitation*, the scintillator emits a photon in the visible light range
  - the light emitted from the scintillator interacts with the *photocathode* of a photomultiplier tube releasing electrons
  - electrons are guided, with the help of an electric field, towards the first *dynode*,
    - dynode is coated with a substance that emits secondary electrons
  - secondary electrons from the first dynode move towards the second and so on
  - final amplification of about 10^6 or higher

Scintillation Detectors



NaI Crystals and Phototube

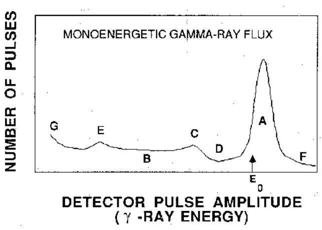
1" x 1" crystals, (damaged)

Typical 2" phototube

Scintillation Detector Examples

- NaI
- CsI
- ZnS
- LiI
- BiGeO (BGO)
- LaBr
- LaCl

Spectral Features



A - Full-energy photopeak

B - Compton background continuum

C - Compton edge

D - Compton valley
(multiple Compton scatters)

E - Backscatter peak

F - Excess energy region
(high energy background gammas)

G - Low energy rise
(electronic noise)

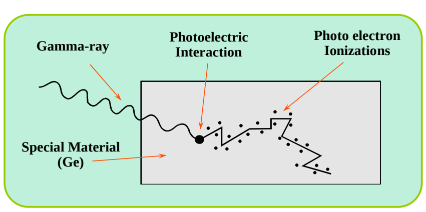
*For photons above 1022 keV there may be single and double escape peaks as well

Source: Reilly et all "PANDA Manual" Pg 53

Semiconductor Detectors

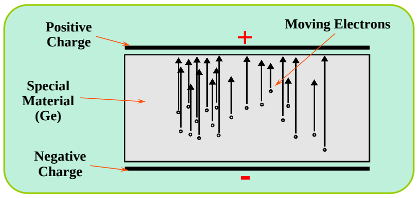
- Semiconductor detectors are *solid-state devices* that operate essentially like ionization chambers
- The charge carriers in semiconductors are not electrons and ions as in gas counters
  - but *electrons and holes*
- Radiation incident upon the semiconducting junction produces electron-hole pairs as it passes through it
- Electrons and holes are swept away under the influence of the electric field
  - proper electronics collects charge in a pulse

Semiconductor Detectors



Liberated photoelectron ionizes atoms in the detector material, liberating an amount of charge proportional to the energy of the original gamma ray.

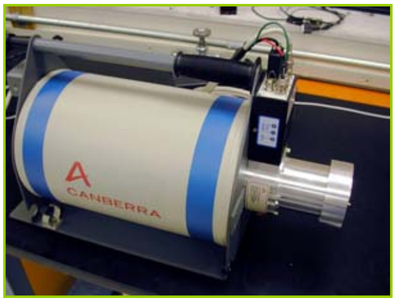
Semiconductor Detectors



The liberated charge is swept toward the positive side of the detector volume by electric forces, causing a sudden burst of charge at that terminal for each such event.

Typical Portable HPGe Detector

(with attached Liquid Nitrogen Dewar)



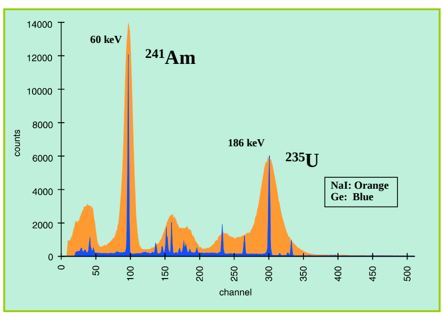
Semiconductor Detector Examples

- Ge(Li)
- Si(Li)
- HPGe
- CdTe
- CdZnTe
- HgI_2

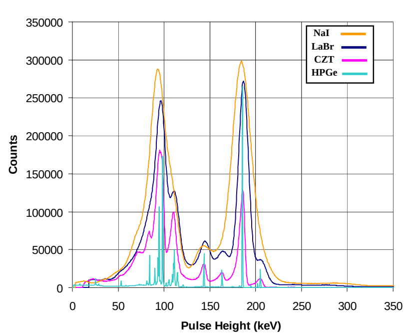
Semiconductor Energy Resolution

- Semiconductor detectors have very high energy resolution because charge is collected directly and no amplification is needed
- One disadvantage is that the detector crystal *must be cooled to about 77^{o}K (for HPGe detectors)*

Energy Resolution of Scintillator Versus Semiconductor Detectors

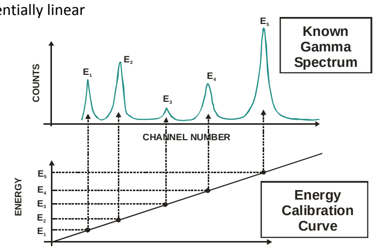


^{235}U Gamma-Ray Spectra (Fresh U)



Energy Calibration

- Energy Calibration is the relationship between channel number in an MCA and gamma-ray energy
  - is essentially linear



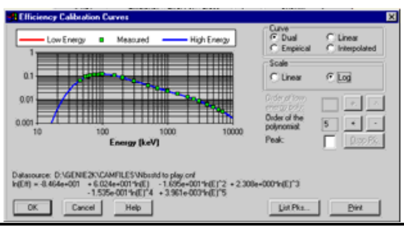
*E_γ (keV) = A * Channel# + B*

Energy accurate to about 0.1 keV

Efficiency Calibration

- Efficiency of a detection system is typically defined as the detector's observed (seen) peak area count rate divided by the expected gamma emission rate for that gamma energy

$$Efficiency = \frac{\text{number of photons registered by detector}}{\text{number of photons emitted by the source}}$$



Neutron Sources

- There are a number of different sources for neutrons:
  - Neutrons from *nuclear reactions*
    - (n,fission)
    - (α,n)
    - (p,n)
    - (γ,n)
  - Neutrons from *spontaneous nuclear decay*
    - spontaneous fission
    - direct neutron emission
  - *Fusion neutrons*
  - *Accelerator sources*
    - spallation neutron sources

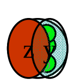
Mechanisms for Neutron Detection

- Generally speaking, neutron detection mechanisms are based on indirect methods
- Since neutrons are neutral in charge they do not interact directly with the electrons in matter
- Thus, neutron detection relies on
  - neutrons interacting with various nuclei,
  - initiating the release of one or more charged particles,
  - the electrical signals produced by the charged particles can then be processed by the detection system

Two General Types of Neutron Detectors

- There are generally two types of neutron interactions used:
  - *scattering* by a nucleus with transfer of some kinetic energy to the nucleus
    - if enough energy is transferred, then the recoiling nucleus ionizes the material surrounding the point of interaction
    - based on interaction of neutrons with low-Z nuclides
  - neutron can cause a *nuclear reaction*
    - the products from the reaction can initiate the detection process
      - products could include protons, α-particles, gamma-rays, and fission fragments
    - some reactions require a minimum energy, but most are dominated by thermal neutron reactions
- Both types can be solid, liquid, or gas

Neutron Interactions

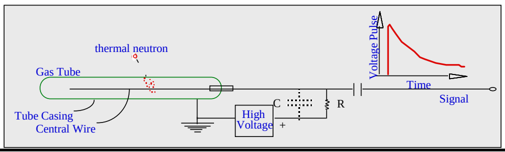


Scattering
- Elastic
- Inelastic

Absorption
- Electromagnetic
- Charged
- Neutral
- Fission

Gas-Filled Neutron Detectors

- Gas-filled detectors may be used to detect either thermal neutrons via nuclear reactions or fast neutrons via recoil interactions
- Detector walls are about 0.5 mm thick and are manufactured from either stainless steel or aluminum
  - performance of either material is quite satisfactory
  - steel walls absorb about 3% of the neutrons
  - aluminum walls absorb about 0.5% of the neutrons
  - thus aluminum tubes are usually preferred because of their higher detection efficiency



BF_3 Tubes

- Uses BF_3 gas enriched in B-10
- The detector uses the following reaction:

$$^{10}B + n \rightarrow {}^{7}Li^{*} + {}^{4}He + 2310 keV$$

- The $^7Li^*$ is left in an excited state 94% of the time and decays by IT:

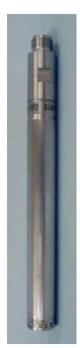
$$^{7}Li \rightarrow {}^{7}Li + 480 keV\ \gamma$$

He-3 Tubes

- Uses He-3 which is produced by separation from tritium
- This detector uses the following reaction:

$$^{3}He + n \rightarrow {}^{3}H + {}^{1}H + 765 keV$$

- Very similar in characteristics to a BF_3 and often difficult to determine which is best for your application



Fission Chambers

- Fission chambers are a variation on the other gas-filled detectors
- They detect neutrons that *induce fissions* in fissionable material coated on the inner walls of the chamber
  - fissionable material is usually 0.02 to 2 mg/cm^2 thickness of HEU
  - thin layer is directly exposed to the detector gas
- After a fission event the *two fission fragment* travel in nearly opposite directions
  - the ionization from the fragment that enters the gas is sensed by the detector

Total vs. Coincidence Counting

- Total counting is sensitive to (α,n), SF, and IF neutrons
- Coincidence counting is sensitive only to SF and IF neutrons
- Total counting compared to coincidence counting is:
  - less sensitive to induced fission neutrons
  - less sensitive to detector efficiency changes
  - more sensitive to changes in background
  - yields better precision

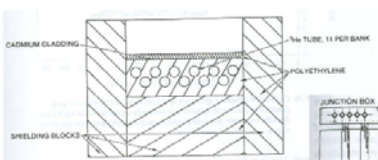
Instruments for Total Neutron Counting

- Instruments are usually:
  - simple and easy to operate
  - less sensitive to multiplication effects and efficiency variations
  - unable to discriminate neutron energy or production source
  - made with ^{3}He tubes with instrument efficiencies up to 20%
- Applications include:
  - verification of Pu metal and compounds
  - verification of UF_6 cylinders and monitoring of UF_6 enrichment
  - measurement of low enriched uranium
  - moisture monitoring

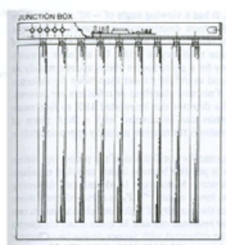
SNAP Detector

- Weighs about 20 pounds
- Rugged and portable
- Indoor or outdoor use
- 2 to 1 front to back difference
- Uses one 10-atm ^{3}He tube
- Applications include:
  - MC&A
  - SNM searching
  - Shipper/Receiver measurements
  - Surveillance measurements

Slab Detector



Shielded Slab Counter



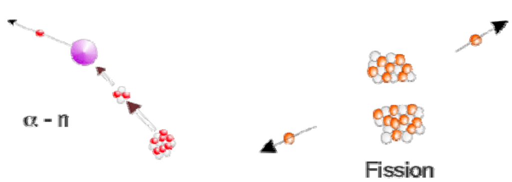
Similar to SNAP detector with better efficiency and directionality.

Used to measure UF_6 and holdup.

Source: Reilly et all "PANDA Manual"

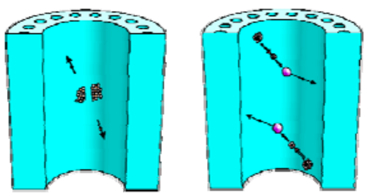
Neutron Coincidence Counting

- Two simultaneous processes:



Neutron Coincidence Counting

- Can we distinguish between two simultaneous (α,n) events and fission?



Active Well Coincidence Counter

Bulk Measurement Methods

Introduction

- Bulk Measurement Methods: measurements of total bulk amounts of matter (solid, liquid, and gas) without regard to the SNM content or chemical composition
  - includes weight, volume, and flow measurements
- Perhaps the most frequently used methods in the nuclear processing industry
- Bulk measurements are used directly or with other measurements to provide material control and loss detection

Advantages

- Advantages:
  - nondestructive
  - easily performed
  - rapid
  - quickly learned without specialized training
  - inexpensive
  - applicable to a variety of materials
- Disadvantages:
  - non-specificity of the measurement with regard to amount of SNM

Weight Measurements

- Very accurate
- Very widely used
- Measures the bulk quantity of SNM-bearing materials
  - including feed, in-process material, intermediate and final products, scrap, and inventory materials
- Weight measurements are used for production, process, and quality control as well as for safeguards

Basic Gravimetric Method

- Basic method:
  - adjust scale to indicate zero weight when the scale platform is empty
  - measuring the weight of the empty vessel
    - (tare weight)
  - measuring the same vessel containing the SNM-bearing material
    - (gross weight)
  - (net weight) = (gross weight) – (tare weight)
- Sometimes you can adjust scales to zero with the empty vessel on the platform to yield a net weight directly

Weight is a Direct Measure of Mass

- Weight is unaffected by temperature or density changes and can be directly related to mass

$$weight = mass \times g$$

  - this is not true for volume or many other measurements
  - g is constant at a specific location but is not constant everywhere on Earth
    - decreases with altitude and with latitude
    - affected by large iron or dense ore deposits nearby
    - etc.
  - effects of changes in g can be eliminated due to calibration by international mass standards

Weighing Equipment

- Mechanical Weight Measurement
  - direct comparison with standards
  - spring distortion
  - load cells
- Electronic Weight Measurement
  - strain gauge load cells
  - force compensation
  - vibrating wire system
  - ferromagnetic load cell

Errors Common to All Weighing Methods

- Some materials processed in fuel cycle facilities exhibit a spontaneous loss or gain of weight that does not result in a loss of SNM
  - could be due to:
    - adsorption or desorption of water
    - oxidation or reduction reactions
    - chemical decomposition
    - loss of non-SNM volatile components
    - other reactions leading to change in the SNM concentration of the material being weighed
  - can lead to serious systematic errors
- Improper zeroing or taring of scales can lead to a systematic error
- Scales that are not properly leveled or are located on unstable platforms
- Scales must be cleaned and recalibrated frequently
- Buoyancy effect

Volume Measurements

- For many processes, we can measure the concentration of SNM in a small volume of material using sensitive DA and NDA techniques
  - but we also then need to know the volume of the tank or vessel that the small sample is from to determine the total SNM quantity

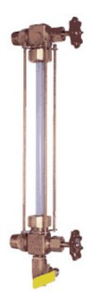
$$m = C \cdot V$$

- Volume measurements generally break into 2 categories:
  - Liquid Level Measurements
  - Chemical and Isotope Dilution Methods

Sight Gauges

- Most direct way of measuring liquid level
- Used if radioactivity near tank is low enough to allow access
- Made by observing the liquid level in a graduated glass tube mounted on the exterior of tank
- Not easily interfaced with computer systems (but can be done)
- Major source of error:
  - different temperature inside and outside the tank

to vapor space



to liquid contents

Chemical and Isotopic Dilution Methods

- When a known amount of chemical or isotope tracer is dissolved in an unknown volume of liquid, the resulting concentration of the tracer in the liquid is inversely proportional to the volume of the liquid

$$V_{tank} = \frac{V_{tracer} C_{tracer}}{C_{tank}}$$

  - obviously the tracer must be in the form of a solution whose concetration is very accurately known and an accurate aliquot of this must be produced to add to the tank

Flow Measurements

- There are two categories of flow meters:
  - Quantity meters
    - measures fluid flow by separating the stream into discrete, isolated quantities of precisely known mass or volume increments
    - the number of these increments is counted to determine the quantity of fluid that passes through the meter
  - Flow rate meters
    - measures the rate of flow of a fluid in a continuous stream
    - integration of the measurement with time is used to obtain the total amount of fluid passing through the meter
- These meters are used mostly from process control not for safeguards

Destructive Assay Methods: Chemical Assay

Chemical Assay Methods

- We are going to discuss chemical assay methods used in safeguards for determining the concentration and isotopic composition of U and Pu
  - there are literally thousands of published methods
  - we will only discuss a small subset of these methods
- Chemical analysis of U, Pu, Th, and higher actinides present special problems to the analyst
  - makes it interesting to work on these materials
  - has forced the development of some special techniques used just for safeguards purposes

General Measurement Scheme

- Bulk weight or volume of a lot or a batch is determined
- Representative sample obtained
- Concentration of SNM in sample is determined using chemical analysis
  - typically beginning with sample dissolution and separation

$$m = C \cdot V$$

- Error in SNM quantity is a combination of
  - bulk measurement error
  - sampling error
  - analytical error

Chemical Separation of U

- Ion Exchange
  - mostly on anion exchange resin with strong HCl solvent
- Solvent Extraction
  - extraction with TBP as organic and HCl as aqueous is widely used
  - requires reduction to remove Pu and Th
- Precipitation
  - infrequently used, poor selectivity

Gravimetry for U

- A weighed portion of material is converted to U_3O_8 by ignition in air
  - applicable only to high-purity compounds
- The final weight of the U_3O_8 is corrected for the nonvolatile impurities present by spectrometric analysis
- Large sample weights (>5g) are required to minimize weighing errors
- Advantages:
  - low operator time per determination
  - no need for dissolution of oxide samples
  - simple laboratory equipment needed
- Similar method can be used for Pu to PuO_2

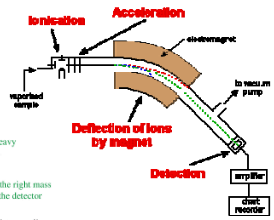
Mass Spectrometry

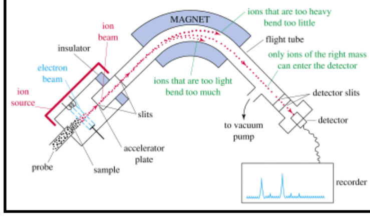
- Mass Spectrometry is an analytical technique used to measure the mass-to-charge ratio of ions
  - most generally used to find the composition of a physical sample by generating a mass spectrum representing the masses of sample components
  - can be used for:
    - identifying unknown compounds by the mass of the compound molecules or their fragments
    - determining the isotopic composition of elements in a compound
    - determining the structure of a compound by observing its fragmentation
    - quantifying the amount of a compound in a sample using carefully designed methods (mass spectrometry is not inherently quantitative)
    - determining other physical, chemical, or even biological properties of compounds with a variety of other approaches

Mass Spec as a Safeguards Tool

- Our interest in mass spectrometry is actually fairly limited:
  - determination of U isotopic composition
  - determination of Pu isotopic composition
  - determination of U and/or Pu concentration
- Mass spectroscopy is in some ways well suited to this analysis
  - performed by ionizing a sample and separating ions of differing masses and recording their relative abundance by measuring intensities of ion beams in a detector
- A typical mass spectrometer comprises three parts:
  - an ion source
  - a mass analyzer
  - detector system

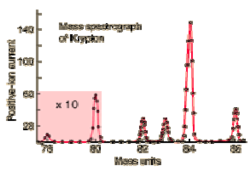
Basic Schematic of a Mass Spectrometer





Mass Spectrographs

- The output from the from the mass spec is a mass spectrum (or mass spectrograph)
  - also sometime called a "stick diagram"
- Mass spectrum shows the relative current produced by ions of varying mass/charge ratio
- The mass spectrum for Kr might look like this:



Gas-Ionization Mass Spectrometry

- Particularly useful for determining U isotopics in UF_6
  - most often employed at enrichment facilities
- Can be used for the analysis of any U compound that can be converted to UF_6
  - however surface-ionization mass-spectrometry is generally preferred for other compounds
- Large samples (10^{-1} g)
- Memory effects
  - gas-ionization technique is subject to a substantial memory effect
  - when a wide range of enrichments is to be determined, it is advisable to have a number of instruments, each dedicated to a narrow band of enrichments

Surface Ionization Mass Spectrometer (SIMS)

- SIMS is the preferred and most widely used method for determining the isotopic composition of U
  - generally applicable to many U-compounds and alloy after dissolution and chemical treatment to obtain purified U fractions
- U fraction is diluted and an aliquot is evaporated on the mass spec filament
- A current is passed through to form a U oxide and to remove acid, water, and any organic matter
- The filament is then heated to vaporize and ionize U
- U quantity used in analysis: 10^{-8} to 10^{-5} g
- For a U standard, expect uncertainties of ~0.005%

Isotope Dilution Mass Spectrometry (IDMS)

- IDMS is used to measure the elemental concentrations in a sample
- This is most frequently applied to the determination of Pu and U in the input accountability tank (IAT) at a reprocessing facility
- IDMS involves the addition of a measured quantity of a highly enriched isotope to an aliquot of the sample
  - the isotope must not be present in the sample (or at least at very small levels)
  - isotope added is referred to as a "spike"
- The sample is then processed and the U and Pu are measured relative to the spike
  - we can then get to the elemental content

References

1. Doug Reilly, Norbert Ensslin, Hastings Smith "Passive nondestructive assay of nuclear materials"

Exercises

Week 10 – Day 2

Containment, Surveillance, and Monitoring

Lecture 1 – Containment and Surveillance
Lecture 2 – Remote Monitoring

Containment, Surveillance, and Monitoring

GNEII Pilot Course

February – May 2011

KUSTAR, Abu Dhabi

**(Dr. Alexander Solodov, Claudio Gariazzo,
Dr. William S Charlton, and Dr. Sunil Chirayath)**

Texas A&M University, USA

SAND 2010_____

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Main Teaching Points

1. Understand the basic principles of containment of nuclear materials
2. Understand common surveillance devices used for monitoring nuclear materials
3. Understand the basic principles of monitoring of stored nuclear materials

Containment and Surveillance

- **Key terms**
  - containment, surveillance, remote unattended monitoring
- **Key concepts**
  - The purpose of containment and surveillance
  - The purpose of remote monitoring
  - Major technologies used for remote monitoring
- **Desired student outcomes**
  - Understand the need for containment and surveillance of nuclear materials
  - Be familiar with main types of equipment for containment and surveillance
  - Understand the main approaches to remote monitoring of nuclear materials
  - Be familiar with main types of equipment for remote monitoring

Containment and Surveillance

Introduction

- Nuclear Material Control (NMC) typically refers to Containment and Surveillance (C/S) and material monitoring/tracking
  - Complementary to Nuclear Material Accountancy (NMA)
  - Control must be applied between accounting practices/measurements
- Containment – implies the protection of material from access
  - Control, hold, surround, and limit
- Surveillance – implies maintaining a continuity of knowledge by upholding the chain of custody
  - Observation, close watch, examination with scrutiny
- C/S provide assurance that material measurements under NMA are valid between measurement campaigns
  - With effective use, C/S detects material theft or diversion

Definitions of C/S

- **C/S technologies –** a component of an integrated systems approach designed to maintain the "continuity of knowledge" of declared nuclear assets and activities.
  - The knowledge that is captured should be sufficient to provide a high level of confidence that activities are occurring as declared.
- **Containment systems –** systems and technologies that are designed to provide secure methods that control, surround, protect, and delay access to nuclear assets.
  - The primary purpose of containment is to facilitate the accountancy and security of nuclear assets.
- **Surveillance systems –** technologies and methodologies designed to watch and record as many activities and attributed as possible associated with nuclear materials and processes.
  - The goal for these systems is essentially to be the "*inspector's eyes in the field*" or to provide verification that activities are occurring as declared.

Surveillance

- Collection of information through observation
  - Detect movements of nuclear material (or other items)
  - Any interference with containment
  - Tampering with IAEA equipment, samples and data
- Surveillance may also be used for observing various operations or obtaining relevant operational data
- IAEA inspectors may carry out surveillance assignments continuously or periodically at strategic points

Surveillance Examples

- Optical surveillance (cameras)
- Two-person rule
- Active monitoring
- Motion detectors
- Radiation detection instruments

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Optical Surveillance

- Optical surveillance is most effective in storage areas with few activities that could be interpreted as the removal of nuclear material
  - Typical application would be two or more cameras positioned to completely cover the storage area
    - Field of view of the cameras such that any movement of items that could be the removal of nuclear material is easily identified
  - Items have to be sufficiently large to be identified and that one or more images have to be recorded during the movement of material

- Image recording
  - Set at periodic frequency (significantly shorter than the fastest possible removal time)
  - Motion-triggered recording

Surveillance Systems

DCM14: Digital Camera Module with CCD camera

ALIS: All-in-one Surveillance Unit (digitally stores images on a PCMCIA card)

SDIS: Server Digital Imaging System (multiple cameras connected to a single recording or communication console)

Containment

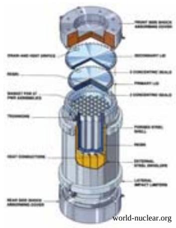
- Structural features of a facility, container, or equipment
  - Used to establish the physical integrity of an area (or items)
  - Maintain the continuity of knowledge of the area (or items)
  - Prevent undetected access to or movement of nuclear material

- Integrity of the containment is assured by periodic inspection and seals or surveillance measures
  - Seals are a large component of an effective containment system

- Currently, containment verification is reliant on seal technology and protocols

Containment Examples

- Walls of a storage room
- Transport flasks
- Storage containers



Seals

- Seal or Tamper-Indicating Device (TID) – a device designed to leave non-erasable, unambiguous evidence of access or entry (typically have **integrity** and **identity**)
  - **Integrity** – the ability of the seal to indicate whether an attack has occurred
  - **Identity** – the ability of the seal to be differentiated between otherwise identically appearing seals
  - Various types of seals:
    - Passive – requires physical inspection to determine breach
    - Active – provides continuous monitoring of seal for breach
    - Anti-evidence – designed to remove or erase specific information or features upon opening
- Lock – security device that can be opened or closed without providing indication of entry
  - Primarily meant to delay, complicate, and/or discourage unauthorized entry
  - Unlike a seal, a lock only exists to resist access

Other Definitions

- Tag – a unique identifier that is used for asset identification
  - Used to facilitate inventory taking, provide security, and protect against counterfeiting
- TIE – Tamper-Indicating Enclosure
  - Designed specifically for safeguards applications (a special type of containment)
- Use protocol – specifically designed procedures developed for a particular seal or safeguards/security system designed to ensure effective use of the seal
- Authentication – the act of establishing or confirming something (or someone) as authentic, that is, that information received is true.
  - Might involve confirming the identity of a person, a sensor, a device, or assuring that a computer program is a trusted one

Uses of Seals

- Sealing systems may be applied on:
  - Safeguarded material or equipment to maintain the continuity of knowledge of the sealed contents between inventory verifications, and during shipment from one facility to another
  - Operator’s equipment (e.g. a crane) to monitor any use that would make possible the undeclared removal of nuclear material
  - IAEA property (equipment, samples, standards, data, etc.) to prevent undetected tampering with it
- Most IAEA seals are applied for extended periods of time
  - Several months ~ years
- Quantitative performance metrics
  - Ease of use
  - Durability
  - Vulnerability

Types of Seals

- Categorized into single use or i situ verifiable
  - Single
    - Loop seals (metallic or plastic)
    - Adhesive seals (leaves residue that is hard to remove once removed)
  - Verifiable
    - Fiber optic seals
    - Electronic seals

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Wire Loop and Metal Cable Seals

- Most commonly used
- Some require special tools for application
- Some multi-piece types

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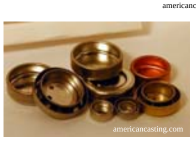

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Bolt-Type Seals

- Typically are two-piece seals with a matching serial number on each piece
  - For identification and validation

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Adhesive-Based Seals

- Typically used on containment that do not have hasps or locking mechanisms
- Clean-up and durability issues exist
- Most uses should be short term


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Other Seals

- Shrink wrap
- Fiber optic
  - Passive (COBRA)
  - Active (VACOSS)
- Image patterns
- Electronic seals


atlanticshrinkwrap.com


iaea.org


iaea.org


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Effective Seal System

- An effective seal system consists of the following factors:
  - Access control
  - TID control and accountability
  - Surveillance
  - Item control
  - Trained personnel
  - Limitations of TIDs
  - Performance testing
- A seal system is only as effective as the implementation protocol

Seals Closing Points

- Seals must be selected with application, environment, and requirements in mind
- Seals that score well in one area (or application) may not score as well in equally important areas (or applications)
- High tech doesn't automatically mean better
- Active seals still require physical inspection
- All seals require effective use protocol
- Cost is not a measure or indicator of seal performance
- Seals only support continuity of knowledge between NMA measurements
- Nothing is tamper proof
- Defeating a seal does not mean the system has been defeated

Containment and Surveillance Systems

- The indication of an anomaly by C/S measures does not necessarily by itself indicate that material has been removed
  - ultimate resolution of anomalies is provided by nuclear material verification
- If any C/S measure has been compromised, the State is to inform the IAEA by the fastest means available
- Seals could be compromised inadvertently or in the case of an emergency

Containment and Surveillance Analysis

- In a storage facility, implemented C/S systems to monitor material movement include
  - Seals
  - Optical surveillance
  - Radiation detection
- Concerns of C/S systems:
  - Nondetection probability – the C/S system will not detect the unauthorized material movement
  - False alarm probability – the C/S system will give a false alarm
  - The time between unauthorized movement and notification of detection
- Preferable to have the nondetection and false alarm probabilities low (dependant on measured signal uncertainty) and the time between movement and detection to be less than 1 material balance period

C/S Using Radiation Detection

- Assume a C/S system for a UO_2 pellet storage facility
- The system contains a portal monitor at the entry/exit point
  - Gross count detectors for a short count time
  - Natural background attributed to stored material in facility
- The portal monitor completely covers the entry/exit point from the storage facility
  - Single access point: all material enters/exits this one monitor
  - Containment is used for assurance

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Monitoring Systems

Introduction

- Unattended Monitoring System (UMS)
  - Automatically monitors flow of nuclear materials 24 hours per day, 365 days per year without human interaction
  - Permanently installed in a nuclear facility
  - Computer-based for data retrieval either on-site or remotely
  - Uses a variety of sensors such as radiation, pressure, temperature, flow, vibration, and electro-magnetic fields to collect qualitative/quantitative data
  - All external components are in tamper-indicating enclosures (TIEs)
- Remote Unattended Monitoring System (RUMS)
  - An UMS yet operated remotely
    - Remote – from a distance
    - Unattended – without people
    - Monitoring – surveillance
- Data encryption and authentication is paramount in both
- Note: **unattended monitoring** does not have be conducted remotely

Monitoring Remotely?

- Unattended monitoring
  - Special mode of application of non-destructive assay or C/S measures, or a combination of these, that operates for extended periods without inspector intervention
  - Optical surveillance used to monitor for safeguards relevant activities over extended periods
  - Unattended radiation detection sensors are used to monitor the flow of nuclear material in a facility process area
- Remote monitoring
  - Technique where safeguards data collected by unattended systems are transmitted off-site via communication networks for review and evaluation
  - Internal recording capability is used for backup purposes
  - Provide better utilization of equipment, better planning of inspections and a reduction in the inspection effort needed to meet verification requirements

Legality of (R)UMS

- INFCIRC/153 – The Structure & Content of Agreements Between the Agency & States in Connection with the NPT
  - PART I, paragraph 4, The Agreement should provide that safeguards shall be implemented in a manner designed:
    - To avoid hampering the economic and technological development of the State … in the field of peaceful nuclear activities, including international exchange of nuclear materials;
    - To avoid undue interference in the State's peaceful nuclear activities, and in particular in the operation of facilities; and
    - To be consistent with prudent management practices required for the economic and safe conduct of nuclear activities.
- As of 2006, IAEA UMS installed in 23 countries:
  - 116 systems installed in 46 facilities
    - 102 Radiation-based
    - 6 Thermo-hydraulic-based
    - 8 Solution Level-based

(R)UMS Implementation

- Goals of RUMS:
  - Provides no loss of safeguards significant data
  - Assurance that data is authentic
- These goals are obtained by
  - Using highly reliable and/or redundant critical components
  - Using uninterruptible power supplies
  - Employing multi-layer security
- Primary objective – to collect safeguards information without inspector's presence
  - Verify flow/inventory of SNM
  - Minimize intrusiveness on facility operator, maintenance, and training
  - Reduce IAEA and operator manpower requirements
  - Decrease radiation exposure
  - Standardize hardware and software

(R)UMS Design Considerations

- Increase cost effectiveness
- Ensure reliability and stability
- Meet IAEA user requirements
- Use facility operator-provided equipment
- Adhere to data authentication requirements
  - Measures needed to ensure that safeguards measurement data is protected and authentic at all times (is data verifiable?)
- Involve IAEA in design/planning stage of development (safeguards by design)
  - Integration of facility specific safeguards features into final plant designs (customized for application)
- Tamper-resistant components
  - Accomplished by using TIDs or TIEs
- Employing redundant systems

Tamper Indicating Features



Source: Photos courtesy of M. Hunt, IAEA, 2010

Tamper Indicating Conduit

Source: Photo courtesy of M. Hunt, IAEA, 2010

Integrated Fuel Flow Monitor

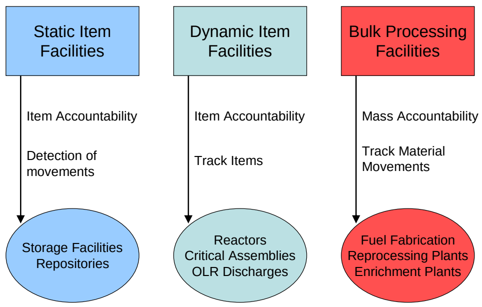
- Fuel flow monitor for online refueling reactor (CANDU 600)
  - "IAEA blue" TIE
  - Uninterruptable power source
  - Provides unattended monitoring
    - Remote data transmission to IAEA headquarters

Source: Photo courtesy of M. Hunt, IAEA, 2010

Other Types of Monitors

- Core discharge monitor (CDM)
  - Radiation monitoring system that monitors the charging and discharging of irradiated fuel bundles to and from the core of an on-load refueled power reactor
- Spent fuel bundle counter
  - Radiation monitoring system that counts irradiated fuel bundles as they are discharged to the spent fuel storage bay of an on-load refueled power reactor
- Reactor power monitor
  - Neutron monitoring system placed outside the reactor biological shield to monitor the power level of the reactor
- Radiation passage monitor
  - Radiation measuring device used to detect the passage of nuclear material through openings in a containment
    - e.g., dosimeters can be used as "yes/no monitors" to confirm the absence of irradiated fuel removals

Monitoring as Items or Bulk



Static Item Facility

- Storage facilities are characterized by a minimum amount of activity
  - The form of the nuclear material does not change over time
- Material is typically monitored by observing
  - Item's attributes
  - Physical characteristics
  - A uniquely identifiable tag or serial number
  - Radiation signature
- Monitoring systems verify the absence of nuclear material movements
  - Digital cameras and software to filter images for motion and automatically identify patterns and images
  - Tags and seals

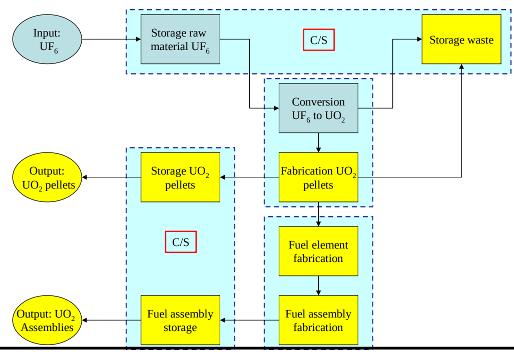
Dynamic Item Facility

- Dynamic item facilities are also characterized by unchanging material forms
  - Though legitimate activities not related to nuclear material diversion can also trigger a video scene change
  - This can make it very difficult and time-consuming to review the surveillance video
- Combining video monitoring and radiation monitoring
  - The radiation system triggers the video images
  - Primary safeguards information comes from the radiation sensors with video used as a secondary

Bulk Processing Facilities

- Nuclear material changes form during normal operations
- Quantitative safeguards must be employed
- Monitoring system must support material accountancy measurements
  - Typically using NDA systems with radiation monitoring and video surveillance
- Inspectors need sophisticated systems to integrate NDA, video, and other safeguards measures to perform efficient inspections
- Most effective measurement method
  - conservation of mass/volume: input = output

Example: U Fuel Conversion and Fabrication Facility



Advantages of (R)UMS

- Continuous operation
- Reduced radiation exposure
- Reduced cost to IAEA
- Reduced cost to facility
- Reduced time to inventory material
- Reduce human errors by limiting human involvement
- Faster reconciliation of anomaly events

Challenges of (R)UMS

- (R)UMS Environments are unique
  - Ionizing Radiation
  - Temperature/Humidity
  - Access Restrictions
  - Isolation
  - Located in "harms way"
- (R)UMS Applications are unique
  - One size does not fit all: standardization at the system level is difficult
  - Standardization at the components level is strongly pursued as a way to reduce impact on Inspectors and Technicians training
  - Consequences of Failure are Severe
  - Loss of Safeguards Data

References

- IAEA Safeguards Glossary pgs 54-61, 69-84
  - Available at http://www-pub.iaea.org/MTCD/publications/PDF/nvs-3-cd/PDF/NVS3_scr.pdf
- IAEA Techniques and Equipment pgs 36-53, 75-82
  - Available at http://www-pub.iaea.org/MTCD/publications/PDF/NVS1-2003_web.pdf
- The Evolution of IAEA Safeguards pgs 59-69
  - Available at http://www-pub.iaea.org/MTCD/publications/PDF/NVS2_web.pdf

Exercises

Week 10 – Day 3

Facility Safeguards

Lecture 1 – Bulk Facility Safeguards
Lecture 2 – Item Facility Safeguards

Facility Safeguards

GNEII Pilot Course
February – May 2011
KUSTAR, Abu Dhabi

(Dr. Alexander Solodov,
Dr. William S Charlton, and Dr. Sunil Chirayath)
Texas A&M University, USA

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Main Teaching Points

1. Understand the primary safeguards systems used in bulk facilities (conversion, fuel fabrication, enrichment, and reprocessing)
2. Understand the primary safeguards systems used in nuclear power systems (Pressurized Water Reactor)
3. Understand the primary safeguards systems used in spent nuclear fuel storage

Facility Safeguards

- **Key Terms** – bulk facilities, item facilities, safeguards approach, material control and accounting, containment and surveillance, measurement systems
- **Key Concepts** –
  - Understand the concept of safeguards approach
  - Understand how to establish Material Balance Areas in various commercial nuclear facilities
  - Understand how nuclear material is tracked as it moves through various commercial processes
- **Desired Student Outcomes:**
  - Describe a material balance area
  - Design a safeguards system for various commercial facilities
  - Describe how existing commercial systems are safeguarded

Bulk Facilities Safeguards

Introduction

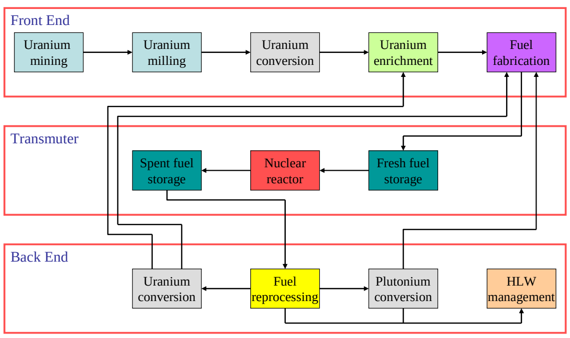
- In previous lectures we discussed a variety of topics covering International Safeguards Regime and its components
- We also discussed various means and instrumentation available to IAEA to carry out its mission of safeguarding nuclear material
  - nuclear material accountancy
  - nondestructive and destructive measurement system
  - containment and surveillance systems
- Today we will talk about how we can put all those components together in application to specific types of facilities

Item and Bulk Accounting

- The IEAE uses both item and bulk accounting
  - Item accounting is used for fuel rods, fuel assemblies, etc.
  - Bulk accounting is used for powders, solutions, and very small items for which counting is not feasible

Bulk Facilities	Item Facilities
Uranium Conversion Plant	Fresh Fuel Storage
Uranium Enrichment Plant	Reactor
Fuel Fabrication Plant	Spent Fuel Storage
Reprocessing Plant	

The Generic Commercial Nuclear Fuel Cycle



Safeguards Objectives

- **Objective 1:** timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection
- **Objective 2:** the detection of undeclared nuclear material and activities in a State or Facility

Design of Safeguards Approach

- A *safeguards approach* is the system of nuclear material accountancy (NMA), containment and surveillance (C/S) and other measures necessary and sufficient to test the diversion assumptions identified by the diversion analysis
  - designed for generic types of facilities (*model approaches*)
  - modified for individual facilities (*facility approaches*)
- Outlined in the Safeguards Agreement (the Subsidiary Arrangement and the Facility Attachment)
- Takes into account a variety of factors

Components of Safeguards Approach

- As a result of system-analytic studies main components of safeguards approach are identified:
  - design and operation characteristics of the facility
  - MBA and KMP structure
  - plausible diversion and concealment assumptions
  - inspection goals
  - recording and reporting requirements
  - NMA features (procedures, timing, composition and location of nuclear material)
  - appropriate combination of C/S measures and the SPs which are to be applied
  - number, duration, timing and mode of routine inspections
  - inspection plan

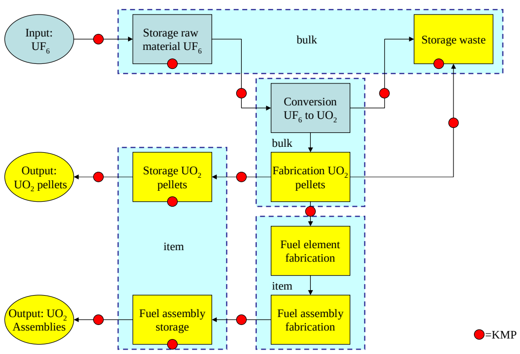
Inspections

- Facility of location outside facility (facility with 1 effective kg of nuclear material or less) with less than 5 effective kg shall not have more than 1 inspection a year
- Other facilities with more nuclear material inspection plans and characteristics will be determined by nominal declared amount of nuclear material
  - number
  - intensity
  - duration
  - timing
  - mode

Bulk Facility Example

- We will use a Uranium Fuel Conversion and Fabrication Facility Example to apply model safeguards approach
- We will establish Material Balance Areas and chose Key Measurement Points
- Then we will discuss what types of measurements we can choose and where it would be appropriate to use surveillance

Example: MBAs in a U Fuel Conversion and Fabrication Facility



Facility Description

- Low Enriched Uranium facility
- Material is received in a form of UF_6, converted into UO_2
- UO_2 powder is blended, milled, granulated and pressed into pellets
- Pellets loaded into tubes producing fuel elements
- Fuel elements incorporated into finished fuel assemblies

- Significant amount of scrap is generated in UF_6 to UO_2 conversion and pellet pressing

Facility Description

- Material is distributed over large processing areas
  - multiple interrelated flows
- Only limited handling precautions are required from the standpoint of toxicity and criticality
  - material is accessible most of the time
- One to four shutdowns per year for Physical Inventory Taking (PIT) (depends on the size and throughput of the facility)

Structure of MBAs

- At least three Material Balance Areas:
  - the feed storage area
  - the bulk material process area
  - assembling and product storage area
- Each MBA has several Key Measurement Points (KMP)
  - Inventory KMP
  - Flow KMP
  - Containment and Surveillance Strategic Points

MBA-1

- Inventory KMPs
  - storage of feed materials
  - storage of waste
- Flow KMPs
  - receipt of feed material
  - reshipment of feed material
  - transfer from MBA-1 to MBA-2 (MBA-2 to MBA-1)
- Containment and Surveillance Strategic Points
  - storage of receipts

MBA-2

- Inventory KMPs
  - intermediate storage locations
  - various points of conversion area
  - various stores (powder, pellets)
  - locations in pellet pressing line
  - analytical laboratory: samples
  - scraps
- Flow KMPs
  - receipt from MBA-1
  - transfer from MBA-1 to MBA-2
  - shipment of discard and scrap (MBA-2 to MBA-1)
  - retransfer of rejected material from MBAs 2 and 4
- Containment and Surveillance Strategic Points
  - intermediate storage of feed (seals)
  - UO_2 powder storage
  - UO_2 pellet storage

MBA-3

- Inventory KMPs
  - intermediate storage locations
  - locations in the fabrication line and testing station
  - fuel rod inspection station
  - fuel assembly inspection station
- Flow KMPs
  - receipt from MBA-2
  - transfer from MBA-3 to MBA-4
  - retransfer of rejected material (MBA-4 MBA-3)
  - rod scanning
  - starting point of item accountancy
  - receipt of fuel assemblies for reworking
- Containment and Surveillance Strategic Points
  - finished rod storage
  - finished assembly storage

MBA-4

- Inventory KMPs
  - fuel assembly final storage
  - fuel pellet final storage
- Flow KMPs
  - receipt from MBA-2 and MBA-3
  - shipping of fuel assemblies
  - shipping of UO_2 pellets
- Containment and Surveillance Strategic Points
  - UO_2 pellet storage
  - fuel assembly storage

Inspection Goals

- The accountancy verification goal is detecting of diversion of nuclear material
  - goal quantity is ≤ 1SQ
  - timeliness detection goal is 1 year
- The basic concept of NMA in careful verification of the material balance on the basis of random sampling

Diversion Analysis

Diversion	Concealment methods	Anomalies	Inspection Activities
Removal of nuclear material in all kinds of bulk form	Substitution of enriched U with natural or depleted U or inert material	Incorrect composition and/or enrichment	NMA, NDA, Sealing
Removal of fuel rods	Substitution with dummies	Incorrect composition and/or enrichment	NMA, NDA
	Substitution with borrowed rods	Rods missing in another MBA	Simultaneous inspection
Removal of fuel assemblies	Changing of s/n and offering for double counting	Assemblies missing	NMA
	Substitution with borrowed assemblies	Assemblies missing in another MBA	Simultaneous inspection

Containment and Surveillance Measures

- The application of C/S measures is often restricted to the sealing of:
  - feed material (UF6 cylinder) at the supplier's plant
  - fuel assemblies or shipping containers before shipment to the power plant
  - batches already measured during physical inventory verification (PIV)
  - nuclear material which could be left sealed between physical inventory takings (PIT)
- Seals are also used to ensure during PIV that all items are inventoried without duplication and to ensure the integrity of samples taken for analysis

Other Types of Bulk Facilities

- Similar approach is used for other types of bulk facilities
- Special attention is paid to uranium enrichment facilities because of additional "complications" specific to them:
  - additional objectives of detection of undeclared activities and introduction of undeclared material to the cascades
  - sensitivity of technology limiting inspector's access to the certain areas
- In a next few slides we will take a look at enrichment plant safeguards

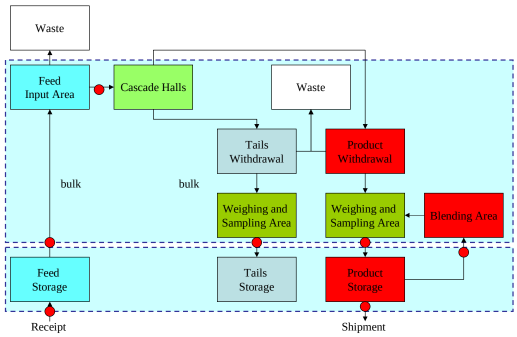
Present Approach for Safeguarding Enrichment Facilities

- The approach consists of only 2 MBAs
  - one over the shipping/receiving/storage area
  - one over the process areas
- Inspection regime:
  - announced routine inspections to perform physical inventory verification (1 per year)
  - Limited Frequency Unannounced Access (LFUA) to the cascade areas to confirm the absence of HEU production (1 per month)
    - regulates delay and maximum duration of the visits, as well as permitted activities of the inspectors
    - includes the use of Environmental Sampling
      - consists in the collection of deposited particles with swipe samples, usually taken during inspections of the cascade areas along the agreed access routes

Safeguards Goal for Objective 1

- This facility contains indirect use material
  - (U enriched to less than 20%)
  - and 1 SQ=75 kg U-235
- Thus, the timeliness goal for this facility is to detect a diversion of a significant quantity (SQ) within 1 year
- We must protect the facility against both abrupt and protracted diversions
  - abrupt=diversion of 75 kg ^{235}U all at once
  - protracted=diversion of 75 kg of ^{235}U by diverting 2% of the product over a 1 year time period

General Layout of Centrifuge Enrichment Plant



Safeguards Goal for Objective 2

- We must be able to detect the production of HEU
- We also must protect the facility against unauthorized insertion of undeclared material into the process stream

Indicators Associated with HEU Production

- Reduced throughput
- Portable feed and withdrawal equipment/stations in cascade area
- Extra UF_6 cylinders in cascade area
- Valve settings
- Piping reconfigurations (e.g., inter-cascade piping, feed/ withdrawal points)
- Radiation signatures indicating HEU

Source: http://lewis.armscontrolwonk.com/archive/1269/iranian-uranium

Source: http://www.h-ytech.net/experience.html

Measurement Methods Used

- Cylinders are weighed upon receipt and upon shipment
- Cylinders are also weighed prior to and after entering the autoclaves
- Gamma spectroscopy is used to confirm the enrichment of the UF_6 in each cylinder
- At present, there are no forms of flow measurement in the cascade area of the enrichment plant
- Thus our material balance measurement system is relatively simple
  - based only on weighing and gamma-spec enrichment measurements

$$MUF = (PB + R - S) - PE$$

Safeguards Approaches at Nuclear Power Reactors

Item Facility Safeguards

Power Reactor Safeguards

- The IAEA has about 239 power reactors under safeguards
  - and about 80 separate spent fuel storage facilities
- In general, these safeguards measures were applied to plants that were already existing or had already been designed
  - i.e., the safeguards system had to be adapted to fit the design of the facility
- There is a push in the reactor design community to design safeguards in to the plant
- To understand how to do this and how this affects the reactor, we need to start by understanding how safeguards is applied at reactors

Safeguards Application at Power Reactors

- Design Information Verification
  - off-load and on-load refueled systems
- Containment and Surveillance
- Material Accountancy

Material Types

- An LWR contains two types of material: LEU and Pu
  - fresh fuel contains only LEU (75 kg, 1 year)
  - fuel in the reactor and spent fuel storage contains LEU burned in the fission process and Pu produced (8 kg, 3 months)
- Although material composition is changing it is still contained within fuel rods and still considered items for accounting purposes
- Yearly inspections of the reactor while only fresh fuel onsite, quarterly once it starts operating

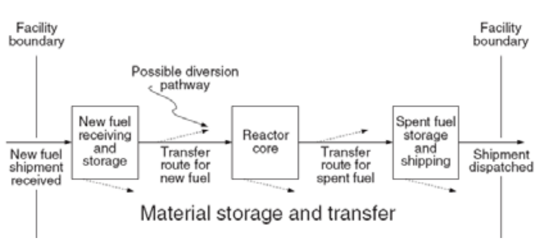
Safeguards Approach

- Power reactors are item facilities
- Goal in safeguards approach: verify that
  - the number of items is consistent with the declaration
  - the integrity of the items has not been breached
    - do not normally measure the total Pu or U content of the fuel, just verify that the items are all still there
- In general, power reactors are designed such that the entire facility is one MBA
  - so movement of fuel in and out of the reactor does not constitute an inventory change
    - only the movement of fuel on and off site
  - however, monitoring the movement of fuel at the site is still a main component of the safeguards measures

LWR Diversion Scenarios

Diversion	Method	Timing/Location
LEU Fresh fuel diversion	Substitution of dummy elements for actual elements	After fresh fuel verification, prior to core loading
Spent fuel assembly diversion	Substitution of dummy element for actual element	From reactor pool, SF pool, or SF transfer cask
Spent fuel pin diversion	Substitution of dummy element for actual element	From SF pool or SF transfer cask
Unreported Pu production	Insertion of fertile targets for irradiation in core fuel – PWR guide tubes or burnable poison rod	From reactor pool, SF pool, or SF transfer cask

Movement of Fuel at a Power Reactor



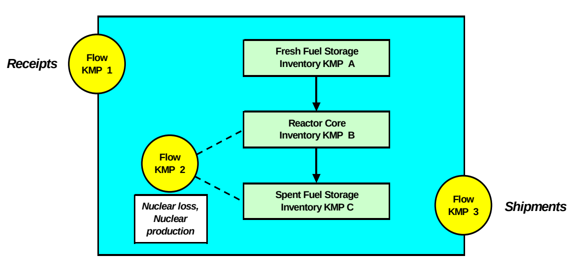
Flow KMPs at PWR

- KMP 1 – Receipts of nuclear material (nominally fresh LEU fuel)
- KMP 2 – Nuclear loss and nuclear production for core fuel discharged
- KMP 3 – Shipments of nuclear material (nominally spent LEU fuel to dry storage or reprocessing)

Inventory KMPs for PWR

- KMP A – Fresh fuel storage (LEU fuel)
- KMP B – Reactor core (LEU fuel and Pu)
- KMP C – Spent fuel pond (spent LEU fuel containing U and Pu)
- KMP D – Any other locations of nuclear material

MBA Structure for PWR



Material Unaccounted For

- So the MUF calculation for this facility is very easy:

$$MUF = (PB + X - Y) - PE$$

- where
  - PB is the beginning physical inventory
  - X is the sum of increases to inventory
  - Y is the sum of decreases from inventory
  - PE is the ending physical inventory

IAEA Safeguards Activities at a Power Reactor

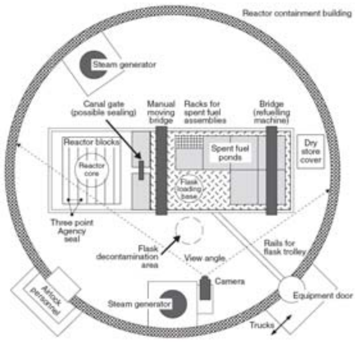
- Surveillance frequency could be continuous or intermittent
  - (depends heavily on the frequency of activity at the facility)
- Loss of surveillance is considered a safeguards concern and results in re-verification

Inspections at LWR

- Once a year before operation starts, 4 times a year after beginning of operation
- IAEA conducts 3 basics activities to verify completeness and correctness of the operator's declaration
  - check NM accountancy (accounting and operating records)
  - verify material itself and item's integrity (visual and NDA techniques)
  - use of containment and surveillance to check that that NM and reactor are not being diverted or misused

Typical Layout of an LWR Type I Plant Design

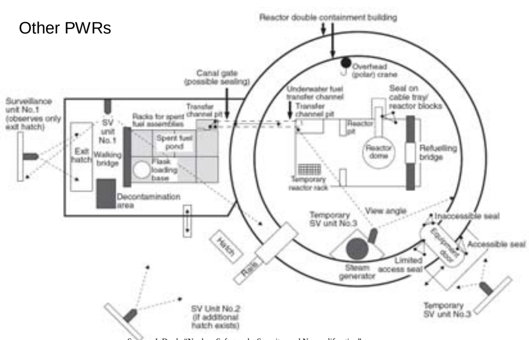
These are mostly BWRs,
VVERs, and
PWRs of Siemens design



Source: J. Doyle "Nuclear Safeguards, Security, and Nonproliferation"

Typical Layout of an LWR Type II Plant Design

Other PWRs



Source: J. Doyle "Nuclear Safeguards, Security, and Nonproliferation"

Conclusions

- We reviewed typical safeguards approaches to bulk and item handling facilities
- Long process of moving from signing CSA to creating facility attachments
  - technical information exchange
  - access negotiations
  - safeguards measures planning
- Agency is moving to wider implementation of remote and unattended monitoring systems to reduce the cost and intrusiveness of inspections and to increase effectiveness at the same time

References

1. IAEA/SG/INF/6, "IAEA Safeguards – Implementation at Nuclear Fuel Cycle Facilities"
   Available at http://www-pub.iaea.org/MTCD/publications/PDF/IAEA_SG_INF_6_web.pdf
2. J. Doyle, "Nuclear Safeguards, Security, and Nonproliferation" 2008

Exercises