Introduction to IAEA Safeguards

Applied Antineutrino Physics workshop
Sponsored by LNL
Wente Vineyards • Livermore, CA
September 24 – 26, 2006

Brian D. Boyer, Ph.D.

Los Alamos National Laboratory

Nuclear Nonproliferation Division, N-4

September 25, 2006

IAEA Safeguards Introduction Topics

- Basic concepts of IAEA Safeguards
- LWR Safeguards
- Issues in LWR Safeguards
- Needs in LWR Safeguards
  - Opportunities for Anti-Neutrino Detector and other new concepts

In the Beginning: Pre-NPT- The Agency's Safeguards System (1961-1968)

- The first system
  - The Agency's Safeguards System (1961)
  - INFCIRC/26
- The 1961 system as extended to cover large reactor facilities
  - The Agency's Safeguards System (1961, as Extended in 1964)
  - INFCIRC/26 and INFCIRC/26/Add.1
- The revised system
  - The Agency's Safeguards System (1965)
  - INFCIRC/66
- The revised system with additional provisions for reprocessing plants
  - The Agency's Safeguards System (1965 as Provisionally Extended in 1966)
  - INFCIRC/66/Rev.1
- The revised system with further additional provisions for safeguarded nuclear material in conversion plants and fabrication plants
  - The Agency's Safeguards System (1965, as Provisionally Extended in 1966 and 1968)
  - INFCIRC/66/Rev.2

Definition of Safeguards - INFCIRC 66

- INFCIRC/66 - limited agreement
- Only Israel, India, Pakistan have this agreement in place
- Technical Aim - "...that special fissionable and other materials, services, equipment, facilities and information are made available by the Agency……and **are not used** in such a way as to **further any military purpose**."

Treaty on Non-Proliferation of Nuclear Weapons (NPT)

- INFCIRC/66 agreements / Limited Agreements precede NPT (1961-68)
- Negotiations Concluded in 1968
- Entered into Force in 1970
- INFCIRC/153 (corr) agreements
  - Comprehensive Safeguards Agreement (CSA) (June 1972)
- INFCIRC/540 Model Additional Protocol (Sept 1997)
  - Strengthened Safeguards System – Post Iraq War (1991)

Definition of Safeguards - INFCIRC 153 (CORR)

- INFCIRC 153(corrected) - full scope safeguards
- Technical Aim - “...the **timely** detection of diversion of **significant quantities** of **nuclear material**...”
- Safeguards under 153 known as:
  - Full Scope Safeguards
  - Comprehensive Safeguards Agreement

Definition of Safeguards - INFCIRC 540 (CORR) - Additional Protocol

- Additional Protocol Provides for more access and information to the IAEA

- For LWR Safeguards – key points
  - IAEA can access auxiliary buildings on site
  - Integrated Safeguards
    - Because of “Broader Conclusion” can reduce some SG effort

Basic Types of IAEA Inspections

- Physical Inventory Verification – PIV
  - **1** x year at LWR
- Design Information Verification – DIV
  - **1** x year at LWR with PIV
- Interim Inspections
  - For timeliness - 4 x year at LWRs (for CF and SF)
  - For verification of domestic and international transfers
- Additional Protocol – INFCIRC 540
  - Complementary Access (CA) Activities
- Special Inspections – INFCIRC 153

“Timeliness” - Material Guidelines

Nuclear Material	Material Form	Conversion Time
Pu, HEU or U-233	Metal	few days (7-10)
Pure Pu components	Oxide (PuO_2)	few weeks (1-3)
Pure HEU or U-233 compounds	Oxide (UO_2)	few weeks (1-3)
MOX	Non-irradiated fresh fuel	few weeks (1-3)
Pu, HEU or U-233	In scrap	few weeks (1-3)
Pu, HEU or U-233	In irradiated fuel	few months (1-3)
LEU and Th	Unirradiated Fresh Fuel	order of 1 year

"Significant Quantity" - Defined

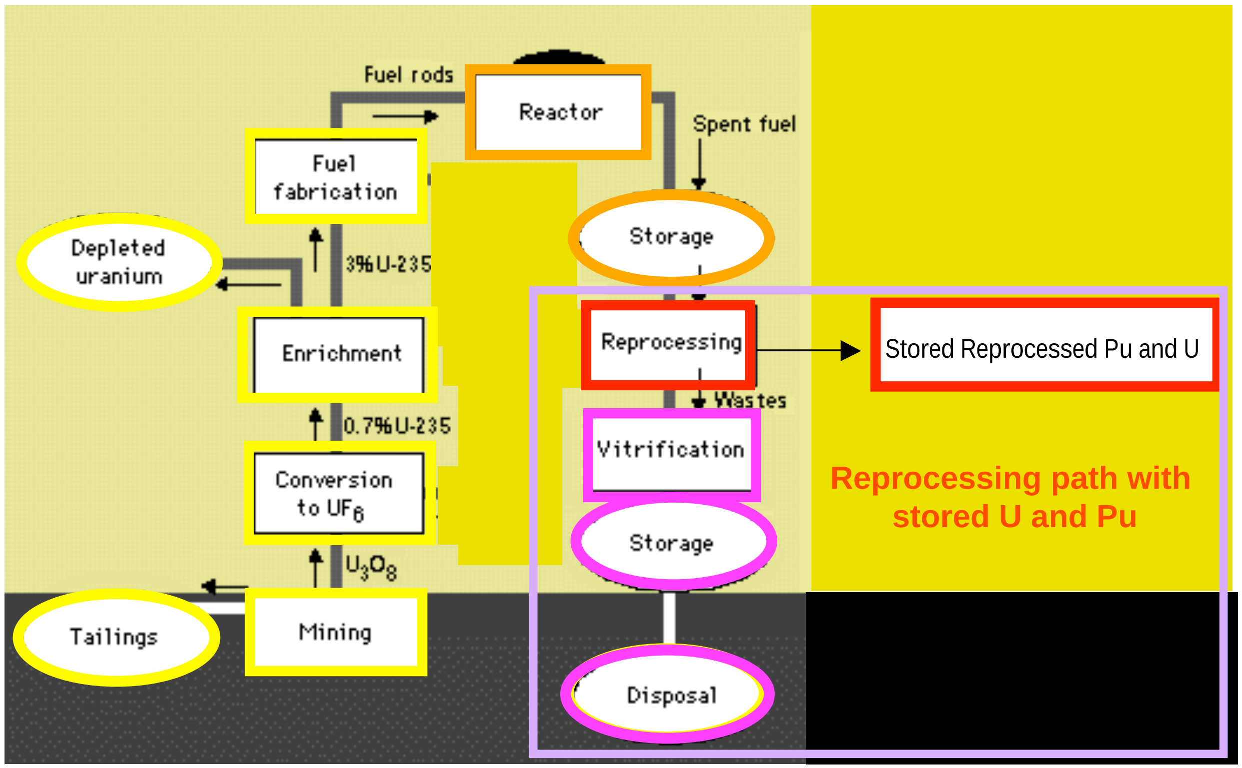
Nuclear Material	SQ in KG
Pu (<20% Pu-238)	8 kg Pu
U-233	8 kg U-233
HEU (=>20% U-235)	25 kg U-235
LEU (<20% U-235 including natural U and depleted U)	75 kg U-235 (or 10 t nat. U or 20 t depleted U)
Thorium	20 t thorium

Timeliness Goal

MATERIAL CATEGORY	EXAMPLES	TIMELINESS GOAL
Unirradiated Direct -Use	HEU fresh fuel, MOX	1 MONTH
Irradiated Direct -Use	Spent fuel, core fuel	3 MONTHS
Indirect -Use	LEU Fresh fuel	1 YEAR

LWR Safeguards – Fuel Cycle Relevance

Nuclear Material Color Key
Yellow – Indirect Use
Orange – Irradiated Direct Use
Red – Unirradiated Direct Use
Pink – Waste
+ No U or Pu
+ OR SGs terminated

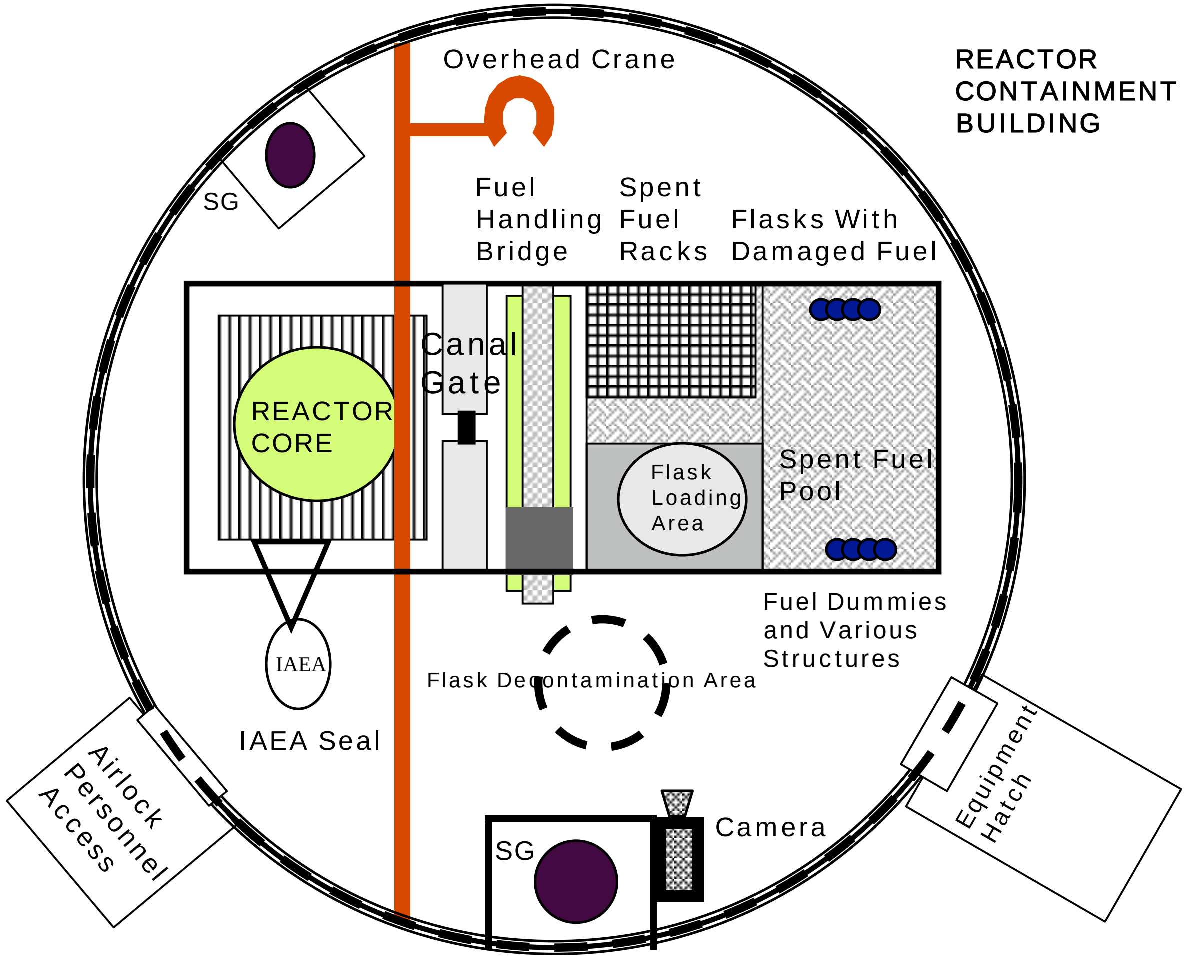


LWR Categories

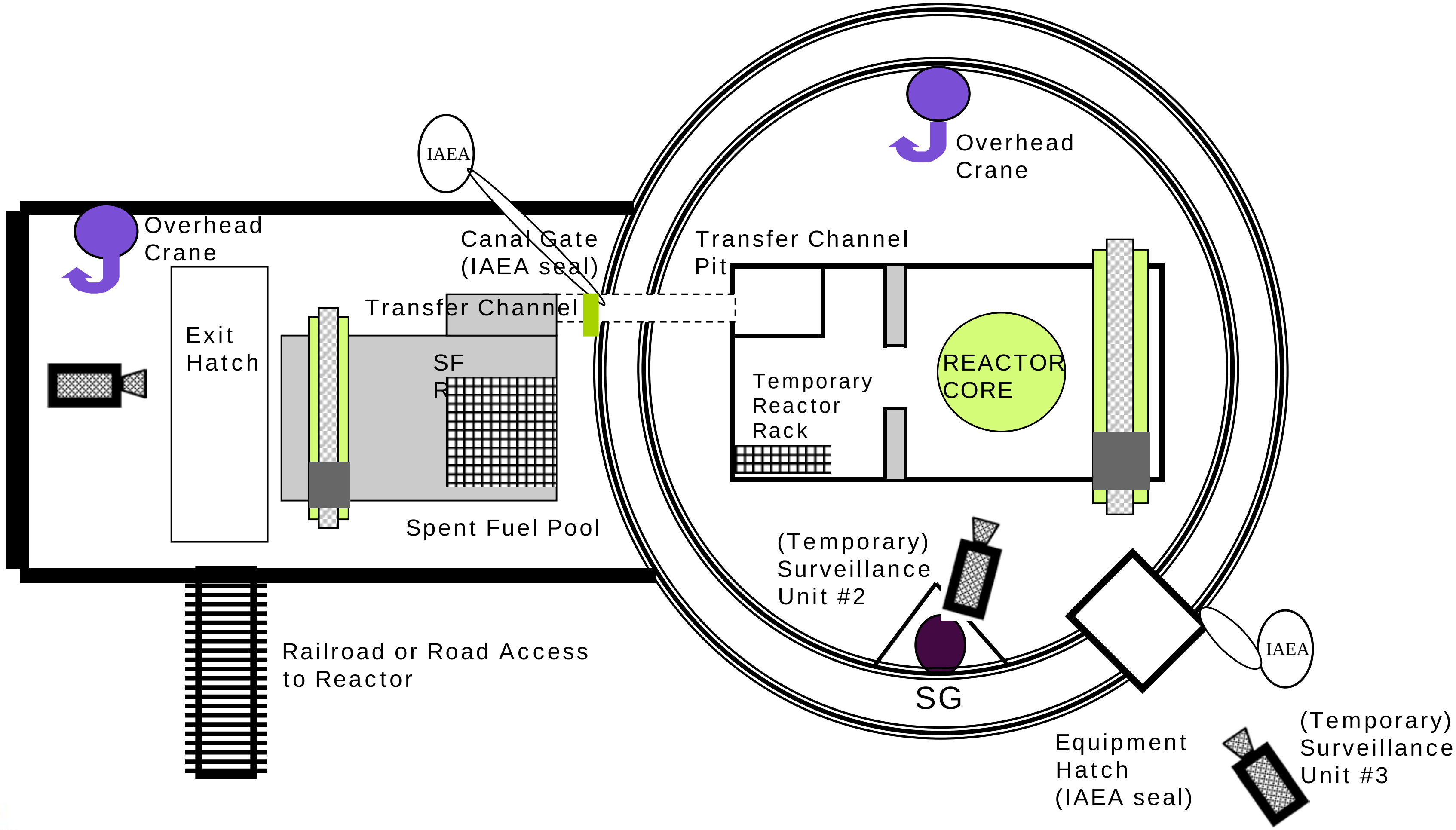
- **Type 1 - Reactor hall includes spent fuel pool**
  - VVER 440 (Loviisa 1-2, Paks 1-4, Bohunice 1-4, Rovno 1-2)
  - VVER 1000 (Kozloduy 5-6, Temelin 1-2, Khmelnitsky 1, Rovno 3)
  - BWRs with SF pool in containment (TVO-1, TVO-2)
  - PWRs with SF pool in containment (*Biblis 1-2*)

- **Type 2 - Spent fuel pool outside of reactor hall**
  - PWRs with SF pool in separate building (Krško, Almaraz 1-2)
  - BWRs with SF pool in separate building (*Liebstadt*)

LWR Layout - Type I Reactor Design



LWR Layout - Type II Reactor Design



Examination of records and reports - Accountancy Side of IAEA Safeguards

- Nuclear Material Accountancy - Terms
  - PIV = physical inventory verification
  - PIL = physical inventory listing
  - LII = list of inventory items
  - MBR = material balance report
  - ICR = inventory change report
- Check the movements of nuclear material
  - Receipts
  - Shipments
  - Transformation - calculate nuclear loss (U) and production (Pu)
- Reactors – LWR, OLRs (On Load Reactors), Fast Reactors
  - Item Facilities – all nuclear material in unit form (Fuel Assemblies)
  - No Material Unaccounted For (MUF) expected
  - Shipper/receiver difference (SRD) from SF sent to reprocessing
    - **Uncertainties on U and Pu inventories**
      - **Operator calculations**
      - **Reprocessing plant measurements**

Physical inventory verification (PIV)

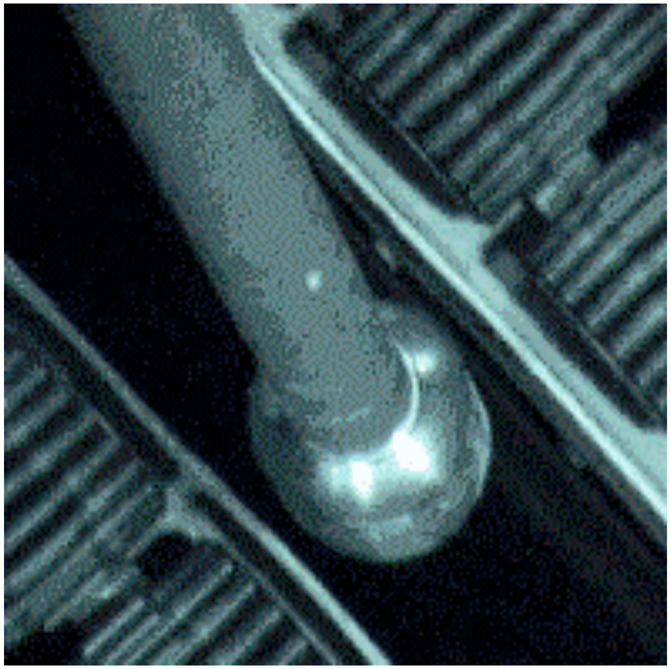
- PIV – yearly - the period between PIVs not to exceed 14 months
  - Performed when core is refueled or opened
  - If core not refueled or opened - PIV done with closed core
  - Multiple cores (VVER 440 - twin reactor per facility)
    - Do PIV during *one* of the core openings
  - Post PIV period does not exceed 3 months

PIV - Fresh Fuel Verification

- FF assemblies and separate fuel pins are:
  - *Item counted*
  - Verified for *gross defects* or by *serial number ID (by random sampling)*

MMCC - Portable Multi-channel Analyser + CdTe Detector

- MMCC Detects 186 keV U-235 γ peak in γ spectrum
  - CdTe detector
    - inserted into fuel assembly
    - gamma spectrum measured
  - Definitive gross defect measurement of
    - Fresh LEU fuel
    - U-235 **is** or **is not** present

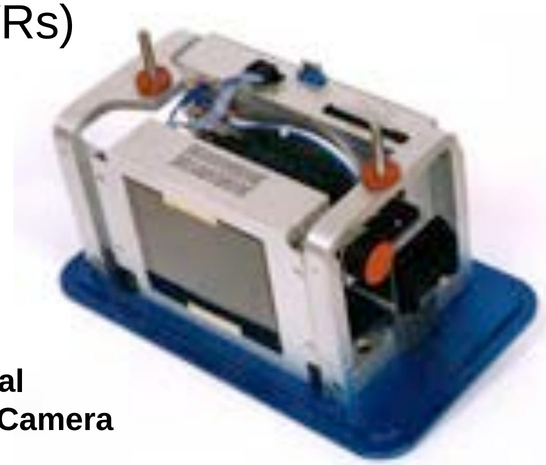


PIV - Core Fuel Verification

- Open core –
  - —Assemblies *item counted* and
  - —*Acceptable C/S maintained* either on
    - ➢Open core or on removal routes
- Discharged core - core is discharged to SF Pool
  - —Verify along with SF
  - — *Acceptable C/S maintained* either on
    - ➢Open core <u>or</u> on removal routes
- Closed cores
  - — If under C/S - the C/S system is evaluated

Surveillance

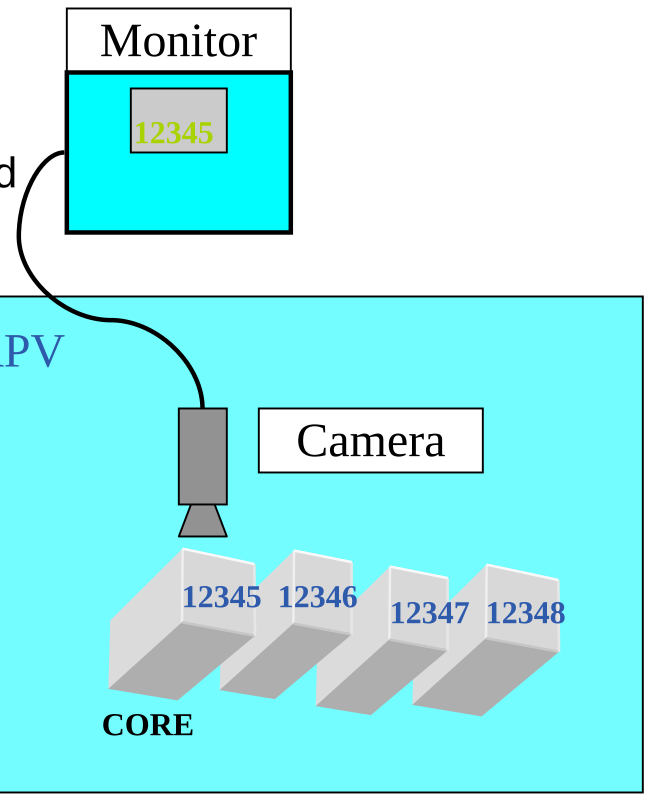
- Surveillance Used in LWRs
  - Reactor Hall
    - ➢ Core Fuel During Refueling: Type 2 LWR
    - ➢ Core Fuel / Spent Fuel / Casks Core Fuel: Type 1 LWR
  - Separate SF Pool
    - ➢ Spent Fuel Pool and/or Exit Routes
  - Exits (Large enough to move SF cask through)
    - ➢ Containment Hatch (Westinghouse PWRs)
    - ➢ Containment Hatch (VVER 1000)
    - ➢ Loading Bay in SF Pool (Type 2 LWR)



DCM-14 Digital Surveillance Camera

UWTV - Underwater TV

- UWTV used to verify Core Fuel during refueling
  - The TV camera pans across the fuel
    - Serial numbers are verified
    - The total number of fuel assemblies counted
    - Compared to the operator's declaration



PIV - Spent Fuel Verification... In practice

- SF Pools verified 100% for Gross Defects
  - Easier to verify all items then to select specific items in pool
  - ICVD - SF and SF Pool conditions determine success of method
    - ➢ Water quality
    - ➢ Fuel assembly burn-up
    - ➢ Residence time in pool by SF

  - With failure of ICVD
    - ➢ Use of SFAT or similar method is attempted
  - IAEA has new intense interest in NON-FUEL items in SF pool

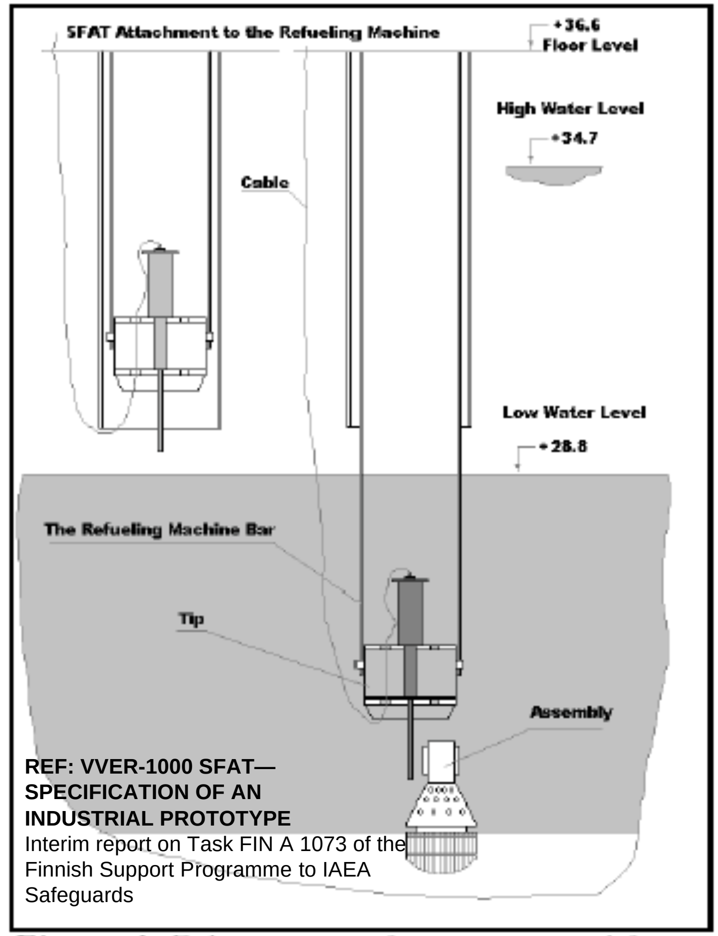
ICVD - Improved Cerenkov Viewing Device

- ICVD Detects Cerenkov Glow From SF and Verifies
  - Spent Fuel
    - Spent Fuel Pools
    - Spent Fuel in…
      - Baskets and/or
      - Casks prior to shipment
  - Core Fuel
    - Core Fuel during refueling
      - To recover from *anomaly*
    - EXAMPLE: Loss of "CofK" of Core
      - Recovered next PIV during refueling

Sweden - CLAB

SFAT - Spent Fuel Attribute Tester

- SFAT Properties
  - Detects
    - Cs-137 660 keV gamma peak
    - Characteristic of fission products
  - Used to verify
    - SF Pool fuel – ICVD not usable
      - Too old - Radiation decaying away
      - Fuel with low burn-up – Too few FPs
    - SF Pool *items* that may be
      - Dummy elements
      - Skeleton assemblies
      - Empty containers
    - ID by lack of a Cs-137 peak

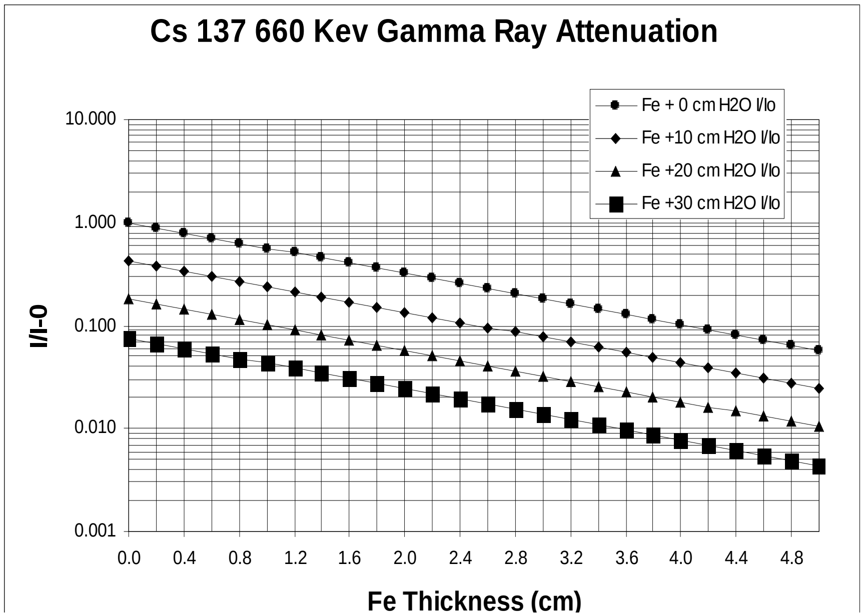


REF: VVER-1000 SFAT—SPECIFICATION OF AN INDUSTRIAL PROTOTYPE
Interim report on Task FIN A 1073 of the Finnish Support Programme to IAEA Safeguards

SFAT Issues

Attenuation of γ Source in SF Pool by Castor Material and H_2O

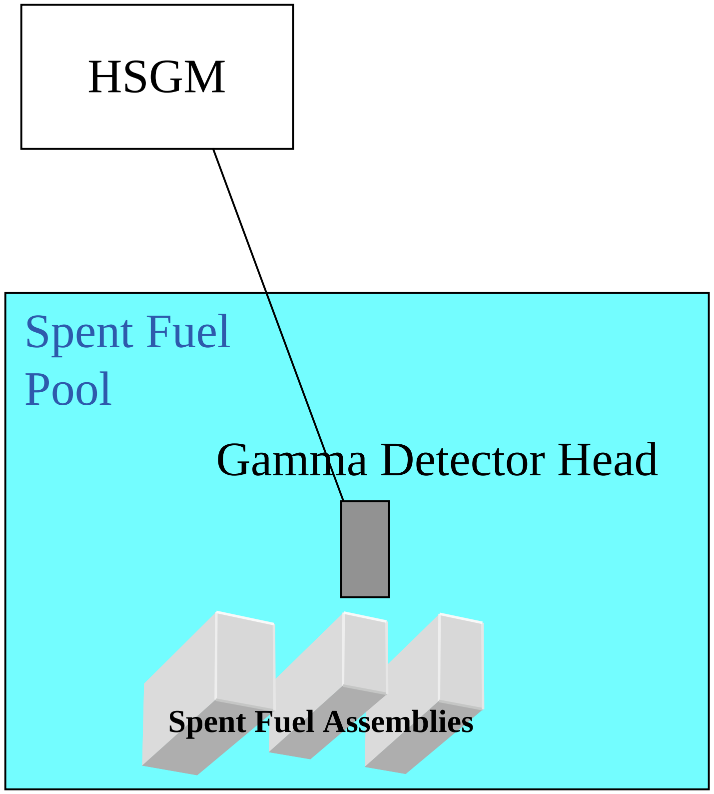
$$I=I_o\, e^{-(\mu_{H2O}x_{H2O}+\mu_{Fe}x_{Fe})}$$



- Castors with iron
  - Attenuates gammas
- Water covering SF in castor
  - Attenuates gammas
- If SFAT not close enough to SF
  - **Inspector SFAT NDA of damaged SF castor**
    - **Difficult to distinguish between…**
      - **Empty irradiated castor**
      - **Castor containing SF**

HSGM - High Sensitivity Gamma Monitor

- HSGM Detects Gamma Radiation from SF
  - Gross defect measurement
  - HSGM and CPMU
    - Both very crude measurements
    - Not very definitive
  - Can give higher measurements from empty container for damaged SF as from full container
  - Dummy element
    - Can be irradiated
    - Gives off gammas



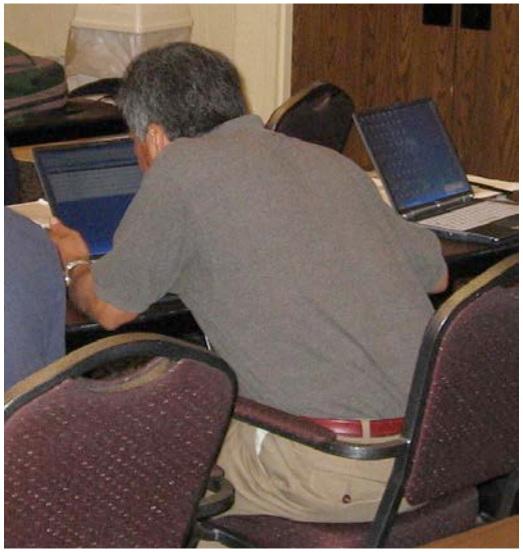
Verification of Domestic and Int'l Transfers Spent Fuel - To Difficult-to-Access

- Transfers of SF into containers for long-term storage under SG but difficult-to-access
  - Item I.D.
  - NDA
    - High detection probability for gross and partial defects
  - Under dual C/S

Verification of Domestic and Int'l Transfers
Fresh LEU Fuel

- Fresh LEU fuel since the last PIV
  - Verified at any inspection
  - *Or* at PIV

Material Balance Evaluation



- Evaluate non-zero SRD
  - (in LWRs normally zero)
- Evaluate non- zero MUF
  - (in LWRs normally zero)
- Evaluate on item count, I.D., and defect test results

Confirm Absence of Unreported Production of Plutonium

- PERFORM
  - Analysis of reactor shows it could not produce 1 SQ of unrecorded Pu per year
- OR
  - C/S on RPV to confirm RPV was closed AND
  - C/S on open RPV to confirm that 1 SQ was not removed from the core AND
  - Empty RPV - confirm CF is in SF and none removed
- AND
  - C/S acceptable on SF pool OR
  - Verify SF Pool after refueling with NDA where appropriate

Design Information Verification (DIV)

- Design info provided to Agency by the State is…
  - Examined
  - Verified

- Once a year re-examined

- Periodic verification of design information
  - To confirm continued validity
  - DIV includes
    - Taking of environmental samples….

Typical Agency Yearly Schedule at LWR

- 3 interim inspections and PIV scheduled
- Special inspections for transfer of SF in casks
  - Verify SF as placed in cask
  - Follow with C/S to maintain CofK

- Pre PIV
  - Verify FF
  - Detach seals on reactor or transfer paths
  - Install temporary surveillance to reactor
- Post PIV
  - Attach seals on transfer paths (canal gate, etc,)

IAEA Containment Sealing Systems

- IAEA Metal Seal

- COBRA Seal (In-Situ verification)

- VACOSS Seal (Electronic Seal with fiber optic wire - can be opened and closed ONCE by operator)

LWR – Containment/Sealing

- Surveillance Instruments (Cameras, Surveillance Cabinets)
- Reactor Hall
  - Vessel Missile Shield (VVER 440)
  - Other means to immobilize Core Fuel
- SF Pool
  - Spent Fuel Racks and Pool Covers
    - Immobilization of SF
  - Loaded SF casks ready for shipment to
    - Interim Storage
    - Dry Storage
    - Off-site
  - Re-fueling crane - temporary measure to avoid losing CofK
- Exit pathways
  - SF Pool canal gate and Exit hatches

Operator/Inspector Measurement System - Definitions

Total (relative) measurement uncertainty

$$\delta_i = (\delta_O^2 + \delta_I^2)^{1/2}$$

METHOD CODES	INTERPRETATION	RELATIVE ERROR RANGES	DETECTABLE DEFECT SIZE
H	Quantitative through NDA (Verification in the attribute mode using the least accurate method), or	$0.0625 < \delta_i \leq 0.125$	GROSS
	Qualitative through NDA (e.g. Cerenkov, bundle counter)	Error can not be assigned	GROSS
F	Quantitative through NDA (Verification in the attribute mode using a better accurate method)	$0.010 < \delta_i \leq 0.0625$	PARTIAL
E	Quantitative through NDA (Verification in the variables mode using the most accurate method) e.g. K-edge densitometer	$\delta_i \leq 0.01$	BIAS
D	Quantitative through DA (Verification in the variables mode using the most accurate method)	$\delta_i \leq 0.01$	BIAS

LWRs and RRCAs

- Research Reactors with 25MWth output have concerns with
  - Unreported Pu Production
- Use of reactor power monitor to observe power output for RRCA
  - Estimate Pu production
  - Thermal-hydraulic and radiation power monitors
- Reactor power monitor - not used in LWRs
  - Intrusive nature
  - Operator supplies thermal output info
  - Possible satellite photo analysis – expensive mode
- Need for tool to give power output information
  - Operational information
  - Possible Pu Production calculations

LWR Safeguards Goal and Issues

- Control of Spent Fuel - source of PU
- Control of SF pool items - targets for Pu production
- Control of LEU fuel -
  - Source of LEU for enrichment
  - Pu production in reactor
    - Understanding of power history of reactor
      - Possible role of Antineutrino Detector
- Control of MOX fuel - source of unirradiated Pu
- Control of transfers - SF that may be reprocessed for Pu

LWR Safeguards Needs

- SF Pool
  - Ability to insure no tampering with SF assembly
  - Assembly removal/substitution by dummy
  - Pin Diversion/substitution by dummy
- Thermal Power of LWRs
  - Verify operator’s declaration
    - Possible role of Antineutrino Detector
- SF assembly inventory (of interest for reprocessing)
  - Operator’s calculations
  - Verify operator’s declaration at reprocessing plant
  - Develop independent means to verify SF
- Undeclared activities - Possible role of Antineutrino Detector