Safeguards Approaches for Gas Centrifuge Enrichment Plants

LANL Safeguards Systems Course – PILOT 2008

Brian D. Boyer

Los Alamos National Laboratory

Nuclear Nonproliferation Division

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What is Safeguards? REVIEW!

INFCIRC 153 Para. 28: The Safeguards Technical Objective

- The **objective of safeguards**
  - The **timely detection**…
  - Of **diversion of significant quantities**…
  - Of **nuclear material**

NOTE:

- **Timeliness**
- **Significant Quantities**

Timeliness and Goal Quantities
Relevant to Gas Centrifuge Enrichment Plants (GCEPS)

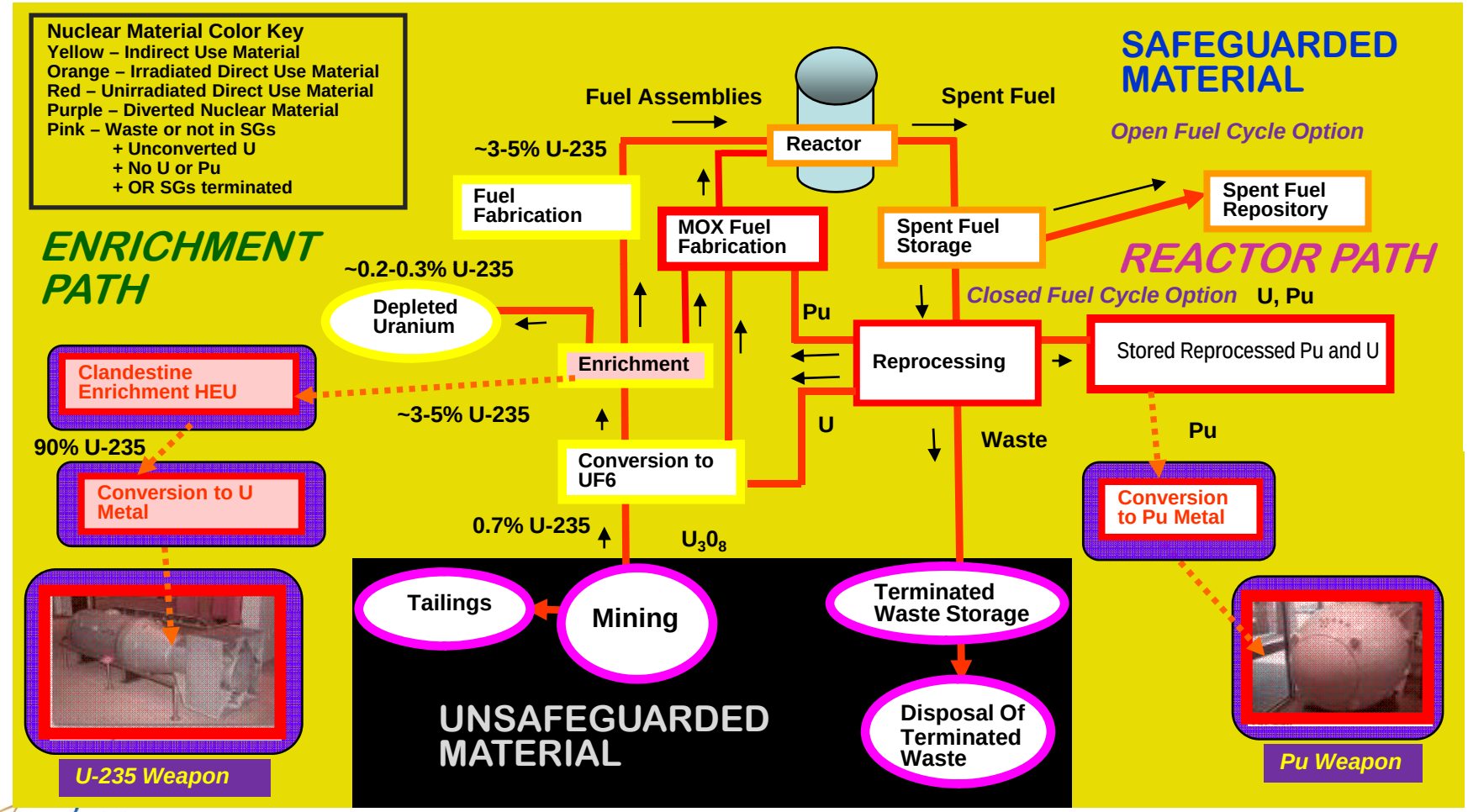
MATERIAL CATEGORY	EXAMPLE	AMOUNT OF SQ	TIMELINESS GOAL
Unirradiated Direct-Use (Undeclared in GCEPs)	HEU UF6	U-235 = 25 kg	1 month
Unirradiated Indirect-Use (Declared in GCEPs)	LEU UF6 NU UF6 DU UF6	U-235 = 75 kg	1 year

NOTE: HEU = U enriched in ^{235}U >20%

(HEU Weapons Grade ~>90%)

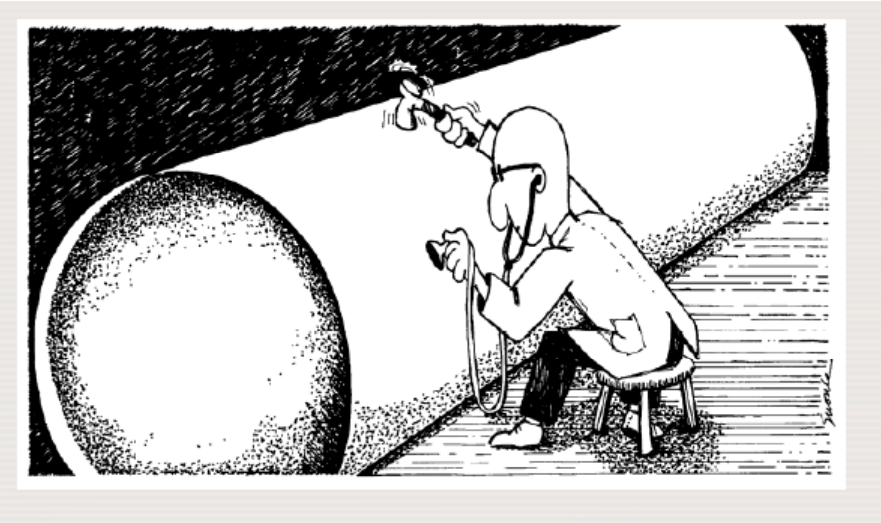
LEU ~4-5% Enriched
NU = 0.711% Enriched
DU ~ 0.2-0.3% Enriched
} ≤ 20%

Nuclear Fuel Cycle – Proliferation Aspects



IAEA Accountancy Verification Methods

- **Three levels of defects to detect with NDA Instruments:**
  - ***Gross defect***
  - ***Partial defect***
  - ***Bias defect***
- **Examples in GCEPS:**
  - ***Gross defect***
    - **No U present**
  - ***Partial defect***
    - **Lower ^{235}U content**
    - **Part of U missing**
  - ***Bias defect***
    - **Lower ^{235}U content bias**



Verification Measurements at GCEPS
(Safeguards Criteria - Section 8)

MATERIAL CATEGORY	MAIN STRATUM	MATERIAL TYPE COMPONENT	DEFECT TYPE	DEFECT DESCRIPTION	MEASURE-MENT REQUIRED	APPLIC-ABLE METHODS	RECOMMENDED INSTRUMENTS
INDIRECT USE	UF6 Cylinder (UF)	LEU	GROSS	No Uranium	Uranium Presence	H	ACOUSTIC + MMCN or MMCG
			PARTIAL	Lower U-235 Content	U and U-235 Content	B+F	LCBS+MMCG+ULTG, LCBS+MMCN
			BIAS	U content Bias	U and U-235 Content	B+D	LCBS+ DA
		NU	GROSS	No Uranium	Uranium Presence	H	ACOUSTIC + MMCN or MMCG
			PARTIAL	Part of Uranium Missing	U Content	B+H	LCBS+MMCG+ULTG, LCBS+MMCN
			BIAS	U content Bias	U and U-235 Content	B+D	LCBS+ DA
		DU	GROSS	No Uranium	U and U-235 Content	H	ACOUSTIC + MMCN or MMCG
			PARTIAL	Part of Uranium Missing	U Content	B+H	LCBS+MMCG+ULTG, LCBS+MMCN
			BIAS	U content Bias	U and U-235 Content	B+D	LCBS+ DA
	Waste (WA)	LEU/NU/DU	GROSS	No Uranium	Uranium Presence	H	MMCN,MMCC,HM-5
	UF6 in Cascade	LEU/HEU		U-235 Enrichment ≥ 20%	Absence of HEU	H,D	CHEM.CEMO,DA

Operator/Inspector Measurement System - Definitions

Total (relative) measurement uncertainty

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

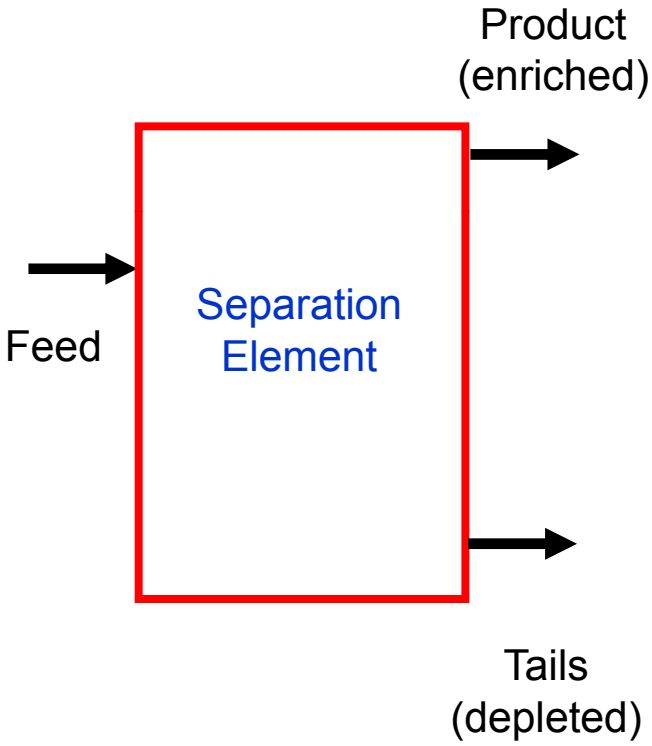
METHOD CODES	INTERPRETATION	RELATIVE ERROR RANGES	DETECTABLE DEFECT SIZE
H	Quantitative through NDA (Verification in the attribute mode using the least accurate method), or	$0.0625 < \delta_i \leq 0.125$	GROSS
	Qualitative through NDA (e.g. Cerenkov, bundle counter)	Error can not be assigned	GROSS
F	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

Characteristics of GCEPS

- **Usually many unit cascades connected in parallel**
  - Large stage separation factor
  - Small specific inventory
  - Short equilibrium time
- **Feed, product, and tails are UF_6**
  - UF_6 cylinder qualities
    - Weighed, sampled and analyzed with high precision and accuracy
  - Define U strata as F=UFN, P=UFE, T=UFD
- **Material balance dominated by flows, not inventories**
  - Cascade gas-phase inventory & solid holdup usually very small
  - Waste streams usually very small
  - UF_6 in process vessels - Well-measured using “switchover” at PIV

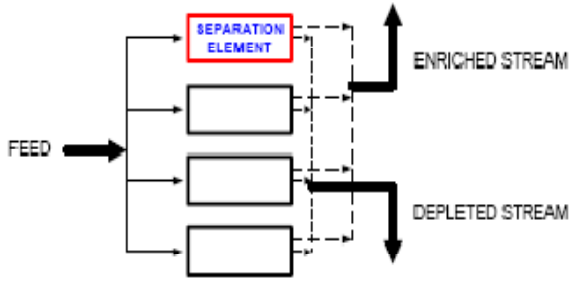
Centrifuges and Cascades - Theory

Single Centrifuge



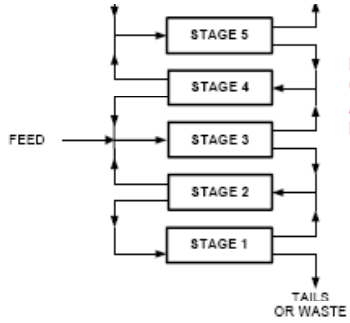
Centrifuges in Parallel

SEPARATION ELEMENTS MAY BE CONNECTED IN PARALLEL TO ACHIEVE HIGHER THROUGHPUT



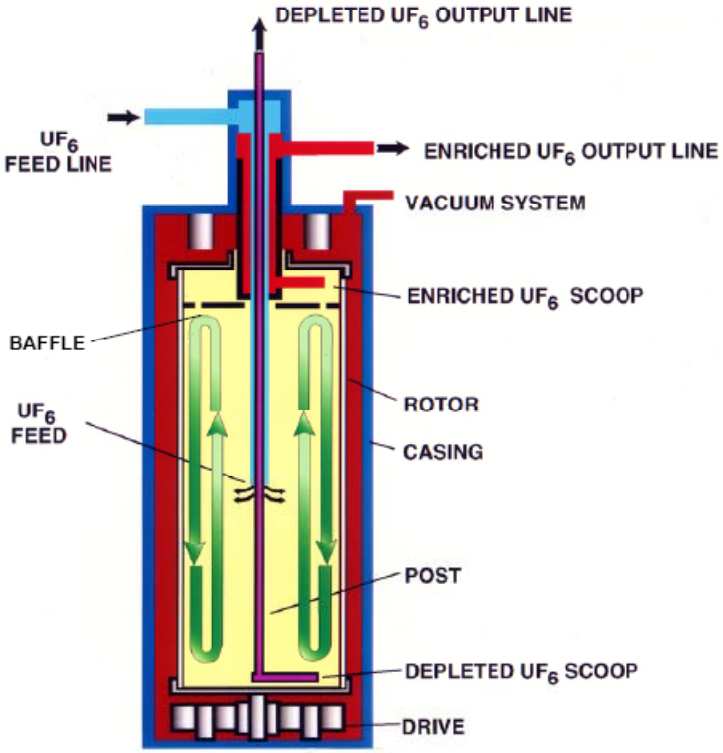
THE DEFINITIVE CHARACTERISTIC OF A STAGE IS THAT IT CARRIES THE ENTIRE THROUGHPUT OF THE CASCADE AT THE COMPOSITION OF THAT STAGE

Cascade



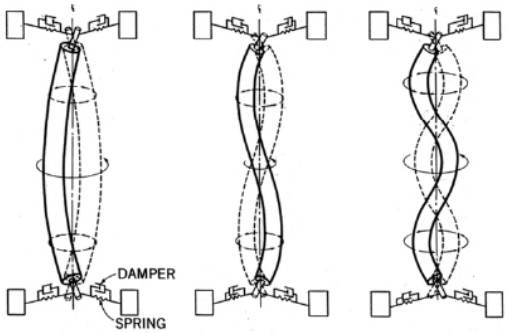
MULTIPLE STAGES ARE CONNECTED IN SERIES TO ACHIEVE USEFUL ENRICHMENTS

What is a Centrifuge?



Schematic of Gas Centrifuge

MODE SHAPES OF FIRST THREE FLEXURAL CRITICALS OF A CENTRIFUGE ROTOR



What is a UF6 Cylinder?
Safe Storage of UF6

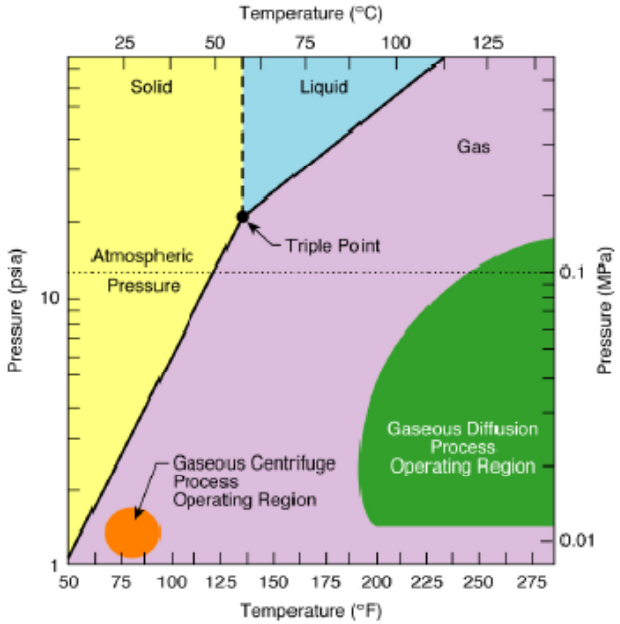
30B Product (2.5 ton)- Product

48G (14 ton) - Tails

48Y (14 ton) - Feed

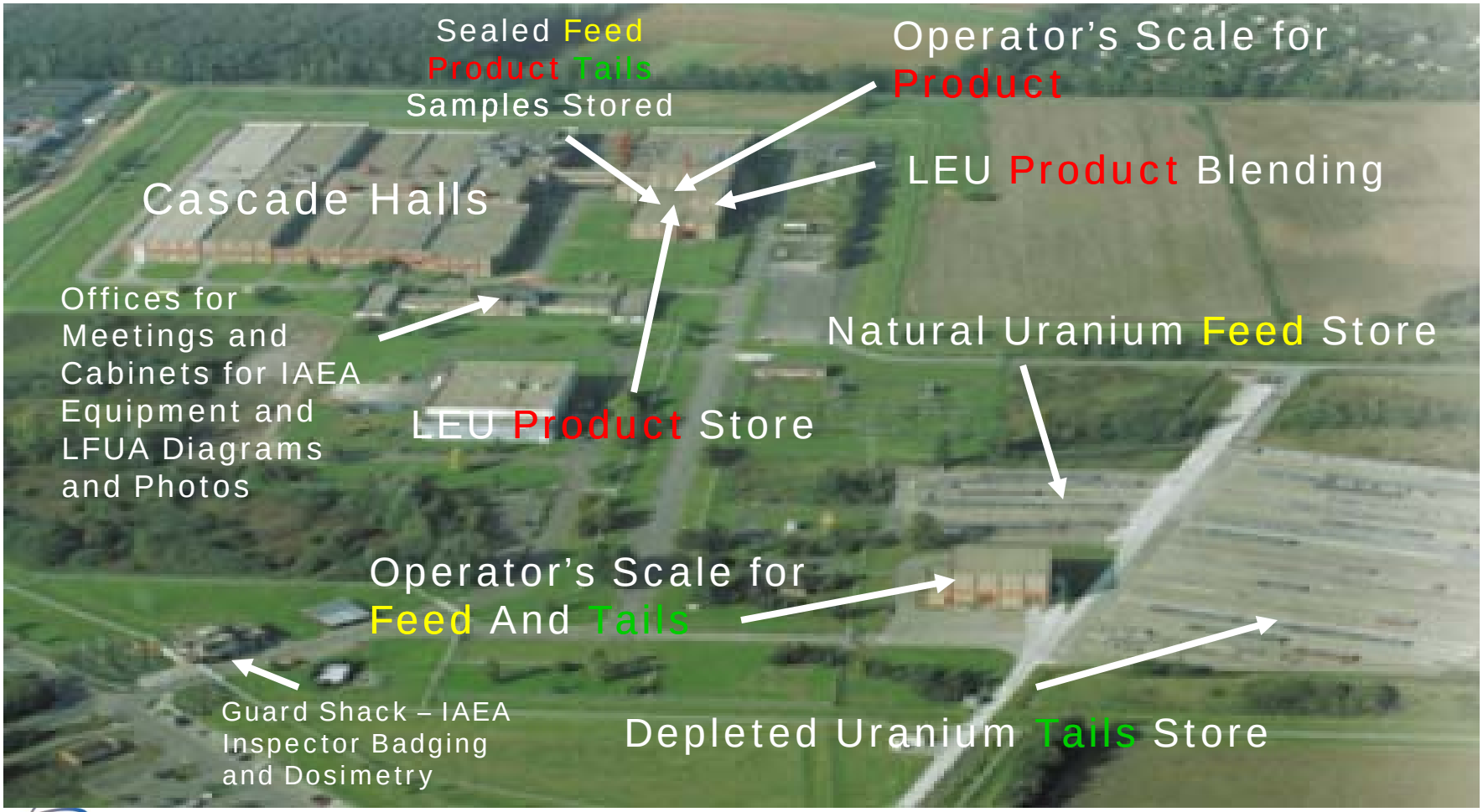
5a (25 kg) - HEU

UF_6 PHASE DIAGRAM



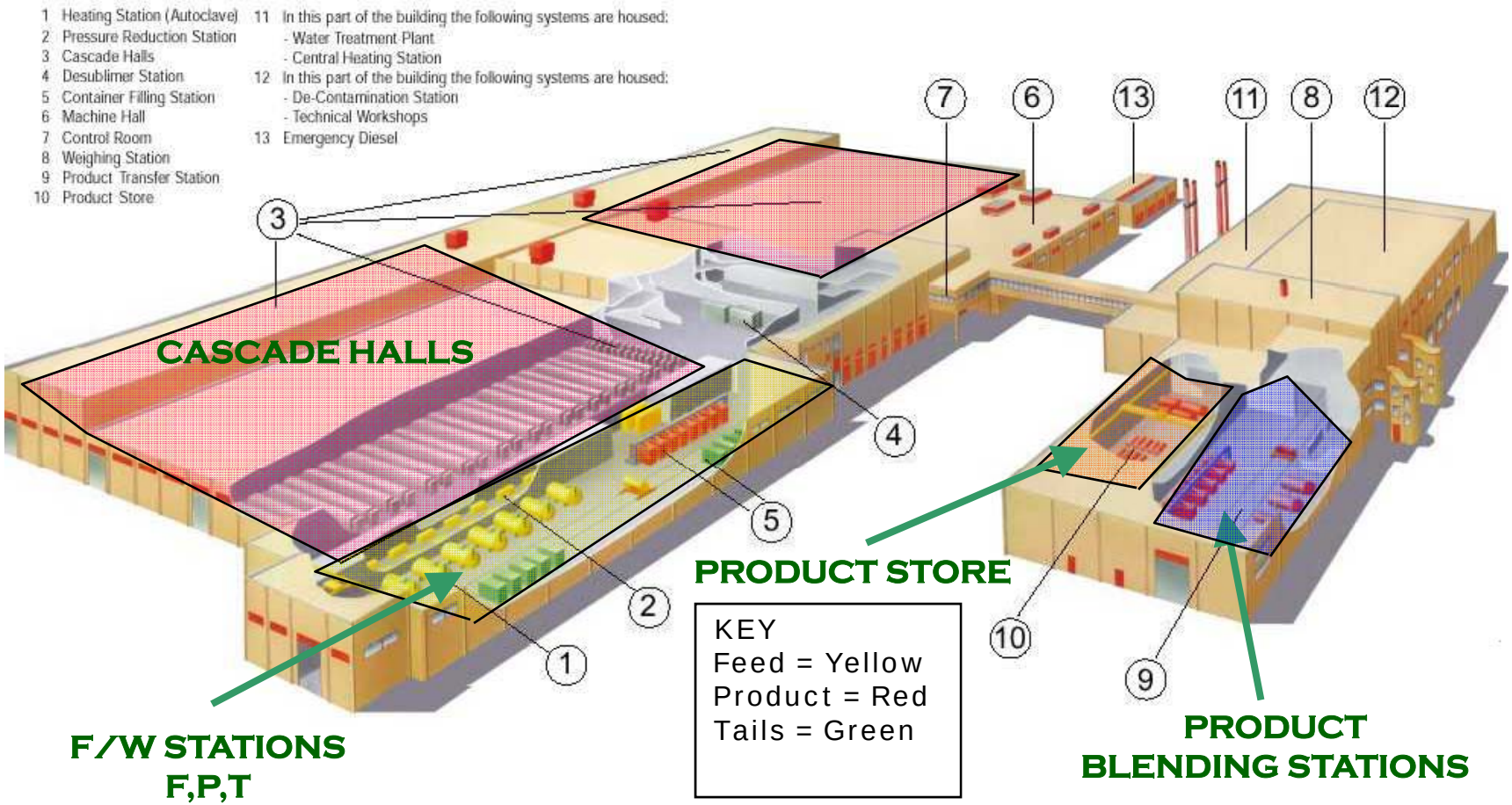
URENCO GCEP

Gronau, Nordrhein Westfalia, Bundesrepublik Deutschland



Gas Centrifuge Enrichment Plant (GCEP)

Process Areas



Safeguards Goals at GCEPs
Goal Quantity and Timeliness

- **Significant Quantity (SQ) Defined**
  - Natural Uranium= 10 MT NU
  - Depleted Uranium= 20 MT DU
  - LEU = 75 kg ^{235}U
  - HEU = 25 kg ^{235}U

- **Timeliness of Material**
  - Related to conversion time to weapon
  - DNLEU = 1 YEAR
  - HEU = 1 MONTH

"Timeliness" - Material Guidelines

Nuclear Material	Material Form	Conversion Time	IAEA Timeliness Goals
Pu, HEU or U-233	Metal	few days (7-10)	1 MONTH
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)	3 MONTHS
LEU and Th	Unirradiated Fresh Fuel	order of 1 year	1 YEAR

Safeguards Concerns at LEU GCEPs

- **Production of a SQ of undeclared HEU (≥20% U-235)**
- **Diversion of a SQ of declared LEU, NU, or DU**
- **Production of LEU in excess of declared amounts**

IAEA Detection Goals

- **Detection of HEU (≥20% U-235) Production**
- **Detection of Diversion of LEU (<20% U-235)**
- **Detection of Diversion of NU and DU**

IAEA HEU Production Detection Goals

- **Detection of HEU (≥20% U-235) Production**
  - SQ = 25 kg U-235 contained in HEU
  - Detection within one month
  - Detection probability = *high confidence (HSP report)*

IAEA Diversion of LEU Detection Goals

- **Detection of Diversion of LEU (<20% U-235)**
  - SQ = 75 kg U-235 contained in LEU
  - Detection within one year
  - Detection probability = 50%

IAEA Diversion of NU/DU Detection Goals

- **Detection of Diversion of NU and DU**
  - SQ = 10 MT of NU, 20 MT DU
  - Detection within one year
  - Detection probability = 50%

Hexapartite Safeguards Project (HSP)
Historical Background on Key GCEP SG Developments

- **HSP convened to:**
  - Establish an effective and efficient safeguards approach for LEU GCEPs
  - Under INFCIRC/153-type agreements

- **Participants included**
  - US
  - Japan
  - Australia
  - UK, Germany, Netherlands
    - "The Troika"
  - IAEA and Euratom

- **Study lasted from November 1980 to March 1983**

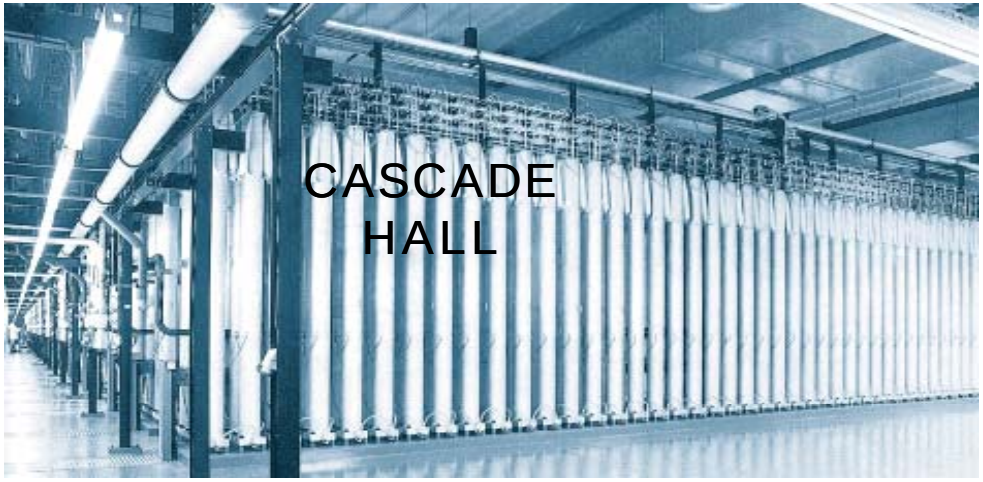
HSP Resulting Guidance

- **Established SG approach that is backbone of current SG Criteria**
- **Measures outside cascade halls to detect diversion of uranium**
- **Measures inside cascade halls-detect HEU production-Use LFUA**
- **Operator – holds feed, product, and tails cylinders for verification**
- **HSP did not address question of undeclared feed**

Limited Frequency Unannounced Access (LFUA)

DIV Technique for HEU Detection

- **(LFUA) Inspections to Cascade Halls**



  - Access is on a random, unannounced basis
  - Access must be provided within 2 hours of request
  - Performed 4 -12 times per year (facilities <1000MTSWU/yr)

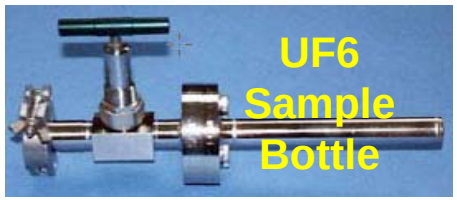
Measures to Detect Undeclared HEU Production

LFUA - Verification Measures include:

- **Visual observation**
  - Detect presence of unreported F/W equipment within cascade areas
  - Detect piping changes indicative of connecting cascades in series

- **NDA measurements on header piping**
  - Cascade Enrichment Header Monitor (CEMO)
  - Detects HEU
  - Only operates at Capenhurst (QCAX)

- **Obtaining of UF_6 samples from cascade**
  - Analyze for enrichment
  - Rare event!



- **Obtaining of environmental samples; analyze for enrichment**

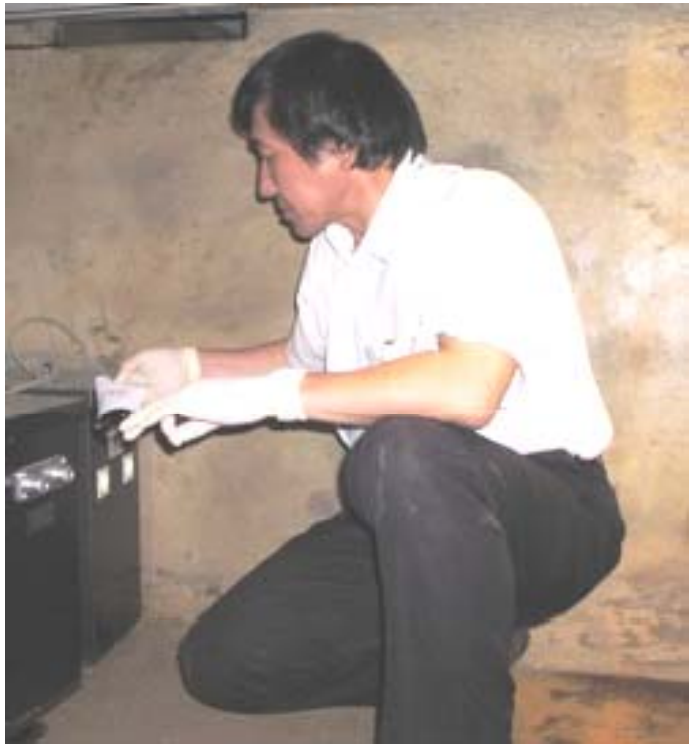
Environmental Sampling (ES)

- **Potentially a very powerful technique**
- **Baseline samples need to be taken**
- **Field trials have occurred**
  - Including sampling inside cascade halls

- **Can detect increasing enrichments as cascades brought on line**
  - Peter Friend (URENCO) confirmed this statement
- **Operators did not take special measures to prevent UF_6 releases**

GCEP Environmental Sampling Points

- Header pipe connections
- Sampling stations
- Chemical traps
- F/W connections
- Surfaces of carts



IAEA Measures to Detect Diversion of Uranium

- **Inspection regime includes:**
  - Annual PIT/PIV
  - 11 monthly interim inspections for flow verification
  - IAEA verifies feed, product, and tails cylinders - receipts and shipments
    - OPERATOR holds feed before feeding to process
    - OPERATOR holds tails and product before shipment off-site
- **Auditing of records and reports (ICR, PIL, MBR)**
- **Verification of nuclear material quantities (flows and inventories)**
- **Material balance evaluation**
- **Application of seals to UF_6 cylinders**

Verification of Nuclear Material Quantities

- **Inventories at PIV**
  - UF_6 cylinders in storage yards
  - UF_6 cylinders
    - Connected to cascades
    - In process vessels (F/W stations)

- **Flows at Interim Inspections and PIV**
  - Feed, product and tails UF_6 in cylinders
  - Minor waste streams (trap material, etc.)

Verification of UF_6
Feed – Product - Tails

- **Weights of UF_6 Cylinders**
  - Verify weight of full cylinder by:
    - IAEA load-cell system (LCBS)
    - Authenticate operator scales
      - Use IAEA check weight
  - Can weigh cylinders to about 1-2 kg
  - Empty cylinder weights usually not verified

- **UF_6 Enrichment Measurements**
  - Gamma-ray NDA - determine enrichment at gross- and partial-defects level
  - Sampling and DA - determine enrichment at bias-defect level

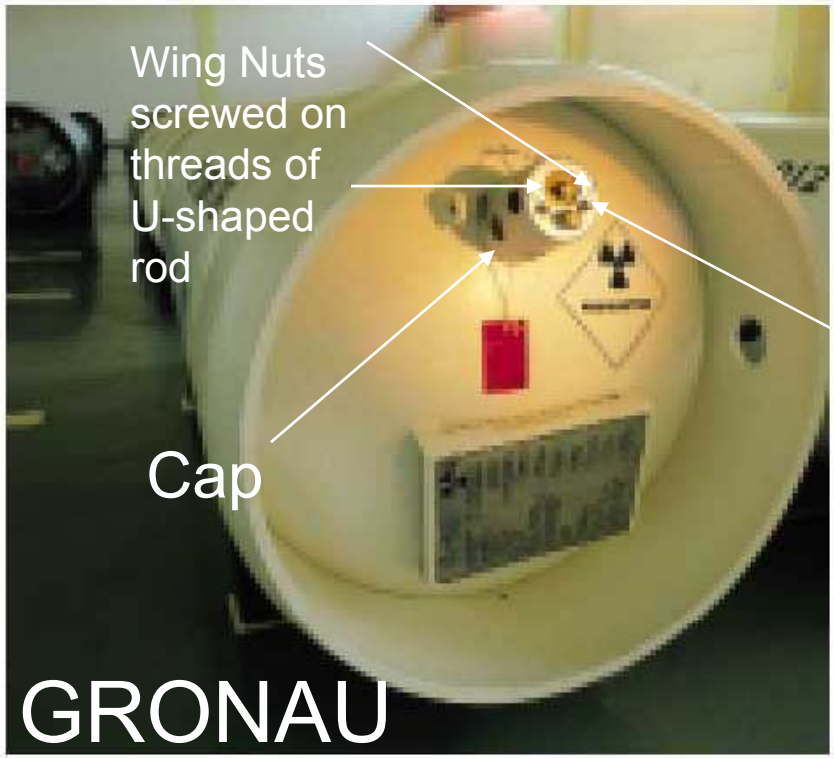
Instruments for Gamma-Ray NDA Measurements

- NaI(Tl)/PMT (MMCN)
  - Usually used for NU feed and DU tails
  - δ_2 ~ 10-20% for NU
  - δ_2 ~ 25-50% for DU

- HPGe (MMCG) + ultrasonic thickness gauge (ULTG)
  - Used for LEU product and sometimes for NU, DU
  - Cooled by liquid nitrogen
  - δ_2 ~ 5% for LEU

Example of Sealed LEU Product Cylinder

Maintaining "CofK"

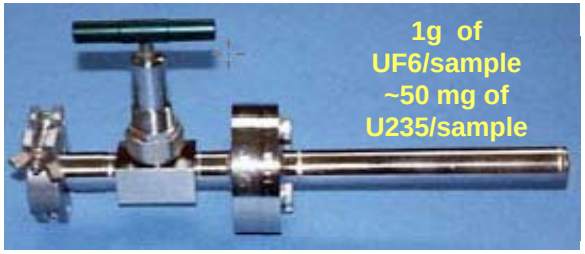


Inspected and Sealed Product-Container

Common Metal Seal IAEA/EUR (also on back drain valve)

Sampling and DA of UF_6

- **Physical sample UF_6 ➔ IAEA selects cylinder – operator samples**
- **Samples to IAEA Safeguards Analytical Laboratory – at PIV**
- **U-235 concentration by Thermal Ionization Mass Spec (TIMS)**
  - ITV Values for uncertainty for TIMS
    - ➢ δ_3 = 0.1% for LEU
    - ➢ δ_3 = 0.2% for NU
    - ➢ δ_3 = 0.5% for DU



A Critique - Weaknesses in Existing Approach

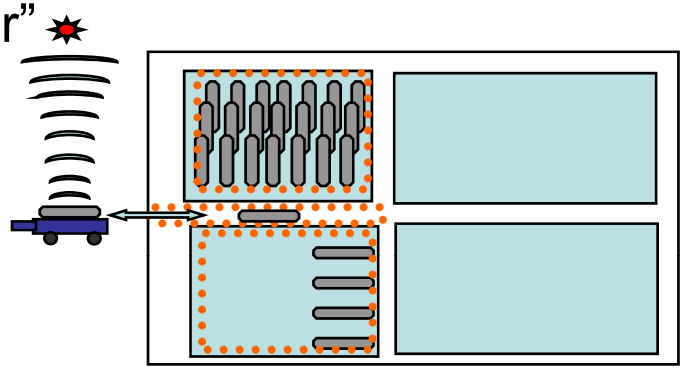
- No significant measures to detect undeclared feed
- At least one LEU diversion scenario not covered
- Unable to meet detection goals for large throughput plants
- New, large centrifuges make it more difficult to see piping
- New cascade designs are less transparent than before

Future? Potential HEU Diversion Detection Techniques

- Enhanced inspector access inside cascade halls
- Enhanced video surveillance inside cascade halls
- Video/radiation monitoring of cascade hall access doors
- NDA measurements on piping inside the cascade halls
- Radiation monitors inside cascade halls
- Installation of unattended monitoring system at the F/W stations
- Enhanced inspector access to buildings on the plant site

Future Safeguards Measures
Introducing Process Monitoring

- **Partial Defect verification - each cylinder**
  - Centralized "Cylinder Portal Monitor"
  - Distributed systems
    - The cylinder identification (ID)
    - Gross weight
    - Enrichment of UF6



- **Surveillance of UF6 handling area**

- **Electronic seals**
  - On product and tails cylinders leaving process

Potential Excess LEU Production Detection Improvements

Present Possibilities and Future Tech

- **Detect undeclared feed cylinders concurrent with**
  - LFUA inspections
  - Establish SNRI regime (SNRI+LFUA)
- **"Mailbox" declarations of declared cylinder operations**
- **Unattended monitoring system – Process Monitoring**
  - Enrichment at feed, product, and tails stations
  - Load cells at feed, product, and tails stations
- **Detect undeclared UF_6 Streams in cascade halls**
  - Enhanced inspector access inside cascade halls
  - Enhanced video surveillance inside cascade halls
  - Video/radiation monitoring of cascade hall access doors

Summary of GCEPS Safeguards

- **GCEPS safeguards – manpower intensive**
- **Desire to close gaps on undeclared feed**
  - Operator “no one would ever divert undeclared LEU product”
- **Mailbox and SNRI – trials at Gronau – “next step”**
- **Unattended monitoring system – in development**
  - RFIDs
  - Process Monitoring
- **Sensitive technology!**