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# Safeguards at Gas Centrifuge Enrichment Plants: Why is Iran a Threat?


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*NEN-5*



June 18, 2014


*With thanks to ISPO and ORNL IAEA Enrichment Course for training and ideas on enrichment tech and safeguards*

*Special thanks to S. Pepper (ISPO – BNL) and J. M. Whitaker (ORNL)*


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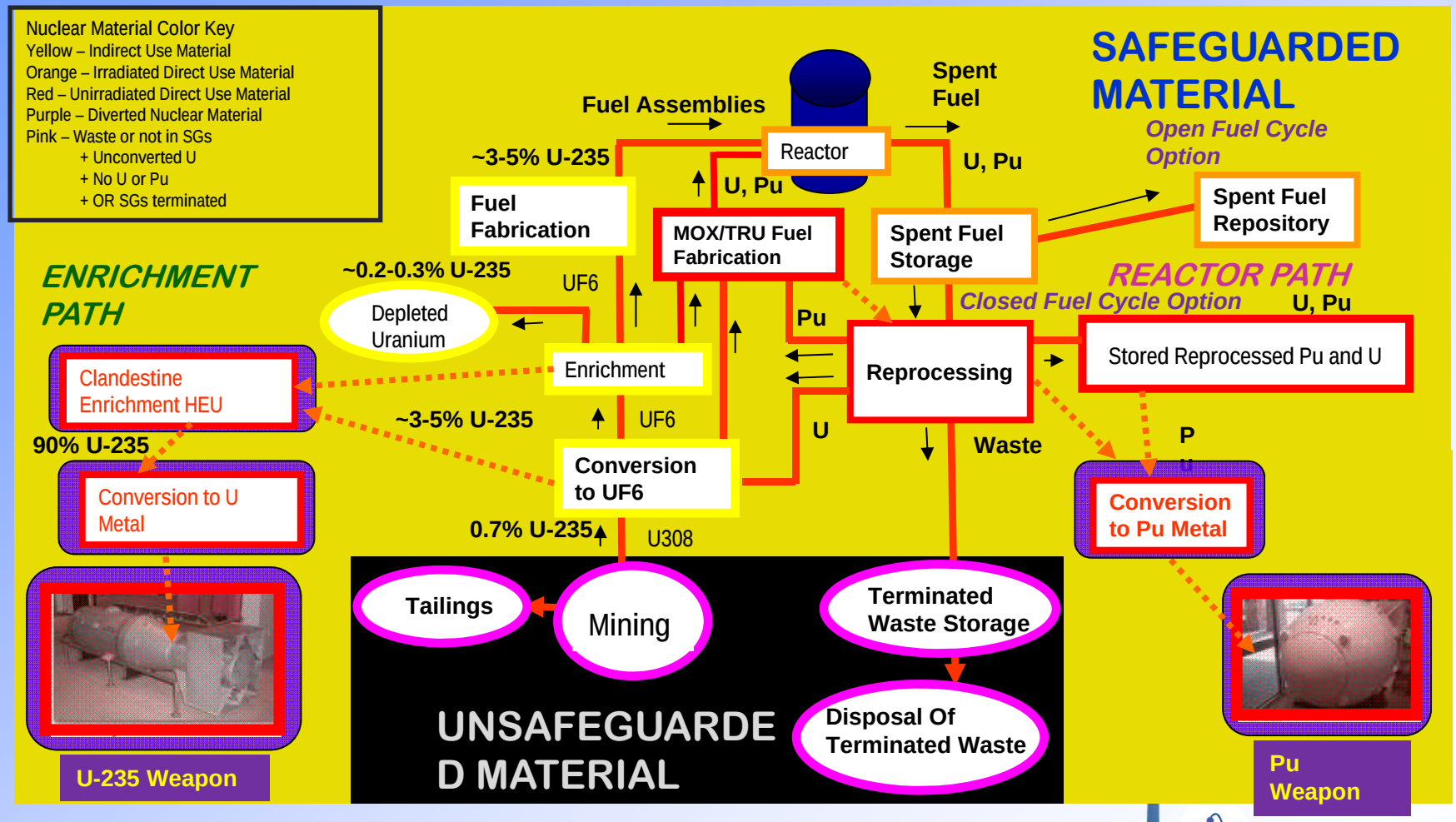
# Nuclear Fuel Cycle – Proliferation Aspects

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# Centrifuges – 21st Century Technology for Enrichment
## Why Such Proliferation Concerns/ Int'l Headlines?

- Small footprint compared to Gaseous Diffusion Plant (GDP) – energy use and size
  - Clandestine plants – possible and likely! Iran facilities – did IAEA find them all? (Shell game)
  - Harder to detect than GDP! 1/50th the electrical consumption – less waste heat
- Compact size of centrifuges – 1-3m tall / 0.5m dia
- Small specific inventory / Short equilibrium time
  - Can change from LEU to HEU production far quicker than GDP
  - Timeliness a concern
- Technology was limited to certain NWS and stable NNWS
  - Khan network starting in Pakistan changed this status quo
  - Iran moved to acquire technology and build own industry
  - Libya, DPRK,…?
- NSG – Trigger List Items – Dual Use
- Iran operates declared plants – ability to reach 3-5%, ~20% enrichment capacity
- Naval reactors – loophole in NPT/INFCIRC 153

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# Safeguards Concerns at LEU GCEPs
## Basic Diversion Scenarios

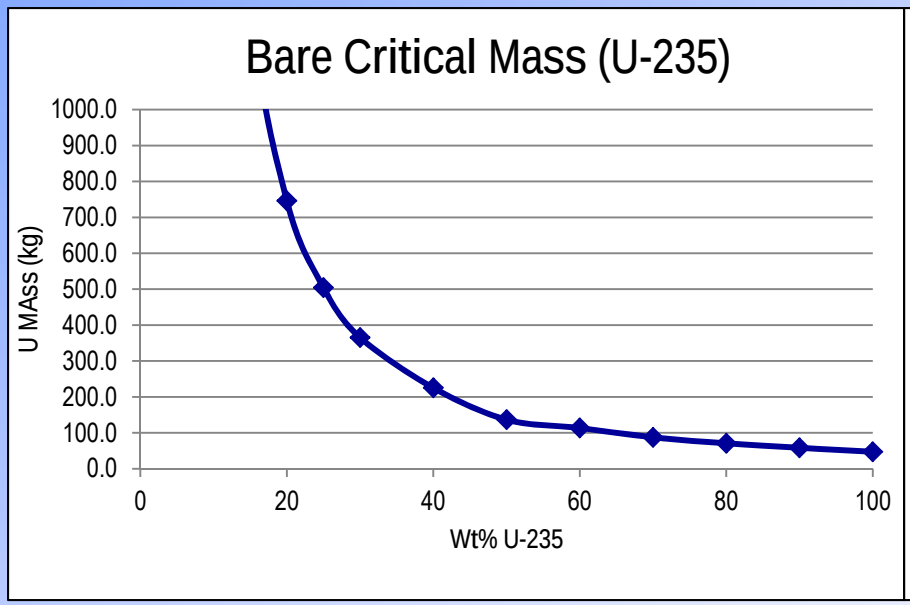
1. *Timely detection* of the misuse of the facility to produce HEU (or any $UF_6$ at higher-than-declared enrichment levels)
2. *Timely detection* of the diversion of declared $UF_6$
3. *Timely detection* of the misuse of the facility to produce undeclared LEU (at declared enrichment levels) from undeclared feed
   - Take undeclared material / enrich as feed for clandestine HEU plant (DU, LEU, lower levels of HEU)

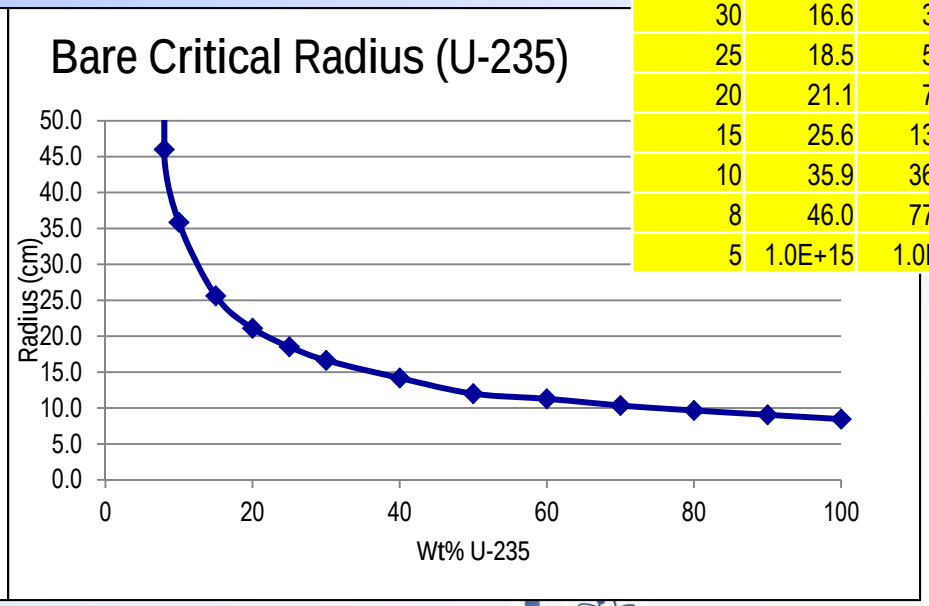
# Safeguards Concerns of U-235
## IAEA Significant Quantities/Timeliness

U-235 --- 75 kg U-235 in U (Wt% of U-235 <20%)
(timeliness = 1 year)

U-235 --- 25 kg U-235 in U (Wt% of U-235 =>20%)
(timeliness = 1 month (unirradiated) / 3 months (irradiated)

| Weight% U235 | R (cm) | Mass (kg) |
|---|---|---|
| 100 | 8.5 | 47.5 |
| 90 | 9.1 | 58.4 |
| 80 | 9.7 | 70.9 |
| 70 | 10.4 | 87.5 |
| 60 | 11.3 | 113.5 |
| 50 | 12.0 | 136.7 |
| 40 | 14.2 | 225.5 |
| 30 | 16.6 | 365.6 |
| 25 | 18.5 | 504.7 |
| 20 | 21.1 | 746.3 |
| 15 | 25.6 | 1334.8 |
| 10 | 35.9 | 3663.2 |
| 8 | 46.0 | 7739.5 |
| 5 | 1.0E+15 | 1.0E+15 |

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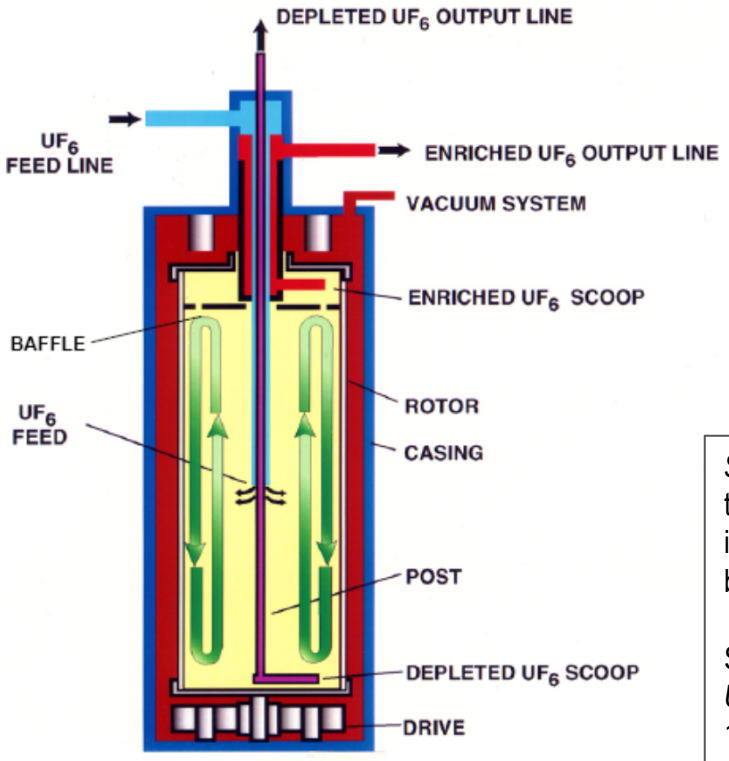
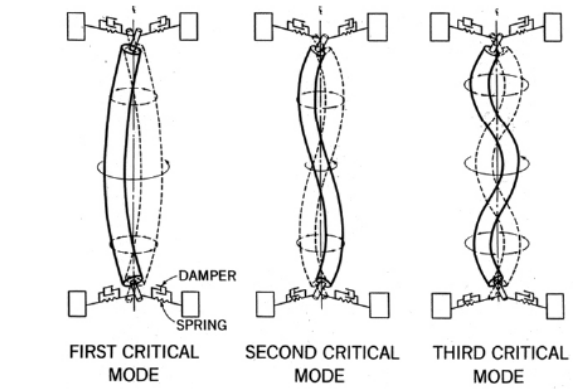
# What Is a Centrifuge?




Schematic of Gas Centrifuge



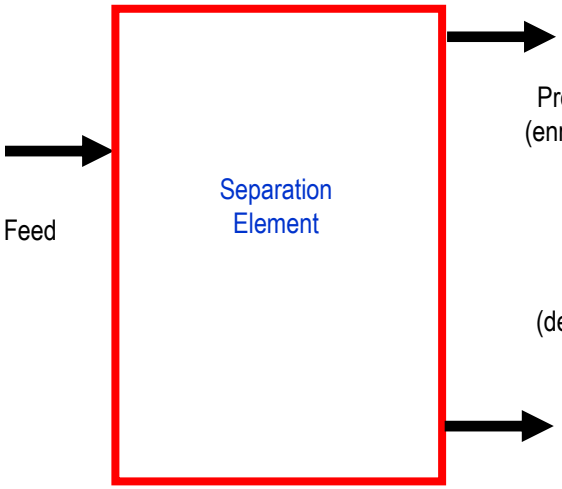

*Separative work unit* (SWU) = function of the amount of uranium processed, the composition of the starting material, and the degree to which it is enriched; it is proportional to the total machine operation time required to achieve this, but is defined independent of the enrichment technology.

Separative work = SWUs, kg SW, or kg UTA (from the German *Urantrennarbeit*)
1 SWU = 1 kg SW = 1 kg UTA
1 kSWU = 1 tSW = 1 t UTA
1 MSWU = 1 ktSW = 1 kt UTA

Alpha = separation factor ..>1.3 for GCEPs

# Centrifuges and Cascades – Theory
## (Plus Example)

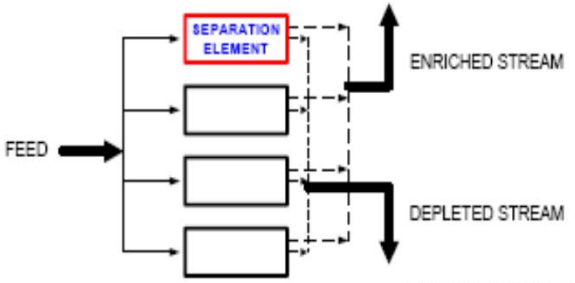
### Single Centrifuge




Key Rule of Thumb ~5000 SWU to make 1 SQ of HEU from Nat U

### Centrifuges in Parallel

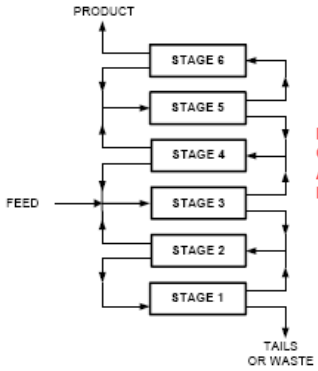
SEPARATION ELEMENTS MAY BE CONNECTED IN PARALLEL TO ACHIEVE HIGHER THROUGHPUT




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

### Cascade

Cascade at Natanz




MULTIPLE STAGES ARE CONNECTED IN SERIES TO ACHIEVE USEFUL ENRICHMENTS

# What is a UF6 Cylinder
## Where Inspectors Find/Verify U and U-235 Material

30B Product (2.5 ton)- Product

48G (14 ton) - Tails

48Y (14 ton) - Feed

5a (25 kg) – HEU – Criticality Safe

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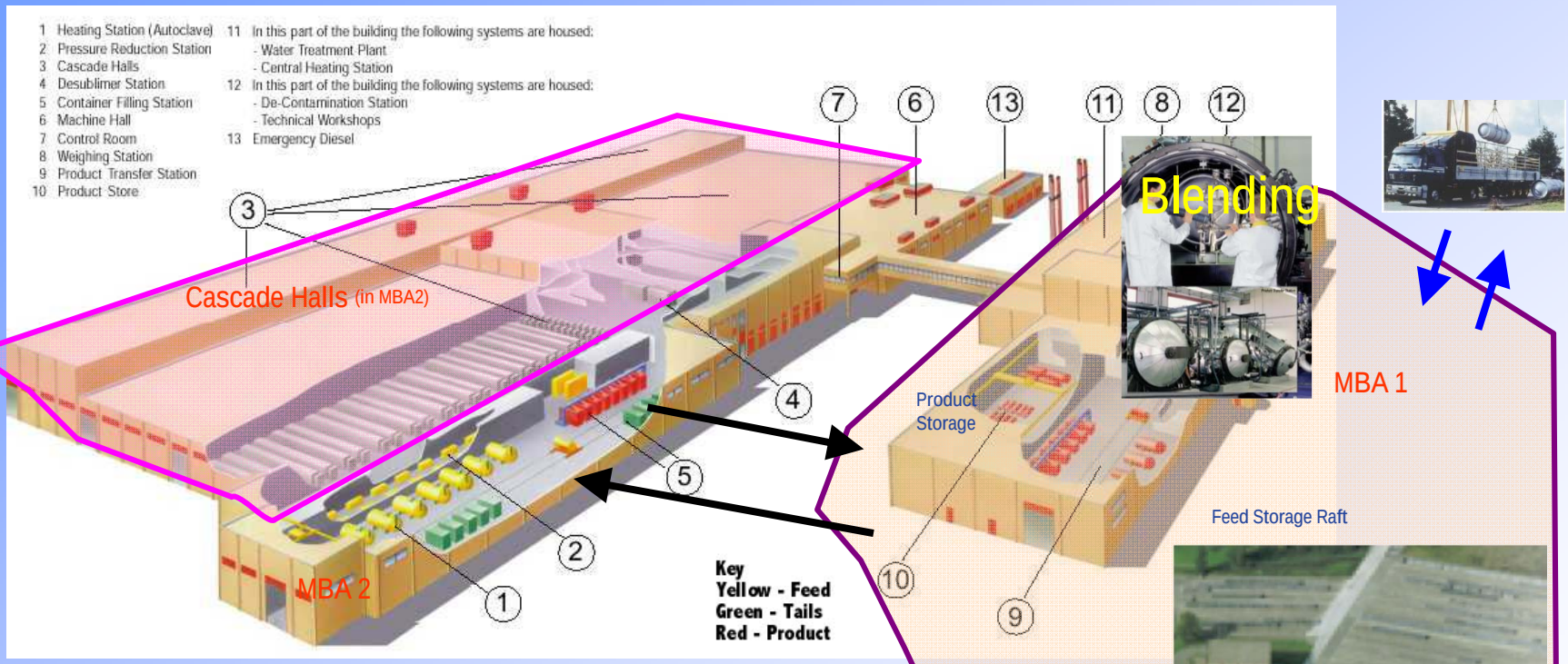
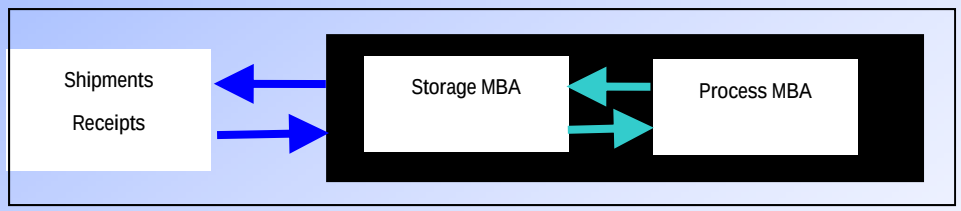
# Gas Centrifuge Enrichment Plant (GCEP)
## Process Areas

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# IAEA Detection Goals - Perspective
## What Shall We Focus on Iran's Paths?

1. *Timely detection* of the misuse of the facility to produce HEU (or any $UF_6$ at higher-than-declared enrichment levels)
2. *Timely detection* of the diversion of declared $UF_6$
3. *Timely detection* of the misuse of the facility to produce undeclared LEU (at declared enrichment levels) from undeclared feed
   - ➢ Take undeclared material / enrich as feed for clandestine HEU plant

# Bushehr (PWR/VVER-1000 Hybrid) Fuel = 3.5% U-235 Enriched

- Iran's Bushehr 1 VVER-1000 Reactor
  - Maximum 3.62% enriched Fuel from Russia
- Sets up declared GCEPs capacity for
  - 3-5% enriched Fuel
- SWUs for production of HEU ~(90%) from LEU?

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| XF | 0.00711 | | XF | 0.00711 | | XF | 0.035 | |
| XP | 0.9 | | XP | 0.035 | | XP | 0.9 | |
| XW | 0.003 | | XW | 0.003 | | XW | 0.003 | |
| ΔU | 5.36 | MTSWU | ΔU | 3.42 | MTSWU | ΔU | 1.981 | MTSWU |
| F= | 43.10902 | kgU235 | F= | 43.62858 | kgU235 | F= | 27.25951 | kgU235 |
| **P=** | **25.0029** | **kgU235** | **P=** | **27.58426** | **kgU235** | **P=** | **25.00634** | **kgU235** |
| W= | 18.10611 | kgU235 | W= | 16.04432 | kgU235 | W= | 2.253175 | kgU235 |

63% of SWUs Done in LEU Stage

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# Teheran Research Reactor (TRR)
# Fuel = 19.75% U-235 Enriched

- Iran declares need for fuel for TRR
  - 19.75% enriched Fuel
- Sets up declared GCEPs capacity for
  - 19.75% enriched Fuel
- SWUs for production of HEU ~(90%)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| XF | 0.00711 | | XF | 0.00711 | | XF | 0.1975 | |
| XP | 0.9 | | XP | 0.1975 | | XP | 0.9 | |
| XW | 0.003 | | XW | 0.003 | | XW | 0.003 | |
| ΔU | 5.36 | MTSWU | ΔU | 5.32 | MTSWU | ΔU | 0.52 | MTSWU |
| F= | 43.10902 | kgU235 | F= | 47.37698 | kgU235 | F= | 25.34033 | kgU235 |
| P= | 25.0029 | kgU235 | P= | 27.80911 | kgU235 | P= | 25.03888 | kgU235 |
| W= | 18.10611 | kgU235 | W= | 19.56787 | kgU235 | W= | 0.301453 | kgU235 |

91% of SWUs Done in TRR Stages (2-Steps)

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# Non-application of Safeguards … In Non-Peaceful Activities

The State shall inform the Agency of the activity, making it clear:

i. That the use of the *nuclear material* in a non-proscribed military activity will not be in conflict with an undertaking the State may have given and in respect of which Agency safeguards apply, that the *nuclear material* will be used only in a peaceful nuclear activity; and

ii. That during the period of non-application of safeguards the *nuclear material* will not be used for the production of nuclear weapons or other nuclear explosive devices;

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# Iran's Navy
# Fuel = 5-90%? U-235 Enriched

- Iran declares need for fuel for naval reactors
  - Can set up need for 50-60% enriched Fuel
- Navy enrichment/fuels program
  - Non-application of safeguards – NPT
  - Plant unsafeguarded by IAEA
  - Need about 5-6 SQs of material (50%-90% perhaps?)
- SWUs to get HEU ~(90%) -100% at (90%) or…

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| XF | 0.00711 | | XF | 0.00711 | | XF | 0.54 | |
| XP | 0.9 | | XP | 0.54 | | XP | 0.9 | |
| XW | 0.003 | | XW | 0.003 | | XW | 0.003 | |
| ΔU | 5.36 | MTSWU | ΔU | 5.22 | MTSWU | ΔU | 0.156 | MTSWU |
| F= | 43.10902 | kgU235 | F= | 43.23926 | kgU235 | F= | 25.10333 | kgU235 |
| P= | 25.0029 | kgU235 | P= | 25.13448 | kgU235 | P= | 25.04736 | kgU235 |
| W= | 18.10611 | kgU235 | W= | 18.10478 | kgU235 | W= | 0.055972 | kgU235 |

97% of SWUs
Done for 54%
enriched reactor
3 Enrichment Stages

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# The Iran Snapshot – Latest Status of UF6




| | Conversion NU UF6 | UF6 Feed to GCEPs | UF6 GCEPs Product | UF6 GCEPs Tails |
|---|---|---|---|---|
| **kg UF6** | 550000 | 134843 | 11870 | 122973 |
| **Purity** | 0.6761 | 0.6761 | 0.6761 | 0.6761 |
| **kg U** | 371855 | 91167 | 8025 | 83142 |
| **Enrichment** | 0.711% | 0.711% | 3.49% | 0.49% |
| **kg U-235** | 2643.9 | 648.2 | 280.1 | 404.1 |
| **SQ DNLEU U-235** | 35.3 | 8.6 | 3.7 | 5.4 |
| **SQ U-235 (25kg)** | 105.8 | 25.9 | 11.2 | 16.2 |
| **Cylinders 48 in** | 44.0 | 10.8 | | 9.8 |
| **Cylinders 30 in** | | | 5.3 | |


Isfahan UCF


Natanz GCEP

Fordow GCEP

## Questions for IAEA BOG and UNSC

- Iran has enough LEU feed for producing SQ of HEU
- ~2/3 to 3/4 of the SWU for getting 90% HEU complete in LEU
- Will Iran divert LEU to a Plant X?
- Will Iran breakout at Natanz, etc… or at a possible secret Plant "X"?
- Can Iran make HEU? Options? Naval reactors?
- Less than optimal LEU production so far but on a learning curve

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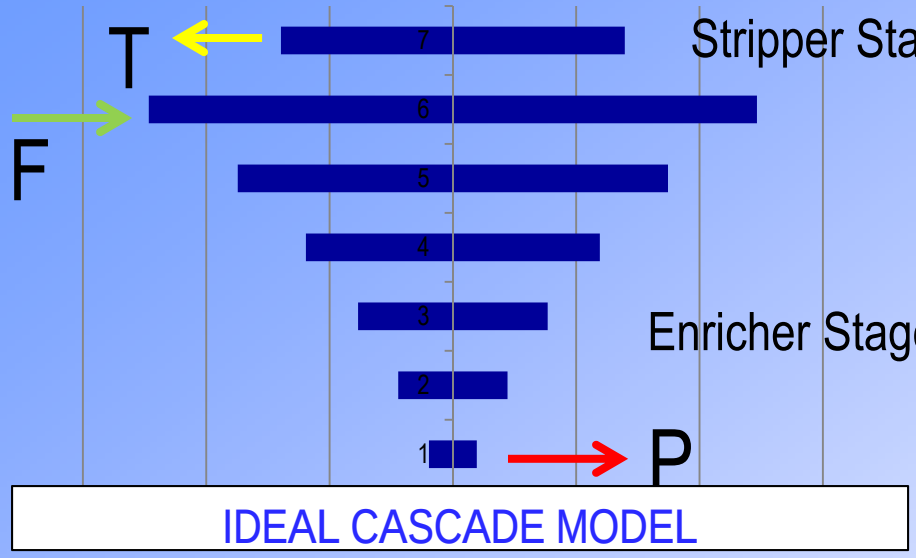
# Ideal Cascade – Use of IAEA Board Reports




| | |
|---|---|
| 1 Centrifuge = | 1 SWU/yr |
| Alpha | 1.71 |

IAEA Former DDG for SGs
Olli Heinonen

IDEAL CASCADE MODEL

| Stage | Xf | Xp | Xw | F | P | W | ΔU | n cent |
|---|---|---|---|---|---|---|---|---|
| 5 | 2.70% | 3.50% | 2.08% | 108.17 | 47.26 | 60.91 | 3.87 | 3.9 |
| 4 | 2.08% | 2.70% | 1.60% | 248.04 | 108.17 | 139.87 | 8.87 | 8.9 |
| 3 | 1.60% | 2.08% | 1.22% | 429.73 | 187.13 | 242.60 | 15.37 | 15.4 |
| 2 | 1.22% | 1.60% | 0.94% | 666.39 | 289.86 | 376.53 | 23.83 | 23.8 |
| 1 | 0.94% | 1.22% | 0.72% | 975.16 | 423.79 | 551.36 | 34.88 | 34.9 |
| 0 | 0.72% | 0.94% | 0.55% | 1378.38 | 598.63 | 779.75 | 49.30 | 49.3 |
| -1 | 0.55% | 0.72% | 0.42% | 779.75 | 338.47 | 441.28 | 27.89 | 27.9 |
| | | | | 4585.624 | | | 164 | 164 |

Ideal Cascade "Back of the Envelope" EXCEL Model

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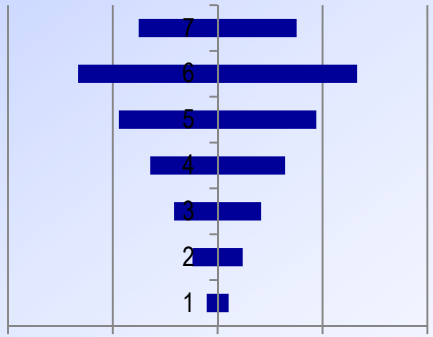
# Ideal Cascade – Open Source Data

- Natanz Model estimated from BOG Reports
- Assume – 54 cascades of 164 centrifuges – 9 MtSWU/yr

| Stage | Xf | Xp | Xw | F | P | W | ΔU | n cent |
|---|---|---|---|---|---|---|---|---|
| 5 | 2.70% | 3.50% | 2.08% | 5841.257 | 2552.25 | 3289.007 | 208.9064 | 208.906394 |
| 4 | 2.08% | 2.70% | 1.60% | 13394.12 | 5841.257 | 7552.859 | 479.0264 | 479.026443 |
| 3 | 1.60% | 2.08% | 1.22% | 23205.32 | 10105.11 | 13100.21 | 829.9138 | 829.913811 |
| 2 | 1.22% | 1.60% | 0.94% | 35985.09 | 15652.46 | 20332.63 | 1286.969 | 1286.96881 |
| 1 | 0.94% | 1.22% | 0.72% | 52658.54 | 22884.88 | 29773.66 | 1883.277 | 1883.27711 |
| 0 | 0.72% | 0.94% | 0.55% | 74432.64 | 32325.91 | 42106.73 | 2662.005 | 2662.00474 |
| -1 | 0.55% | 0.72% | 0.42% | 42106.73 | 18277.39 | 23829.34 | 1505.903 | 1505.90268 |
| | | | | 247623.7 | | | 8856 | 8856 |

| Alpha | 1.71 |
|---|---|




IDEAL CASCADE MODEL
164 X 54

| | | | | | | |
|---|---|---|---|---|---|---|
| F= | 26382 | kgU/yr | 188 | kgU235/yr | 0.711% | U235 ENR |
| P= | 2552 | kgU/yr | 88.2 | kgU235/yr | 3.5% | U235 ENR |
| W= | 23829. | kgU/yr | 101 | kgU235/yr | 0.42% | U235 ENR |

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# Diversion/Breakout/Clandestine Pathways

## Acquisition Pathways

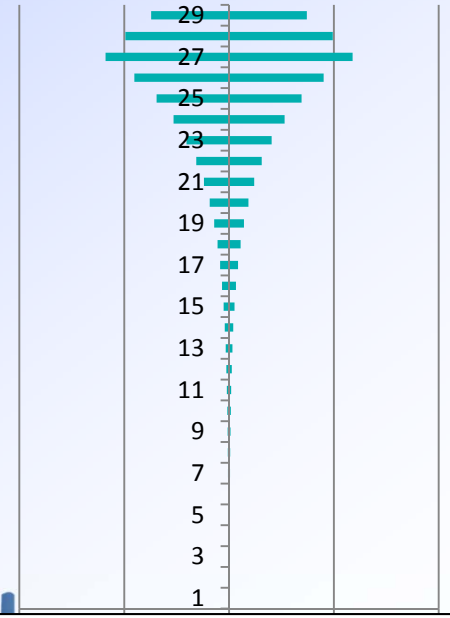
1) Breakout or misuse at Natanz declared 54 cascades x 164 machines
   - Take LEU and enrich to HEU - up to 4 stages total
2) Diversion of LEU to Possible Plant “X” – clandestine HEU enrichment plant
3) Diversion of tails to Possible Plant “Y” – clandestine HEU enrichment plant
4) Clandestine NUF6 at Possible Plant “Z”
   - Clandestine conversion or acquisition of NUF6
   - Enrich – NU to HEU at Plant “Z”

# Path 1 - Breakout or Misuse at Natanz

- Take LEU at Natanz as feed ~8400 kgUF6 available ~(4x30B)
- Stage 2 – F 3.5%, P 19.2%, T 1.9% (Alpha = 1.88)
  - 104 days – produce 770 kgUF6, 521kgU, 100 kgU235
- Stage 3 – F 19.2%, P 61 %, T 11.2% (Alpha = 1.88)
  - 11 days – produce 124kgUF6, 84kgU, 51kgU235
- Stage 4 – F 61 %, P 91%, T 46% (Alpha = 1.88)
  - 2 days – produce 42kgUF6, 28.6kgU, 26.2kgU235
- 1 SQ of U235 produced – 117 days of production
- ~4 months to breakout or misuse Natanz
  - Can safeguards detect misuse? How to deter breakout?

# Path 2 - Diversion of LEU to Possible Plant "X"

- Take LEU at Natanz as feed - ~8400 kgUF6 available ~(4x30B)
- Divert ONE 30B to possible Plant "X" – attempt to hide diversion
- Plant "X" = 2900 centrifuges ~ similar to Fordow plant – secret location
- Built as one *optimized cascade* to go from LEU to 91% HEU
  - 20 stages up/2 stages down – P=91% U235, T=1.59% U235
  - 21 enrich / 2 strip
  - 140 days – produce 40.7 kgUF6, 27.5 kgU, 25 kgU235
  - Feed for 1 SQ = 1916 kgUF6 at 3.5% enrichment (<1 X 30B)
- ~5 months to use Plant "X" to process secretly LEU




OPTIMAL LEU to HEU CASCADE MODEL

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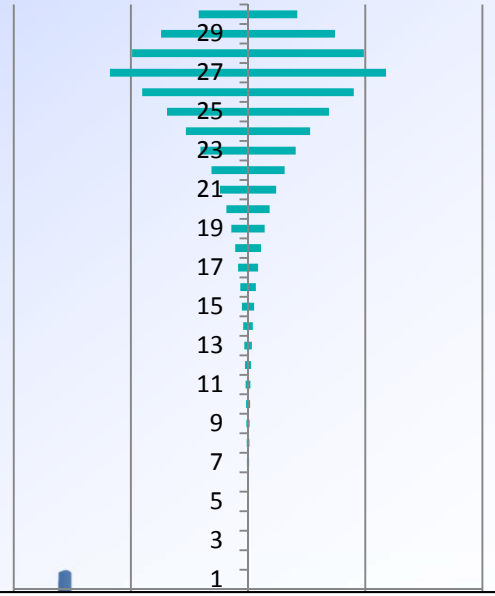
# Path 3 - Diversion of DU tails to Possible Plant "Y"

- Take DU at Natanz as feed - ~123 tonnes UF6 available ~(10x48Y)
- Divert 48Y (10%) to Plant "Y" – attempt to hide diversion – 12,500 kgUF6
- Plant "Y" = 2900 centrifuges ~ similar to Fordow plant – secret location
- Built as one *optimized cascade* to go from DU to 87% HEU
  - 26 stages up/3 stages down – P=87% U235, T=0.17% U235
  - 27 enrich / 3 strip
  - ~3 years – produce 46 kgUF6, 31 kgU, 27 kgU235
- Clandestine plant designed to enrich NU to HEU
  - Can use ONE tails cylinder to produce SQ of HEU (87%)




OPTIMAL DU to HEU CASCADE MODEL

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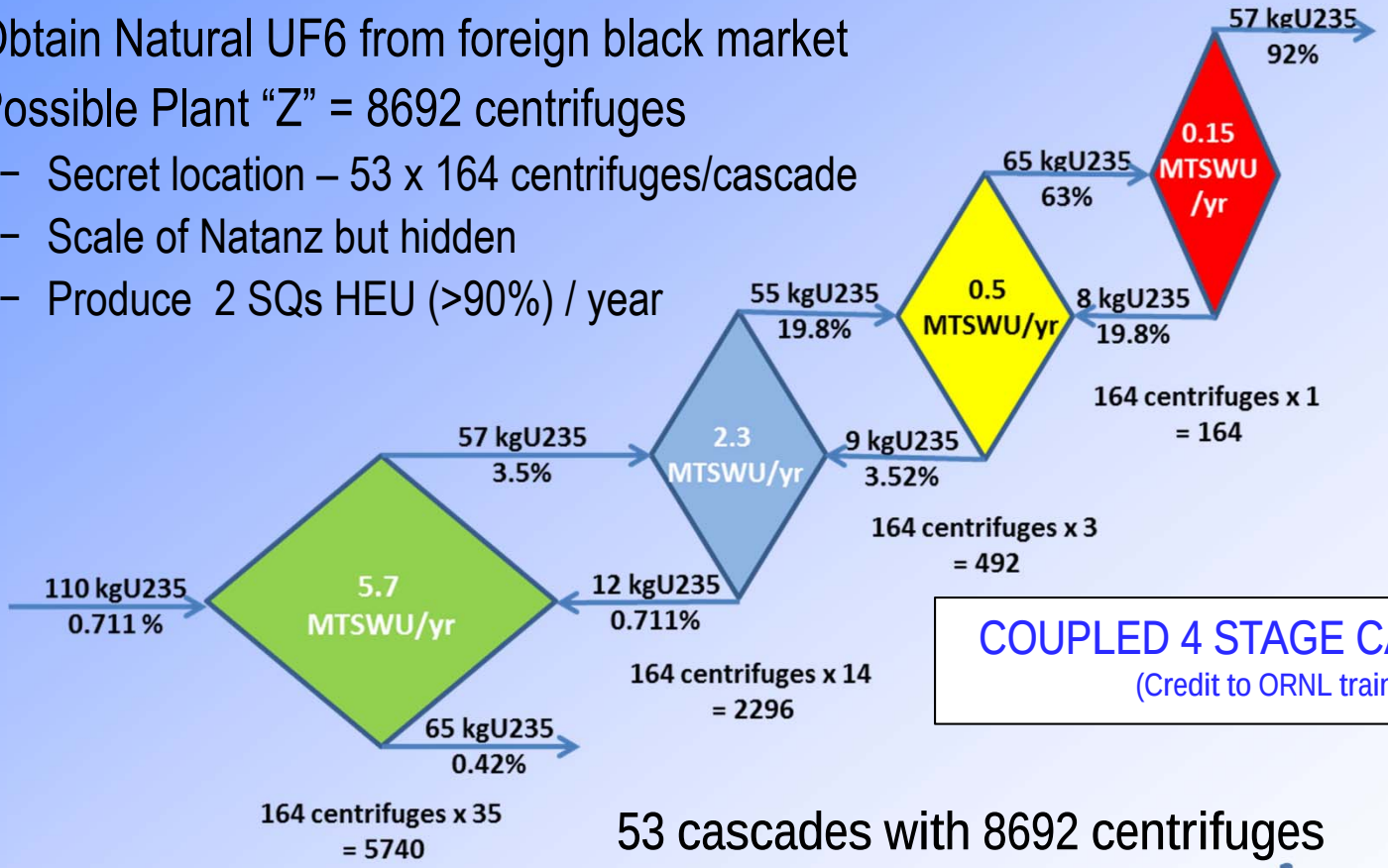
# Path 4 - Clandestine Ops - Possible Plant "Z"

- Mine U ore clandestinely and convert to UF6 in possible clandestine NU conversion plant
- Obtain Natural UF6 from foreign black market
- Possible Plant "Z" = 8692 centrifuges
  - Secret location – 53 x 164 centrifuges/cascade
  - Scale of Natanz but hidden
  - Produce 2 SQs HEU (>90%) / year




COUPLED 4 STAGE CASCADE MODEL
(Credit to ORNL training module)

53 cascades with 8692 centrifuges

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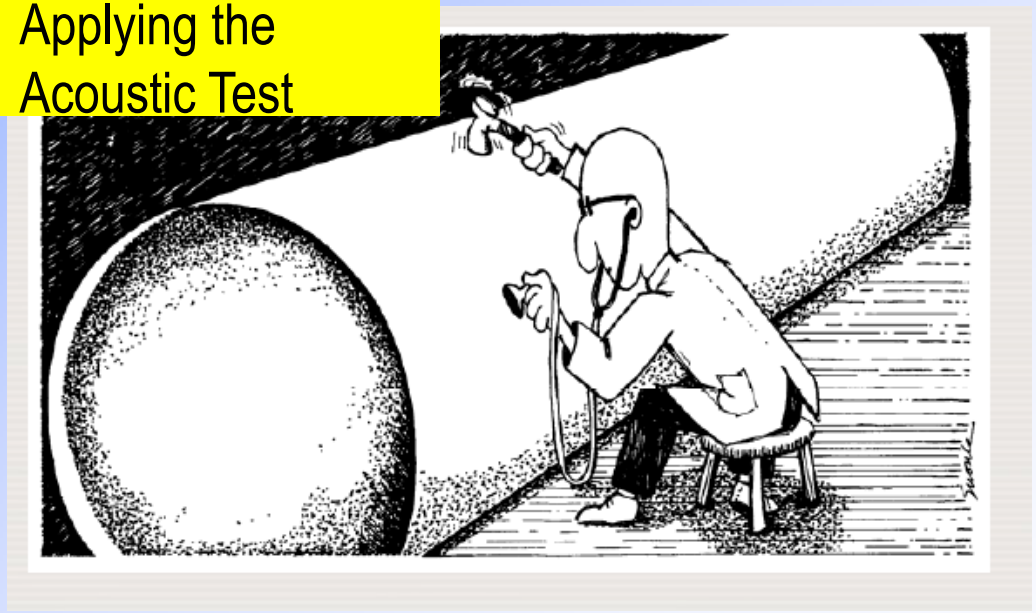
# IAEA Accountancy Verification Methods
## GCEPS Applications to DETECT Diversion

- 3 levels of defects to detect with NDA Instruments – Key concept
  - *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

Applying the Acoustic Test



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# Iran Status and Timescales for Detecting Diversion/Misuse

- Detection of HEU (≥20% $^{235}U$) Production
  - Detect 25 kg $^{235}U$ in U in one month
- Detection of Diversion of DNLEU (<20% U-235)
  - Detect 75 kg $^{235}U$ in U in one year

# Verify Design Information via LFUA

- Low Frequency Unannounced Access (LFUA) Inspections


  - 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)
  - Protection of proprietary information by negotiated procedures

# IAEA Measures to Detect Diversion of Uranium

- Inspection regime includes:
  - Annual PIT/PIV
  - 11 monthly interim inspections for flow verification (scale of facility)
    - Iran how many times? Scale of operations? 1x, 4x, 12x???
  - 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 containment/surveillance to facility
- Environmental Swipe Samples – powerful tool to detect HEU
  - For declared facilities and looking for undeclared activities and facilities

# 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 1-5 kg
  - Empty cylinder weights usually not verified


- $UF_6$ Enrichment Measurements
  - NDA - enrichment at gross- and partial-defects level
    - 5% to 25% uncertainty
  - DA – determine enrichment at bias-defect level
    - >1% uncertainty (0.1% to 0.5% uncertainty range)

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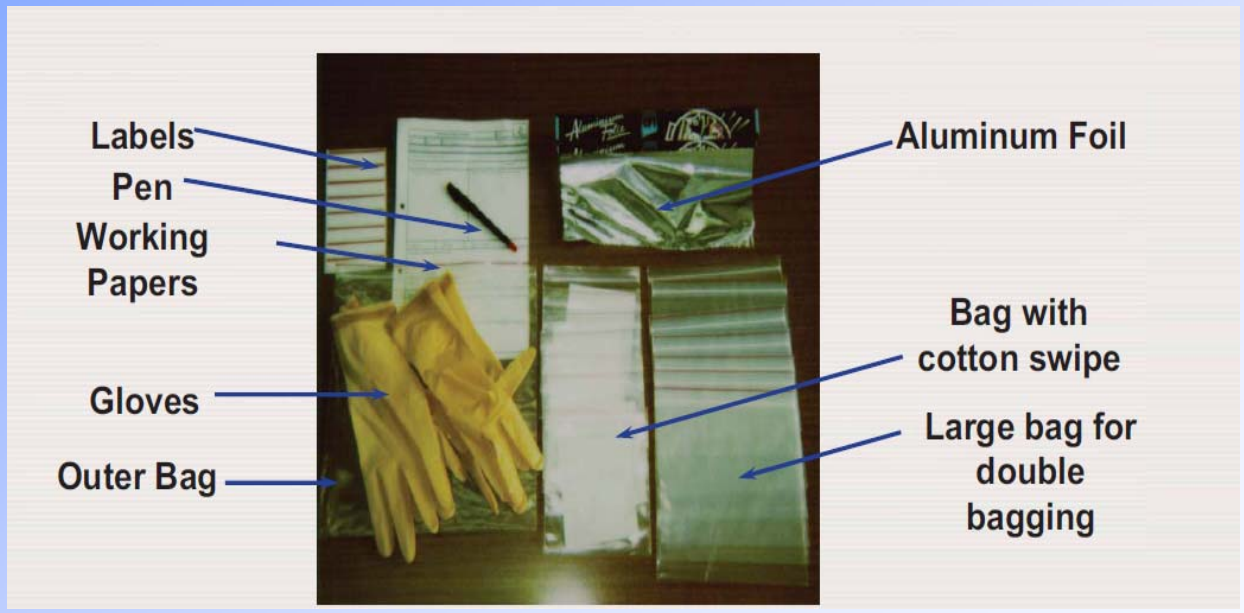
# Environmental Swipe Samples

- Environmental Sample Swipe Kit
  - Powerful tool for undeclared activities
  - Detect HEU where not declared
  - Where to swipe?
  - Avoid Contamination / Understand site legacy





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# Summary of Iran GCEPs

- GCEPS safeguards (Desire to close gaps on undeclared feed)
  - Timely detection of the misuse of the facility to produce HEU
  - Timely detection of the diversion of declared UF6
  - Timely detection of the misuse of the facility to produce undeclared LEU
  - Operator “no one would ever divert undeclared LEU product”
  - Breakout vs. Clandestine Ops (CSA and AP safeguards options)
- Tightened coverage of GCEPs – declared operations (SNRI,C/S)
- Unattended monitoring system – in development for GCEPs
  - Load Cells – Monitoring cylinders / weight
  - On-Line Enrichment Monitoring
  - Cylinder Verification Station – NDA, Weight,…
  - UF6 Cylinder Tracking - UID

Centrifuges From Libya

- Sensitive technology! Khan network and undeclared facilities

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