Advanced Safeguards and Proliferation Resistance of the Future Nuclear Fuel Cycle Systems

Presented at 3rd UC Forum, June 11th, 2009

Y.Kuno

Japan Atomic Energy Agency (JAEA)

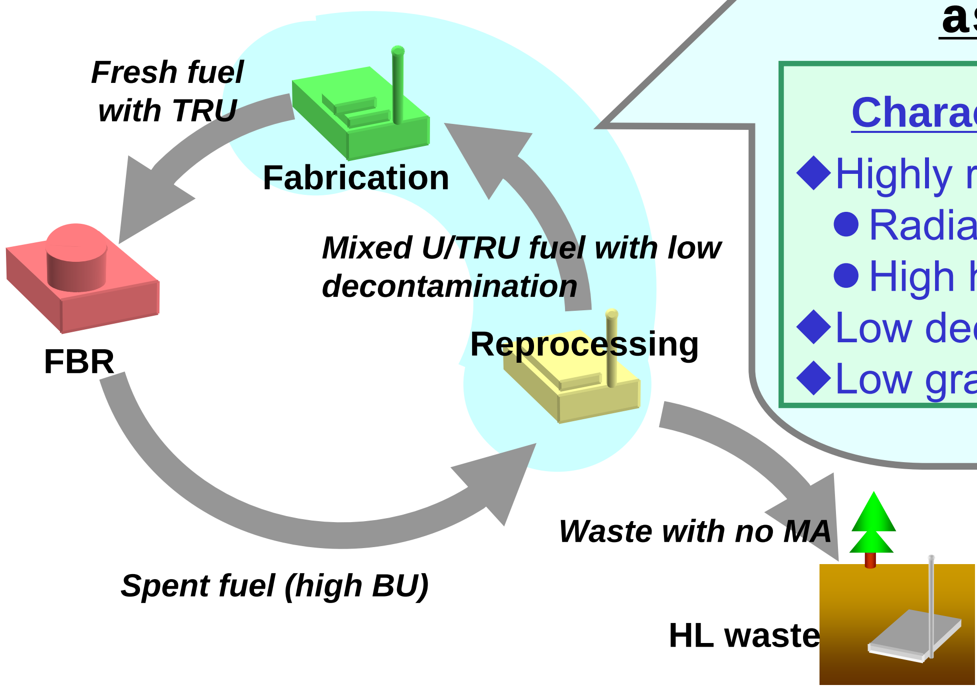
&

The University of Tokyo (UT)

Non-proliferation Measures for Future Nuclear Fuel Cycle

- The number of power reactors should increase against world energy demand, and accordingly large scale fuel cycle for such reactors is to be required for efficient use of nuclear material resources, where much larger amount of plutonium than that in the present time must be recycled.
- It is essential to incorporate Proliferation Resistance (PR) technologies and Safeguards into its early design stages, in order to demonstrate robust proliferation-resistant future NFC in an efficient, effective and economically viable manner.
- The proliferation-resistant technology impedes diversion by host states seeking to acquire nuclear weapons or other nuclear explosive devices.
- International Safeguards including Comprehensive Safeguards Agreement (CSA) and Additional Protocol (AP) is the most effective institutional measures among many PR measures.

Proliferation Resistance (PR) Strategy of FR Cycle



Example of Proliferation Resistance aspects of the Fuel Cycle

Characteristics

- ◆Highly radioactive
  - ●Radiation dose
  - ●High heating rate
- ◆Low decontamination
- ◆Low grade Pu

From PR&PP

- ◆ Hard to access
- ◆ Difficult to handle
- ◆ Difficult to divert

Key for PR = **Unattractive for diversion**

We need to prevent nuclear proliferation from Fuel Cycle Technologies.

Key Proliferation Resistance Measures to be considered during designing NFC

INPRO
- States' Commitments（UR 1）
- Attractiveness of NM and Technology（UR 2）
- Difficulty and Detectability of Diversion（UR 3）
- Multiple Barriers（UR 4）
- Optimization of design（UR 5）

GEN IV
- Technical Difficulty（TD）
- Proliferation Costs（PC）
- Detection Probability（PT）
- Material Type（MT）
- Detection Probability（DP）
- Detection Resource（DR）

Key PR Measures（Barriers）

1. Detection of Diversion and Misuse
2. Difficulty to Modify Process for Separation of Pu
3. Material Type Barriers

Reasonably Economical Designing

Effect

- **Detect Diversion/Misuse in Timely Manner (SG by Design)**
- Delay Diversion/Production of Nuclear Weapon

Proliferation Resistance : Technical Issues

Proliferation Resistance – detection : Based on Institutional system

<u>High detection probability by SG and other techniques</u>

- Design information
- Accountability
- C/S
- Detectability of material-diversion / misuse
- Operational transparency
- etc

Proliferation Resistance - technical difficulty and Material type

<u>Hard to access / Difficult to handle / Difficult to divert</u>

- Lower Pu Grade (Isotopic Composition)
- High Radiation Dose
- High Heating Rate
- High Neutron Emission Rate
- No pure Pu; Low decontamination (chemical physical property)

JAEA

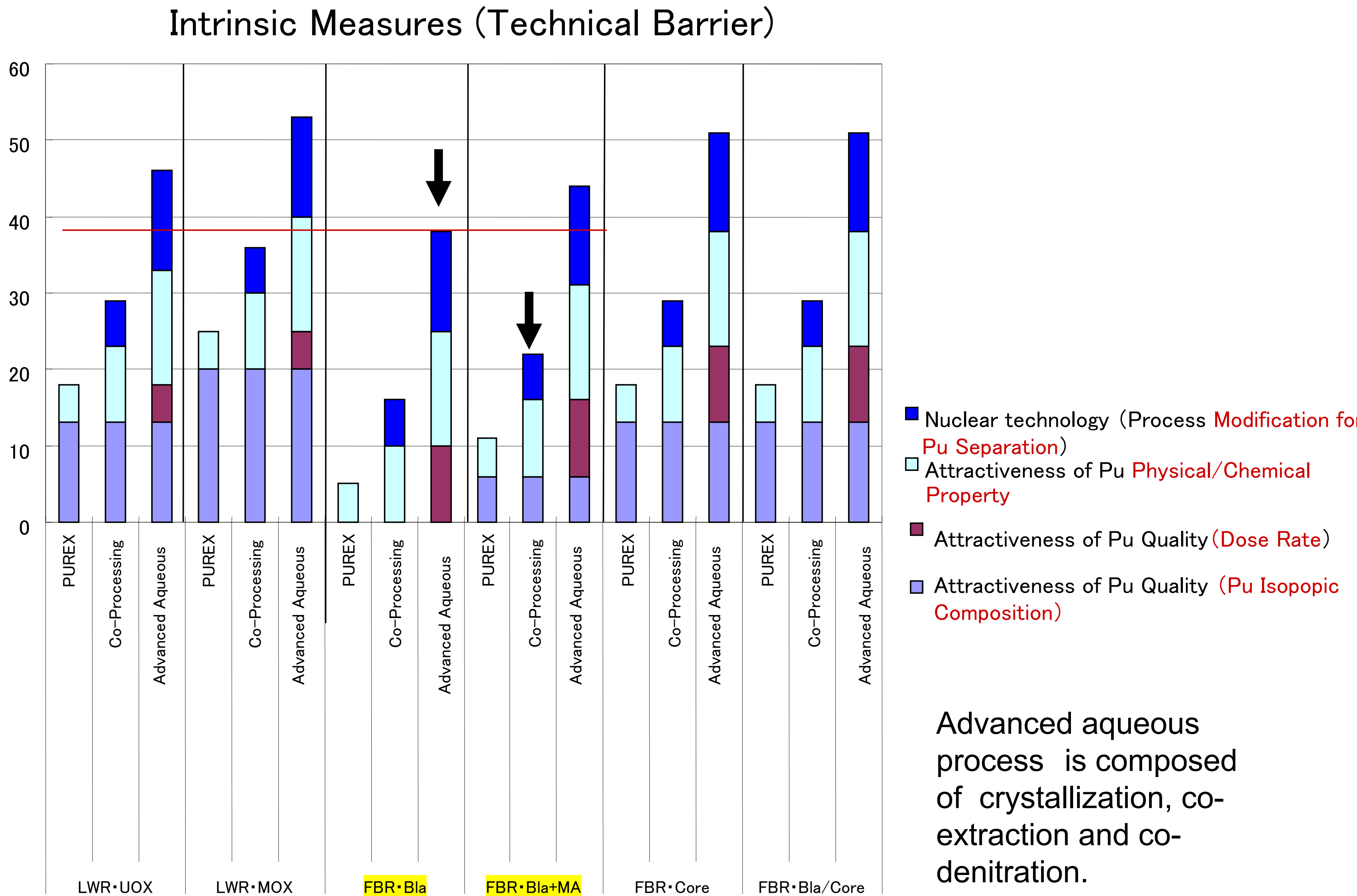
THE UNIVERSITY OF TOKYO

Attractiveness of NM and Technology (Technical barrier)

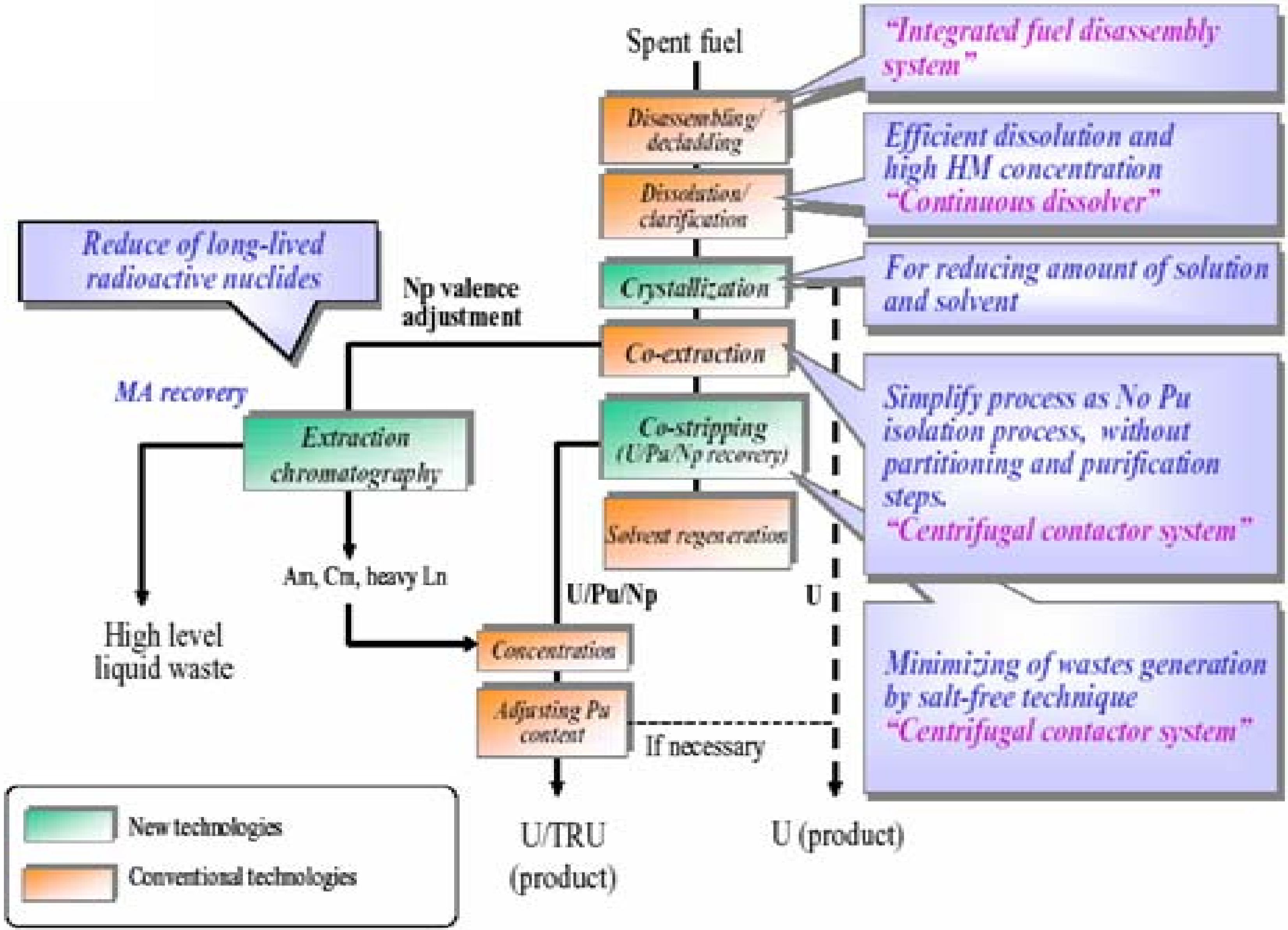
INPRO-based-modified by JAEA: 100points in total

<table>
<tr><td>Indicator: IN</td><td colspan="2">Evaluation Parameter</td><td colspan="20">Rating</td></tr>
<tr><td rowspan="7">IN2.1Quality of Material /AL2.1 (60points)</td><td rowspan="2">Isotopic Composition</td><td rowspan="2">239Pu/Pu (wt%)</td><td colspan="5">VW</td><td colspan="5">W</td><td colspan="5">S</td><td colspan="5">VS</td></tr>
<tr><td colspan="5">>93 (0)</td><td colspan="5">80-93(6)</td><td colspan="5">50-80 (13)</td><td colspan="5"><50 (20)</td></tr>
<tr><td rowspan="2">Dose rate</td><td rowspan="2">Dose at 1m (mGy/hr)</td><td colspan="4">VW</td><td colspan="4">W</td><td colspan="4">M</td><td colspan="4">S</td><td colspan="4">VS</td></tr>
<tr><td colspan="4"><150 (0)</td><td colspan="4">150-350 (5)</td><td colspan="4">350-1000 (10)</td><td colspan="4">1000-10000 (15)</td><td colspan="4">>10000 (20)</td></tr>
<tr><td rowspan="2">Heat Generation</td><td rowspan="2">W/Kg</td><td colspan="12">W</td><td colspan="8">S</td></tr>
<tr><td colspan="12"><120 (0)</td><td colspan="8">>120 (20)</td></tr>
<tr><td>Neutron</td><td>240+242Pu/Pu</td><td colspan="20">Dependent on above-239Pu</td></tr>
<tr><td rowspan="2">IN2.3 Material Property/ Form (20points)</td><td rowspan="2">Chemical Physical Property</td><td rowspan="2">Pu form</td><td colspan="4">VW</td><td colspan="4">W</td><td colspan="4">M</td><td colspan="4">S</td><td colspan="4">VS</td></tr>
<tr><td colspan="4">(Pure) Metal (0)</td><td colspan="4">Oxide/Soln (Separated) (5)</td><td colspan="4">Pu mixture (E.g. : MOX) (10)</td><td colspan="4">Spent Fuel, MA-contained Pu mixture (15)</td><td colspan="4">Waste (20)</td></tr>
<tr><td rowspan="2">IN2.4 Nuclear Technology (20points)</td><td colspan="2" rowspan="2">Extraction of fissile materials, Process modification for Pu separation</td><td colspan="5">VW</td><td colspan="5">W</td><td colspan="5">S</td><td colspan="5">VS</td></tr>
<tr><td colspan="5">No process change (0)</td><td colspan="5">Changeable with software (6)</td><td colspan="5">Changeable with soft/hardware (13)</td><td colspan="5">Require complex soft/hardware change (20)</td></tr>
</table>

Example of evaluation of Technical Barrier (Reprocessing, including LWR, LWR-MOX, and various FBR Options)



Advanced aqueous process is composed of crystallization, co-extraction and co-denitration.



NEXT Process

1. Case for States that potentially have intention to divert nuclear materials

a) Take out Pu from NFC under Safeguards → △Take out, separate Pu at clandestine facility, and produce nuclear weapon (NW)

△ Modify process to separate Pu, produce weapon at the facility

b) Abrogate (break-out) Safeguards Agreement → ○ Modify process to separate Pu, produce NW at the facility

2. Case to be attacked by terrorists

→ ○ Take out, separate Pu at clandestine facility, and produce NW

○ Modify process to separate Pu, produce NW at the facility

△ : unlikely
○ :likely

Measures

a) *Strengthened Safeguards*, *Universalization of Additional Protocol*; → Very little chance to succeed in proliferation under Integrated Safeguards

b) Make lengthy delay for production of NW with

1) *Very difficult process to separate Pu* even if modified after abrogation

2) *Low value-added Pu (material)*, low Pu fissile, Pu containing high Pu-238

Terrorists: Difficult to access/handle/process (PP), and *the same measures as b).*

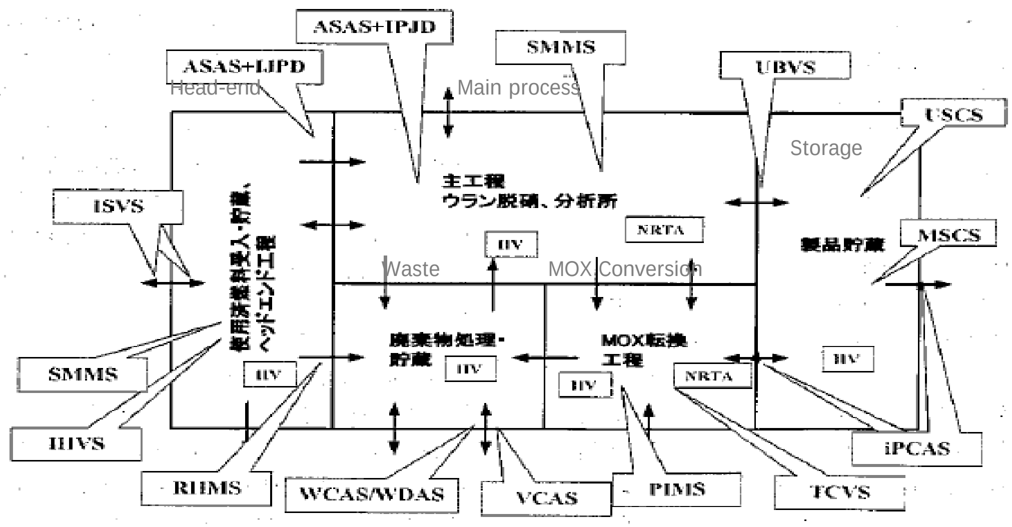
Proliferation Resistance – *Detection*: Based on Institutional Systems

High detection probability by Safeguards (SG) and other techniques:

- Design information
- Material accountability
- Containment/Surveillance (C/S)
- Detect-ability of material diversion and misuse
- Operational transparency
- Etc.

SG for Large Scale Reprocessing（SG Approach in RRP）

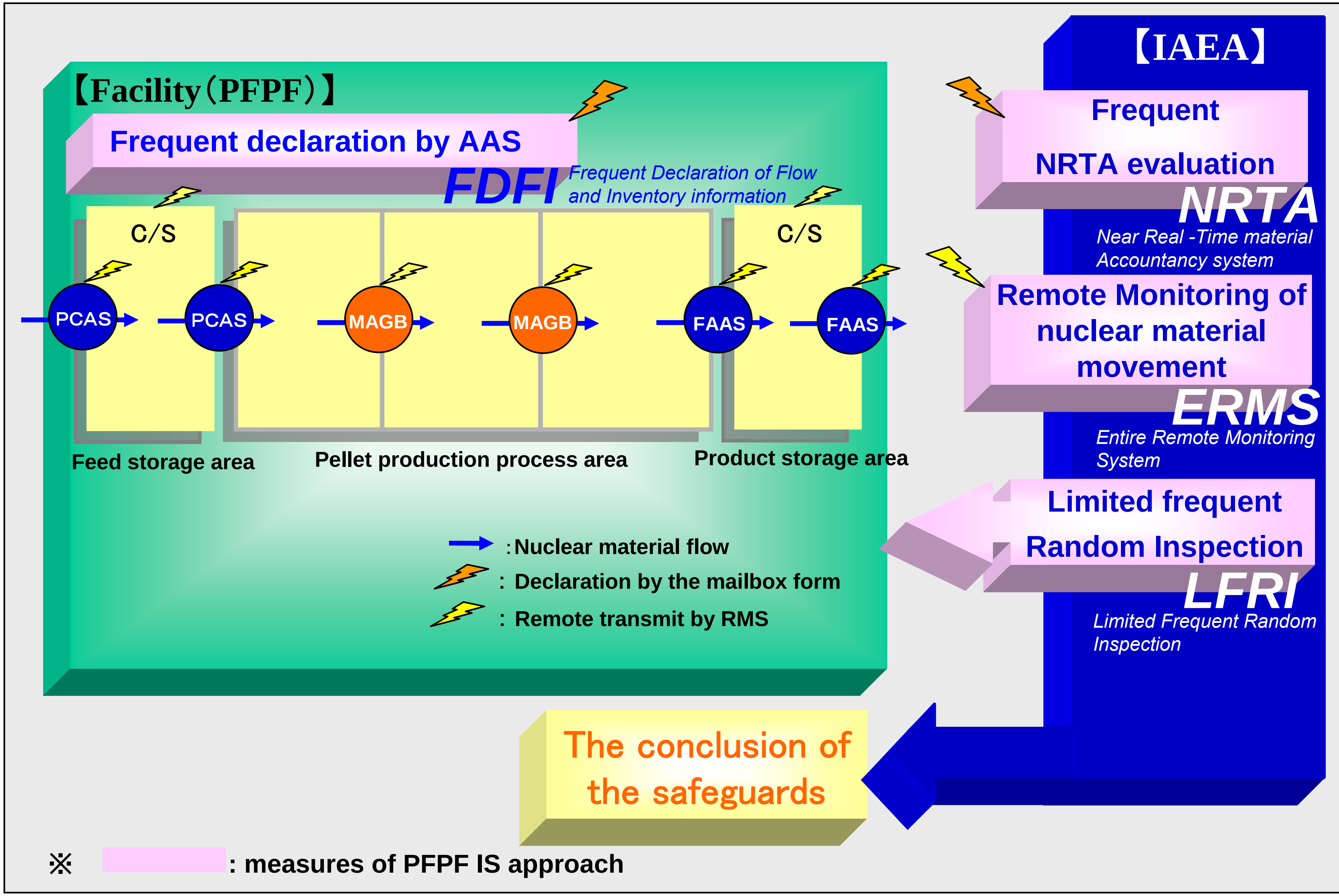
- DIQ/DIV
- Dual C/S（Surveillance Cameras, Radiation Detectors）
- Process Monitoring（Hull Monitoring, Solution Monitoring、PIMS etc）
- NRTA
- Unattended Mode Inspection, Centralized Collection of Inspection Data
- Various NDAs
- Advanced Accountancy System
- On-Site-Laboratory (Rapid Verification Measurement)



注)

ISVS：Integrated Spent fuel Verification System	SMMS：Solution Monitoring and Measurement System
IHVS：Integrated Head-end Verification System	RHMS：Rokkasho Hulls Drum Measurement System
ASAS：Automatic Sampling Authentication System	IJPD：Inspector Jug Passage Detector
WCAS：Waste Crate Assay System	WDAS：Waste Drum Assay System
VCAS：Vitrified Canister Assay System	PIMS：Plutonium Inventory Measurement System
TCVS：Temporary Canister Verification System	iPCAS：Improved Plutonium Canister Assay System
MSCS：MOX Storage C/S System	UBVS：Uranium Bottle Verification System
USCS：Uranium Storage C/S System	

IS Approach at Pu Fuel Production Facility



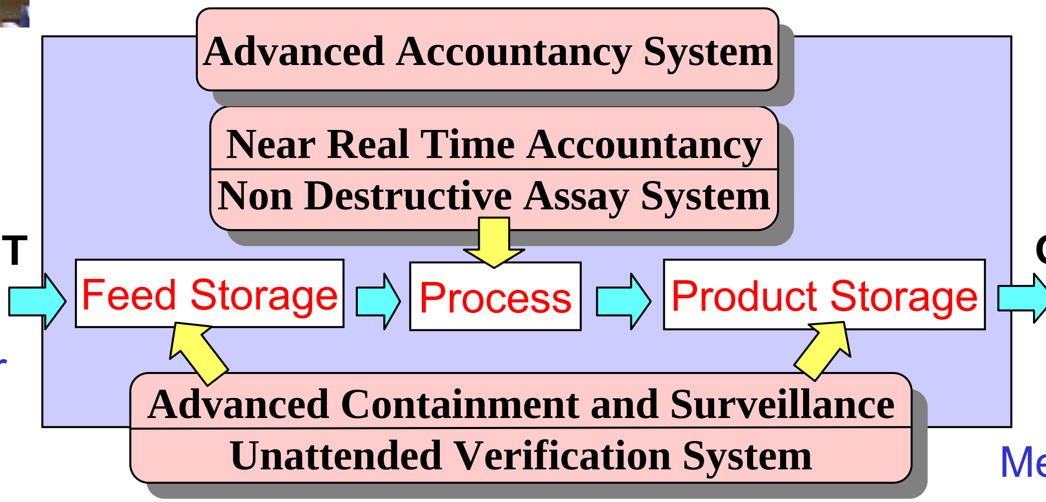
Unattended Verification System and Material Accountancy System at PFPF

AAS
(Advanced Accountancy System)

SBAS
(Hold-up Measurement System)

WDAS
(Waste Drum Measurement System)

INPUT



OUTPUT

PCAS
(Plutonium Canister Measurement System)

FAAS
(Fuel Assembly Measurement System)

AC/S

(Advanced Containment and Surveillance System)

Integrated Safeguards

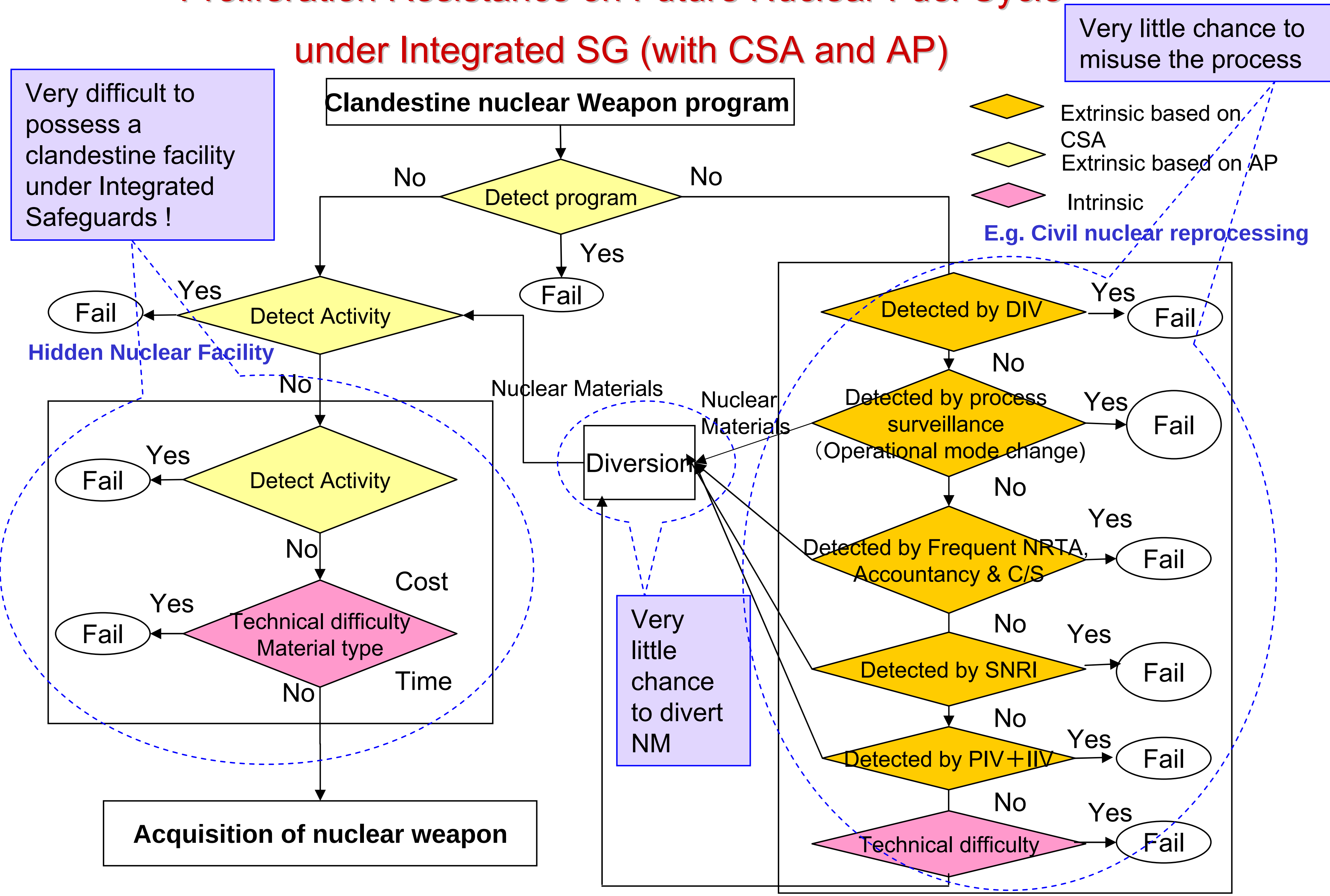
- For States with CSA and AP in force for which IAEA has drawn a broader safeguards conclusion (Neither diversion of nuclear materials nor undeclared nuclear materials/activities in State), the level of safeguards activities applied under those agreements can be optimized in light of the added safeguards assurances.

  This optimization is referred to as “Integrated Safeguards (IS)”. [Need to get the conclusion every year]
- IS started in Japan from Sept. 2004, as the first nuclear non-weapon state with full-scale nuclear fuel cycle. May 2005 to broaden the discussion of the IS approach to the Plutonium Fuel Production Facility (PFPF) to include other facilities in the JNC-1 site as an IS approach for the overall site.
- IS has been extended to JNC-1 site (Pu handling area) in August 2008. It was the first case in the world where IS approach is applied to the Pu handling facilities with bulk forms.

Image of Integrated Safeguards

Example

Proliferation Resistance on Future Nuclear Fuel Cycle under Integrated SG (with CSA and AP)



Objectives of Safeguards (I)

INF/CIRC. 153/Para 28

The objective of safeguards is the timely detection of the diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other explosive devices or for purposes unknown and deterrence of such diversion by the risk of early detection.

Objectives of Safeguards（II）

INF/CIRC. 540

Article 4… the Agency shall have access to any location … in order to assure the absence of undeclared nuclear material and activities

Article 6… the Agency may carry out … collection of environmental samples;

Significant Quantities (SQ)

	Nuclear Material	SQ
Direct-Use	Pu	8kg
	^{233}U	8kg
	HEU($\geq$20% 235)	25kg
Indirect Use	U (<20% 235)	75kg
	(10 t natural, 20t depleted)	
	Th	20t

Detection Method

Gross & Partial Defect: Nondestructive Assay (NDA)

Bias Defect: Destructive Analysis (DA):

Verify operator’s measurement system

- Detect protracted diversions
- Qualify operator’s accountancy measurements

Expected Accountancy Capability (E)

Minimum loss of nuclear material which can be expected to be detected by material accountancy (bias defect)

$$E = 3.29 \times A \times de$$

3.29	=	factor corresponding to a detection of 0.95 and a false alarm of 0.05
A	=	amount of material (larger of inventory or throughput).
de	=	accepted measurement accuracy, specified for a facility (as a relative standard deviation).

Example: 5t throughput reprocessing, 0.05% accuracy is required for minimum loss <8 kg Pu

Timely Detection

Goal Detection Time = Conversion Time

Time required to convert different forms of nuclear material to the metallic components of a nuclear device

	Conversion Time		Timeliness Goal
• Pu, HEU or ^{233}U metal	7 - 10 days		
• Pu, HEU or ^{233}U in pure compounds	1 - 3 weeks	→	1 month
MOx pure mixtures			
Pu, HEU ^{233}U scraps			
• Pu, HEU ^{233}U in spent fuel	1 - 3 months	→	3 months
• LEU with ^{233}U and Th	1 year	→	1 year

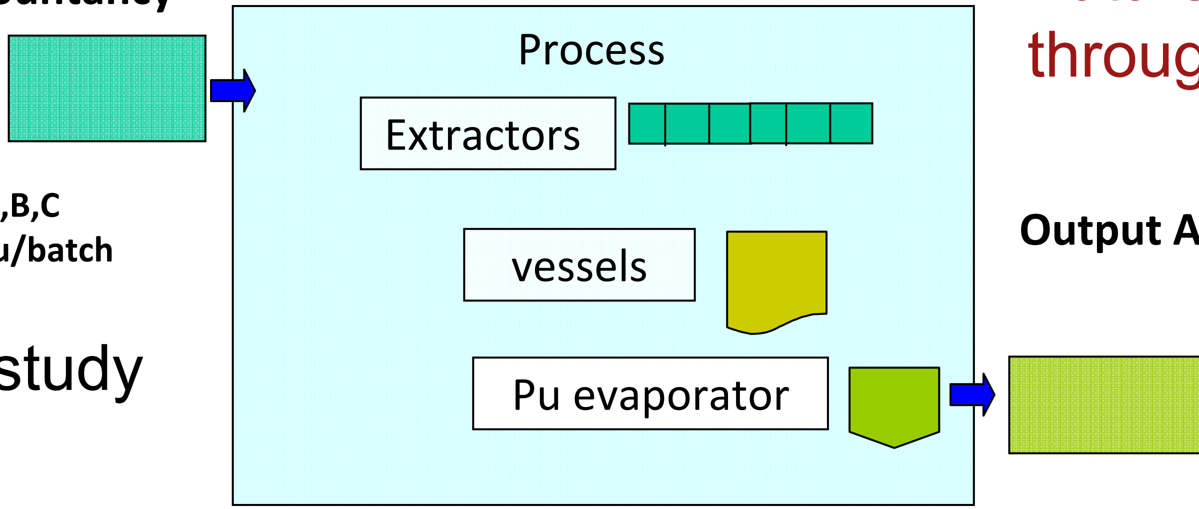
Reprocessing Throughput : 12,000 kgPu/year

Primary challenge for Future NFC is large throughput.

Input Accountancy

Case A,B,C
60kgPu/batch

Case study



Output Accountancy

Case A
200 kgPu/batch

Case B, C
15 kgPu/batch

	Flow		Total Inventory (Process+Accountancy)	Errors (Flow & Inventory)
	Input	Output		
Case A	**60 kgPu x 200 batches** (12,000 kg Pu/year)	**200 kg Pu x 60 batches**	**400 kg Pu**	**ITV2000 (for accountancy tanks)** + **Process control level measure**
Case B		**15 kg Pu x 800 batches (smaller Pu tank)**	**90 kg Pu (very small inventory)**	
Case C			**170 kg Pu**	Sampling & Measurement : **All: ITV 2000** Volume:0% (total Pu is directly obtained without volumer measurement , i.e. by IDMS-tracer techniques)

Assumption for calculation

To Estimate Inventory σ_{MUF} : process-control measurement level

Error for volume measurement : 1%

Error for sampling : 0.5%

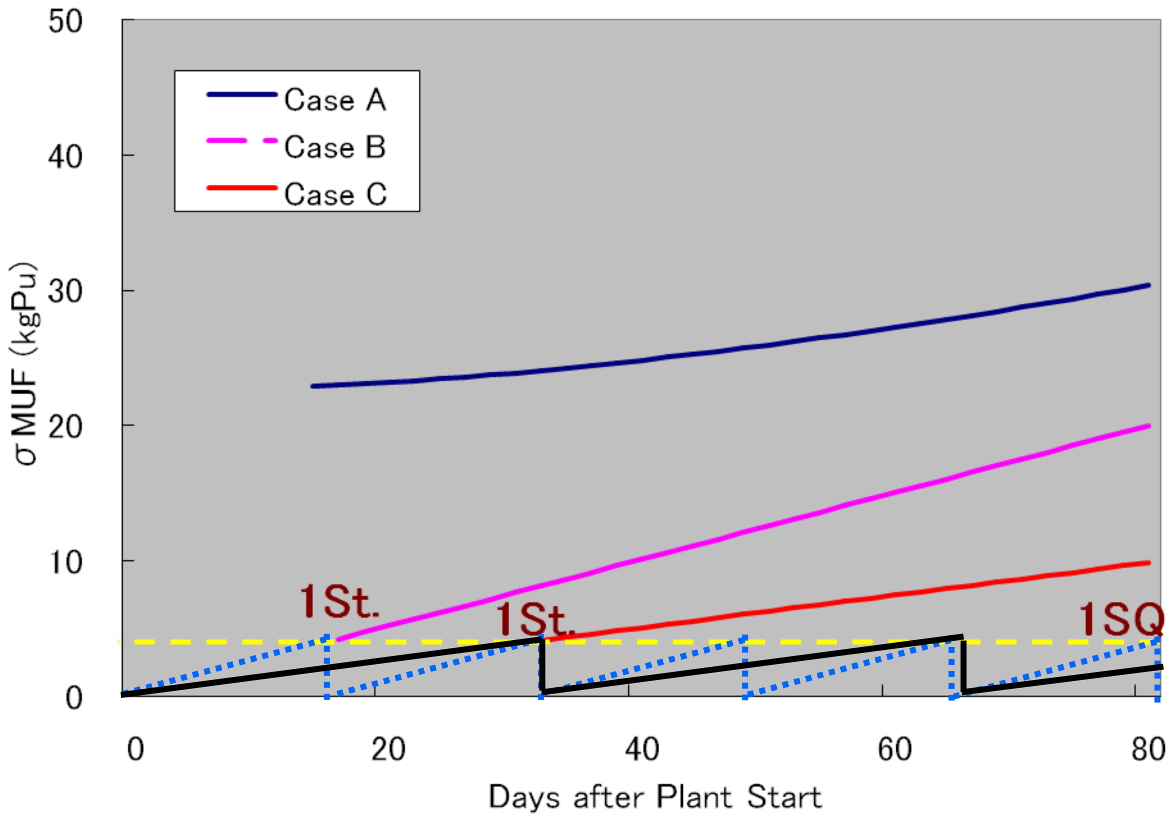
Error for conc. Measurement : 10%

To Estimate Flow σ_{MUF}*: ITV 2000*

ITV 2000	Input Pu		Output Pu	
	Random, Relative %	Systematic Relative %	Random, Relative %	Systematic Relative %
Volume	0.3	0.2	0.3	0.2
Sampling	0.3	0.2	0.2	nd
Pu-conc. (IDMS)	0.2	0.2	0.15	0.1

Improvement of σ'_{MUF}

Image of accountancy performance



Control of NM with σ'_{MUF}< 1SQ-Pu may be realized by monthly IIV.

Improvement of Safeguard-ability

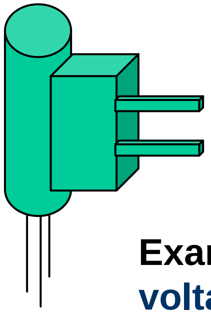
"Safeguards by Design" (Reprocessing example)

(1) Improvement of Nuclear Material Accountancy

- **Small process inventory**,
- **More accurate and timely accountancy**:
  - Interim Inventory Taking / Verification in practically possible frequency [e.g. quality of monthly IIV(IIT) ≒PIV(PIT)]
  - Determine total amount of NM by IDMS (Isotopic Dilution Mass Spectrometry) without measuring solution volume
- Accountancy-friendly operational mode (e.g. computerized)

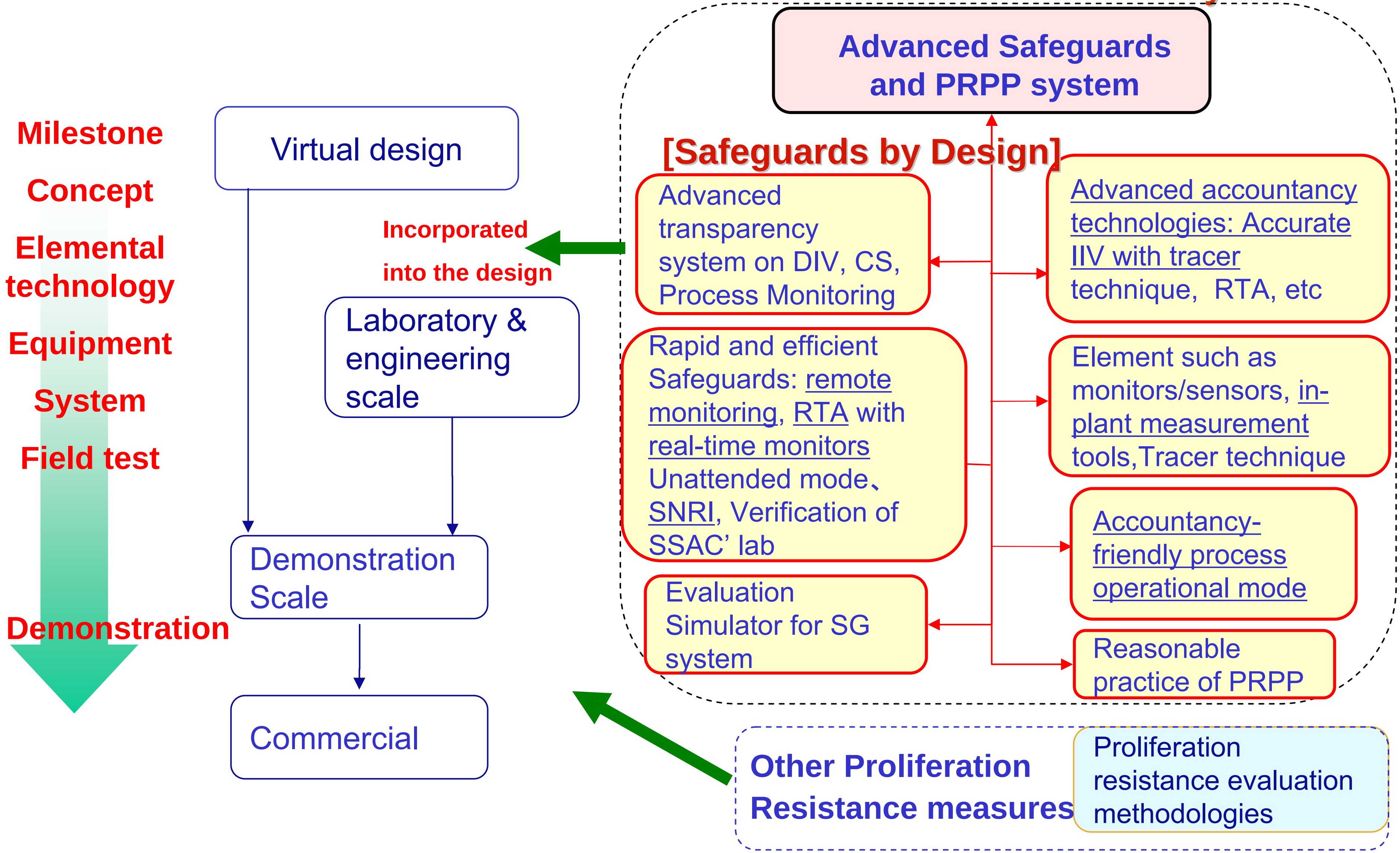
(2) Improvement of Detectability

- **NRTA→RTA**
- **Real time process monitoring (+concentration)** with remote monitoring - C/S, NDA etc for RTA, for detection of process condition change etc
- **More sophisticated monitors/sensors for Pu/U/(H^+)** concentration / isotopics, volume etc.



Example of U･Pu Real-Time Monitor
voltanmetry + density measurement

An Idea towards Future SG/PR for Advanced Fuel Cycle



Institutional barriers with high detect-ability should be principle measures for PR evaluation, complemented by other technical barriers

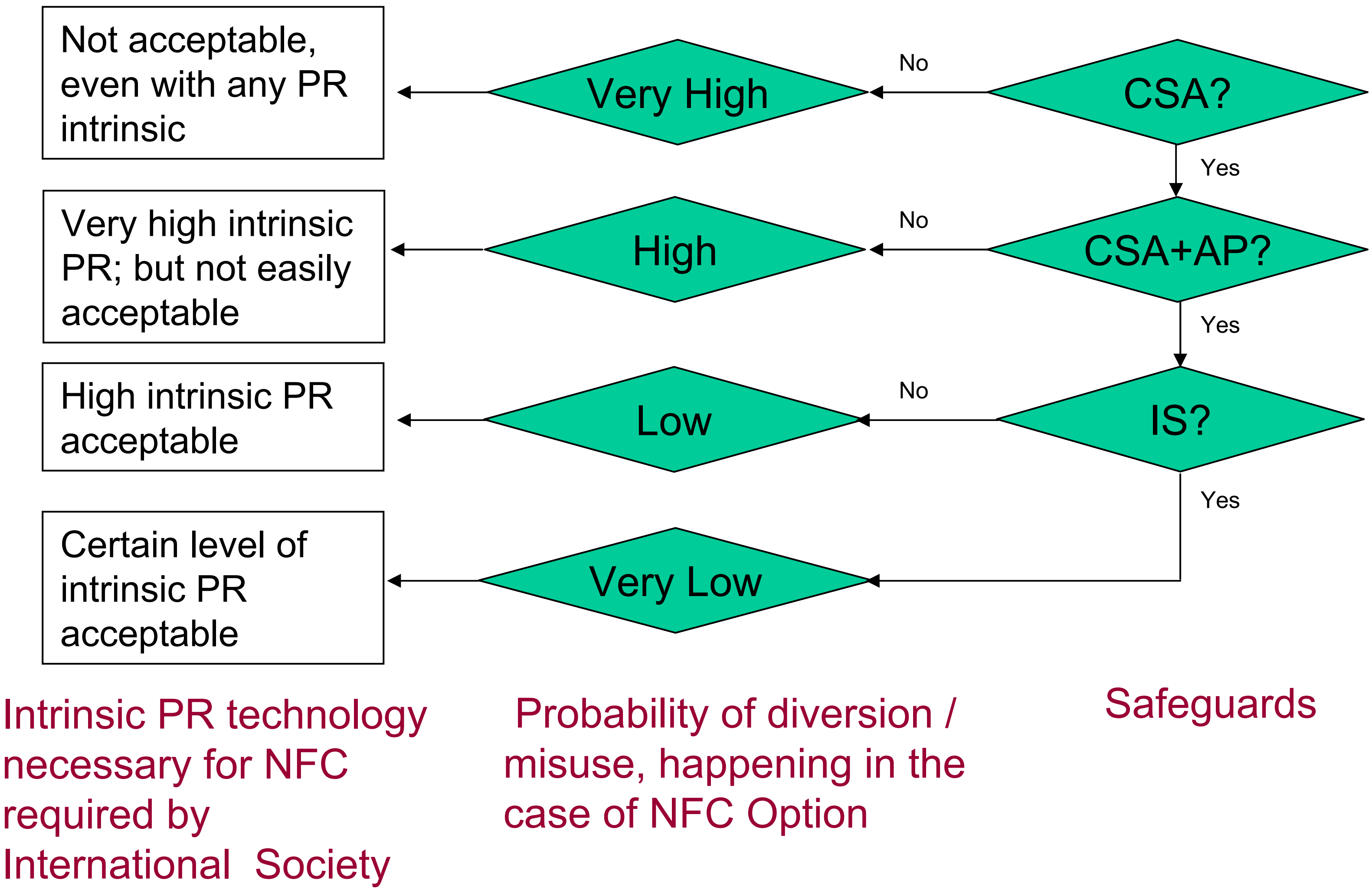
When Intrinsic measures work if a complete package of Safeguards is implemented?

Simply put, "in the case of break-through of institutional system (abrogation)"

What probability should be considered for such an abrogation for State that is in Integrated Safeguards?

How long is sufficient for the "lengthy delay"? Worthy to invest such intrinsic measures?

Safeguards and Intrinsic PR Technologies



Thank you for your attention