2014 International Pyroprocessing Research Conference
(IPRC)

A Preliminary Analysis of Hazard Events in Accident Scenarios for a KAERI's Reference Pyroprocess Facility

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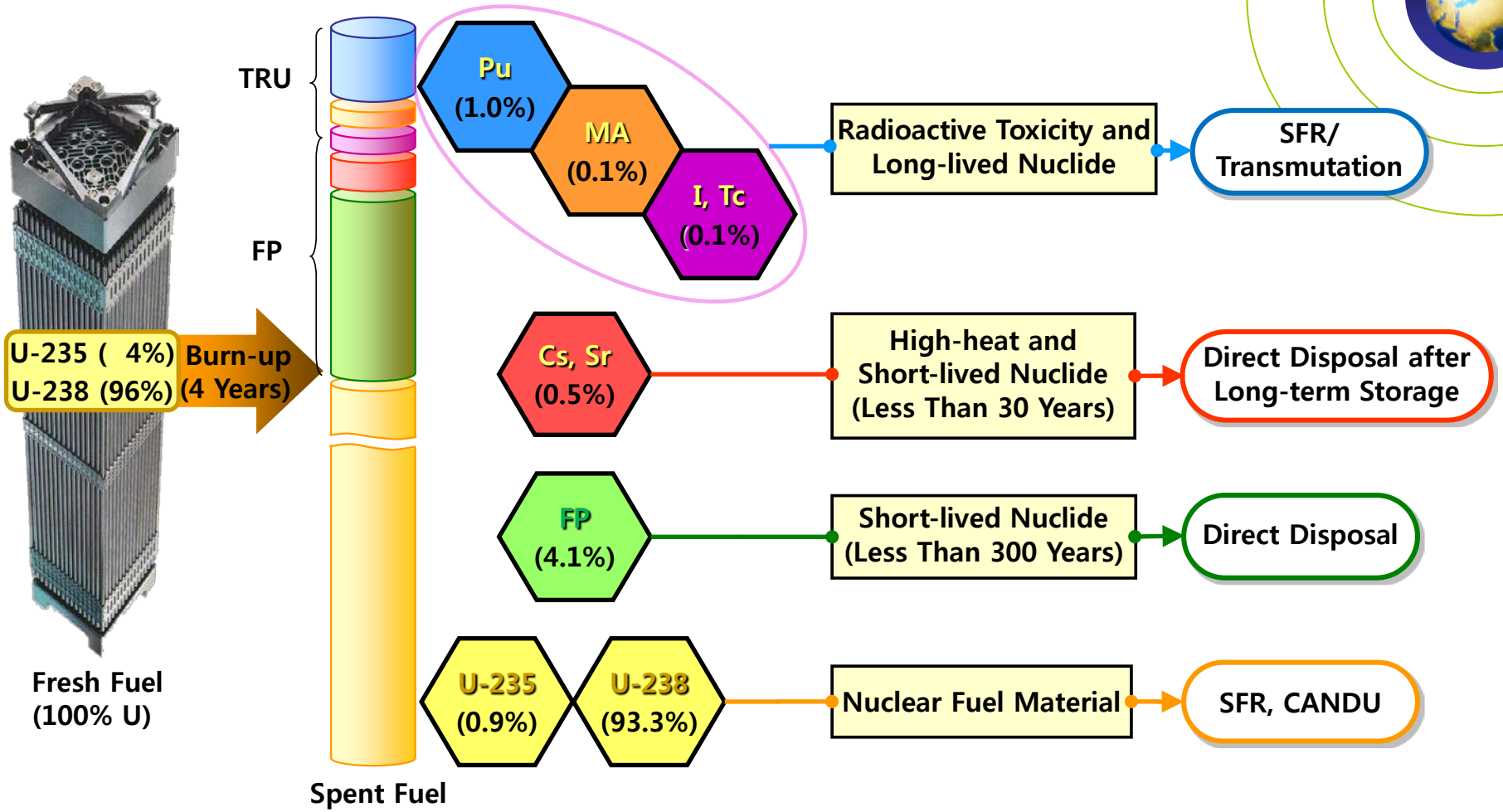
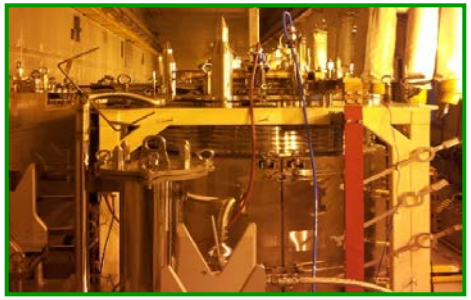
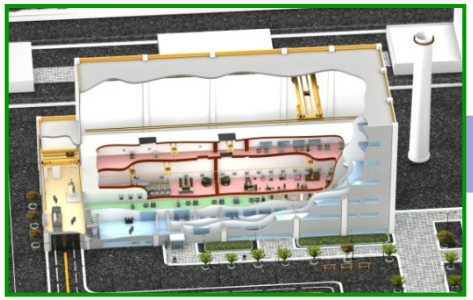
Strategy for effective management of spent fuel



→ Development of Nonproliferative and Environmentally-friendly Recycling Technology

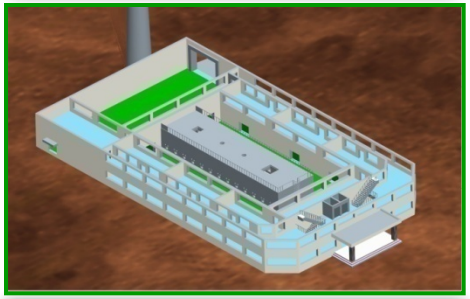
TRU : Trans Uranics
MA : Minor Actinides (Np, Am, Cm)
FP : Fission Products

Long-term plan for pyroprocess technology development

Lab Scale Exp. (1997 ~ 2012)	Engineering Scale (2012 ~ 2016)	Engineering Scale (2016 ~ 2020)
		
Lab-scale Demonstration	PRIDE Operation	PRIDE Improvement
PRIDE (Inactive with Eng. Scale)	Integrated Process Demonstration	Integrated Process Improvement and Demonstration
ACPF/DFDF (Active)	Electro-reduction Demonstration	Electro-reduction Improvement and Demonstration
JFCS (Active)	Integrated Process Demonstration	Process operation Fuel irradiation test

Review of Technology, Economics, Proliferation

Future Activity (2020 ~)



Pyroprocessing Facility

PRIDE: PyRoprocess Integrated inactive Demonstration facility, ACPF: Advanced fuel Conditioning Process Facility
DFDF: DUPIC Fuel Development Facility, JFCS: Joint Fuel Cycle Study

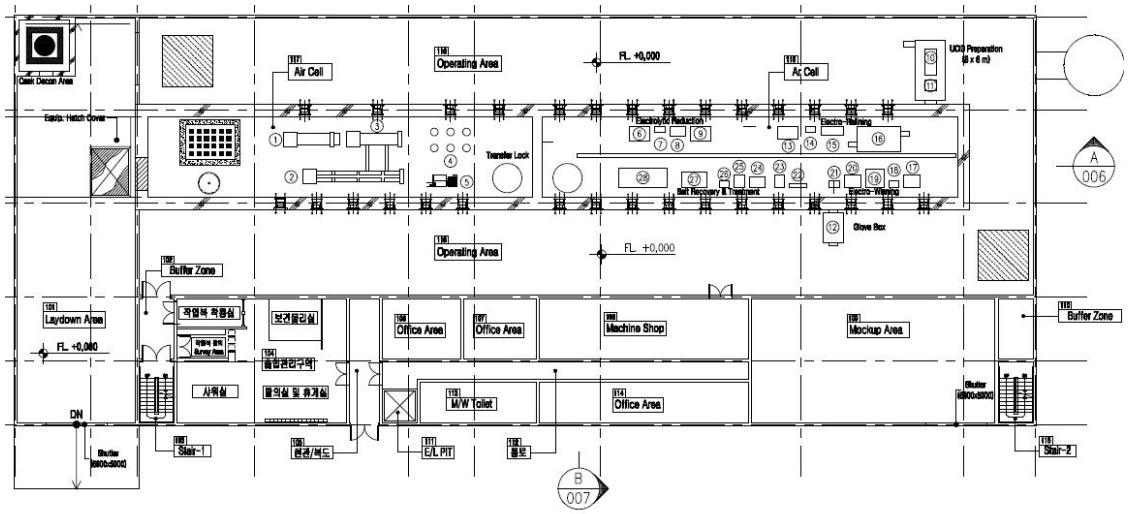
Preliminary conceptual design of REPF

- **Reference Engineering-scale Pyroprocess Facility (REPF)**
  - Imaginary test facility to demonstrate integrated engineering-scale pyroprocess
- **Preliminary conceptual design of REPF**
  - To study and demonstrate the pyroprocess technologies related to the process control and integration, safety, safeguards and security, scale-up, etc.

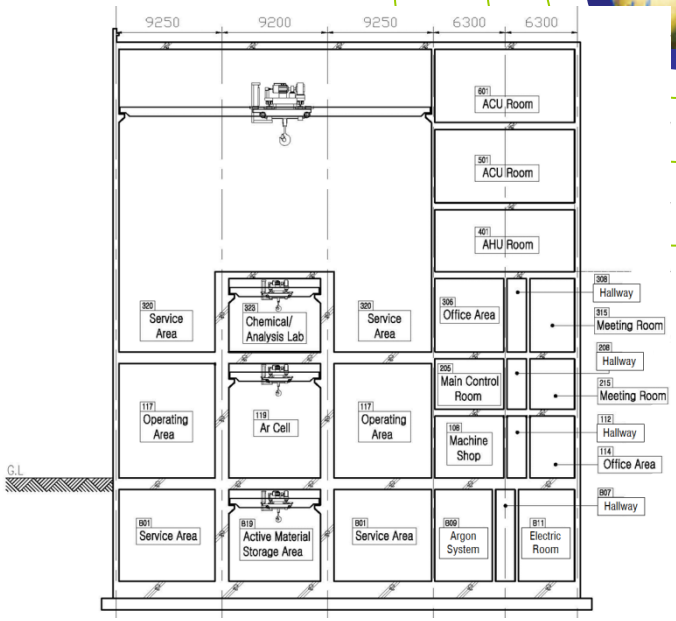
Item	Requirements
Capacity	· 10tHM/year
Reference spent fuel	· 16X16 PWR Type, 4.5wt.% U-235 · 55,000MWD/MTU, 10 Years Cooling
Availability	· 70% (in Consideration of O&M Outage) · 200 Equivalent Full Operating Calendar Days
Design life	· 40 Years (Building and Cell Structure) · 20 Years (Equipment)
Input	· PWR Spent Fuels
Output	· U Metal Ingot as LLW, U-TRU-RE Metal Ingot for SFR Fuel · Wastes (Ceramic, Metal, Vitrified)
Main function	· Temporary Material Storages (PWR Spent Fuel, Metal Ingot, Waste) · PWR Spent Fuel Disassembling, Rod Chopping · Decladding, Voloxidation, Electrolytic Reduction, Electro-Refining, Electrowinning, CD Distillation, Cathode Processing · U and TRU Metal Ingot Fabrication · Salt Waste Recycling, Waste Treatment, Off-gas Treatment

Top-tier Requirements of REPF

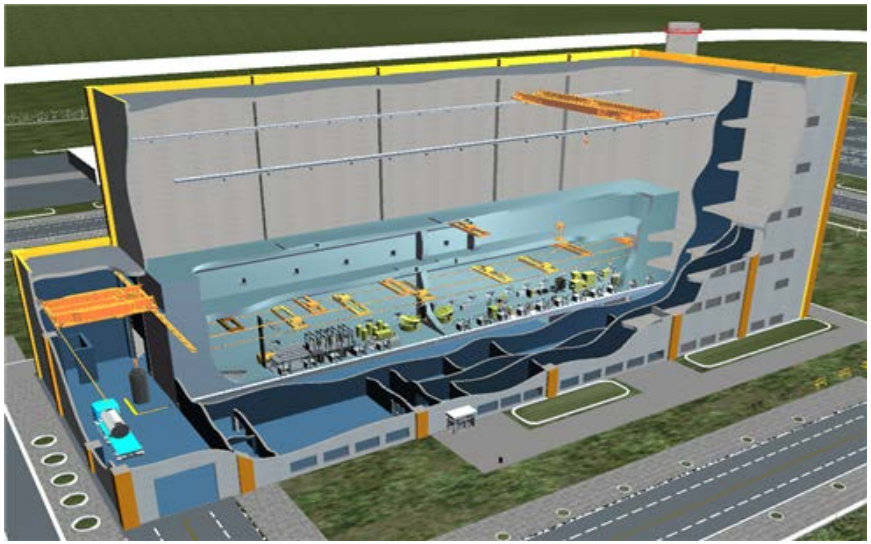
Preliminary conceptual design of REPF



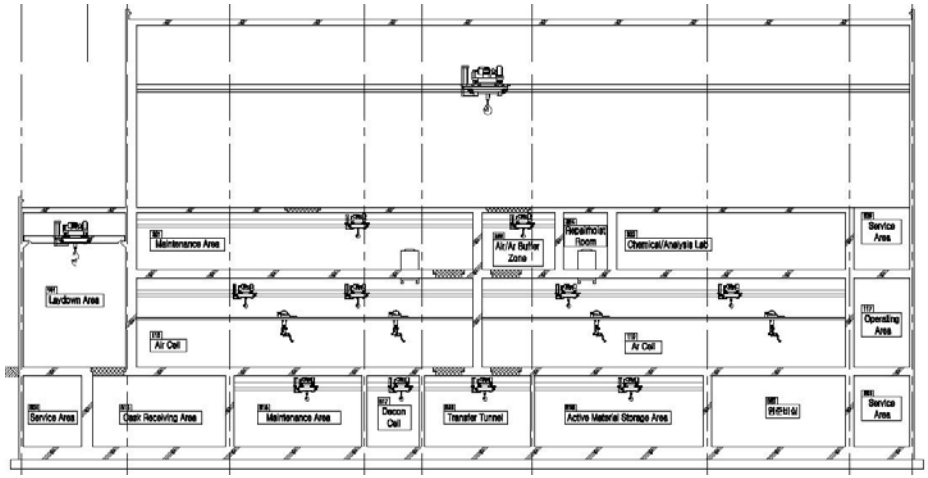
Layout of the 1st Floor



Side Section View



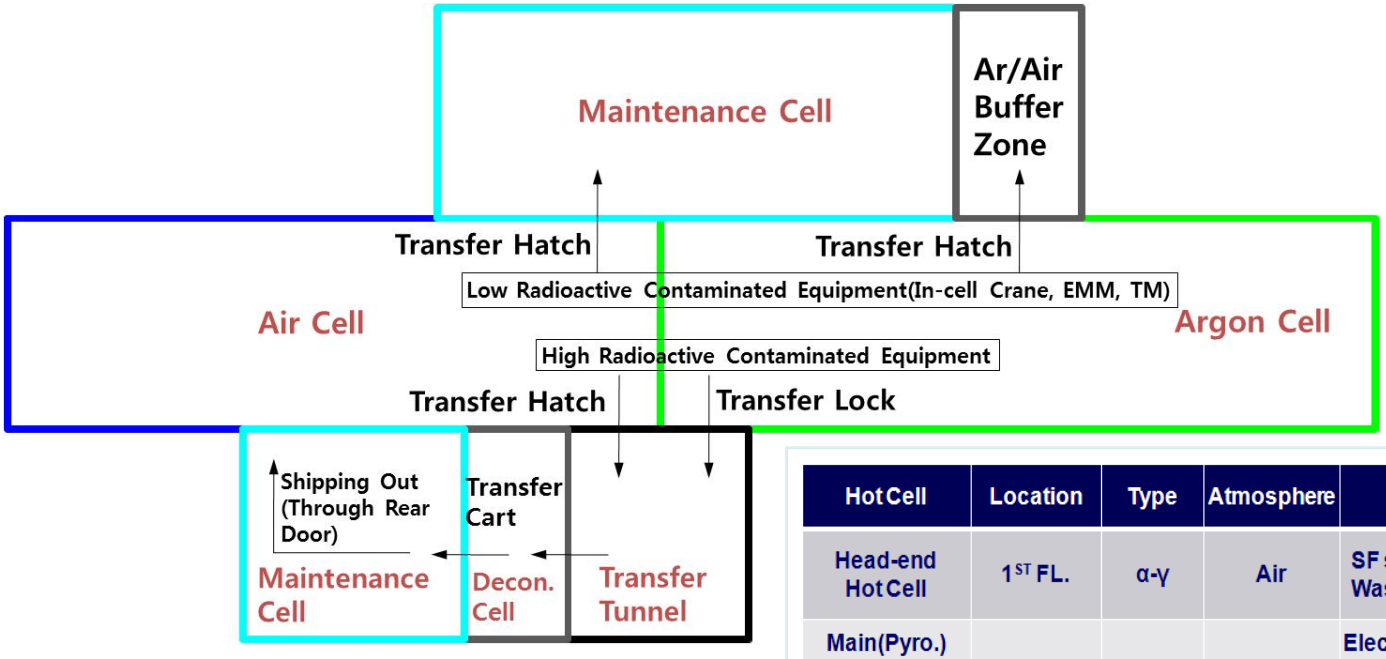
Bird's-eye View of REPF



Front Section View

Preliminary conceptual design of REPF

- Concept of Hot Cell Line and Maintenance



Hot Cell	Location	Type	Atmosphere	Main Function
Head-end Hot Cell	1ST FL.	α-γ	Air	SF storage vault, Head-end Process, Off-gas Treatment, Waste Hull Treatment
Main(Pyro.) Process Hot Cell	1ST FL.	α-γ	Argon	Electrolytic Reduction, Electro-Refining, Electro-Winning, Salt Recovery & Waste Solidification, U ingot Fabrication, Products and Waste Handling
Maintenance Hot Cell	3rd FL.	α-γ	Air	Maintenance of Process equipments & Hot Cell equipments
Maintenance Hot Cell	Under. FL.	α-γ	Air	Maintenance of Process equipments & Hot Cell equipments
Buffer Zone Hot Cell	3rd FL.	α-γ	Air Argon	Buffer Zone for changing of Process equipments in Ar atmosphere Hot Cell
Storage Hot Cell	Under. FL.	β-γ	Air	Storage Area of Products and Wastes
Decon. Hot Cell	Under. FL.	β-γ	Air	Decontamination of Process equipments & Hot Cell equipments
Chem. Analy. Hot Cell	3rd FL.	α-γ	Argon	Chemical analysis of Process Sample (Pneumatic transfer)

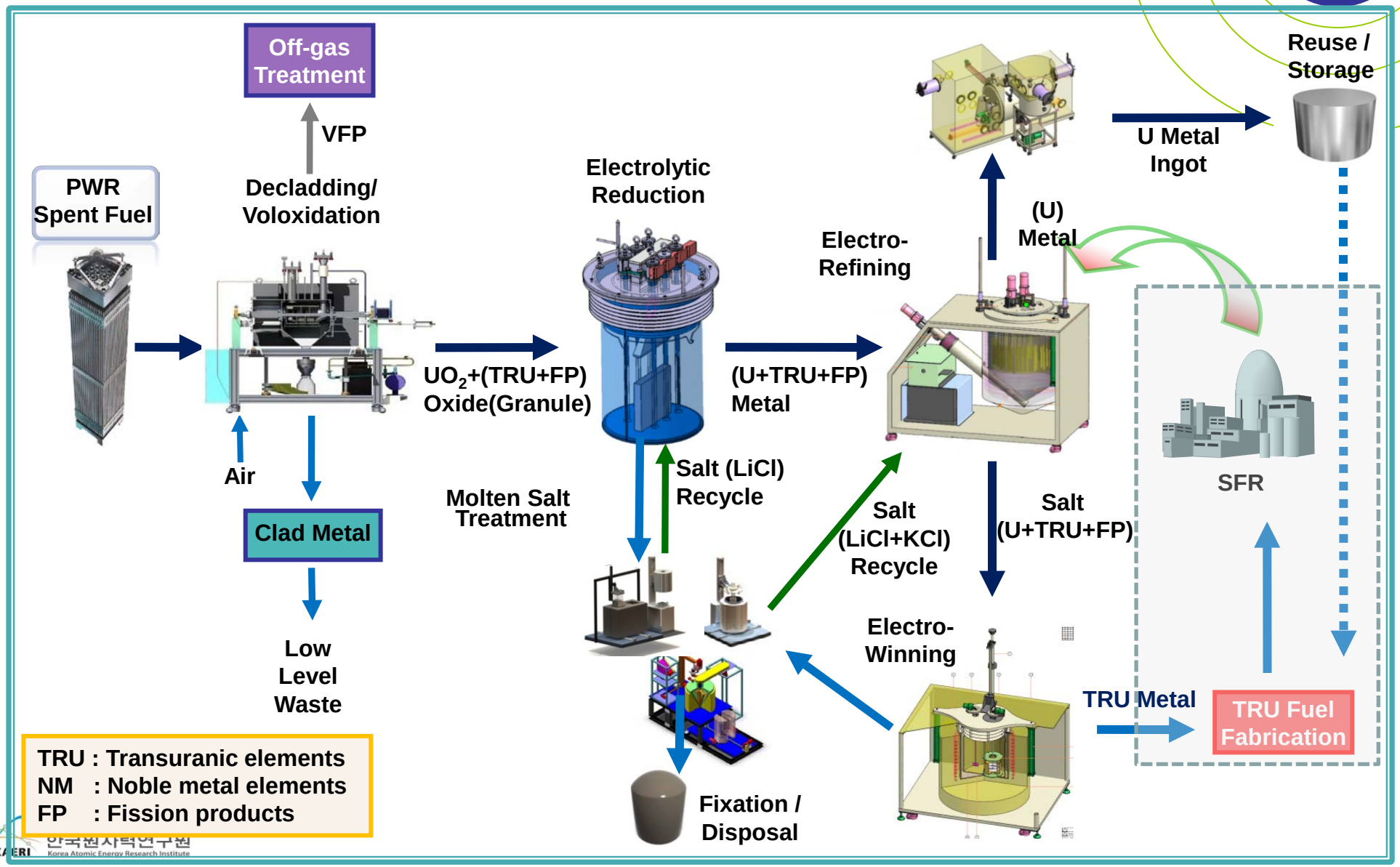
Preliminary conceptual design of REPF

- Major equipment and devices

Main Facility	Description
Hot cell	- Process hot cell: α-γ type/argon atmosphere/air atmosphere - Maintenance hot cell: α-γ type/air atmosphere - Decontamination hot cell: α-γ type/air atmosphere
Remote handling device	- Sealed type master slave manipulator - Power manipulator(EMM) or telescopic manipulator - In-cell crane and crane trolley hoist
Shielded window	- Lead glass with assembled alpha frame(double seal)
Transfer lock system	- Large scale and small scale transfer lock with argon purging system
Feed-through	- Hot cell penetration for piping and cable connection (assembly plug type for each process & facility equipment)
Argon system	- Argon system: argon supply/purification/cooling & circulation/relief system
Utility supply system	- Electric power(w/ emergency power), cooling water, demineralized water, compressed air(PA, IA), argon gas
SF unloading & Storage	- Truck bay, cask handling device, SF storage vault
Radiation monitoring system	- Area monitor, air monitor, duct monitor, stack monitor, γ prove, criticality alarm system, CCTV, server and software, etc.

Preliminary conceptual design of REPF

- Basic processes and material flow

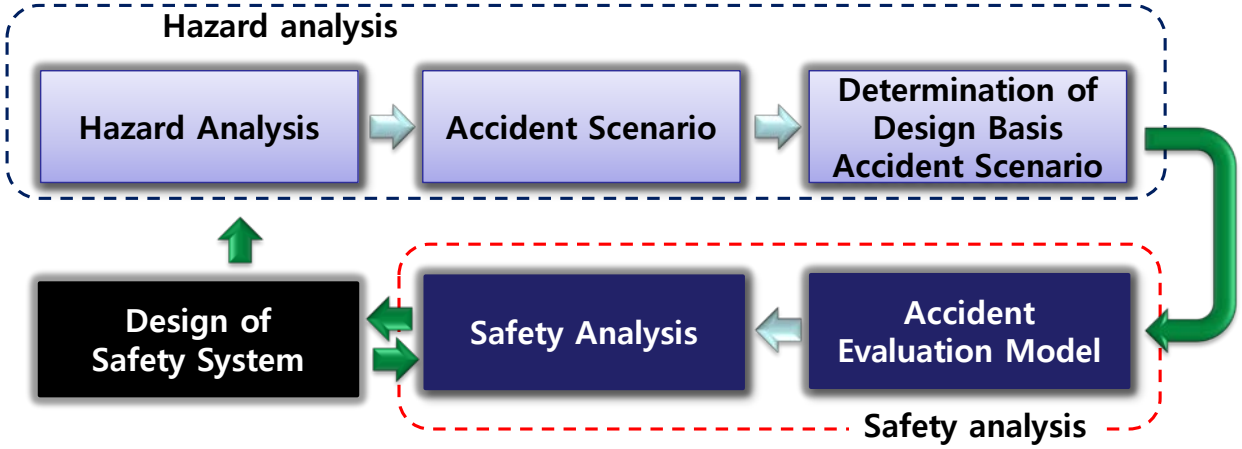


Hazard and accident analyses

- **Objectives**
  - ❖ To identify safety SSCs, ACs, or TSRs needed for protection of facility workers, collocated workers, and the off-site public and environment (supporting activities)
    - Identify hazard
    - Identify potential accident scenarios
    - Assess the frequency and unmitigated consequences
    - Identify the potential preventive and mitigative controls
    - Identify a limited set of unique and representative accidents

SSCs: Structure, system, and components
ACs: Administrative controls
TSRs: Technical Safety Requirements

- **Role**
  - ❖ To develop a complete set of potential accident scenarios
    - basic analysis approach: postulate accident events, identification of cause, consequences, and preventive and mitigative features and programs that provide a safety function



<Hazard Evaluation Model>

DOE-STD-3009: Preparation Guide for US DOE Nonreactor Nuclear Facility **Documented Safety Analyses (DSA)**

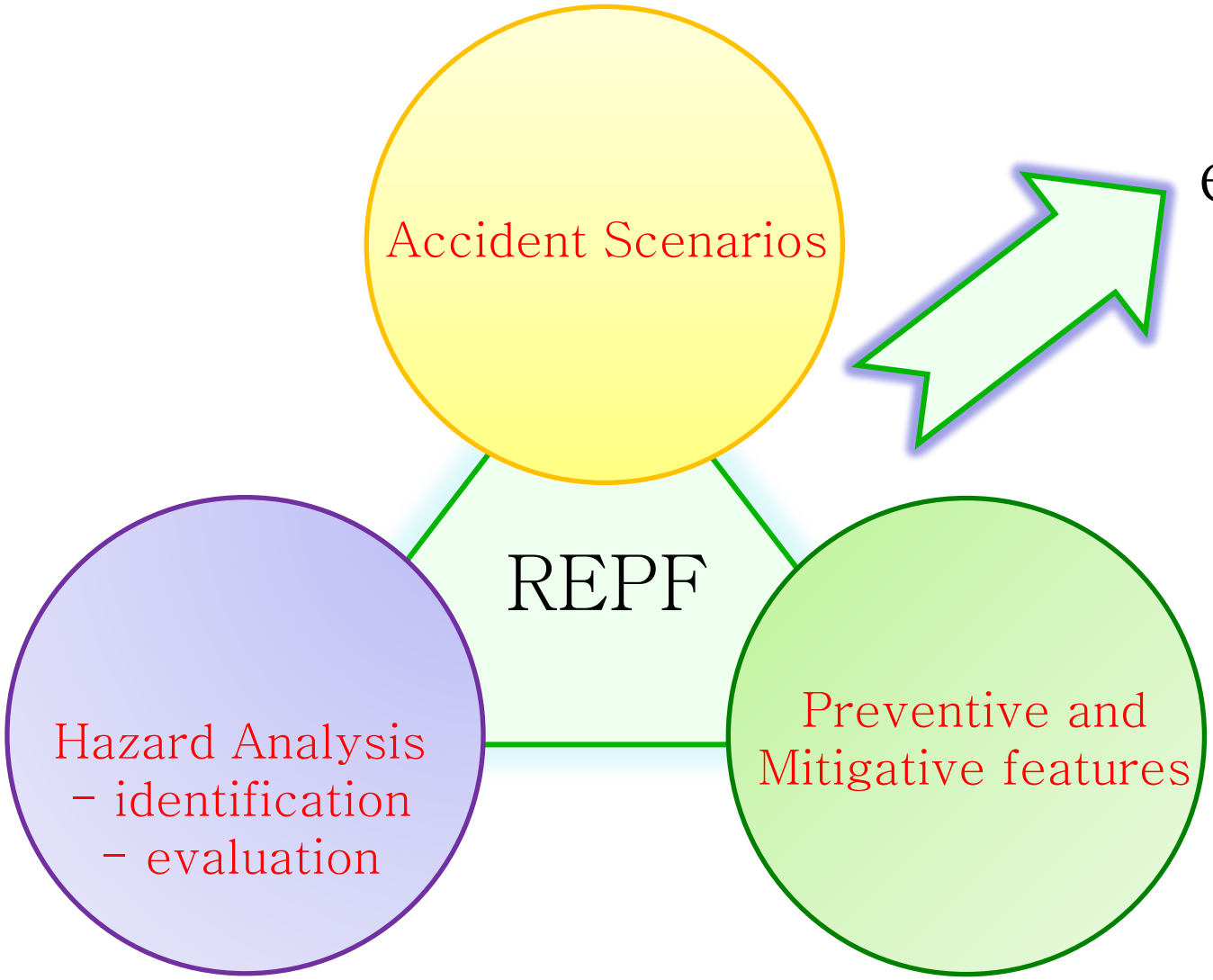
Hazard and accident analyses

- **Facility hazard categorization**
  - ❖ Hazard category 1: Significant off-site consequences
    (Reactor facilities having a steady-state power level greater than 20MWt)
  - ❖ **Hazard category 2**: Significant on-site consequences (FCF, REPF)
  - ❖ Hazard category 3: Significant localized consequences
  - ※ DOE-STD-1027, Hazard Categorization and Accident Analysis Techniques

- **Scope of hazard and accident analyses**
  1. **Consider the complete spectrum of accidents** that may occur
  2. **Analyze potential accident consequences** to facility workers, collocated workers, the off-site public, and the environment
  3. **Estimates likelihood** of occurrence
  4. **Identify associated preventive and mitigative** safeguards or controls
  5. **Identify a subset of accidents** that are designated evaluation basis accidents (EBAs)

  → **Evaluation covers**
  (1) all major process equipment
  (2) operation and activities + potential equipment failures, human errors, and process problems

Objective



Safety
enhancement

Hazard identification

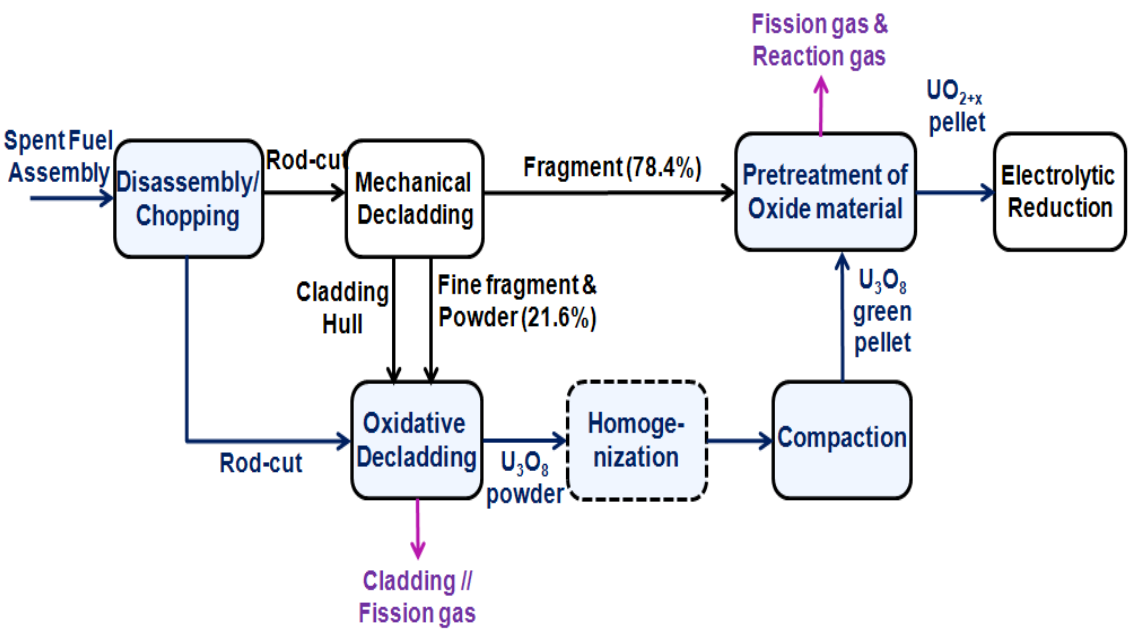
- Hazard: “a source of danger”
  - potential to cause illness, injury, or death
  - damage to an operation or to the environment

✓ The radioactive and hazardous materials
✓ Potential energy sources and potential initiating events

Hazard	Hazard Source	Concern
Fissionable Materials	Fissionable materials in **SF storage vault, process vessels and active material storage area**	Potential for a nuclear criticality
Radioactive Materials	Radioactive materials in **SF storage vault, process vessels and active material storage area**	Potential radioactive material release and/or direct radiation exposure hazard to the facility workers, the collocated workers, the off-site public and/or the environment
Hazardous Materials (e.g., toxic chemicals)	Hazardous materials in process vessels (e.g., **liquid cadmium, chlorine**)	Potential hazardous material release and subsequent chemical exposure hazard to the facility workers, the collocated workers, the off-site public and/or the environment
Fire, Explosion	Pyrophoric metals (e.g., **uranium**); combustible materials and/or waste	Potential fire or explosion and subsequent loss of containment resulting in a material release, leading to a radiological or chemical exposure hazard to the facility workers, the collocated workers, the off-site public, and/or the environment
Electrical Energy	Electrical panels, electrical utilities, instrumentation and controls	
Kinetic Energy	Moving loads: cask transfer cart or truck, hydraulic ram, cask, rotating equipment (e.g., crane, fans)	Potential to cause a loss of containment, resulting a material release, leading to a radiological or chemical exposure hazard to the facility workers, the collocated workers, the off-site public, and/or the environment
Potential Energy	Suspended loads: crane, hoist, lift, electromechanical manipulators (EMMs)	
Pressure	Compressed gas	
External Events	Fire, aircraft crash	
Natural Phenomena	Earthquake, extreme wind, flood, lightning	
Potential Asphyxiants	**Argon gas**	Simple asphyxiants do not pose a chemical toxicity hazard but may cause injury to facility workers due to oxygen displacement in confined spaces.
Thermal Energy	Steam, process equipment, lights	No direct hazard but may cause injury to facility worker

Hazard identification

Pretreatment process



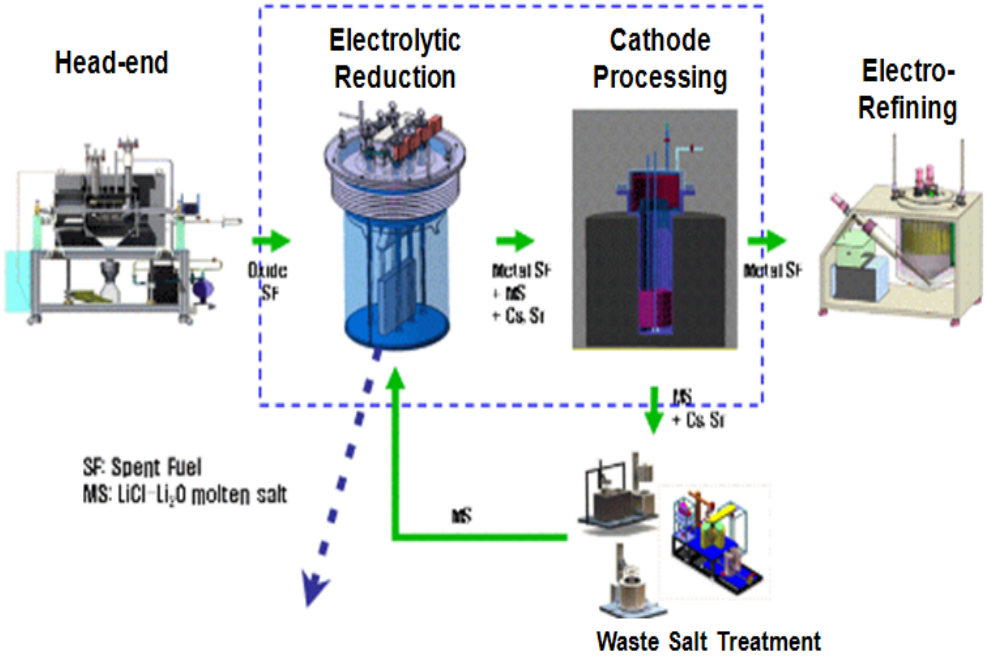
$$*UO_{8/3}(U_3O_8) \xrightarrow{Ar(0.001\%H_2O)} UO_{2.1} + 1.7/6\ O_{2(g)} \xrightarrow{4\%H_2-Ar} UO_{2.0} + 0.1H_2O_{(g)}$$

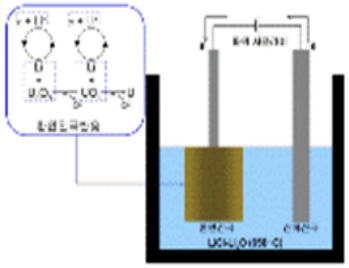
- ❖ Fragment(size : 0.5~5 mm) : 78.4%
- ❖ Fuel material adhered to cladding hull + Fine fragment & powder : 21.6%

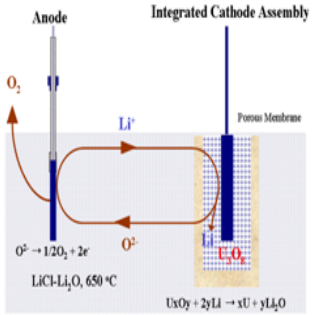
Process	Hazardous event
Disassembling & Chopping (Air hot cell)	**- Drop of SF assembly** **- Leakage of gap scrap**
Oxidative decladding (500 °C air)	- Leakage of SF powder - **Failure of temperature control** - **Leakage of cooling water**
Homogenization (Air hot cell)	- **Spill out of SF powder**
Pretreatment of metal oxide (1200 °C air /4% H_2)	- Leakage of SF powder - Failure of temperature control - Leakage of cooling water - **Overpressure of systems**

Hazard identification

Electrolytic reduction process





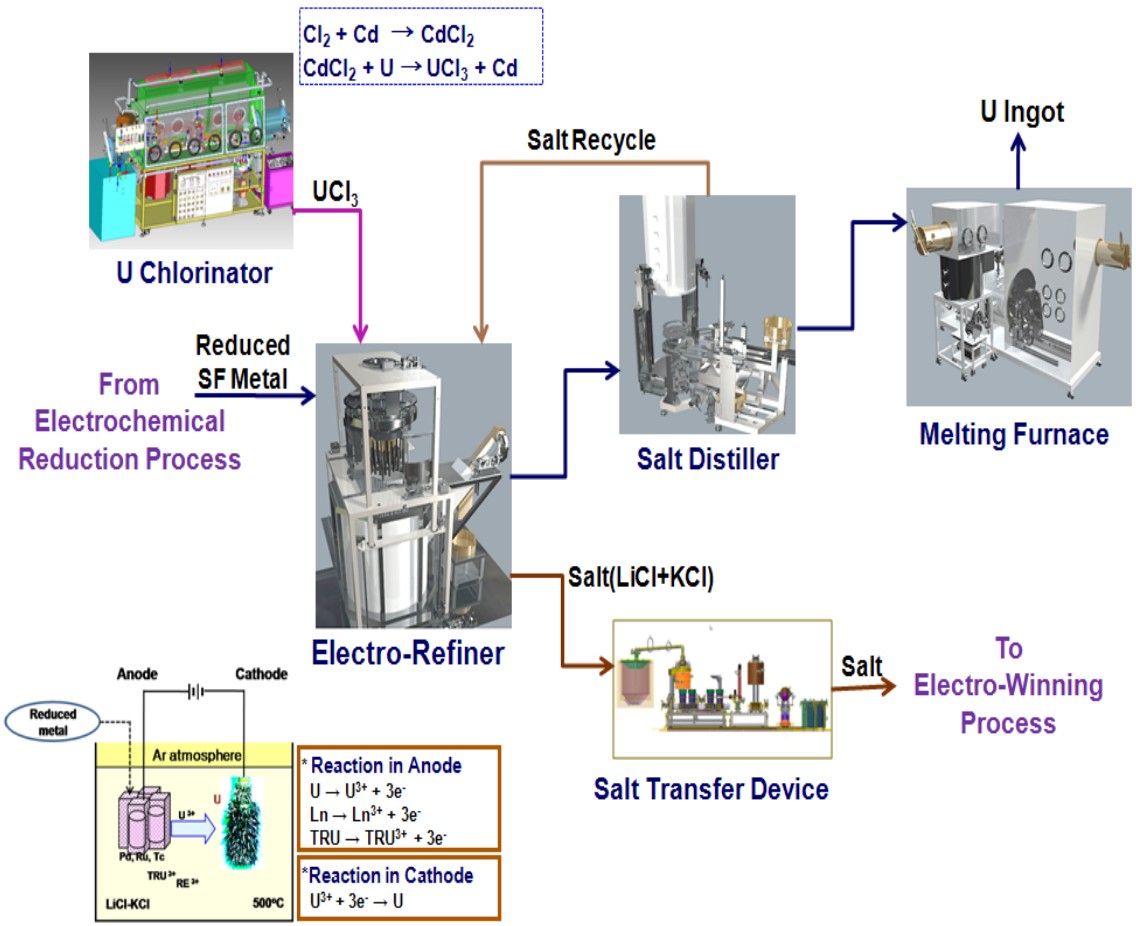


* Oxide Material convert to Metal in LiCl+Li_2O Salt
* Removal of Cs, Sr (Heat Generation Nuclides) – Residue in Salt Phase

Process	Hazardous event
Electrolytic reduction (LiCl-Li2O, 650 °C, Ar hot cell)	- Failure of temperature control - Leakage of cooling water - Overpressure of systems (release of molten salt & vapor) - **Leakage of O_2**
Cathode process (700 °C, vacuum)	- Drop of materials - Failure of temperature control - **Failure of vacuum pump** - Overpressure of systems - **Rupture of off-gas piping**

Hazard identification

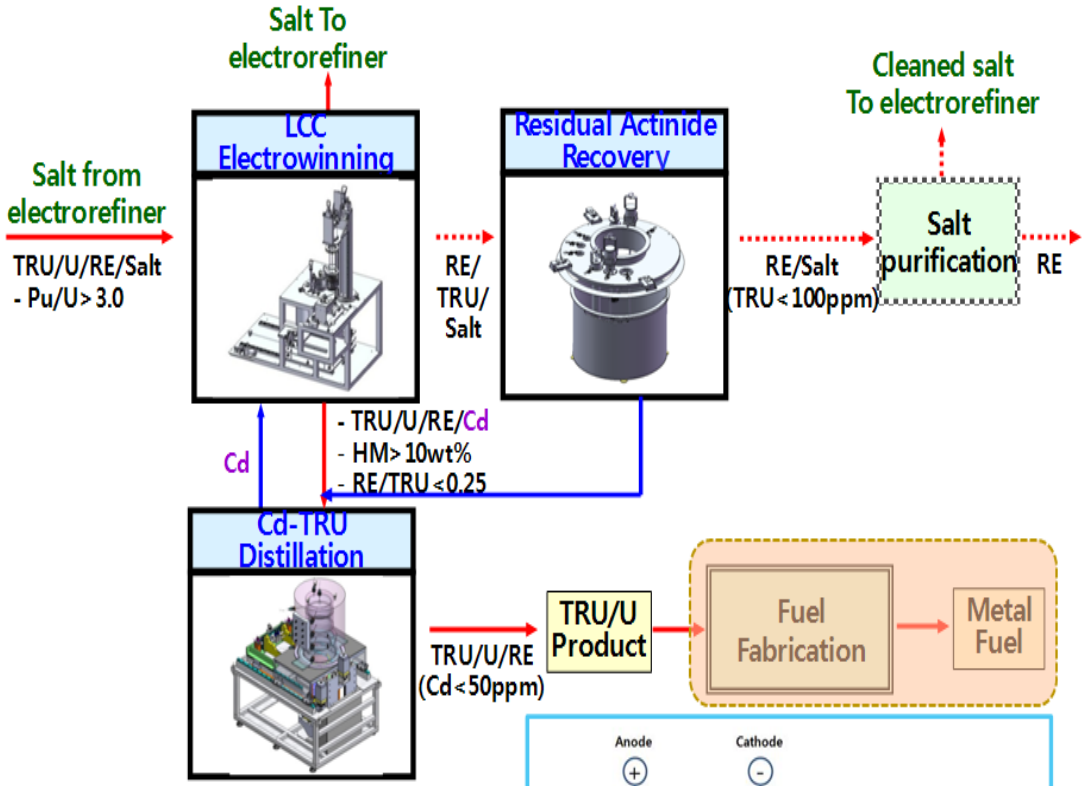
Electro-refining process

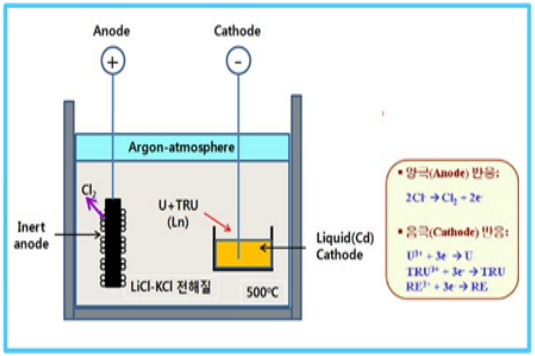


Process	Hazardous event
Electro-refining (LiCl-KCl, 500 °C, Ar hot cell)	- Drop of materials - Failure of temperature control - Overpressure of systems (release of molten salt & vapor) - **Leakage of U deposits**
Salt distillation (700 °C, vacuum)	- Drop of materials - Inert failure & fire (O_2 exposure) - Leakage of salt vapor - Failure of temperature control - **Failure of vacuum pump** - **Overpressure of systems**
Ingot casting (1300 °C, vacuum)	- Drop of materials - Failure of vacuum pump - Failure of temperature control - **Overpressure of systems** - Leakage of salt vapor - **Inert failure & fire** (O_2 exposure)
U chlorination ($LiCl+KCl+UCl_3$ Cl_2 gas 600 °C, Ar)	- **Leakage of Cd and Cl_2** - Failure of temperature control - Overpressure of systems - **Failure of Cl_2 scrubbing**

Hazard identification

Electro-winning process





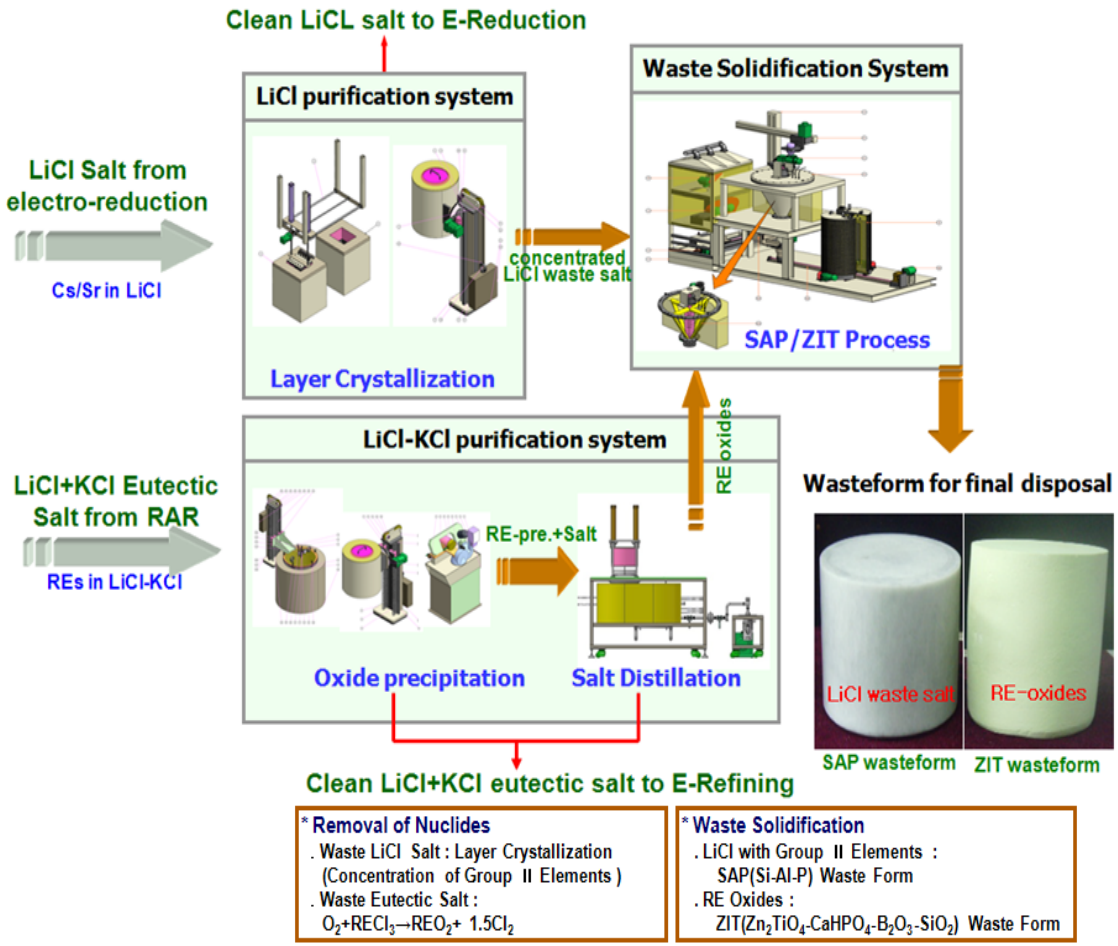
* Separation of Residual TRU/U
(after Electro-Refiner 20 batch operation)

$TRUCl_3$ or $UCl_3 \rightarrow$ U or TRU + 2/3 Cl_2

Process	Hazardous event
Electro-winning (Liquid Cd, 500 °C, Ar hot cell)	- **Leakage of Cd** - Failure of Cl_2 scrubbing - Failure of temperature control - Blocking of piping - Overpressure of systems (release of salt & Cd vapor)
Cd distillation (600/800 °C, vacuum)	- **Release Cd vapor** - Failure of temperature control - Failure of vacuum pump - **Blocking of cold trap & piping** - Overpressure of systems
Residual Actinide Recovery (RAR) (500 °C, vacuum)	- Failure of temperature control - Overpressure of systems - Leakage of Cd and Cl_2 - **Failure of Cl_2 scrubbing** - Blocking of cold trap & piping

Hazard identification

Salt waste treatment process



Process	Hazardous event
LiCl purification (650 °C, Ar hot cell)	- Failure of temperature control - Overpressure of systems - Blocking of piping - Leakage of salt
LiCl+KCl purification (650/1000 °C, Ar hot cell)	- Leakage of Cl_2 and O_2 - Failure of temperature control - Blocking of cold trap & piping - Overpressure of systems
Waste form fabrication (650/1100 °C, Ar hot cell)	- Failure of temperature control - Overpressure of systems - Leakage of Cl_2 and O_2 - Failure of Cl_2 scrubbing - Blocking of cold trap & piping

Hazard evaluation

- A qualitative hazard evaluation
  - **To determine potential release mechanism and event sequences** (potential hazard events and their potential causes)

> • Internal events: as a result of facility operation
> • External events: occur independent from facility operations (fires, explosions, releases at nearby facilities or operations)
> • NPHs: earthquakes, extreme winds, floods, snow, and lightning

Consequence Category	Public	Environment	Collocated Worker	Worker
(H) High	• Immediate health effects	• Significant off-site contamination requiring cleanup	• Immediate health effect	• Loss of life
(M) Moderate	• Latent health effects	• Moderate to significant on-site contamination • Moderate off-site contamination	• Latent health effects	• Severe injury or disability
(L) Low	• Irritation or discomfort but no permanent health effects	• Moderate contamination of facility • Minor onsite contamination • Minor off-site contamination	• Irritation or discomfort but no permanent health effects	• Lost time injury but no disability
(N) Negligible	• No significant offsite impacts	• Major contamination of facility • Negligible onsite contamination • Negligible off-site contamination	• No significant impacts	• Minor or no impact or disability

Consequence Category

Likelihood Category	Description	Frequency (per year)
(A) Anticipated	Events that are expected to occur during the lifetime of the facility	10^{-2} to 10^{-1}
(U) Unlikely	Events that may occur, but are not anticipated in the lifetime of the facility	10^{-4} to 10^{-2}
(E) Extremely Unlikely	Events that while possible will probably not occur in the lifetime of the facility	10^{-6} to 10^{-4}
(B) Beyond Extremely Unlikely	Events that are considered too improbable to warrant further consideration	Less than 10^{-6}

Likelihood Category

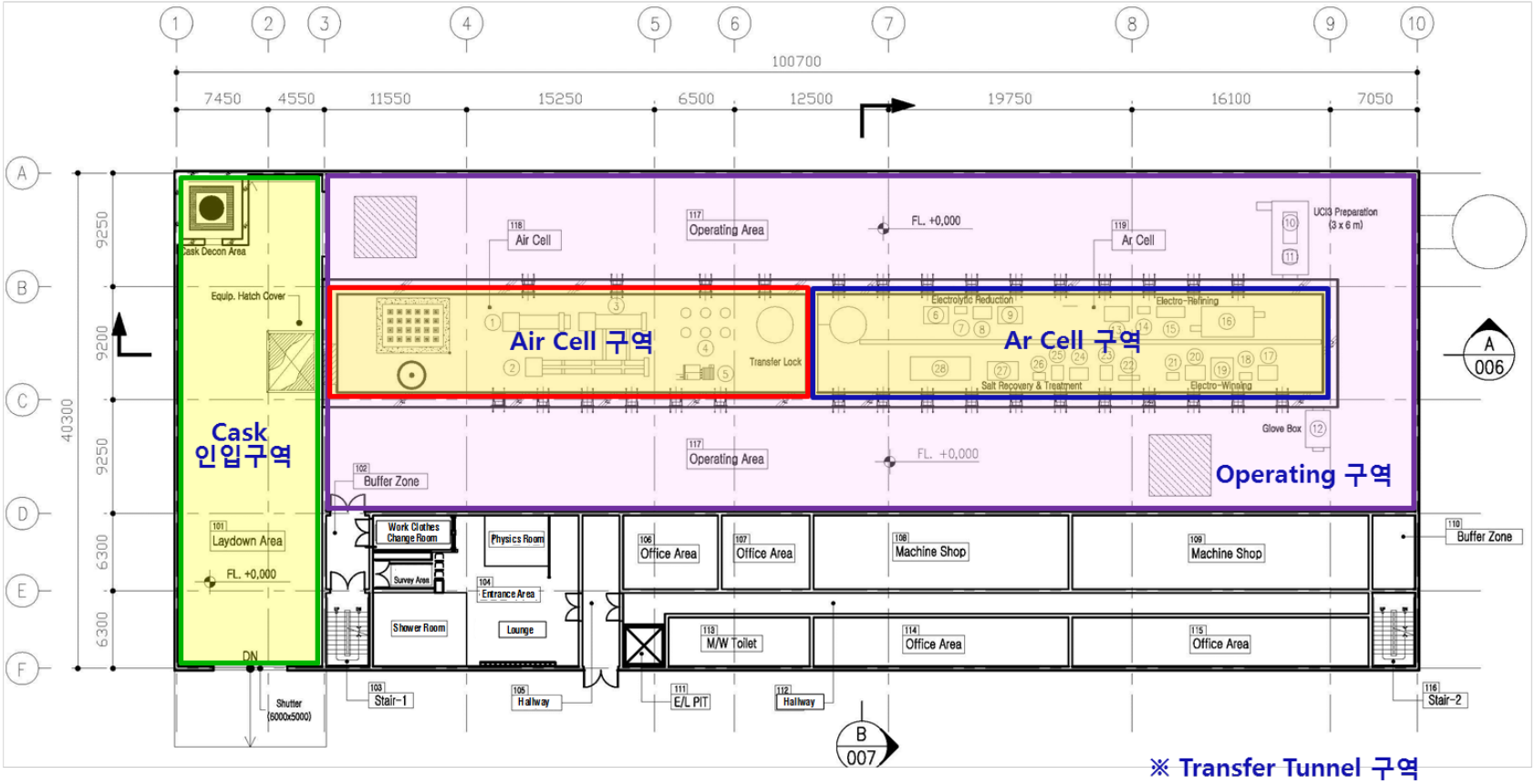
Consequence Category	Frequency Category			
	A	U	E	B
H	1	2	2	3
M	1	2	3	4
L	2	3	3	4
N	3	4	4	4

Risk Ranking Matrix

Hazard evaluation

❖ Hazards evaluation

- Check the Hazard elements for Argon cell, Air Cell, Cask receiving area etc.
- Derive the possible initial events
- Evaluate the hazards according to the hazards evaluation system



Division for Hazard Check Area of REPF

Hazard evaluation

Example of preliminary hazard analysis results

No.	Hazardous Event	Initiator/ Cause	Frequency	Consequence Severity		Risk Ranking
1	• **Fire and Explosions:** Air enters argon cell via open, active penetration (transfer lock) resulting in exposure of pyrophoric materials to air and release of radioactive material	Active penetration is inadvertently open to air	A	Off-site public: Collocated workers: Facility workers: Environment:	N L L N	2
2	• **Radioactive Material Release:** Damage and meltdown of spent fuel assembly resulting in release of radioactive material	Loss of cooling in spent fuel storage vault	U	Off-site public: Collocated workers: Facility workers: Environment:	H H H H	2
3	• **Direct Radiation Exposure:** Loss of air or argon cell shielding resulting in direct radiation exposure to facility workers	Inadvertent loss of damage to shielding Mechanical failure	U	Off-site public: Collocated workers: Facility workers: Environment:	N N M N	2
4	• **Inadvertent nuclear criticality:** Inadvertent nuclear criticality in argon cell or waste storage cell	Fissionable material inadvertently arranged in sufficient mass and geometry for criticality to occur	U	Off-site public: Collocated workers: Facility workers: Environment:	N L H N	2
5	• **Nonradioactive Hazardous Material Release:** Chlorine gas release	Inadvertent loss of damage to pipe	U	Off-site public: Collocated workers: Facility workers: Environment:	N N M N	2
6	• **Natural Phenomena Hazards:** Earthquake results in severe building structural damage/collapse and results in radioactive material release	Evaluation basis earthquake	U	Off-site public: Collocated workers: Facility workers: Environment:	L M H N	2

Hazard evaluation

No.	Hazardous Event	Preventive and Mitigative Features	
		Design	Administrative
1	• **Fire and Explosions**: Air enters argon cell via open, active penetration (transfer lock) resulting in exposure of pyrophoric materials to air and release of radioactive material	***Transfer lock dual door airlocks*** Argon cell atmosphere monitoring Transfer lock door positions monitored Hot cell exhaust system Building exhaust system Building structure	***AC(s) on transfer lock operation*** ***AC on quantity of exposed pyrophoric material inside argon cell*** ***AC on transfer lock leak rate*** Operator training Approved procedures
2	• **Radioactive Material Release:** Damage and meltdown of spent fuel assembly resulting in release of radioactive material	***Storage vault design*** to prevent damage of spent fuel Storage cooling system Building exhaust system Safety exhaust system	Radiation protection program
3	• **Direct Radiation Exposure:** Loss of air or argon cell shielding resulting in direct radiation exposure to facility workers	***Air and argon cell structure*** ***Air and argon cell shielding***	***AC on direct radiation exposure restrictions*** ***Radiation protection program*** Operator training
4	• **Inadvertent nuclear criticality:** Inadvertent nuclear criticality in argon cell or waste storage cell	***Argon cell shielding*** *Waste storage cell shielding* Building structure	***AC on personnel access restrictions***
5	• **Nonradioactive Hazardous Material Release:** Chlorine gas release	***Evacuation System*** Chlorine gas monitoring system and alarms	Operator training Approved procedures
6	• **Natural Phenomena Hazards:** Earthquake results in severe building structural damage/collapse a nd results in radioactive material release	***Cell structure*** Building structure	***AC on quantity of pyrophoric material inside argon cell*** ***Ac on REPF radioactive material inventory*** ***Emergency management program***

Development of accident scenarios

Process & Work Type	Accident Scenario	Hazard Type
SF Cask Unloading	- Truck fire during SF cask unloading	Fire (radiological contamination, release)
SF Assembly Storage, Withdraw	- Cooling system failure in SF storage vault - Drop of SF assembly during withdraw to hot cell	Radiological (contamination, release)
Head-end Process	- Release of SF fragments during chopping processing - Leakage of SF powder from Voloxidizer - Spill out of SF powder during filling up	Radiological (airborne release)
Off-gas Treatment	- Rupture on off-gas transfer piping - Leakage in retention tank(Xe/Kr)	Radiological (fission gas release)
Electrolytic Reduction	- Leakage of salt vapor in reactors - Release of O_2 gas from electrolyzer - Leakage of salt during molten salt transfer	Radiological & Toxic (airborne release), Fire(Explosion)
Electro-Refining	- Leakage of salt vapor in reactors - Failure of inert atmosphere during U metal handling - Leakage of Cl_2 gas on UCl_3 fabrication processing - Leakage of salt during molten salt transfer	Radiological(airborne release), Toxic(gas release), Fire(metal)
Electro-Winning	- Leakage of salt vapor in reactors - Leakage of Cd vapor in Cd distiller	Radiological & Toxic (airborne release)
Salt Waste Treatment	- Leakage of salt vapor in reactors - Release of Cl_2 gas from salt refiner	Radiological(airborne release), Toxic(gas release)
Ar Gas System	- Leakage of a large amount Ar gas cause by piping rupture	Suffocation

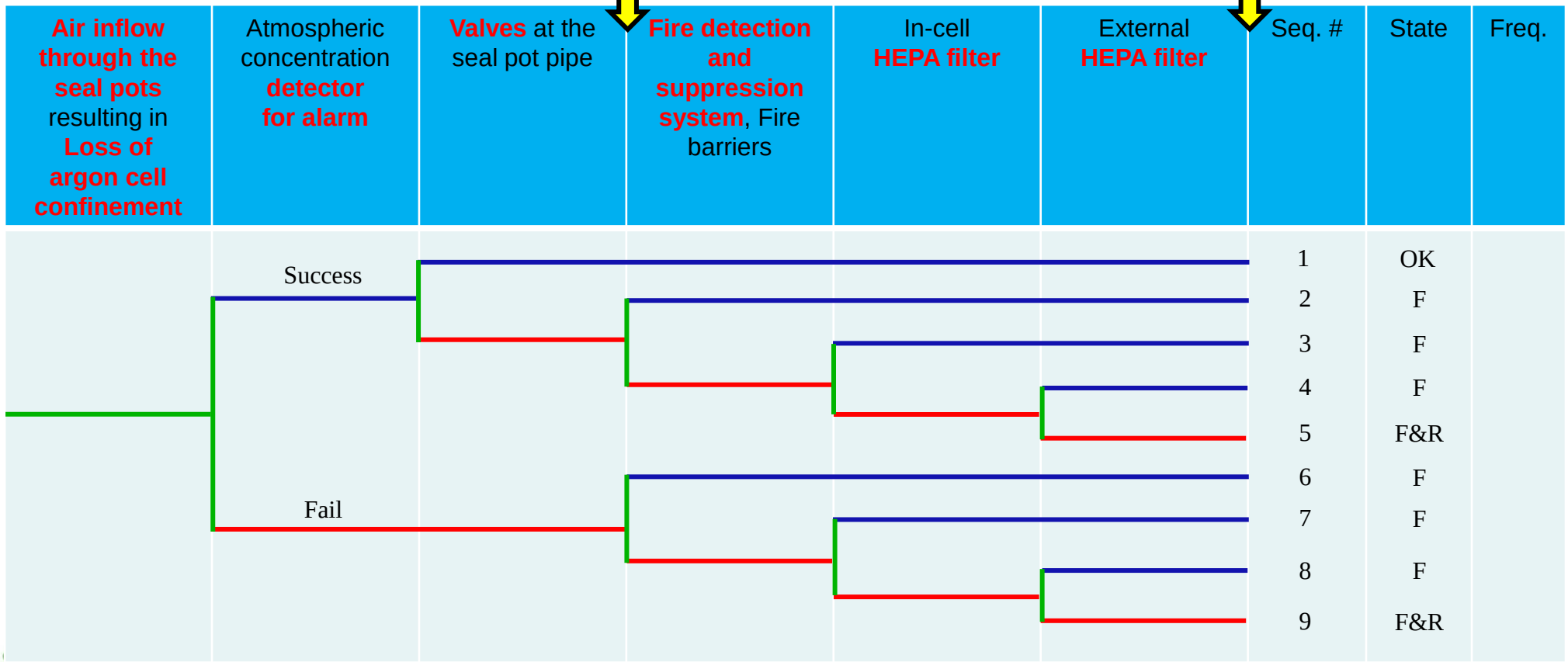
Development of accident scenarios

Event tree

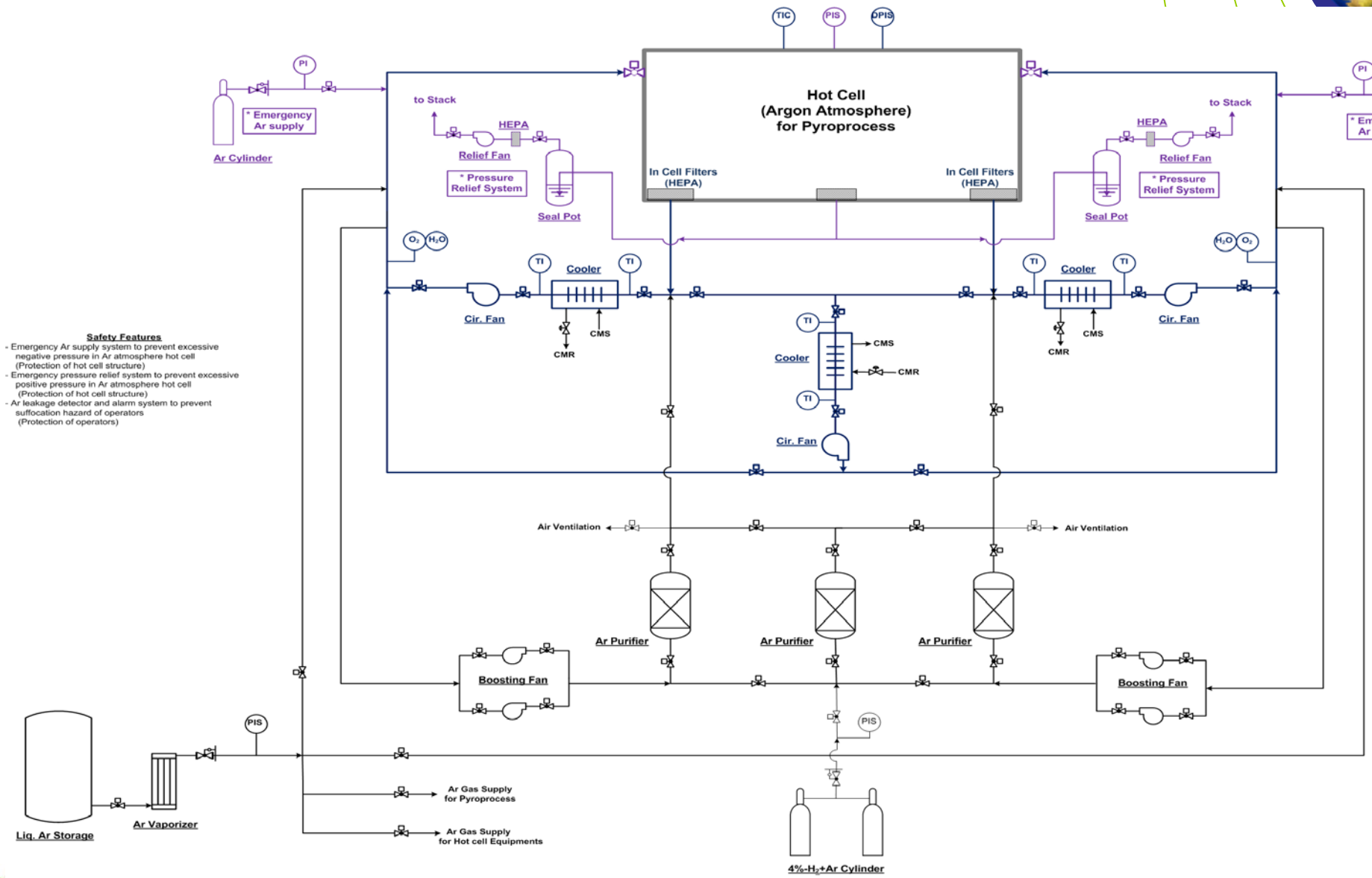
Initial event: Malfunction of argon cell pressure control

Exposure of pyrophoric materials to air → Fire occurs (F)

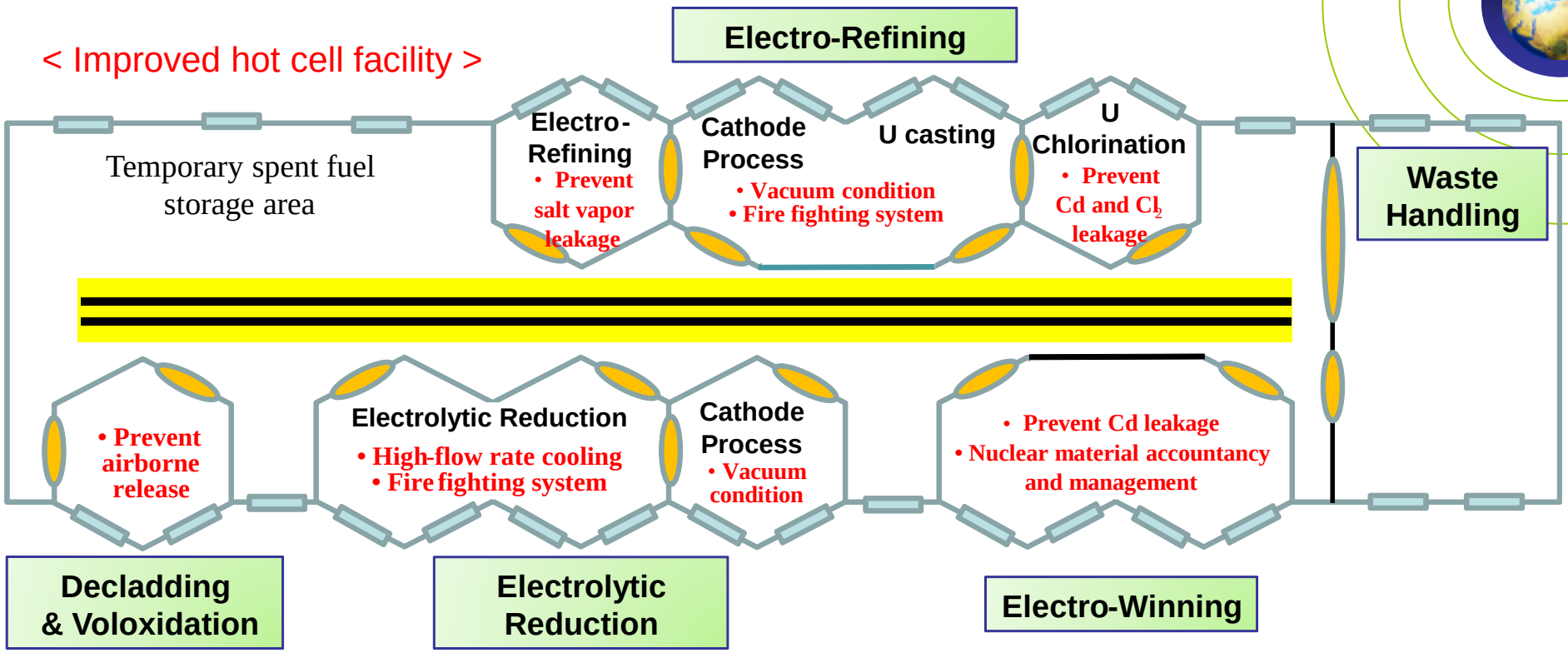
Release of radioactive materials (R)



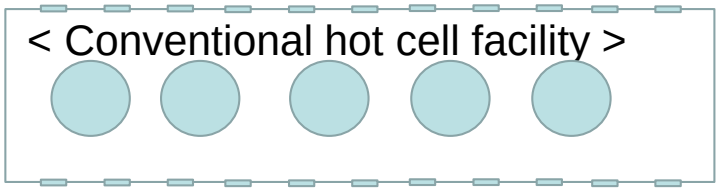
Draft P.&I. diagram (Ar supply system)



Modular partitioning confinement structures



Shielded window& MSM **Transfer lock** **Transfer rail**



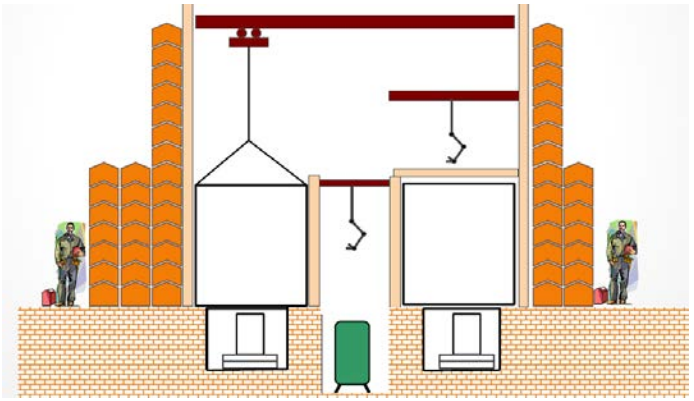
< Modular partitioning confinement structures >

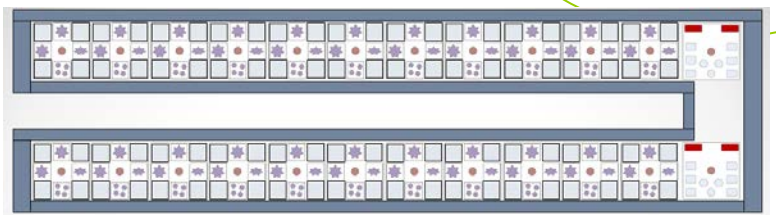
1. Visual angle
2. Confinement structure
3. Negative pressure
3. Risk reduction
4. Fire protection system
5. Safeguardability

Modular partitioning confinement structures

RIAR

Unify Technology Unit (UTU)

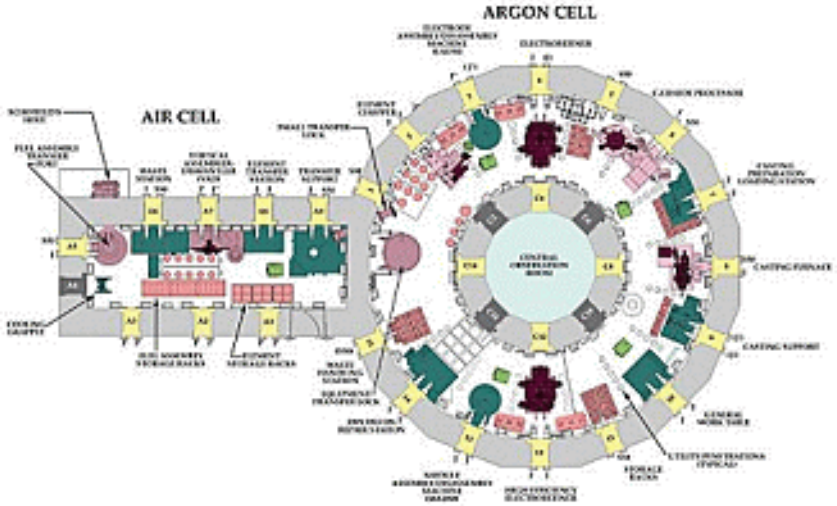




Technical unit ↔ Safety unit

INL

Fuel Cycle Facility (FCF)

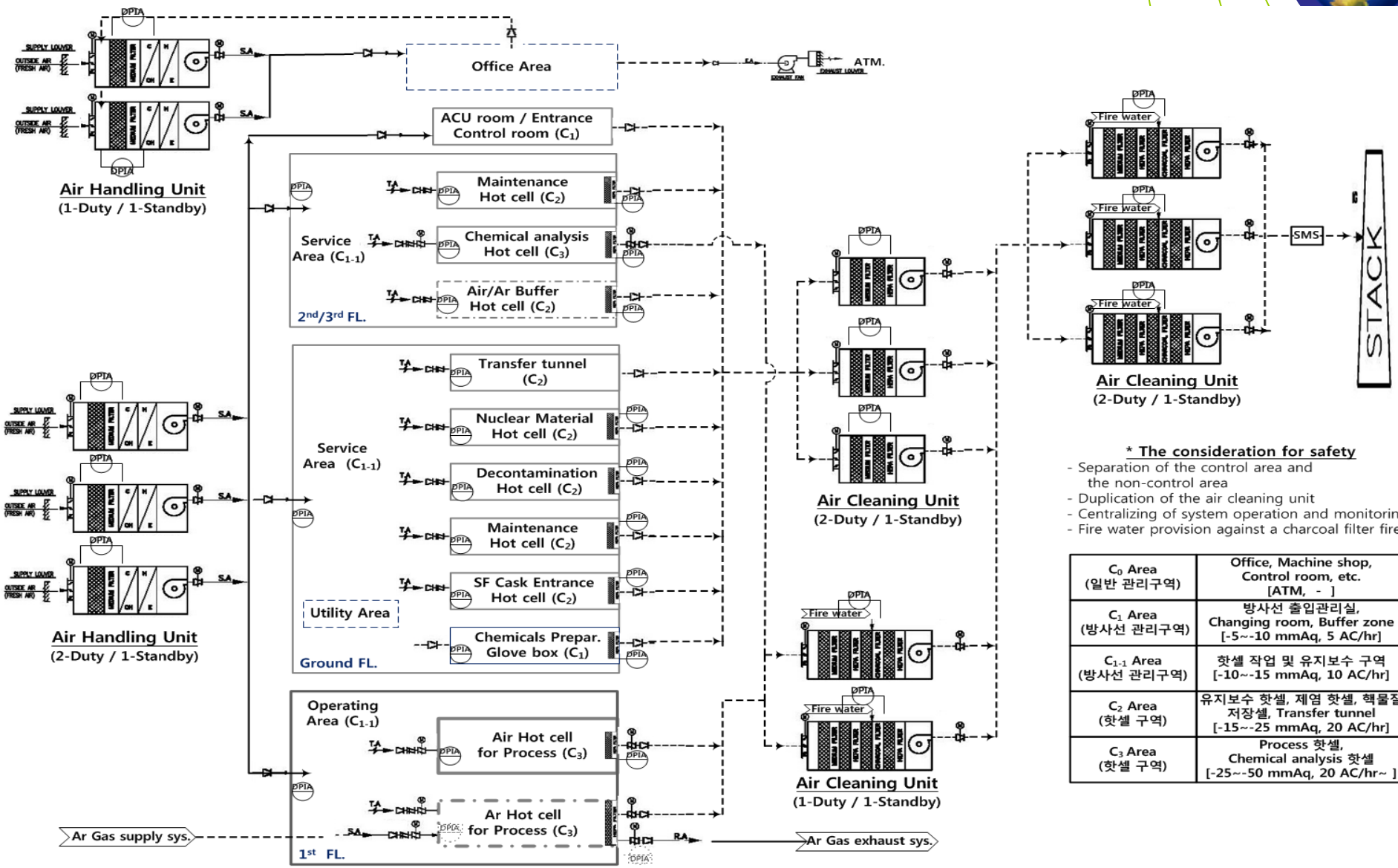


Concluding remarks

- **Pyroprocess** as an environmentally-friendly recycling process **is regarded as one of the most essential technologies** to a country which has limited capacity of the land for underground disposal sites such as Korea.
- **Profound safety analysis** for a pyroprocess facility **is required for licensing and construction** of the facility.
- **Accident scenarios are established** by examining **hazard identification** and **hazard evaluation**, followed by **preventive and mitigative features**.
- A **modular partitioning confinement structure** was proposed based on the accident scenarios to prevent or mitigate their effects to the facility, workers, and environment. It seems that it is **advantageous** in aspects of safety than conventional Pyro facilities.

Thank you
for your attention !

Draft P.&I. diagram (HVAC system)



*** The consideration for safety**

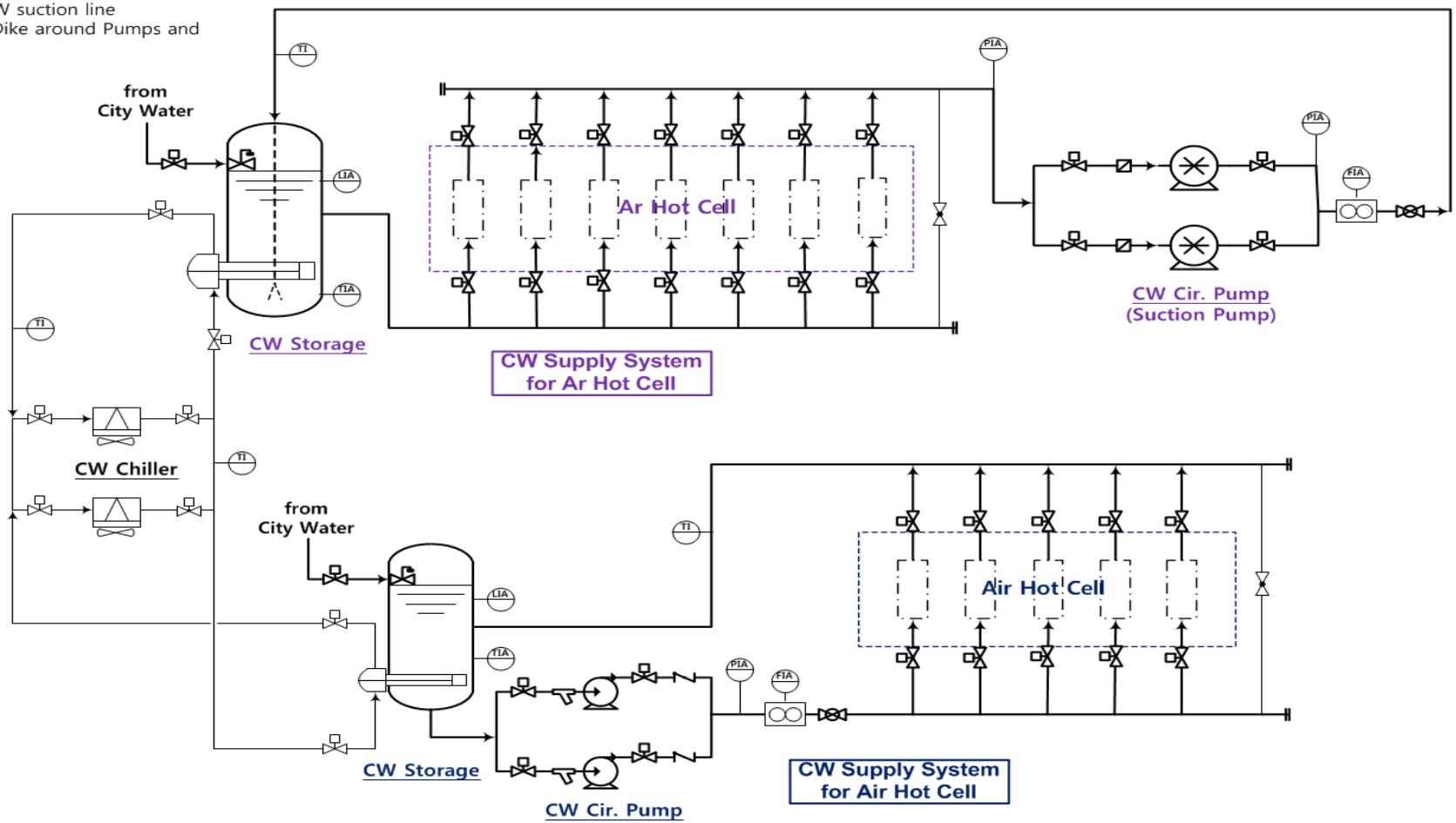
- Separation of the control area and the non-control area
- Duplication of the air cleaning unit
- Centralizing of system operation and monitoring
- Fire water provision against a charcoal filter fire

C_0 Area (일반 관리구역)	Office, Machine shop, Control room, etc. [ATM, -]
C_1 Area (방사선 관리구역)	방사선 출입관리실, Changing room, Buffer zone [-5~-10 mmAq, 5 AC/hr]
C_{1-1} Area (방사선 관리구역)	핫셀 작업 및 유지보수 구역 [-10~-15 mmAq, 10 AC/hr]
C_2 Area (핫셀 구역)	유지보수 핫셀, 제염 핫셀, 핵물질 저장셀, Transfer tunnel [-15~-25 mmAq, 20 AC/hr]
C_3 Area (핫셀 구역)	Process 핫셀, Chemical analysis 핫셀 [-25~-50 mmAq, 20 AC/hr~]

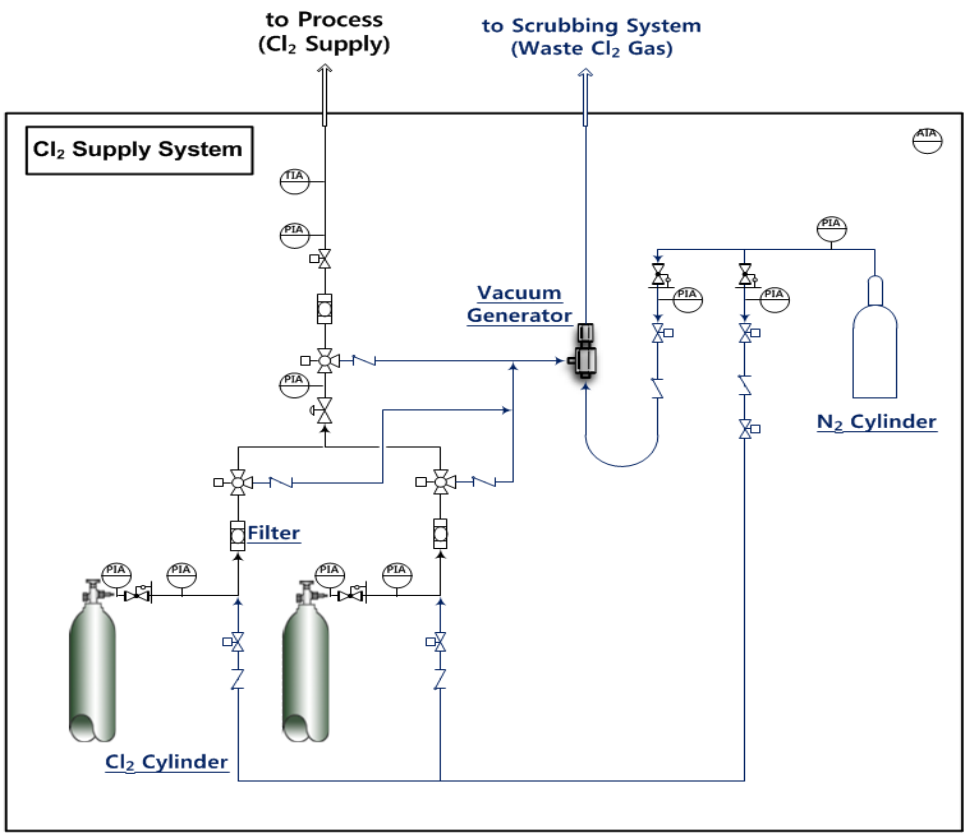
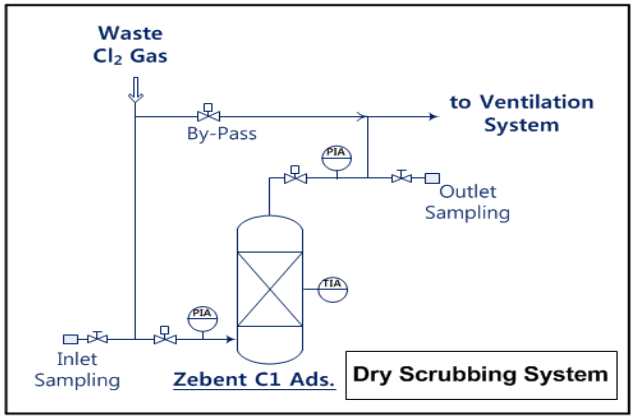
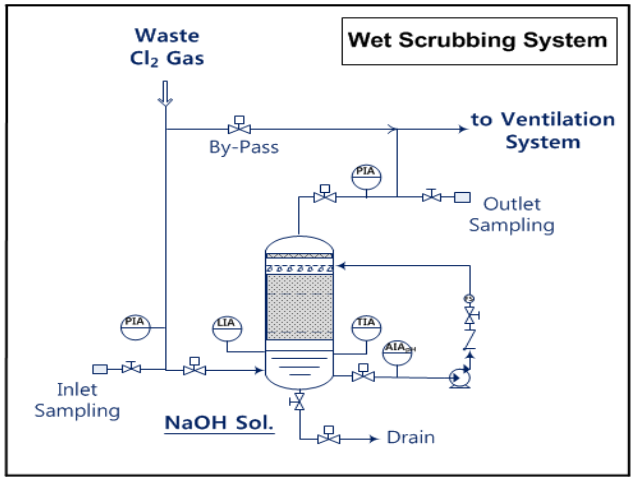
Draft P.&I. diagram (Cooling water system)

Safety Features

- Separation of Cooling Water System for Ar Hot Cell and Air Hot Cell
- Selection of CW Cir. Pump Type for Ar Hot Cell : Suction Pump (Min. Suction Head : 6 m)
  * for Provision of Negative Pressure against leakage in CW suction line
- Installation of Dike around Pumps and CW Storage



Draft P.&I. diagram (Cl_2 supply system)

Safety Device

- Cabinet Container & Evacuation System
- N_2 Purging & Vacuum System
- Cl_2 Scrubbing System (Dry & Wet Type)
- Leak Detector and Alarm System
- Valve Shutter
- Line Heater
- PLC Control and Sequence System