IAEA Technical Meeting on Proliferation Resistance Features of Fast Reactors and Associated Fuel Cycles

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Headquarters, Vienna, Austria

Track 3: Proliferation Resistance Considerations for Nuclear Fuel Cycles

Tuesday, August 19, 2025

EXPERIENCES IN METAL FUEL FABRICATION TECHNOLOGY TOWARDS A REMOTE RE-FABRICATION FACILITY

T.V. PRABHU, R. LAVAKUMAR, V. SURESHKUMAR, J. JAGADEESHCHANDRAN, G. YATHISH KUMAR, A. PRAFULLA KUMAR, MAYANK RAWAT, M. SAI SUBBALAKSHMI

Indira Gandhi Centre for Atomic Research, Kalpakkam 603 102, INDIA
Email: prabs@igcar.gov.in

Content

- Overview of Metal fuel program for Fast reactors
- **AERB Safety Guides – covering protection of nuclear material**

- Sodium bonded metal fuel fabrication & Characterisation facility (gram level) – Safety related equipment's
- **Process: Casting** technologies

- **Pyro processing R&D – lab scale in grams**
- **Spent metal fuel by pyro process in hot cells (gram level)**
- Engineering scale Pyro processing development (Kg level – 'U' handling)

- **Proliferation Resistance concepts – International manuals (INPRO etc)**
- Future – FBTR 2 with Metal Fuel Demonstration Facility (MFCDF) implementing PR in design stage

Overview : Metal fuels in Fast Reactors (Our perspective)

- Metal fuel was used in EBR- I & II, BR-5, Dounreay, etc., in the earlier years.
- Due to limitation in achieving high sodium outlet temperature and apprehension that high burnup not realizable led to abandoning of the program.
- Renewed interest in metal fuels (Internationally)
  - **Proliferation resistance fuel cycle**
  - Confidence to attain high burnup
- Japan, Korea, US, Russia pursue interest in metal fuel program.
- For rapid growth & sustainability of fast reactors, metal fuel having short doubling time and an integrated fuel cycle with Pyro-chemical reprocessing & re-fabrication is the ideal option (India Perspective).
- The processing of high burn-up fuel, processing of contaminated recycled fuel & re-fabrication facility in hot cells possesses inherent proliferation resistant features.

Need for metal fuels in future FBRs

- **Metal fuel gives the highest Breeding Gain and lowest Doubling Time**
- **India needs metal fuel program for its accelerated growth in nuclear power segment and hence metal fuel is the ideal choice. Thus, R&D is directed towards metal fuel.**

R&D program on Metal fuel – Irradiation Plan in FBTR

- Thermo-physical/Chemical prop. (K, Cp, Phase transf., U/Pu determin., Isotopic compn.
- QC of fuel slugs (accept. Criteria, C, S, O, minor, metallographic phases, homogeneity)
- Recycle, 0.01% PUF, storage, BU analysis

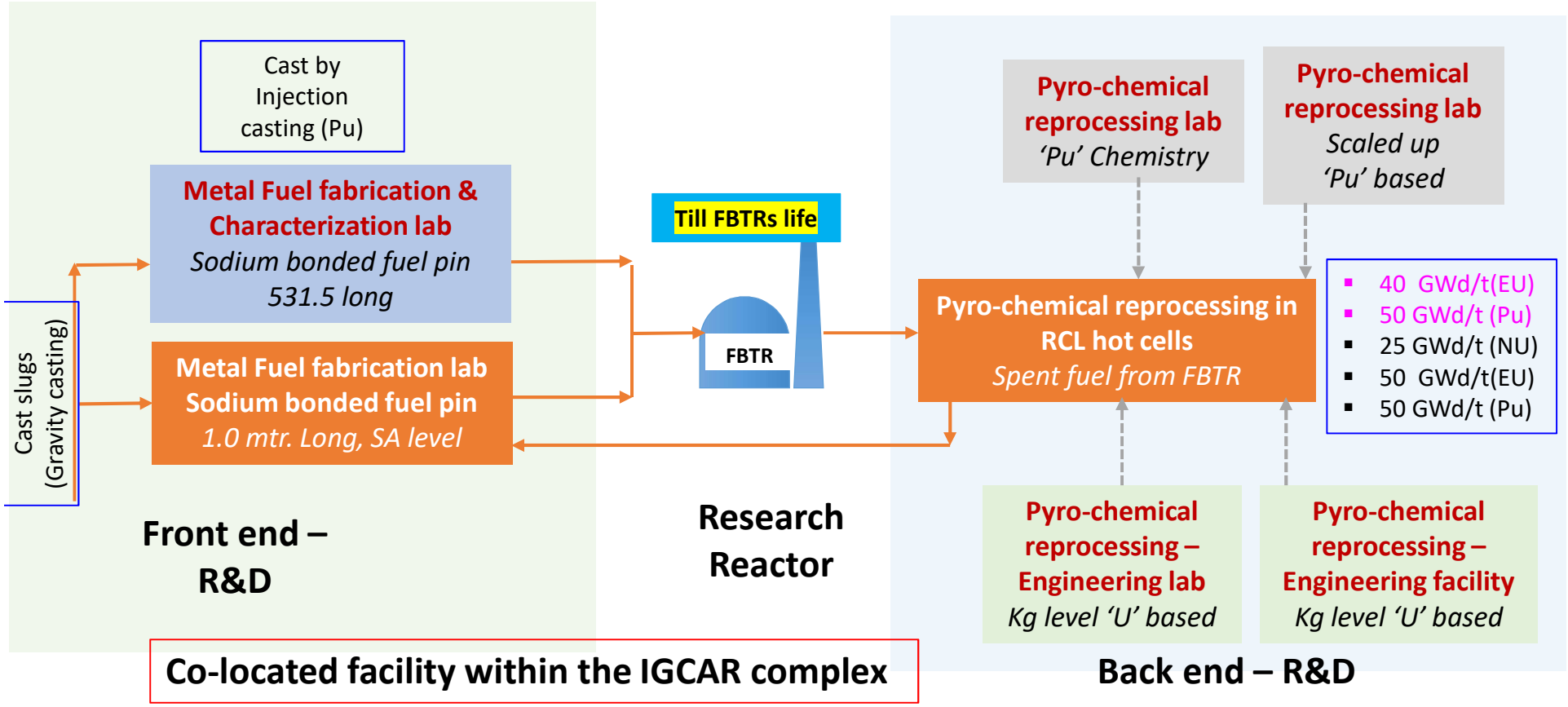
Pin level irradiation in FBTR

25, 50, 100 GWd/t burnup

37- pin design of power reactor

Aim of test irradiation in FBTR

- **Testing of Various composition leading to FBTR-2 fuel specification.**
- **Higher LHR possible in FBTR with EU**
- **For various PIE studies to ascertain its performance**
- **Pyro in stages of BU.**



Co-located facility within the IGCAR complex

AERB's Role:

- AERB is the competent authority in India for regulating nuclear and radiation-related activities. The primary objective is to protect site personnel, the public, and the environment from undue radiation hazards. AERB achieves this through various means, including developing safety codes & guides.

- "Safety Guide" and guidance provided by the AERB & Unit level Internal Documents (ID no.) are related to the safe handling and control of Special Nuclear Materials (SNM). The document outlines the controls and safety measures for SNM.

- Guideline for Regulation of NFCF as per SG/ G-2

SG/G-2 specifies the regulatory requirements in setting up the Nuclear Fuel Cycle Facility.
Regulatory body may assess the hazard potential of the facilities and carry out the safety assessment accordingly.

- In general, a 3-tier review process is followed by the regulatory body before any major stage .
- 3-tier review process, may be retained only for the highly hazardous facilities of the nuclear fuel cycle (e.g. Fuel fabrication plants, spent fuel reprocessing plants, etc).
- 2-tier review process for less hazardous facilities of the nuclear fuel cycle/laboratories.

General: Allows a specified activity or set of activities dealing with siting, construction, commissioning, operation or decommissioning of a nuclear fuel cycle facility;

GUIDE NO. AERB/NF/SG/G-2

1) Consent for Siting

2) Consent for Construction

(iii) Security features to be implemented in order to reduce risk of unauthorised removal of nuclear material, to minimise sabotage on the facility and to **minimise the risk of adverse impact during above acts are to be delineated.**

3) Consent for Commissioning

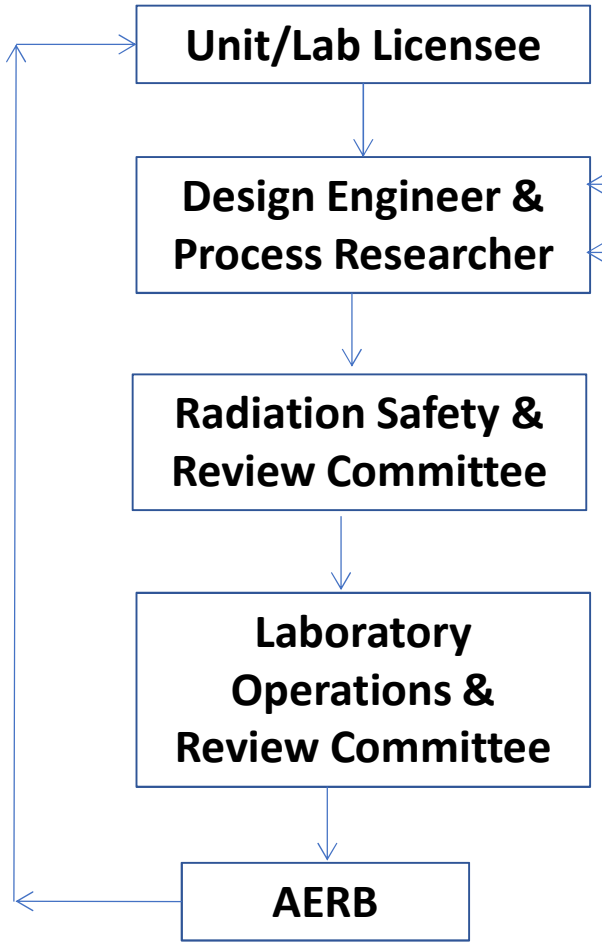
4) Consent for Operation

The consent may initially be restricted to operation of the facility to process only a limited quantity of the feed material and/or for a limited period, in order to gain operating experience, or for test production of the end product to verify the quality and grade. This may also enable the consentee to rectify deficiencies, such as malfunctioning of equipment, off-grade final product, leakages from systems, etc.

5) Renewal of Consent for Operation

6) Consent for Decommissioning

Consenting: Standing order & Procedure (covers protection of material)



GUIDE NO. AERB/NF/SG/G-2

- Check list
- Standard Operating Procedure
- Institutional measures to control access
- SNM Material flow – time motion studies
- Hazard analysis (Process)
- SNM control, MBA, KMP, MUF etc.
- Cold runs using Uranium
- Mock trials
- Preliminary Safety Analysis Report
- Clearance for limited runs
- Final Safety Analysis Report
- Hot commissioning – limited Pu runs
- Clearance for gradual scaling up in stages up to the rated capacity.

ANNEXURE- 2

CONTENTS OF SITE EVALUATION REPORT

The contents of the site evaluation report should cover all items under the following broad categories:

1. **Salient features of the proposed site**

   (a) Geography, Demography and Topography

   (i) The site and its location should be described with the aid of maps of suitable scale. The present and foreseeable uses of surrounding area should be described. Data on food/ milk production and on dietary habits in the area should be compiled, with special attention to food processing or any other sensitive industry.

   (ii) Existing or planned industrial and public facilities in the neighbourhood (5-10 km depending on the hazardous nature of the facility), such as roads, railways, waterways, transport of dangerous goods, chemical plants, military installations, gas pipelines, airports, archaeological monuments and places of pilgrimage, including anticipated changes in their utilisation and distance from the proposed facility should be described in such a way as to facilitate the evaluation of the risks which they may pose to the nuclear facility and vice versa.

3. General description of plant covering basic design features, e.g.

(i) overall safety approach

(ii) codes and standards applicable to the design

(iii) safety margins in prevention of accidental criticality, red oil explosion etc., where applicable

4. Nuclear security

(a) Impact of site and surroundings on nuclear security

(b) Physical protection system, physical barrier, communication, etc.

5. Interaction of the facility with its environment

(a) Radiological and Chemical Impact

(i) All necessary ecological data from the site and its surrounding area, that are important for review and assessment of the radiological/ environmental impact of the nuclear facility, such as biological systems and critical pathways, should be presented.

(ii) In case such data still needs to be generated, program for the generation of the same may be given. In the mean time conservative assumptions/ approaches could be used with respect to the radiological impact. The purpose is to get an assurance that the requirement regarding specified dose limits are met.

(iii) A description should be given of the organisation and conduct of an environmental monitoring program, to establish base line data on radioactivity levels.

Salient features in the guide:

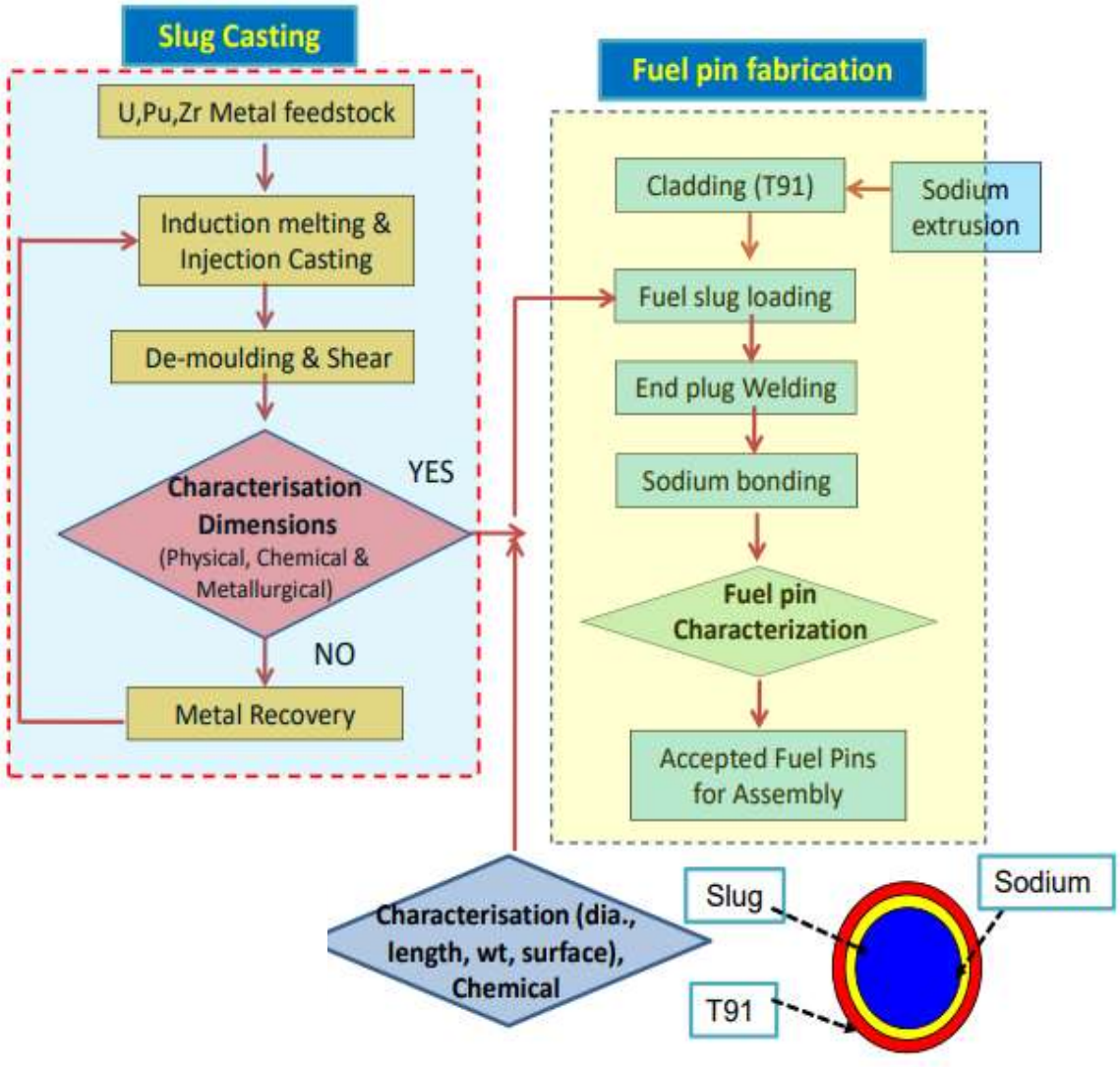
- **Physical protection:** Measures to prevent theft, loss, or unauthorized access to SNM, intrinsic protective barriers,
- Threat scenarios , diversion paths within facility
- Shielding & critical mass calculations (mass, isotopic composition, dose rate etc)

- **Inventory control:** Procedures for tracking and accounting for all SNM.
- **Transportation:** Guidelines for the safe movement of SNM.
- **Storage:** Requirements for secure and safe storage of SNM.
- **Disposal:** Procedures for the safe disposal of SNM.
- **Personnel training and qualification:** Ensuring personnel handling SNM are properly trained and qualified.
- **Emergency preparedness:** Procedures for responding to potential emergencies involving SNM.

Subject interest: Provides guidance for establishing and maintaining physical protection systems to prevent the unauthorized access, theft, or sabotage of nuclear material and facilities. It outlines measures to protect against both malicious acts and accidents.

I. METAL FUEL FABRICATION & CHARACTERISATION

Developed the Flow sheet of sodium bonded metal fuel pin fabrication



- Ternary alloy metal fuel slugs
- Injection Casting & Gravity Casting
- Blankets binary alloy by Continuous casting

A Metal Fuel pin Fabrication Facility (MFPF) has been set-up and is in operation at the Radiochemistry Laboratory (RCL) in IGCAR, Kalpakkam

Casting of fuel slugs, Blanket slugs

CIC equipment with safety features

De-moulding machine

Material category (Un-irradiated & Irradiated), Quantity (not more than 200 gms in each glove box – lab – facility), Accessibility & Accountability, Containment & Surveillance measures, NDA & analysis for flow of nuclear material, online monitors, centralised data acqusition.

SNM control : Melting & casting – Demoulding – shearing – Heel – Crucible – Dross – Damaged mould – Quartz – KMP point at each stage

Inherent characteristics

Injection casting system for casting U-Zr slugs

❑ Commissioning of crucible lifting mech

- Loading crucible with charge
- Fail safe gripper
- Tested with dummy loads

Crucible with charge

❑ Argon purification system

- Leak testing of piping circuit
- Integration with GB
- Pressure control system

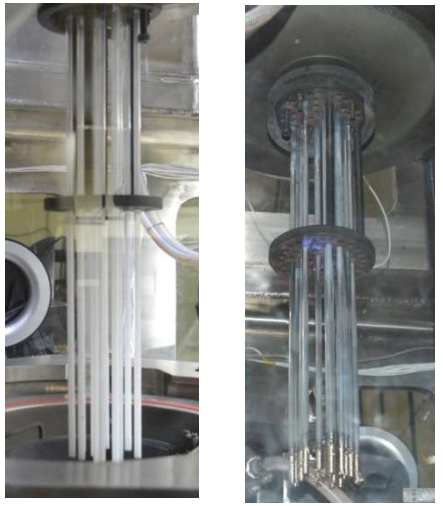
Consolidated Ingot

❑ Casting campaigns

- Testing of vacuum & pressurization circuit
- Testing of induction & Mould heater
- Testing of chilled water system
- Casting parameters of U-Zr slugs

  charge , Length - 485 mm

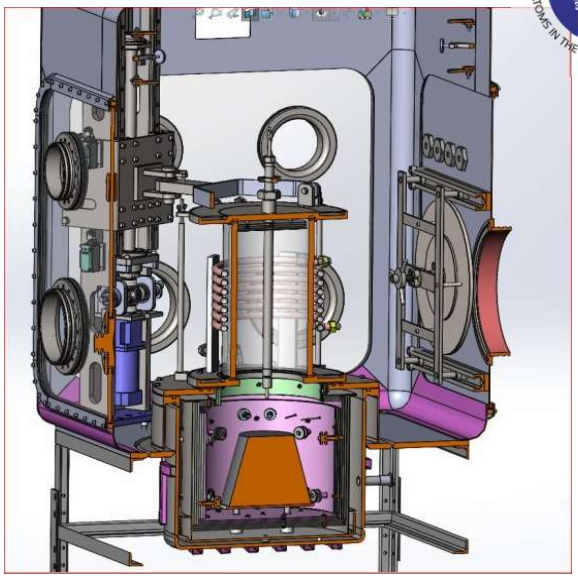
- U-Zr slugs – 50 No's, length-300mm



Mould bunch

Casting of fuel slugs, Blanket slugs

Induction coil testing with automation

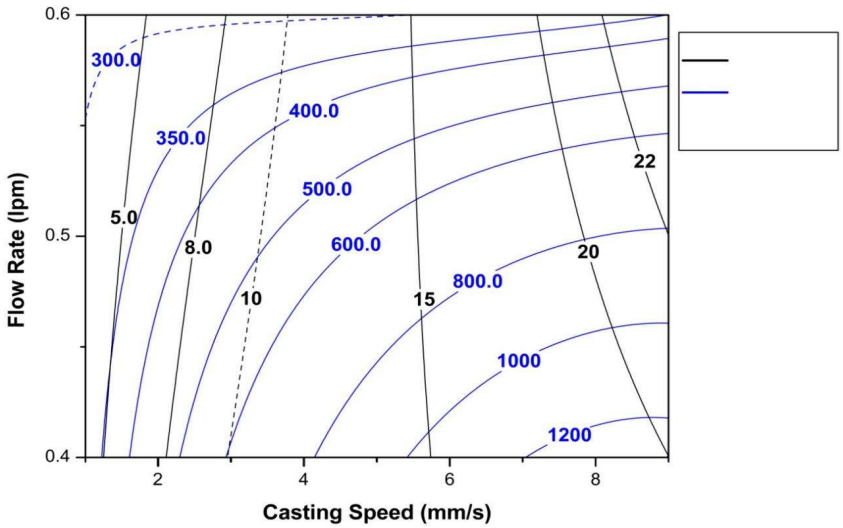


Gravity casting system

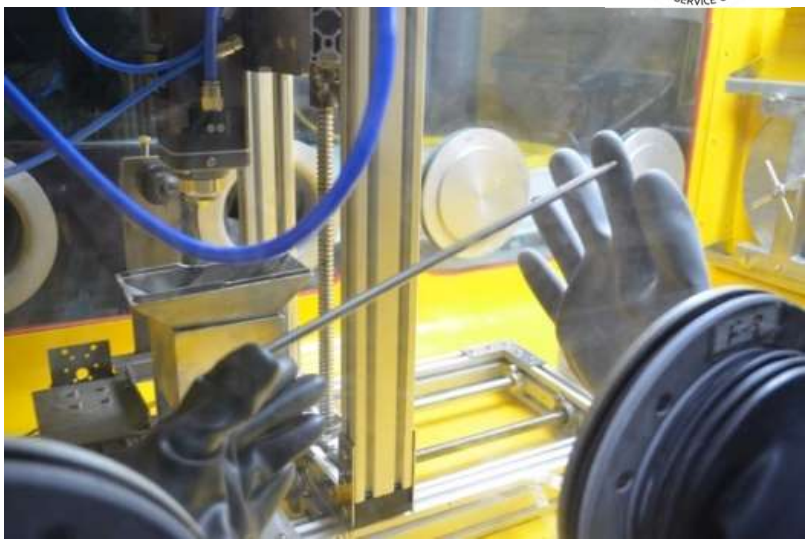
Technical design features, Operational modalities

- Solid induction coil – Maintenance free, water free, phased AC's for EMS
- Gravity casting – High alloying element, vaporisation losses are minimised, maintenance free, minimised solid waste (quartz)

Shearing of cast slugs & processing



Temperature analysis in continuous casting

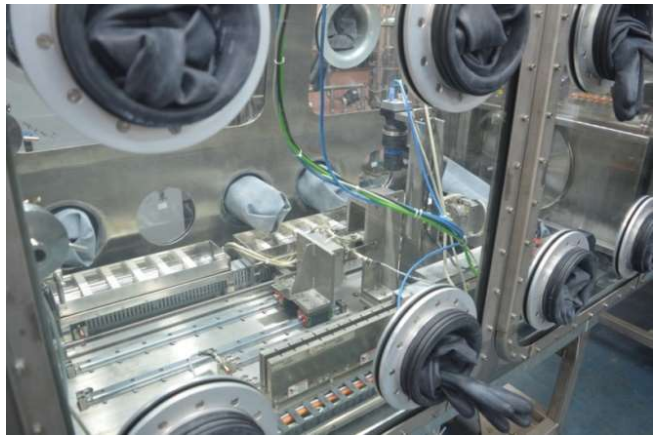


Trial cutting of U-6Zr slugs using fibre laser

- High through put, process steps minimized

- Debris losses are minimum

Inspection of slugs, Characterization lab



Machine vision based slug inspection

- One slug at a time (49 gms each)
- ECT, Gamma scanning

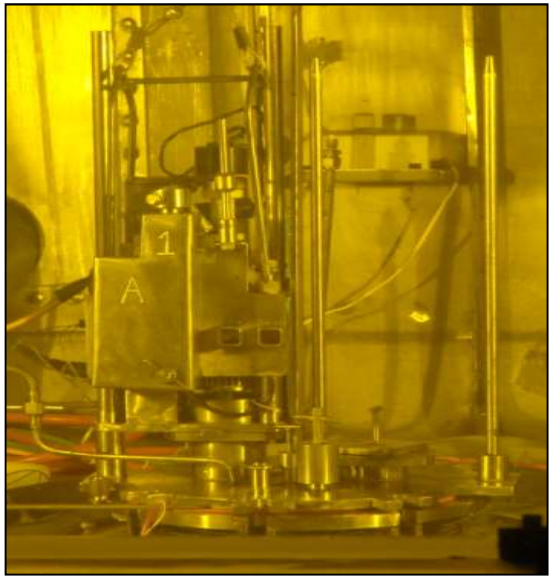
Characterisation bench

- Cutting (mg), polishing, metallography, physical, chemical & metallurgical

II. METAL FUEL Reprocessing by Pyro-processing & Waste management

Back end – Pyro processing studies

Cutting of fuel pin



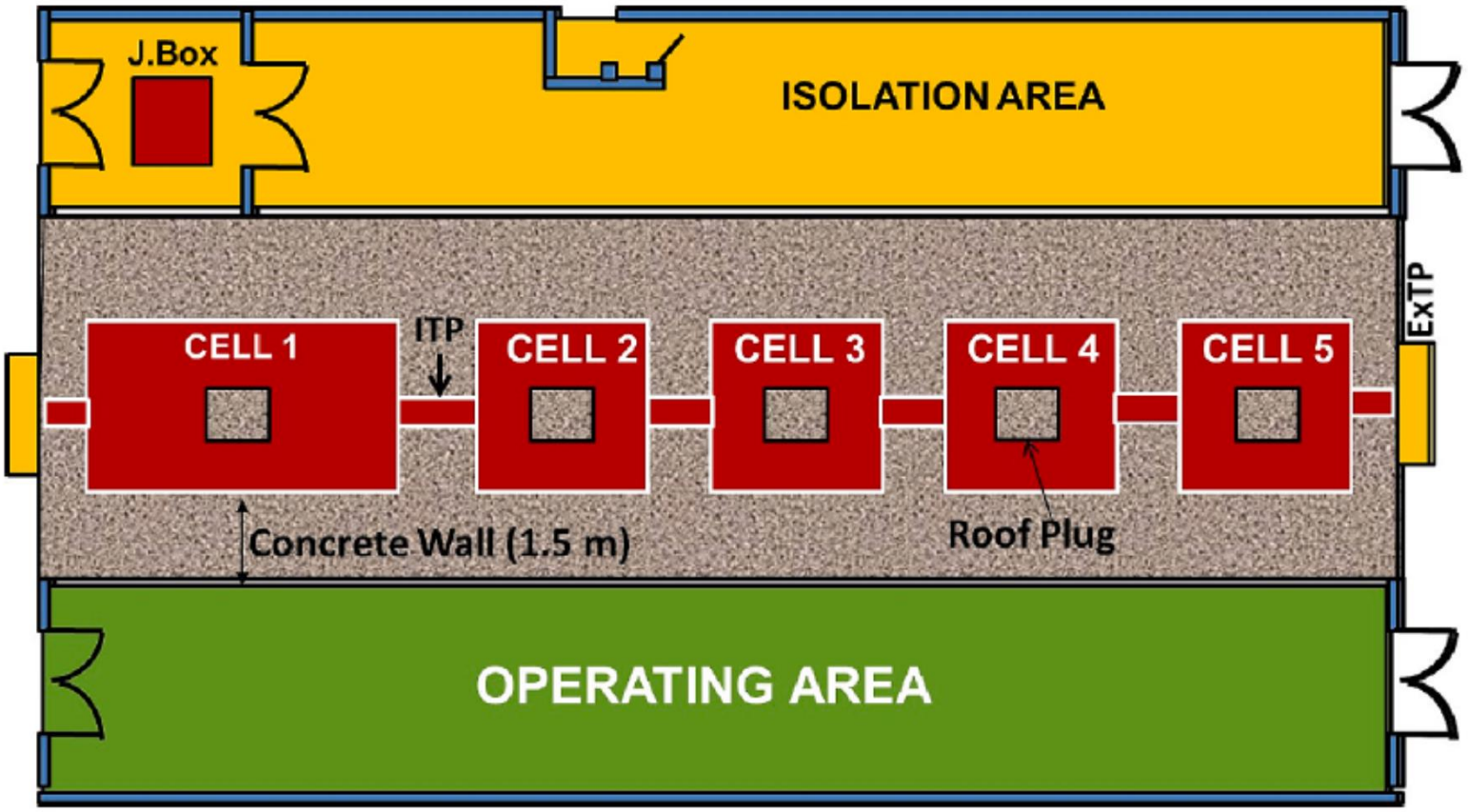
Electro refining

Kg level ER

- Spent fuel after target BU
- Gram level capacity
- ER, Cathode consolidation, salt distillation, Actinide draw down process
- Eutectic salt at high temperature
- Contaminated fuel, low DF - ~1000

- Decontamination,
- Wash down, m/l balance

Back end – Pyro processing studies



Layout of the hot cell – surveillance monitoring

Back end – Pyro processing studies

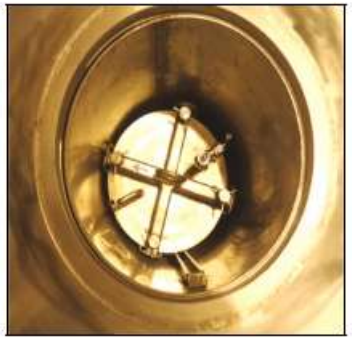
Fixed Automation in pyro hot cell

Sampling for material balance

Back end – Pyro processing studies

(a)

(b)



(c)

Fig. 15. Photograph of electrode assembly with top flange and reaction crucible.

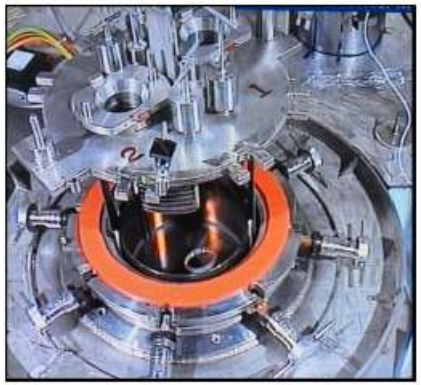


Fig. 16. Photograph of the ER cell along with top flange.

Dimension control

- ER vessel
- Transfer vessel
- Flask
- Alpha tight quick transfer

III. Re-fabrication flow sheet is being conceptualised - designed

Remote operation in hot cells

- Long fuel pins
- Long sub-assembly
- Material control
- Process adaptation
- Slug stacking etc.

International experience - Methodologies

1) Concepts of proliferation resistance (INPRO Manual) are being studies & internal notes generated.

Would be Implemented by retrofits & augmentation process:

- **Intrinsic features and extrinsic measures**
- **Cost-effective optimization**
- **Assessment method *(Published)***
- **Basic principles**
- **Knowledge sharing – In house training**
- **Complementary framework**

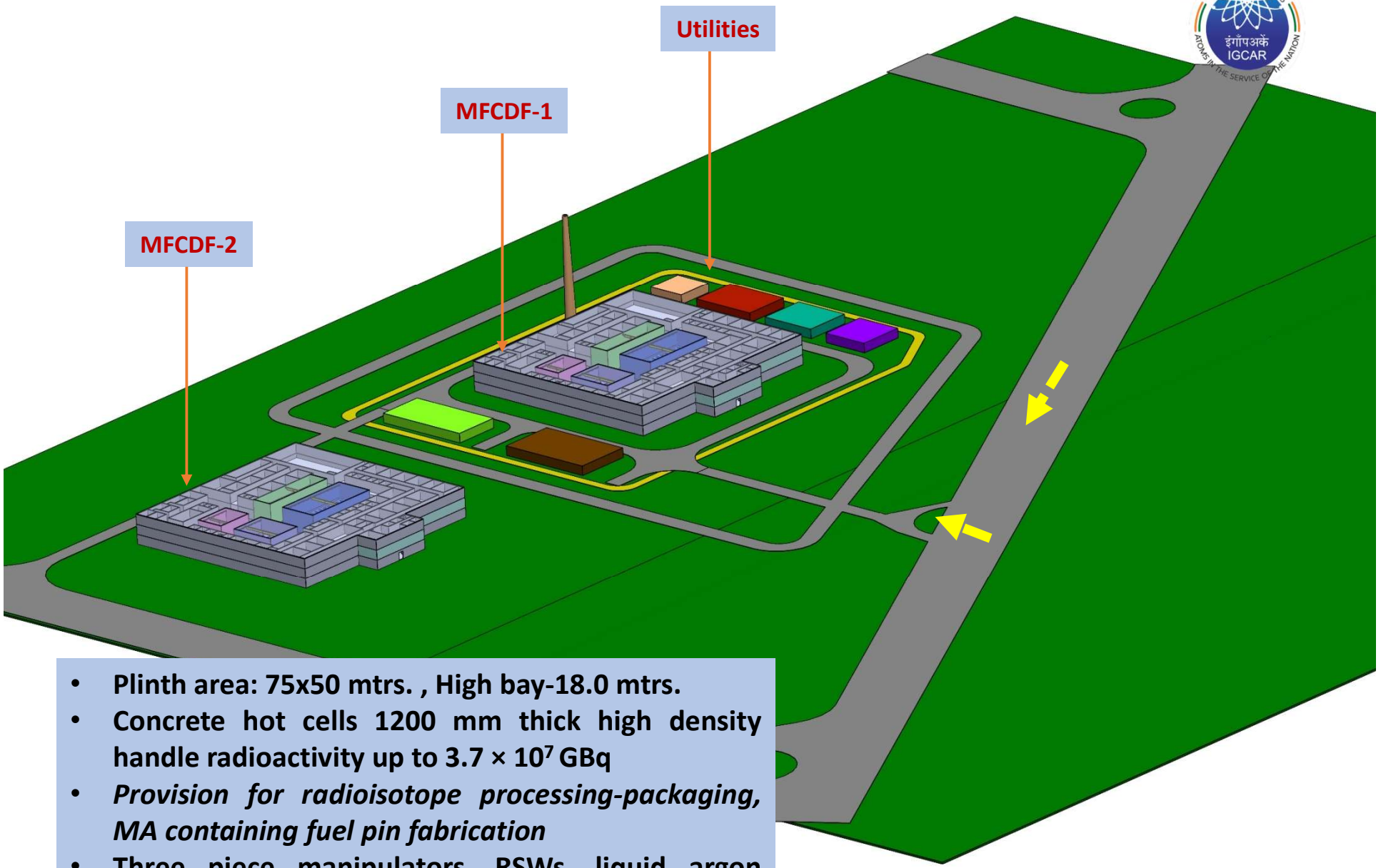
2) Generation IV Forum (GIF)

Practices for designers:

- SIX measures: Technical Difficulty (TD); Proliferation Cost (PC); Proliferation Time (PT); Fissile Material Type (MT); Detection Probability (DP) and Detection Resource Efficiency (DE)
- ***To simplify the assessment process – Facility specific***

To introduce at early design stage to strengthen the proliferation resistance – Facility specific

Metal fuel cycle demonstration facility (MFCDF) – Plant layout



- Plinth area: 75x50 mtrs. , High bay-18.0 mtrs.
- Concrete hot cells 1200 mm thick high density handle radioactivity up to 3.7×10^7 GBq
- *Provision for radioisotope processing-packaging, MA containing fuel pin fabrication*
- Three piece manipulators, RSWs, liquid argon system, Maintenance cells
- 3 SAs/year, MBA & control

Conclusion

We have gained experience in metal fuel fabrication, irradiation in FBTR (research reactor), Pyro processing of spent fuel (gm), Engineering scale uranium handling (kg) where the facilities are co-located in Kalpakkam **(PR addressed with intrinsic features).**

- Future: We are proposing a new research reactor FBTR-2 with co-located Metal Fuel Demonstration Facility (MFCDF) where the PRPP would be implemented in accordance with our national regulatory guidance.
- Task force committees: Tables & Check list, indicators, evaluation parameters are being prepared in the area of PR in house to be vetted by regulators.

References

[1] Updating and Enhancing the INPRO Proliferation Resistance Methodology for Better Sustainability Assessments; Proceedings of the INMM & ESARDA Joint Annual Meeting May 21-25, 2023; C. Scherer et al., 1International Atomic Energy Agency, Austria.

[2] ***INPRO Manual — Proliferation Resistance;*** *Volume 5 of the Final Report of Phase 1 of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO);* **IAEA-TECDOC-1575 Rev. 1**

[3] CONSENTING PROCESS FOR NUCLEAR FUEL CYCLE FACLITIES AND RELATED INDUSTRIAL FACILITIES OTHER THAN NUCLEAR POWER PLANTS AND RESEARCH REACTORS; **AERB Safety Guide; GUIDE NO. AERB/NF/SG/G-2**

[4] Proliferation Resistance and Physical Protection, Position paper by UKNNL

Thank You IAEA

the Organizing committee for giving me an opportunity!