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

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1. OVERVIEW

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 [1]. The technology development work on fabrication of sodium bonded metal fuels and reprocessing the spent metal fuel by pyro-chemical reprocessing route in hot cells is undertaken at Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam. The sodium bonded metal fuel pins in capsules are undergoing test irradiation in Fast Breeder Test Reactor (FBTR) and the discharged fuel pins after target burn-ups are undergoing post irradiation examination (PIE) in hot cells. The results of the PIE have been used as vital inputs for design of metal fuel pins for higher burn up in FBTR and will be reference for future metal fuelled test reactors. The technology involved in metal fuel fabrication & pyro-chemical reprocessing necessitates considering features like receipt form, storage, technical design of equipment, shielding, physical barriers & operational guidelines which has intrinsic proliferation resistance features. The processing of high burn-up fuel, processing of contaminated recycled fuel & re-fabrication facility in hot cells possesses inherent proliferation resistant features.

2. METAL FUEL FABRICATION & CHARACTERISATION

A Metal Fuel pin Fabrication Facility (MFPF) has been set-up and is in operation at the Radiochemistry Laboratory (RCL) in IGCAR, Kalpakkam. The facility led to the development of flow sheet & technology for fabrication of sodium-bonded metallic fuel pins. The facility has demonstrated fabrication of sodium bonded metal fuel pins with U-Zr binary alloy & U-Pu-Zr ternary metal alloy of varied composition [2]. The facility comprises of a fuel fabrication laboratory with glove box line for fabrication of sodium bonded metal fuel pins with plutonium rich metal alloy fuels. An adjacent characterisation laboratory is facilitated with a glove box line housed with process equipment to handle rejected fuel pins & analytical instruments for quality control of fuel alloy & fuel pins. It involved setting up the high purity inert atmosphere glove box line with Programmable Logic Controller (PLC) based control logic for automatic argon gas recirculation and purification system to maintain oxygen / moisture impurities to less than 10ppm. Sodium bonded metal fuel pins containing Nat U-6%Zr, 14.5%EU-6%Zr and U-19%Pu-6%Zr have been fabricated in the facility which were assembled in capsule sub-assembly before loading in FBTR. In continuation to the irradiation programme on metallic fuels in FBTR, metal fuel pins with higher fissile content 71%U[19%EU]-23%Pu-6%Zr to derive higher LHR was fabricated. Metal fuel slugs containing EU-6Zr, U-19Pu-6Zr, 71%U[19%EU]-23%Pu-6%Zr were produced & supplied by Bhabha Atomic Research Centre, BARC, Mumbai.

Currently, programs are underway to fabricate 37 pin sub-assembly (SA) of ferritic steel material (91) hex-can containing metallic fuel pins of higher enrichment to reach higher power & burn-up in FBTR. The new fuel fabrication and SA construction line has been cold commissioned. The new line is equipped with high throughput process equipment to fabricate metal fuel pins of ~1.0 mtr. length. Various fuel fabrication equipment in the glove box line include sodium extrusion process, compact injection casting system (CIC), modular de-moulding machine, slug shearing machine, sodium bonding furnace with kinematic mechanism to handle multiple fuel pins, end plug welding station for ferritic steel (T91) clad tube, post weld heat treatment (PWHT) furnace, alpha tight quick transfer systems attached to transfer ports of glove box etc. FIG.1 shows the qualified compact injection casting equipment & FIG.2 shows a de-moulding machine inside glove box. To improve quality in each stage of fuel pin fabrication process, data monitoring-cum-capturing related to each process has been established for data analytics.

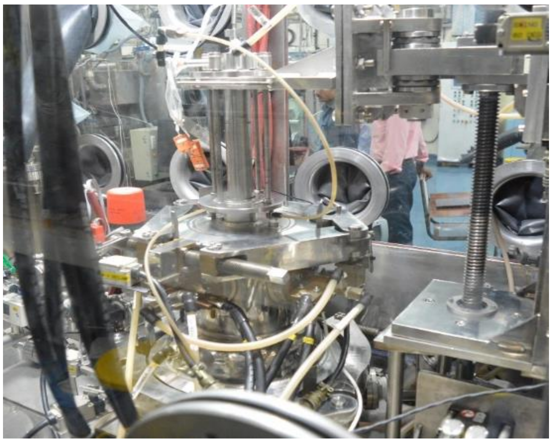


FIG.1 CIC equipment with safety features

FIG.2 De-moulding machine

The CIC furnace for melting & casting is qualified to cast fuel slugs of ternary alloy composition in a batch mode. The dual frequency induction heating furnace equipped with pulse width modulation (PWM) circuit is designed for a pouring temperature of 1450°C-1550 °C & electromagnetic stirring for better alloy homogeneity. The glove box housing casting system is designed with engineered safety features & defense in-depth concept to handle high temperature hazard involving reactive material. The solid induction coil with power electronics complies to safety regulations to be adhered inside inert atmosphere glove box (FIG.3). The glove box line also houses a gravity casting system (GCS) with vacuum induction system for melting charge containing high melting point alloying elements (Zr, Mo) to melt/cast ternary alloy and to optimise alloy making process. The design features of GCS is shown in FIG.4. The GCS addresses the over pressure issues in other casting methods inside glove box and facilitates flexibility in casting fuel slugs of varied alloy parameters.

FIG.3 Induction coil testing with automation

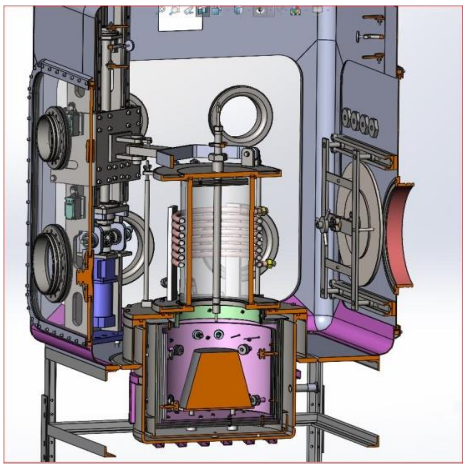
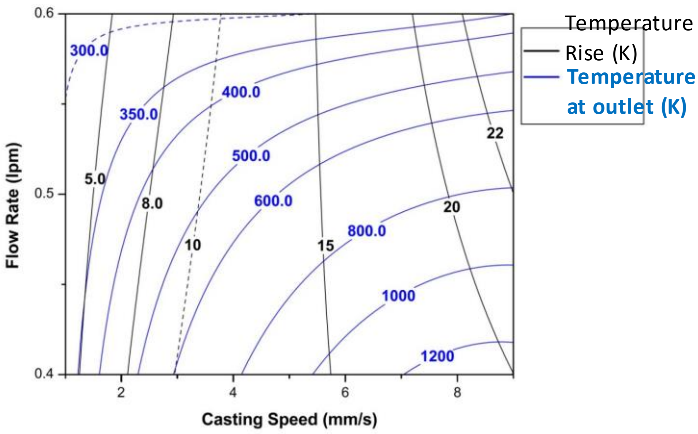


FIG.4 Gravity casting system

The uranium handling laboratory houses facilities for producing blanket fuel slugs of U-6Zr. The facilities include an automated injection casting equipment of 10.0 kg capacity inside glove box to produce blanket slugs in large numbers. Each batch can produce ~50 slugs with an acceptance rate of ~75% and the rejects are recycled in the next batch [3]. A continuous casting system of 1.0 kg capacity has been developed & commissioned to avoid the left-out heel in the graphite crucible in other casting process and to produce slugs at a high casting rate with preferable grain structure. During initial runs with graphite mould failures like slug breaking during withdrawal was encountered. After modifying the mould design with a silicon nitride liner, U-6Zr blanket slugs could be cast without remains in the crucible. Casting modeling & heat transfer analysis was carried out using commercial software to find out the optimum conditions such as the inlet velocity with the graphite mould at a pre-heat, so that the molten liquid uranium alloy on travel does not solidify in the middle and reaches the bottom of the cast. Variation of the outlet temperature of the U-Zr cast slug & the temperature rise of cooling water at different casting speeds and flow rate is shown in FIG.5. The liquid fraction contour was predicted for a quantitative measure of the amount of liquid metal that is undergoing phase change to solidify. Defect free U-6Zr blanket slugs could be produced and it is established that continuous casting is a promising route for uranium based binary alloy blanket slugs. Towards remotisation, fibre laser based cutting of binary alloys slugs is being optimized (FIG.6).



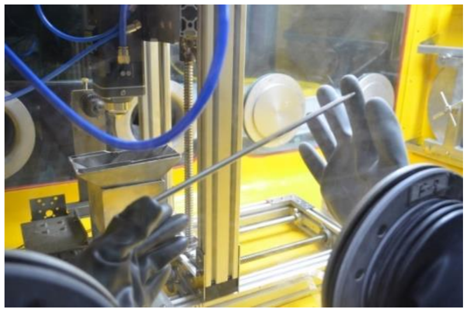


FIG.5 Temperature analysis in continuous casting FIG.6 Trial cutting of U-6Zr slugs using fibre laser

The quality control laboratory is equipped with a glove box line which houses machine vision based slug inspection system, sodium bond quality check system, pin cutting & sodium retrieval, puncturing & gas analysis, metallography systems etc. [4] FIG.7 shows the machine vision based slug inspection system inside glove box & FIG.8 shows the fuel characterisation facility inside glove box.

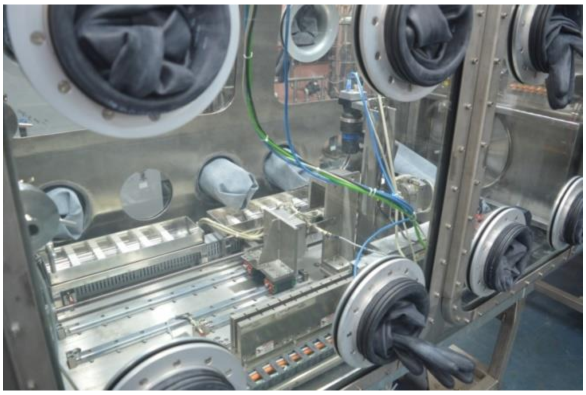


FIG.7 Machine vision based slug inspection FIG.8 Characterisation bench

3. PYRO-CHEMICAL REPROCESSING OF SPENT METAL FUEL

Spent metal fuel pins haven been taken up for pyro-chemical reprocessing in hot cells. The existing hot cell design meant for chemistry related PIE has been exhaustively refurbished for handling & pyro-processing the spent sodium bonded metal fuel pins. The hot cell houses receipt of chopped fuel, automated high temperature electro-refining cell, salt storage vessels, cathode deposit storage vessels etc. FIG.9 shows chopping of sodium bonded metal fuel pins, FIG.10 shows electro-refining process on low burn-up spent metal fuel and FIG.11 shows the automation setup for pyro-processing of 'U' alloy in containment box [5]. Adjacent hot cells are being facilitated with cathode distillation & consolidation, salt distillation, actinide draw down system etc.

A large scale R&D facility for uranium based pyro-processing involving 1 kg & 10 Kg U alloy/Batch is in progress. The facility has demonstrated automation & remotisation of important process steps of pyro-chemical reprocessing at engineering scale. Uranium electro-refining & cathode product consolidation campaign have been successfully completed in this facility. The fixed automation systems incorporated for various processes in hot cell will give feedback while designing a complete hot cell based shielded facility for metal fuel in future.

FIG.9 Chopping of pins

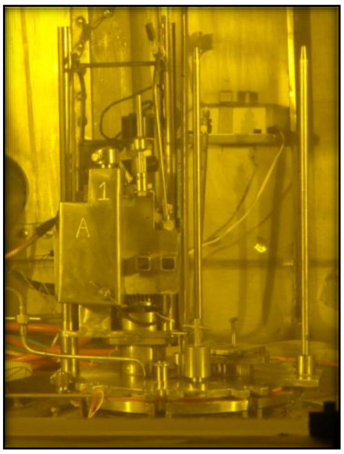


FIG.10 ER cell inside hot cell

FIG.11 Automation for pyro process

The shielded facility is envisaged in the next plan which will be a compact hot cell operated by articulated manipulators where, one line will cater to the pyro-chemical reprocessing of spent fuel and a parallel line will cover remote re-fabrication to demonstrate the closed fuel cycle.

The metal fuel cycle technology has been demonstrated in gram scale involving fresh fuel fabrication & pyro-processing of low burn-up metal fuel in hot cells is completed successfully. Taking the technology to next scale is under development & yet to be demonstrated. In the ongoing metal fuel program each fuel cycle laboratory & test reactor (FBTR) is co-located at the same site.

The technology of pyro-chemical reprocessing & re-fabrication facility in hot cells possesses inherent proliferation resistant features. In the process of design of a new facility, due considerations are given to facility layout, accessibility, physical barriers, detection techniques, material balance, equipment design, interlocks in process automation etc. in perspective of proliferation resistance.

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CONCLUSION

The paper has highlighted the design, operation & maintenance and remote handling experiences gained during the metal fuel fabrication campaigns for the irradiation program in FBTR, hot cell up-gradation to house pyro-processsing equipment & pyro-chemical reprocessing of spent metal fuel from FBTR, engineering scale pyro processing facility of uranium alloy and the conceptual hot cell design concepts. Apart from the inherent technological characteristics of metal fuel cycle technology in terms of proliferation resistance, due importance is being given in this perspective at every stage of design of the facility.

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