FABRICATION OF SIMULATED MID-BURNUP CANDU FUEL IN THE RFFL

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ABSTRACT

Prediction of the coefficient of void reactivity for CANDU® reactor cores is key to modeling postulated loss-of-coolant scenarios to support safety analyses. To reduce the uncertainty in these predictions, computer codes used to generate the predictions have to be well validated for cores at equilibrium burnup. To this end, a COG*-funded project was launched to resume mixed oxide (MOX) fuel fabrication operations in the mothballed Recycle Fuel Fabrication Laboratory (RFFL) at CRL, and produce $(U,Pu)O_2$ fuel simulating mid-burnup CANDU fuel for physics testing in the ZED-2 reactor.

In August 1996, rehabilitation of the RFFL was completed, and MOX operations were resumed in the facility. An up-to-date description of the RFFL, including the upgraded safety systems and process equipment, is presented. An overview of the fabrication campaign to produce 37 MOX fuel bundles for ZED-2 tests is given. The fabrication process used to manufacture the fuel from the starting powders to the finished elements and bundles is summarized. Fabrication data including production throughputs and inspection results is discussed.

1. INTRODUCTION

Prediction of the void reactivity for CANDU lattices is key to modeling postulated loss-of-coolant scenarios to support safety analyses. Good validation of the computer-code prediction of void reactivity exists for cold, clean lattices, but not for cores at equilibrium burnup.

The experimental difficulty and cost of conducting tests on highly radioactive fuel bundles in ZED-2 have so far precluded code validation on mid-burnup fuel. However, the option of simulating the neutronic characteristics of mid-burnup fuel without the intense radioactivity,

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* COG: CANDU Owners Group, consists of AECL, Ontario Hydro, Hydro Quebec and New Brunswick Electric Power Corporation.

coupled with the recent development of substitution techniques in reactor physics testing make such experiments practical and cost-effective.

During in-reactor service, the U-235 in natural uranium CANDU fuel is burned, while Pu and fission products are produced. Accordingly, the simulation of mid-burnup natural uranium CANDU fuel required MOX fuel consisting of 0.30% Pu in depleted U (0.37% U-235) plus 0.05% dysprosium to simulate the fission products. The ZED-2 experimental set-up requires a sufficient number of MOX fuel bundles to assemble a 7-channel array, each channel consisting of 5 fuel bundles.

Based on the results of a feasibility study in 1993, COG Working Party 25 (Radiation and Reactor Physics) recommended that the batch of MOX fuel bundles be fabricated in the Recycle Fuel Fabrication Laboratory (RFFL) at CRL. The RFFL, a facility designed to fabricate various types of MOX fuel, was operational from 1979 to 1988 [1]. However, since 1988, it had been in a state of active standby, a condition where no fuel fabrication activities were conducted, but the monitoring and ventilation systems in the facility were maintained. Following endorsement by the Technical Committee, a COG-funded project was launched in November 1993 with the following objectives:

- Rehabilitate the RFFL and secure regulatory approval to resume MOX operations, and
- Fabricate 37 MOX fuel bundles for ZED-2 tests.

2. RFFL REHABILITATION

2.1 Scope of Rehabilitation

A series of Fitness-for-Service studies and a Hazards and Operability (HAZOP) analysis were conducted to define the scope of the rehabilitation of the RFFL. These assessments generated numerous recommendations for specific action. Major "hardware" actions included bracing the building to meet the most current (1990) National Building Code of Canada seismic standards, replacement and upgrade of the Radiation Protection (RP) systems, addition of an alpha-in-air sampling system between the primary and secondary High-Efficiency Particulate Air (HEPA) filters in the ventilation exhaust train, and extension of the alarm display system.

The rehabilitation project also included a considerable "software" component, including extensive new and revised documentation with particular emphasis on safety and licensing, and staffing and training activities to re-staff the facility. All activities were done with extensive liaison with AECL's internal safety body (the Safety Review Committee, SRC) and with the Atomic Energy Control Board (AECB).

2.2 Laboratory Services and Process Equipment

As identified in the fitness-for-service assessments, renovations and upgrades required in the structural, electrical, mechanical services, and security areas were completed. Several structural braces were installed in the facility and the surrounding building to upgrade the facility's seismic qualification to meet the National Building Code of Canada 1990 standards. Modifications to the ventilation system (due mostly to the new glove boxes) were installed. In addition, all HEPA filters in the facility were replaced as part of the re-balancing of the ventilation system.

All of the equipment in the process line were tested for functionality, and repairs and overhauls were done as required. Some components were identified as needing replacement including dies for the final press, controllers for the sintering furnaces, and several balances. The Fitness-for-Service review indicated that some equipment should be replaced, such as those for metallographic preparation and examination (i.e., cut-off saw, grinding and polishing equipment, and microscope). Chemical analytical capability was re-acquired, and two new glove boxes were installed housing dissolution equipment, a furnace, and a high precision balance. In addition, a coulometer to measure Pu concentrations in samples was installed in one of the fume hoods.

New components were also brought in to update the capabilities of the facility. A new PuO_2 reception glove box was installed housing the can opener, which is used to de-can welded PuO_2 containers both for the production line and for purposes of sampling and re-packaging. A mastermix high-intensity blender was acquired to enable a double-stage blending operation for homogeneous mixtures containing dilute concentrations of MOX fuel. A new helium leak detector was procured for quality inspection of welds.

2.3 Radiation Protection

Radiation protection in the RFFL is based on the following principles:

- Division of the facility into zones of progressively greater contamination hazard with personnel monitoring at each boundary on exit,
- Operation of a system of alpha continuous air monitors (CAMs), distributed through the facility and set to alarm at a pre-determined level of airborne alpha activity, and
- Operation with Personal Air Samplers (PAS) for all staff doing work in the facility. The PAS filters are analyzed daily as a routine, and as required (e.g., if an alpha CAM alarms).

The distributed alpha CAM system that had been used in the facility during previous operation was replaced with a state-of-the-art commercial system. To optimize the number and location of the sampling heads, particularly in terms of response time to activity release, a quantitative air-flow study was conducted in the main fabrication room. Other radiation protection equipment that were replaced include the hand and foot monitors for personnel monitoring and the criticality monitor.

2.4 Operations Quality Assurance

The RFFL is a licensed nuclear facility that comes under the AECL Nuclear Operations Quality Management Program. The RFFL Conduct of Operations Manual complements the AECL Nuclear Operations Quality Manual, and, together with the operating procedures, comprises the QA documents that describe the system for assuring the quality of operations in the RFFL. The Manual describes the RFFL organization, responsibilities, processes and controls that demonstrate application of the principles and practices specified in the standard, CAN/CSA-N286.5-M87 Operations Quality Assurance for Nuclear Power Plants. It also describes how MOX fuel is fabricated to the requirements of the CAN/CSA Z299.2 QA program standard. Thus, the Manual, comprising of 40 procedures, describes the measures implemented in the RFFL to ensure both operational safety and product quality.

2.5 Nuclear Materials Accountability

As part of the Rehabilitation Project, a new system was developed to meet International Atomic Energy Agency (IAEA), AECB and AECL requirements for nuclear material inventory control, and to support Operations' responsibility for criticality avoidance. This system, RFFL Nuclear Materials Accountability System (RNMAS), was developed in Microsoft Access® V2.0 in accordance with the software QA provisions of CAN/CSA-N286.7. The system runs on a dedicated Pentium-based PC with dedicated data backup, and features graphical point-and-click operations, and predefined pick-lists to optimize user-friendliness. RNMAS was developed, tested and commissioned during the Rehabilitation Project, and was successfully implemented in the ZED-2 fabrication campaign.

2.6 Staffing and Training

RFFL staff involved in its previous operations are no longer with AECL, and new technical staff were recruited, evaluated and trained for the facility. This process followed a comprehensive training plan, which was developed in accordance with AECB-approved Company policies and practices. As part of the plan, an extensive job/task analysis and personal needs analyses for the job candidates were conducted to determine training requirements. This was followed by the development of facility-specific training materials to complement existing company generic courses.

Implementation of the training plan involved Nuclear Operations Training School (NOTS) for science fundamentals, equipment principles, and AECL generic policies and procedures; Radiation Protection Training for Group 3, Group 2 and Group 1 training requirements; facility-specific classroom training for job-specific knowledge; and on-the-job training (OJT) to develop and evaluate operational skills.

2.7 Documentation

Many documents were prepared and issued during the rehabilitation project, which could be categorized into the following general areas:

- Safety and Licensing - Examples include the Safety Analysis Report, the updated Principles and General Rules for the RFFL, the Facility Authorization, the Facility Authorization Basis Document, Fitness-for-Service Reports, HAZOPs report, the Criticality Safety Document, Technical Basis for Internal Dosimetry in Pu Handling Facilities, Environmental Assessment Report, Security Plan, and the Safeguards Design Information Document.

- Quality Assurance - including the Project QA Plan, Conduct of Operations Procedures, the Commissioning QA Plan, and the Software QA Plan.
- Staffing and Training - including the Training Plan, Job/Task Analysis Summary, RFFL Organizational Analysis Report, RFFL Training Objectives, Training Course Materials, and the Manual of OJT Guides.
- Nuclear Materials Control - including the Statement of Requirements for Fissionable Material Accountability in the RFFL, the Software Development Plan, System Requirement and Design Document, General Test Plan, Unit Testing Procedures, Integration Testing Procedures, User Acceptance Testing Procedures, and the Technical/User Manual.
- Commissioning - including the Commissioning Plan and the Commissioning Procedures for each of the seven systems.
- Operations - including the Emergency Procedures, the Manual of Operating Procedures, the Maintenance Plan, the Waste Management Plan, and the Post-Campaign Plan.

2.8 Commissioning

For the commissioning phase of the project, the Commissioning Plan was prepared to define the systems to be commissioned and the objectives for each. The Commissioning QA Plan defined the roles and responsibilities for each member of the project, and provided the link between AECL's Commissioning QA Program and the RFFL activities.

The task of commissioning the RFFL proved to be much more extensive than anticipated. Preparation of commissioning procedures and completion of remaining field work on the systems and equipment that would be commissioned (e.g., the distributed alpha CAM system and the ventilation system) took longer than originally estimated. It should be noted that while there are only seven systems that needed to be commissioned, each system consists of several sub-systems and equipment as follows:

- Electrical services - Class I (telephone system), Class III and Class IV power.
- Mechanical services - service air, breathing air, fire water, service water, service steam, storm drains, sanitary drains, active drains, communications system, and waste management.
- Heating, ventilation and air conditioning - supply, recirculation, exhaust, and integrated systems.
- Manual fire suppression - portable fire extinguishers, manual mode of the built-in Halon system, manual alarm stations, and fire hoses.
- Confinement - perimeter walls and doors, and glove boxes.
- Instrumentation and Control - fire detection and alarm systems, alpha-in-air alarms, criticality alarm, flood alarms in glove boxes and working rooms, glove box differential pressure alarms, exhaust fan failure alarm, low hazard gamma radiation alarm, and their interfaces with the integrated graphic display panel and the various slave panels.
- Fuel Fabrication - from powder reception and blending through welding and alpha scanning of the finished elements.

To illustrate the extensive nature of the commissioning activities, the commissioning procedure for the Instrumentation and Control system alone, including checklists and datasheets, was 61 pages long. This was one of the first applications of the Company's commissioning QA program. In addition, non-conformances discovered during commissioning needed to be resolved. Some non-conformances were minor, e.g., related to procedures, but some were quite significant and safety-related. One notable example is the ventilation system. During the commissioning activities, it became obvious that the ventilation system was not operating according to design intent, and in essence, this was the very first time this system was being commissioned. Overall, it was found that a much larger scope of work was involved in the commissioning activities.

Commencement of commissioning of the fuel fabrication line was conditional on completion of the commissioning of the other facility services, and resolution of safety-related action items from both the Fitness-for-Service Assessments and HAZOPS. Any unresolved safety-related item on any system affecting the equipment in the process line was identified, and the affected equipment tagged out until the item was dispositioned. Two 10-kg commissioning batches of depleted UO_2 (without any Pu) were processed through the whole fabrication line, and the finished fuel elements were used to assemble a commissioning bundle.

All facility operating procedures, including normal, special and maintenance operating procedures, were reviewed and approved for use. Modifications made during commissioning were incorporated as revisions, which were issued for MOX operations. These procedures were also used during OJT sessions on the process line. Following this successful commissioning phase, the Rehabilitation Project was declared complete, and the facility ready for the introduction of Pu and resumption of MOX fuel operations.

3. ZED-2 FABRICATION CAMPAIGN

3.1 Fabrication Process in the RFFL

Subject to special precautions because of the presence of Pu (e.g., essentially all operations are done inside glove boxes), the processes employed in the RFFL follow conventional natural UO_2 practice. The fabrication line was designed for the production of sealed individual fuel elements, starting from UO_2 or ThO_2 powders as the major component and PuO_2 as the minor component.

The fabrication process adopted in the RFFL is outlined in Figure 1. The starting PuO_2 is first sieved through a 44-micron screen, and the appropriate amount corresponding to the MOX batch size is weighed. The PuO_2 (and the Dy_2O_3 for this particular campaign) is then blended with the UO_2 using a high-intensity mixer to produce a mastermix containing about 3 wt.% Pu. This mastermix is then blended with more UO_2 to arrive at the final concentration of the MOX powders. Final blending is done using a Turbula blender. This two-stage blending helps achieve better homogeneity in the finished fuel.

After final blending, the MOX powder is pre-pressed using an isostatic press, to convert the mixed powder into compacts, which are, in turn, fed into a granulator. Zinc stearate (for die lubrication) is mixed in with the resulting free-flowing granules, which are then suitable for final pressing into green pellets using a single-cavity hydraulic press.

The green pellets are placed into molybdenum trays, and loaded into one of two batch furnaces, where sintering is done in a dilute hydrogen cover gas (10% H_2 in N_2) at a temperature of 1700°C. Sintered pellets are then centreless ground to a specified diameter and surface finish. The pellets are washed and then dried in warm air. Acceptable pellets are formed into specified stack lengths, and loaded into empty sheaths that already have one end cap welded and all appendages brazed in place (these sub-assemblies are supplied by commercial fabricators). The second end cap is welded to the loaded sheath using a tungsten inert gas (TIG) welding system. The sealed elements are then helium leak-tested, scanned for surface alpha contamination, weighed and visually and dimensionally inspected prior to bundle assembly.

3.2 Production Throughput

The fabrication campaign to produce thirty-seven $(U,Pu)O_2$ bundles for reactor physics tests in ZED-2 was started in August 1996, and it was successfully completed in March 1997. In the RFFL, the batch-type fabrication process was originally designed to have a throughput of one 15 kg-batch of MOX fuel per day. During the recently concluded fabrication campaign, production throughput averaged 0.6 batch (each batch weighing 11 kg MOX) per day, with a peak throughput of 1.2 batches (about 13 kg MOX) per day. Overall, 77 batches of MOX fuel totaling about 820 kg of finished MOX fuel pellets were fabricated into more than 1370 finished fuel elements over a period of 26 weeks.

3.3 Fabrication Data

In accordance with the Manufacture, Inspection and Test Plan (MITP), several in-process inspections were conducted during the ZED-2-96 campaign. An important parameter to monitor is the immersion density of sintered pellets; this is indicative of the consistency of pressing and sintering operations. Also, to simulate the fuel weights contained in actual CANDU fuel bundles, the sintered density of the pellets must be as close as possible to the specifications. As shown in Figure 2, pressing and sintering was quite consistent resulting in sintered densities between 95 and 98% of the theoretical value (10.96 g/cc).

Of prime importance in this fabrication campaign is the fuel composition - its actual value and the batch-to-batch consistency. To maintain control over this parameter, weights of the starting powders were strictly monitored and recorded. Chemical analysis (coulometry for Pu content; high performance liquid chomatography for Dy content) of the finished pellets was used to confirm the accuracy of the batch components. As shown in Figure 3, the fuel composition was maintained at 0.30 wt.% Pu and 0.05 wt.% Dy in H.E. with very little variability. These calculated concentrations were confirmed by the measured values from chemical analyses of finished pellets. In most cases, the calculated value was within the precision of the chemical analysis. When the calculated and measured concentrations are compared, the average difference for the Pu and Dy contents is about 1% and 3%, respectively. Of the 77 batches processed, there is one batch whose chemical analysis indicated a difference of about 8-9% from the calculated values of Pu and Dy contents - Batch 30. Further repeats of the chemical analysis confirmed the low Pu and Dy contents. A non-conformance was raised against this batch, and an investigation identified the cause. This information was relayed to the customer.

One inspection technique of interest is alpha autoradiography used in combination with image analysis to determine Pu particle size and distribution. Preliminary data analysis indicates that the average Pu particle size was about 20 microns, with a maximum of about 50 microns. Further work in correlating the information obtained from autoradiography with X-ray wavelength dispersive spectrometry (WDS) to quantitatively determine local Pu concentration and provide an accurate Pu distribution profile is continuing (see related paper in this conference by Z. He et al.).

4. CONCLUSIONS

To reduce the uncertainty in the predictions of the coefficient of void reactivity for CANDU cores, a COG-funded project was launched to produce $(U,Pu)O_2$ fuel in the RFFL. This fuel simulates mid-burnup CANDU fuel, and will be used in physics tests in ZED-2 to validate the codes used to predict void reactivity.

In August 1996, rehabilitation of the RFFL was completed, and MOX operations were resumed in the facility. The new RFFL, together with its upgraded safety systems, refurbished process equipment, and fully qualified technical staff, is now operational. The fabrication campaign to produce 37 MOX fuel bundles for ZED-2 tests was successfully completed in March 1997, demonstrating the capability of this strategically important facility. Fabrication data, especially those crucial to the ZED-2 tests, are being analyzed, consolidated, and documented for the customer.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] CARTER, T.J., “The Recycle Fuel Fabrication Laboratory at Chalk River”, Proc. Int. Conf. CANDU Fuel, 1986, Chalk River, Ontario, Canada, (I.J. Hastings, ed.), Canadian Nuclear Society, Toronto (1986), pp. 168-176.

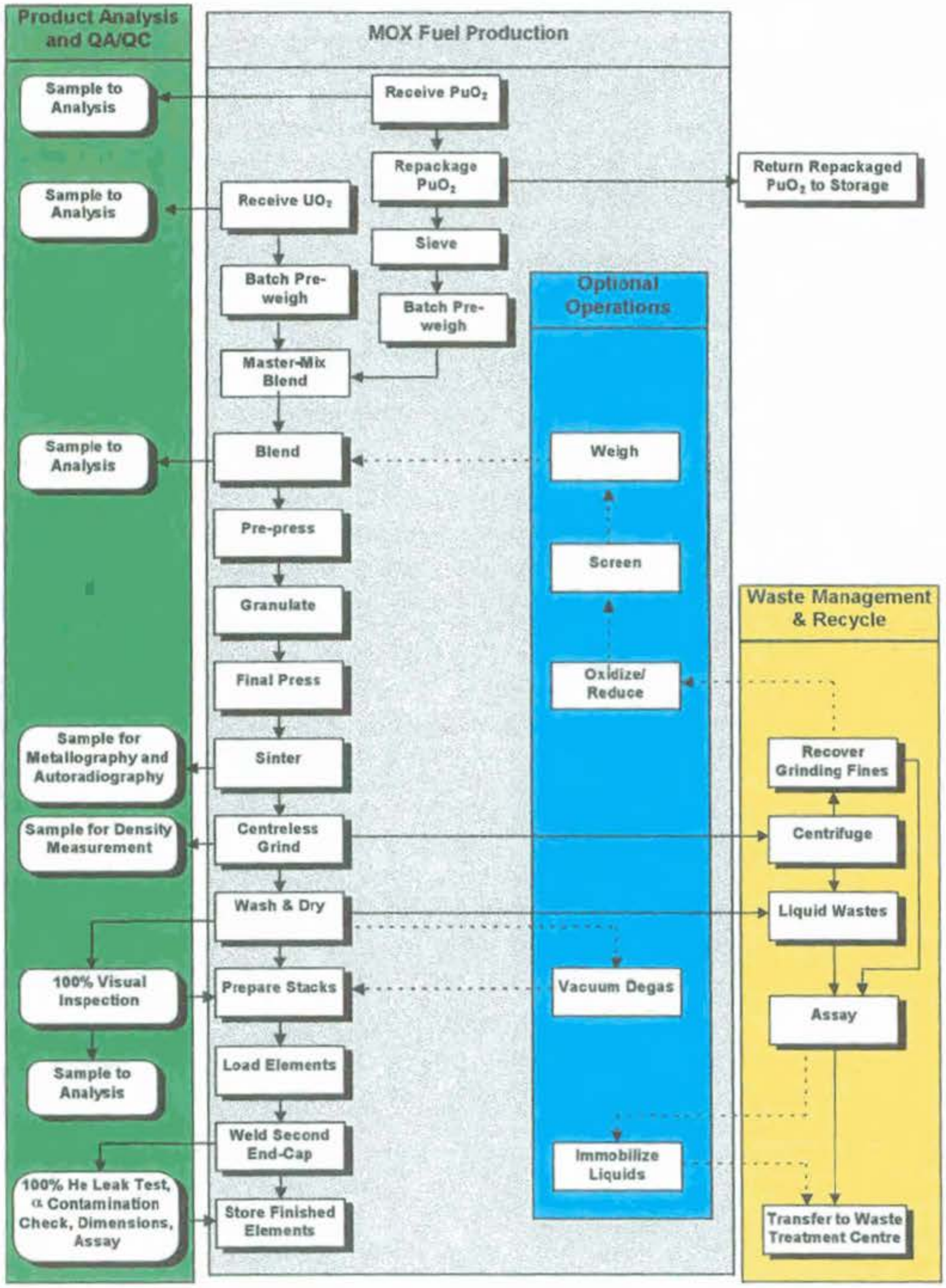

FIGURE 1. RFFL FABRICATION PROCESS FLOWSHEET

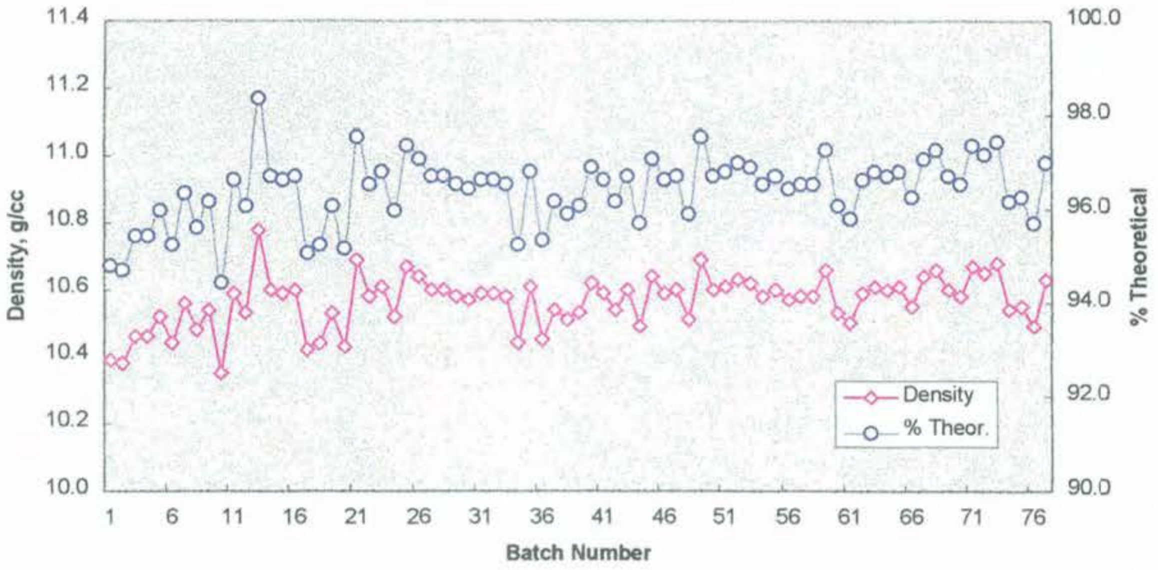

FIGURE 2. IMMERSION DENSITY OF SINTERED MOX FUEL PELLETS DURING THE ZED-2-96 FABRICATION CAMPAIGN

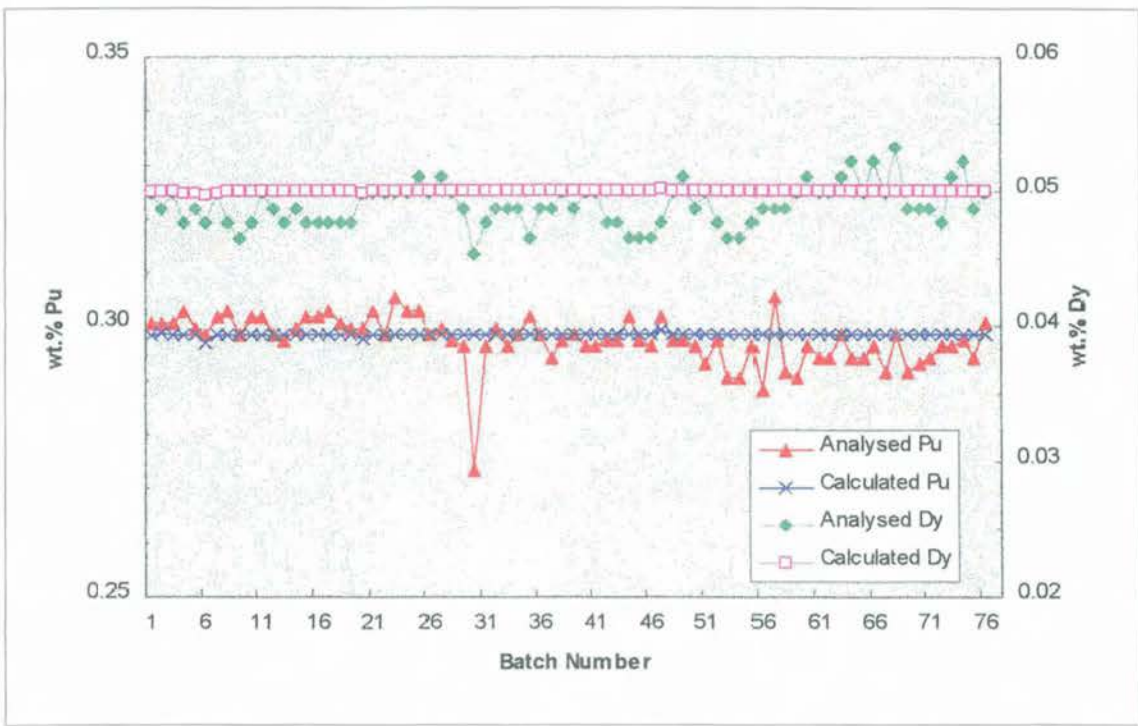

FIGURE 3. COMPOSITION OF MOX FUEL BATCHES OF THE ZED-2-96 CAMPAIGN