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Advances in Metallic Fuel Database Development and Data Qualification

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INTRODUCTION

The Fuels Irradiation and Physics Database (FIPD [1]) is a comprehensive repository of data and documents related to Uranium-Zirconium based metallic fuel test pins. This database stores operational conditions of these pins, calculated using a suite of Argonne National Laboratory analysis codes developed during the Integral Fast Reactor (IFR) program. Key calculated data include axial distributions of power, temperature, fluence, burnup, and isotopic densities. Additionally, the FIPD holds post-irradiation examination (PIE) data such as fission gas release, gas chemistry measurements, and axial distributions derived from profilometry, gamma scanning, and neutron radiography. Complementing these data is an extensive archive of documents related to various pins and experiments. These include raw PIE records, design details, safety analyses, and operational reports. More detail about FIPD can be found in ref. [2].

The database development is an ongoing effort covering metallic fuel experiments from the Experimental Breeder Reactor II (EBR-II) and the Fast Flux Test Facility (FFTF). The recent improvements to the database and the data QA status are summarized in this paper.

EBR-II METALLIC FUEL DATA

Data stored in FIPD cover an extensive range of materials and operating conditions to accommodate industry and other stakeholders needs. The fuel compositions include U-xPu-10Zr (with 'x' values of 0, 3, 8, 19, 22, 26, 28), and U-xZr (with 'x' values of 2, 6, 10). Three fuel cladding types are included; 316SS, D9, and HT9. The smeared density of the fuel pins covers a range from 58% to 90%. The plenum to fuel volume ratio of the fuel pins varies from 1 to 3. The fuel diameter ranges from 0.168 to 0.313 inches (or 0.427 to 0.795 centimeters). Detailed fuel fabrication data of the fuel pins are available in FIPD.

The fuel pins were irradiated at different conditions. In FIPD, the peak burnup of the metallic fuel pins ranges from 0.5–20 at%, and their cladding temperature ranges from 490 to 660 °C. The peak linear power of the fuel pins covers a range from ~10-19 kW/ft (~33–62 kW/m). These operating parameters were determined using Argonne's physics and thermal hydraulics codes, previously applied in EBR-II simulations, including REBUS, EBRFLOW, RCT, and SUPERENERGY-II, etc.

Considerable work in developing FIPD involved gathering, reviewing, processing, and integrating PIE data. A substantial amount of PIE data, over 90% of the PIE data from the EBR-II fuel pins irradiated during the IFR program have already been incorporated into FIPD. Table I lists the primary types of PIE data that are currently going through a data qualification process.

TABLE I. Key PIE Data in FIPD

Type	Measurement & Analysis
Contact profilometry	Fuel cladding diameter/swelling
Laser profilometry	Fuel cladding diameter/swelling
Neutron radiography (NRAD)	Fuel slug axial and diametral swelling
Isotopic gamma scan data	Isotopic axial distribution; fuel slug axial swelling
Fission gas release data	Fuel plenum volume and pressure; amount of fission gas
Fission gas chemistry data	Fission gas composition and isotopic analysis of Xe and Kr
Metallography data	Microstructure; fuel-cladding chemical interaction (FCCI)

FFTF METALLIC FUEL DATA

During the IFR program, several key experiments were performed in FFTF, including IFR-1 and Metal Fuel in FFTF (MFF) series experiments [3]. The effort to incorporate the PIE data of these experiments into FIPD was initiated in 2023, supported by the Department of Energy (DOE) Advanced Fuel Campaign (AFC). Top priority was given to adding three experiments to FIPD: IFR-1, MFF-3, and MFF-5. Fig. 1 displays the IFR-1 experiment, now part of FIPD, where raw PIE data can be downloaded. Fig. 2 shows an example of the raw PIE data: raw contact profilometry data from fuel pin 181175. The raw data follows the measurement descriptions given in the contact profilometry specification [4]. Corresponding digitized data are available in ref. [5]. The qualification process for both PIE and operational data of FFTF metallic fuel experiments

is ongoing. Ref. [6] shows an example of use of operational data, and profilometry of some of the MFF pins.

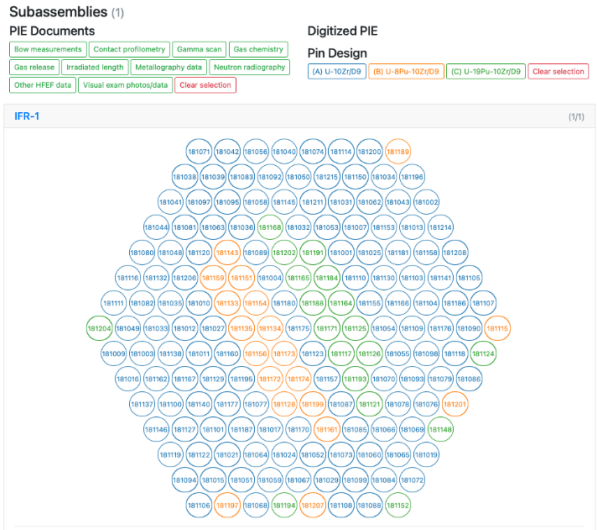

Fig 1. FFTF IFR-1 experiment in FIPD.

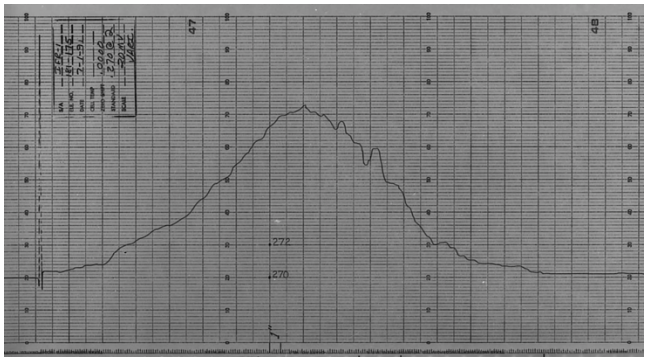
Fig 2. Raw contact profilometry data from fuel pin 181175 irradiated in FFTF IFR-1 experiment.

DATA QUALIFICATION STATUS

Qualified metallic fuel data are essential for the licensing of advanced reactor designs that utilize metallic fuel. It also supports various activities such as modeling and simulation, fuel performance code development, material model development, and serves a range of end users including different DOE programs (e.g., Nuclear Energy Advanced Modeling and Simulation (NEAMS), and the Advanced Reactor Demonstration Program (ARDP)), as well as educational institutions.

QUALITY ASSURANCE PROGRAM PLAN

To manage the extensive volume of data and associated documents in FIPD, and to qualify the data to support metallic fuel licensing activities, Argonne has established a Quality Assurance Program Plan (QAPP) [7] for the legacy metallic fuel data in the FIPD. The QAPP serves as the principal policy document that outlines the methodology for assuring quality in the SFR legacy metallic fuel data. In 2020, the Nuclear Regulatory Commission (NRC) concluded its review of the QAPP and determined that it satisfied the quality assurance (QA) requirements of Appendix B to Title 10 of the Code of Federal Regulations (10 CFR) Part 50. Subsequently, an NRC audit was conducted on the implementation of the QAPP, which concluded that the appropriate quality controls were implemented for the qualification of the legacy data and the associated documentation.

Among the qualification methods allowed in the QAPP, the peer review method has been chosen to qualify the metallic fuel data. This method assesses whether the original employed QA methodology is acceptable, whether confidence is warranted in the data acquisition or developmental results, or if the data have been used in a similar range of applications [8]. One or more subject matter experts (SMEs) with expertise in fuels and materials are assigned to perform the data evaluation. Their assessment is based on the requirements described in the NQA-1 standards, and they are tasked with determining whether the data are acceptable.

FIPD DATA SPECIFICATIONS

The raw PIE data in FIPD were sometimes difficult to interpret due to the limited supporting documents available. For example, for some of the contact profilometry measurement, the top and bottom of the fuel pins were typically not given in the raw data, as shown in Fig. 2. The scales for the x and y axes were sometimes manually drawn. And there is no description of measurement accuracy. These pieces of information are vital for FIPD developers and data analysts for data interpretation, digitization, and qualification. For later profilometry data, for most of the MFF pins, the data were digitally recorded and many of the problems found in earlier contact profilometry measurements were avoided.

To further resolve those issues relevant to other measurements, a specification document has been developed for each type of PIE measurement. These documents outline the principles of data interpretation and provide additional relevant information to comprehend the measurement process. The process begins with gathering measurement records, instrument manuals, calibration records, and previous QA documents from Argonne and INL. Utilizing this collected data, one or more SMEs commence drafting the specification. Upon completion, the draft is sent to an external reviewer, who possesses extensive experience and knowledge in the measurements. The reviewer's feedback is addressed. Following concurrence of the external reviewer, the specification is then shared with some of the FIPD users for their review. Should any revision requests arise, the SME(s) will reassess and respond to the comments from the users. Involving both external SMEs and industry users in the review process improves both the quality and practicality of the specification.

At the time of publication, the specifications for five types of PIE data have been finalized and published in reports, which are now openly accessible via the U.S. Department of Energy Office of Scientific and Technical Information (OSTI). These include:

- ANL-CFCT-22-19 – Specification of EBR-II Gamma Scan Data from the Precision Gamma Scanner [9]
- ANL-CFCT-22-20 – Specification of EBR-II Contact Profilometry Data [4]
- ANL-CFCT-22-21 – Specification of EBR-II Laser Profilometry Data [10]
- ANL-CFCT-22-22 – Specifications of EBR-II Neutron Radiography Method Description and Digitization Approach [11]
- ANL-CFCT-23-15 – Specifications of FIPD Fission Gas Release Data [12]

Other PIE data specifications, such as those for fission gas chemistry and metallography data, are currently being drafted, and planned to be published soon.

DATA QUALIFICATION WORKFLOW

As previously stated, the peer review method has been selected for qualifying the metallic fuel data. The QA process, conducted by SMEs, begins by identifying the specific data for qualification, such as the raw contact profilometry data. The SME(s) then retrieve the original data from the FIPD, which may be in various formats, including hard-copy (PDF scans) or digital files. Following data acquisition, the SME(s) compile relevant documents to aid in the data qualification process. These documents might include data specifications discussed in the previous section, research papers, reports, lab memos, and other resources available in the FIPD library. The SMEs proceed to examine the raw data and its associated documents. During this process, any discrepancies, missing values, or errors in the metallic fuel data are identified. These issues are then documented in the Data Qualification Report (NFD-DQR-5.3). References to examples of such reports can be found in ref. [13]. In the data qualification report, the SMEs also provided the accuracy of the measurements based on the specification. Furthermore, SMEs advise on the valid usage range for the data that are deemed qualified. This report is subsequently submitted for review and approval as part of the QA plan, ensuring that the findings are accurate, relevant, and clearly presented. The review may result in suggestions for revisions, updates, or clarifications to enhance the quality of the report. After incorporating feedback from the review, the data is recommended as either qualified or not qualified. Once complete, the report is signed and filed in the official documents and records repository.

The final qualified data package contains five key components:

- Data Qualification Report (NFD-DQR-5.3): This report, developed under the QAPP, pertains to a specific dataset. It includes data identification, traceability, and description; general issues with the data; previously applied quality programs, procedures, and documentation; evaluation measures; qualification criteria; and the results of the evaluation.
- Measurement Record: This component comprises copies of original or transmitted records, which are qualified hard-copy data.
- Digital Data: This component consists of data digitized from the measurement record.
- Data Specification: This specification provides guidance for interpreting the metallic fuel data and summarizes QA-relevant information about the measurement (see the "FIPD Data Specifications" section for more details).
- Other QA Documents: These are necessary references cited by the data specification and the data qualification report. They may include the original operation manual of the facility, procedures for obtaining the measurements, relevant publications, lab memos containing relevant data, and more.

In addition to the aforementioned data qualification process, selected qualified data packages are also being provided to an external third party for an additional layer of peer review. This step is undertaken to enhance the overall quality and reliability of the information. This supplementary review process by a third party ensures a more comprehensive and unbiased evaluation, thereby strengthening the credibility of the data. It also provides an opportunity to identify any potential oversights or areas for improvement that might have been missed during the initial review stages. The inclusion of this external review step demonstrates a commitment to maintaining high standards of accuracy and thoroughness in the data qualification workflow.

The qualified metallic fuel data are readily available for direct download from the FIPD database by allowed users. Meanwhile, the complete qualified data package can be obtained through a formal request to the FIPD team.

SUMMARY

The FIPD currently contains most of the essential metallic fuel experiment data from EBR-II and a significant amount of PIE data from FFTF, crucial for aiding fuel behavior analysts and reactor designers, and facilitating industry licensing for fast reactors using metallic U-Zr fuels. This database is being progressively expanded with additional legacy data and documents. The metallic fuel data within the FIPD are undergoing a thorough QA process, by implementing the NRC-approved QAPP.

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