Nuclear Archaeology in Action
Preserving the History of the JEEP II Reactor

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Abstract. Deeper reductions in the nuclear arsenals will require better understanding of historic fissile material management and production. The concept of "nuclear archaeology" has been considered since the 1990s to provide the tools and methods to develop independent production estimates, primarily based on nuclear forensic techniques. Here, we propose to add a framework for reconstructing the history of a nuclear program that complements traditional nuclear archaeology techniques by examining the role of operating records to support such an effort. As a test case, we use the JEEP II reactor, a 2 MW civilian research reactor at Norway's Institute for Energy Technology (IFE), in operation for more than fifty years, however, recently shut-down permanently. We have collected, analyzed, and started to preserve the reactor's operating records, which exist on both analog and digital media, and to simulate parts of its history using OpenMC/ONIX neutronics calculations. A particular focus of this project has been on digital data curation and preservation to confirm and maintain the integrity, authenticity, and provenance of these records. In developing guidelines for best practices that conform to existing standards for long-term digital preservation and curation, we hope this project can help lay the basis for future nuclear archaeology efforts to support nuclear arms control and disarmament.

Background

Plutonium and highly enriched uranium are the key ingredients in nuclear weapons. Worldwide, there currently exist enough of these fissile materials for more than 200,000 of weapons, but the uncertainty of the global stockpile is significant and equivalent to thousands of nuclear weapons. Deeper reductions in the nuclear arsenals will require a much better understanding of historic fissile material management and production in all states, nuclear weapon states in particular. The concept of nuclear archaeology has been proposed in the 1990s to provide the tools and methods to draw conclusions about past activities and to develop independent fissile material production estimates.[1]

Standard nuclear archaeology techniques envision forensic analysis of physical samples, but such samples may not always be available, or it may be considered too expensive or impractical to acquire them. Here, we consider a framework that uses the available operating records to reconstruct the history of a nuclear facility. Such an approach could be pursued independently or complement traditional archaeology.

The idea of using operating records to reconstruct the history of a nuclear program is not new. In fact, in June 2008, North Korea made available 18,000 pages of paper records to corroborate the plutonium declaration it had made as part of the Six Party Talks.[2] At the time, the U.S. Government also tabled a verification plan that envisioned an extensive review of documents; accordingly, experts would be given *"full access to records (fully preserved and maintained), including originals, and information systems [...] documenting nuclear material production, handling, and disposition, as well as other nuclear-related activities."*[3] Unfortunately, little is publicly known about the outcome of this effort.

Beyond the immediate scope of nuclear archaeology, i.e., to understand historic production of fissile material unsafeguarded nuclear facilities, document-based nuclear archaeology could have other important benefits. Importantly, it could help develop best practices for documentation and archiving of historic records in both military and civilian nuclear facilities. Similarly, document-based archaeology could also offer benefits for ongoing and future decommissioning efforts; here, for example, it could help inform calculations to characterize spent fuel inventories using modern computer codes and cross-section data. These calculations could then help guide and be compared with ongoing and planned measurements. Concepts and findings could be shared with operators of other research reactors and the broader scientific community. More generally, we believe it is important to document and preserve the history of a nuclear facility as part of a modern, responsible, and transparent decommissioning process.

Relevant Scenarios & Operating Records

Nuclear archaeology is relevant for both civilian and military nuclear facilities that have been operated without adequate safeguards, and test beds for nuclear archaeology, including those in non-nuclear weapon states, may offer important opportunities to develop the relevant concepts. Such efforts are not aimed at "scrutinizing" existing records or past practices; in fact, in trying to emulate the conditions relevant for true nuclear archaeology at unsafeguarded facilities, we may even want to assume that records and other information that have been prepared specifically to support treaty-based safeguards activities are not available for such an exercise.

In general, the most important proliferation-relevant scenarios for a research reactor in the megawatt-range are related to undeclared plutonium production, diversion of spent fuel, and perhaps placement of undeclared targets. A first-order nuclear archaeology effort could therefore focus on records documenting activities that are relevant for these hypothetical scenarios. Information could include the power level of the reactor, the core configuration, core management operations (fuel discharges, storage, movements, and reloads), and possibly fuel receipts and shipments offsite. Consistency checks could be based on documents or propose measurements that could be made as part of a true nuclear archaeology effort to confirm results based on records and calculations. Exploring these baseline scenarios would also help understand the particular challenges associated with records available in analog and digital formats, determine what equipment and "tacit knowledge" are needed to read and correctly interpret the data, and consider ways to best preserve the records and ensure their integrity. An early application of the proposed methodology may help identify possible gaps, redundancies, or irrelevant information in the archived data.

Case Study: The JEEP II reactor

Norway initiated its national nuclear research program in 1951 with the commissioning of the Joint Experimental Environmental Pile (JEEP) as part of a cooperation with the Netherlands. After experiencing safety issues, the reactor was taken out of operation in December 1966, and the new JEEP II reactor was commissioned. JEEP II operated at a power level of 2 MW, was heavy-water moderated and cooled, and used low-enriched fuel that was fabricated onsite (Figure 1). JEEP II was in operation through December 2018. Active decommissioning will begin once the facility has been transferred to a new governmental organization established on purpose for this particular task.

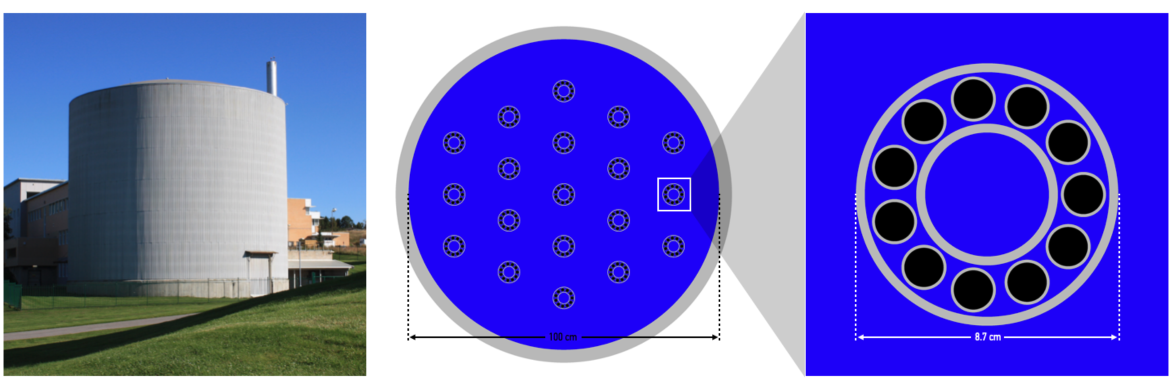

Figure 1. The JEEP II Reactor. Located at the Institute for Energy Technology (IFE), an independent research foundation, in Kjeller, Norway, the reactor operated between 1966 and 2018 at 2 MW thermal. Also shown are a simplified OpenMC model of the reactor core (center) and the standard fuel assembly (right). *Source: IFE and authors.*

One reason for considering the JEEP II as a first archaeological test case is the consistency of operational routines and practices throughout the life of the reactor. The reactor, the core, and the fuel design have all remained the same. At the same time, operation of the reactor offers some interesting features: JEEP II was designed and used as a neutron source for basic research including scattering experiments, isotope production and, in the last 25 years, neutron transmutation doping of silicon.[4] This multipurpose mission required frequent shutdowns and startups of the reactor, typically several times per day. Given JEEP II's relatively simple design and operating history, it is easily possible to perform full-core calculations and simulate the entire operational history of the reactor. During a typical refueling, one of the nineteen fuel assemblies was discharged, a few were repositioned in the core, and one new fuel assembly was loaded. Normally, a fuel assembly stayed in the core for 10–15 years. The spent fuel discharged from the reactor over the entire 52-year history is stored onsite and is in principle accessible for inspection or measurement purposes.

To support this nuclear archaeology effort, we developed an OpenMC model of the reactor.[5] Combined with the depletion code ONIX,[6] we can use this model to simulate selected time periods with information extracted from the operating records.

The JEEP II Operating Records and Sensors

While there are no regulations specifying how long historical operating records have to be kept, fortunately, most JEEP II records have been preserved and are stored in a secure archive onsite. In July 2021, we have been able to review all records, both analog and digital, that could play a role for a reconstruction of the reactor's history (Figure 2). As expected, numerous physical quantities were recorded on a regular or continuous basis. In particular, daily routine operation was documented in logbooks. These were recorded manually (handwritten) by operators, logging every startup and shutdown of the reactor along with important process variables. These logbooks have remained handwritten during the entire operation of the reactor with relatively minor changes in their format and content.

During this "analog era" of the JEEP II several electro-mechanical strip chart recorders, which use paper rolls to store the information from multiple data channels were used to log sensor data for the control system. A typical recorder wrote at 10 mm/hr or about 12 meters per week. During this period, up to 11 recorders produced on the order of one kilometer of paper records per year. In practice, taking into account longer shutdown periods, during which most recorders were stopped, about 700 meters of paper records were produced in a typical year. About 75 rolls covering the time period from 2008–2013 remain available today.

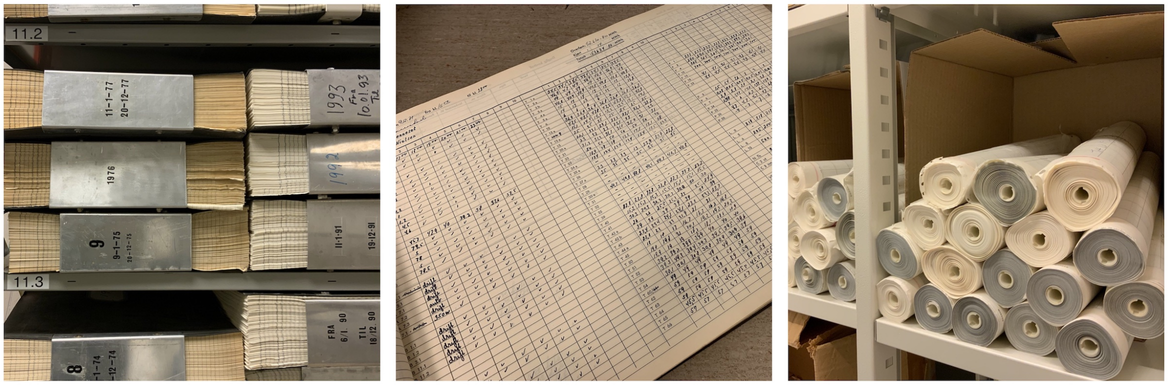

Figure 2. Views from the archive. Manually recorded logbooks (left), example page from a logbook (center), and paper rolls from electro-mechanical strip-chart recorders (right) *Source: IFE and authors.*

Analog systems were gradually replaced by digital recorders beginning in the early 2000s. These so-called paperless recorders, such as the Yokogawa DX200-series,[7] gradually replaced several of the old strip-chart recorders until they were all removed around 2011. The digital recorders stored process data on a compact flash (CF) memory card with manual backups. Each logged file contains a weeks worth of data from multiple channels of the nuclear instrumentation.

Several types of sensors were located at multiple locations throughout the reactor, and their readings monitored and recorded. For the purposes of this first demonstration, we wanted to confirm the operational status of the reactor at any given time over the course of a week. We selected two sensor types for the analysis below:

Ion(ization) chambers: These detectors are located in a thermal shield around the reactor tank; some of the ionization chambers are lead-shielded to increase the neutron-to-gamma ratio. The current generated in the chamber scales with the radiation level, and therefore also with the fission rate and the thermal power of the reactor. This current is monitored and recorded by the instruments in the control room. Originally, the data were constantly written to paper rolls using standard strip-chart recorders; in the 2000s, these recorders were gradually replaced by so-called paperless recorders storing the same information digitally.

Temperature sensors: There are numerous temperature sensors installed throughout the reactor measuring the temperature of the heavy water in the core and primary loop, and the temperature of the ordinary water in the secondary loop. Where accurate measurements were required, platinum resistance thermometers (PRTs) are used. As illustrated below, the temperature difference between two measurement points can be used to estimate the reactor power; in fact, for a specific water flow rate, a constant

ΔT between two specific sensors has been used by the operators of JEEP II to confirm that the reactor power is constant and nominal.

Importantly, these sensors measure fundamentally different physical quantities and are completely independent. This is, obviously, important for safety reasons but also helps in the context of nuclear archaeology to cross-check and validate the authenticity of the data. Interestingly, for the example discussed below, temperature was recorded analogously, while the current generated in the ionization chamber was recorded only digitally in the last two decades of operation.

For nuclear archaeology purposes, two main types of information are needed: First, records documenting the hour-by-hour operations, shutdowns, and power level of the reactor. This information is critical for determining the capacity factor of the plant, which would be relevant for almost any scenario and true archaeology application. This is the primary focus of the analysis below. Second, understanding fuel management, discharge of spent fuel, loading of fresh fuel, and movements of fuel in the core would be relevant for a longer-term reconstruction of the reactor's history and, hypothetically, fissile material production.

Sample Analysis

To illustrate the basic concept, we (arbitrarily) chose a week of operation from early 2010. For this particular time period, some data were recorded on paper records, others were recorded digitally. In the case of the paper records, data from several months of operation are available on a single paper roll; in the case of the digital records, data are recorded every 20 seconds and collected in an output file once a week (30,240 entries per channel per week).

Figure 3 shows some sample data recovered from the analog and the digital records for Saturday, February 6, 2010. Here, we are interested in establishing the operational status of the reactor. On this particular day, the reactor operated at nominal power of 2 MW thermal with six shutdowns over a 24-hour period. The durations of these routine shutdowns depend upon the particular activities that had to be performed, but they typically lasted 40–180 minutes. The figure shows corresponding logs from the digital and the analog archives. For this example, the temperature across the inlet and outlet of the reactor is compared against the digitally logged sensor response from the ionization chambers. The capacity factor for February 6, 2010, can be determined to 67.1%, and to 66.9% for the respective week, i.e., to 4.68 effective full power days or 9.36 MWd for the seven-day period from January 31 through February 6, 2010.

With these first insights, we could gradually reconstruct the operational history of the reactor. In particular, if this was a reactor suitable for plutonium production, we

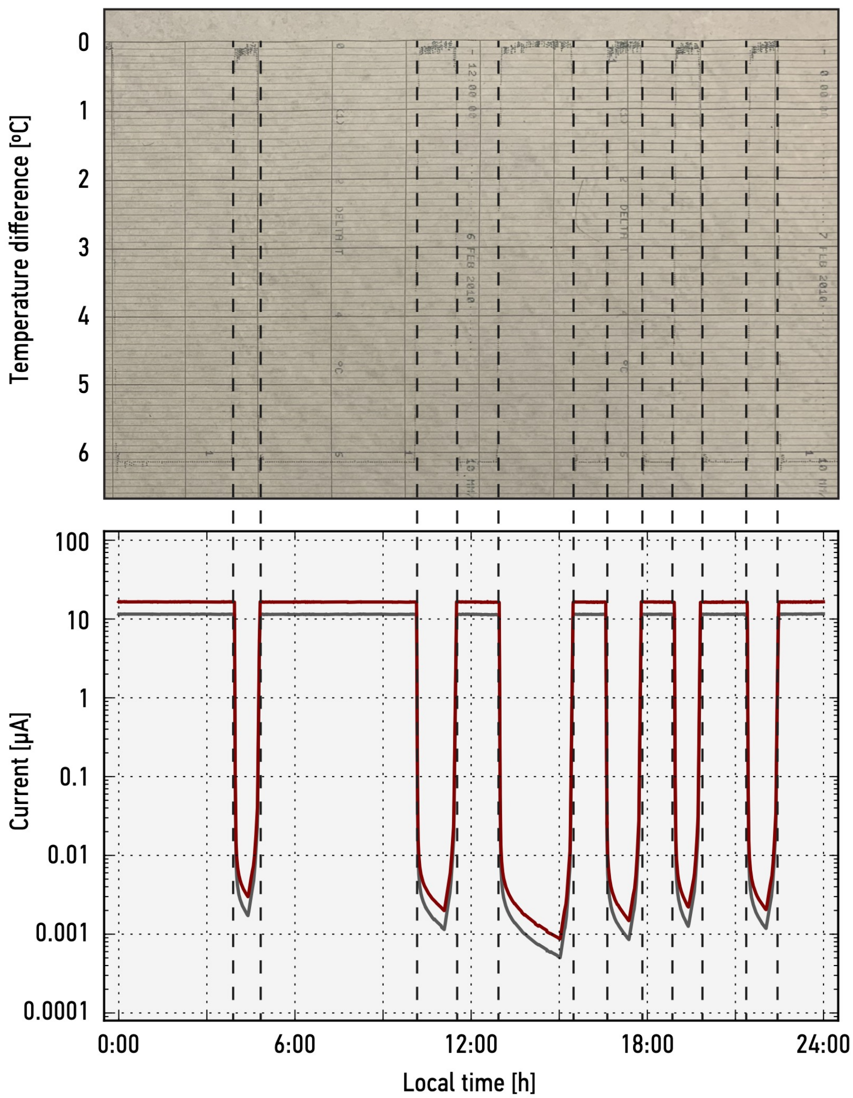

Figure 3. Analog and digital records from February 6, 2010. At nominal power, the temperature difference between the core outlet and the core inlet is 6.15 °C. Similarly, at nominal power, the current in two ionization chambers is 16.5 μA (Log-1 Signal) and 11.5 μA (Log-2 Signal). At least once an hour, these values are also recorded manually in the logbook by the reactor operator.

could begin by determining the total energy released between two reactor refuelings and, with knowledge of the conditions at the beginning of the cycle, calculate the plutonium buildup in the core and the isotopic makeup of all fuel assemblies at the end of the current cycle.

In the meantime, in order to provide confidence in the authenticity and integrity of the records later on, we can already commit to the data stored in these records. For example, data from six separate channels is available in the digital file (`13100000.txt`) we accessed for readings of the ionization chambers. Combined with additional meta data, the file size is about 4.9 MB. The SHA-512 hash of this file is:[8]

```
f8280965ff581cd8334515152ebdc862
38958bf9791343753c702f223b583b00
51c9d085792d367d20c866918d4fcee7
d9558abf6e0d4c97bc530f79d21f0ef5
```

Future analysts could use this hash to confirm that the data file for this particular week in 2010 has not been modified since we accessed it in July 2021. The cryptographic hashes of all other digital files could in principle also be published. Similarly, paper records could be digitally archived and their SHA-512 hash generated and published.

A First Set of Guidelines for Document-based Nuclear Archaeology

Nuclear archaeology is a time critical effort as staff with operating experience are retiring. Also, the original equipment that produced the data may or may not be available indefinitely; in particular, the respective equipment may be dismantled and disposed of as part of the decommissioning process. The different types of operating records pose unique challenges: Analog records require significant amounts of storage space and are eventually often discarded. When they are kept, they can last for years and decades.[9] On the other hand, digital records are easier to store, but also more easily corruptible if sufficient precautions are not met. Preservation of digital records requires continuous active monitoring, and digital records are much more difficult to maintain than analog records because of the significant amount of active work and attention that they require.

In order to archive and preserve the set of analog records and digital objects required for the nuclear archaeology activities described above, we recommend an approach that follows standards and best practices in the fields of archival science and digital preservation. Establishing guidelines for the preservation of these records is particularly important given the lack of established best practices for the preservation of records in the nuclear sector.[10] While non-nuclear-weapon states can be expected to have produced extensive documentation, in particular as part of the requirements for NPT verification, little is known about the practices in nuclear-weapon states.

Analog records. Given the different types and formats of analog records, and the anticipated use cases discussed above, we recommend non-destructive digitization for the logbooks and other physical records. This will involve steps such as assessing each type of record's suitability for digitization based on criteria such as rights and physical properties, as well as making determinations about what properties of the physical records should be preserved in the digital surrogates.[11] After digitization, the physical items should be housed and stored in a secure, climate controlled archival environment. This will include appropriate arrangement and description practices, following metadata standards that follow best practices and align with the needs and expectations of the organization managing the records.

Digital objects. Preserving and providing access to the digitized records, as well as the born-digital files, will involve decisions about topics such as file formats, metadata standards, digital object management systems, fixity, and access systems. We recommend that the digital objects be stored in a repository that follows the Open Archival Information System (OAIS) model,[12] and that meets the criteria for certification as trustworthy under either the ISO 16363 or CoreTrustSeal repository certification systems.[13,14]

Conclusion and Outlook

No systematic efforts currently exist to archive and preserve the historical records of nuclear facilities at a level required for potential nuclear archaeology applications. Deeper reductions in the nuclear arsenals will however require a much better understanding of historic fissile material production. This article has explored the potential of using operating records to do so. As part of this effort—to our knowledge, the first of its kind—we have collected, analyzed, and started to preserve the operating records of the JEEP II research reactor to reconstruct and simulate parts of the reactor's operating history. A first analysis of sample records suggests that meaningful and difficult-to-spoof information can indeed be extracted from these records. These efforts are time critical, however, as staff retire and records are often discarded.

A particular emphasis has been on digital data curation and preservation to confirm and maintain the integrity, authenticity, and provenance of these records. In developing a first step of guidelines for best practices that conform to existing standards for long-term digital preservation and curation, we hope this project can help lay the basis for future nuclear archaeology efforts to support nuclear arms control and disarmament.

We believe that research reactors operated for peaceful purposes could provide excellent test beds for developing and demonstrating many of the concepts and technologies needed for successful "true" nuclear archaeology efforts later on. Projects like the one outlined here could help develop best practices for documentation and archiving of historical records to support ongoing and future decommissioning efforts. More generally, we believe it is important to document and preserve the history of nuclear facilities as part of a modern, responsible, and transparent decommissioning process.

Revision 2

Endnotes

[1]Steve Fetter, Nuclear Archaeology: Verifying Declarations of Fissile-Material Production, *Science & Global Security,* 3 (3–4), 1993; Thomas W. Wood, et al., The Future of Nuclear Archaeology: Reducing Legacy Risks of Weapons Fissile Material, *Science & Global Security,* 22 (1), 2014.

[2]Sue Pleming, North Korea Hands Over Plutonium Documents, *Reuters,* May 8, 2008.

[3]*Verification Measures Discussion Paper*, non-paper, undated (2008).

[4]*Neutron Transmutation Doping of Silicon at Research Reactors*, IAEA-TECDOC-1681, International Atomic Energy Agency, Vienna, 2012.

[5]Paul K. Romano et al., OpenMC: A State-of-the-Art Monte Carlo Code for Research and Development, *Annals of Nuclear Energy,* 82, August 2015.

[6]Julien de Troullioud de Lanversin, Moritz Kütt, and Alexander Glaser, ONIX: An Open-source Depletion Code, *Annals of Nuclear Energy,* 151, February 2021.

[7]M. Takahashi, S. Katsuoka, Y. Hosaka, and K. Kakihara, DAQSTATION DX100/200 Series of Paperless Recorders, *Yokogawa Technical Report,* 30, 2000.

[8]We generated this cryptographic hash with the command `shasum -a 512 filename` on MacOS and with the command `certutil -hashfile filename SHA512` on Windows. For more, see *Hash Functions*, National Institute of Standards and Technology, Gaithersburg, Maryland, 2017/2020.

[9]The ink used by strip chart recorders, however, can fade significantly over time; a fact we observed when examining JEEP II records available on paper rolls.

[10]M. Claxton and R. Sharpe, "Digital Preservation Techniques to Facilitate Knowledge Management in the Nuclear Sector," International Conference on Knowledge Management in Nuclear Facilities, IAEA-CN-153, International Atomic Energy Agency, Vienna, June 2007.

[11]Janet Gertz, Preservation and Selection for Digitization, Section 6.6 in *NEDCC Preservation Leaflets,* Northeast Document Conservation Center, Andover, Massachusetts, 1999/2021.

[12]*Reference Model for and Open Archival Information System (OAIS)*, Magenta Book CCSDS 650.0-M-2, Consultative Committee for Space Data Systems, June 2012.

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[14]Ingrid Dillo and Lisa De Leeuw, CoreTrustSeal, *Mitteilungen Der Vereinigung Österreichischer Bibliothekarinnen und Bibliothekare,* 71 (1), 2018.