Reconstructing nuclear histories: a field study

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Abstract

Reconstructing how much fissile material was produced in nuclear facilities could become a key element in the verification of future arms control or disarmament agreements. The past production of plutonium can be modelled with reactor simulations, using information on both reactor design and operating history. That information is typically provided by the inspected state and must be independently verified. In a first step, the available documentation of the reactor program can be thoroughly examined, for instance by studying its self-consistency. In a second step, forensic measurements, *e.g.*, of samples from inside the reactor core, can be used to verify the documentation. For both these methods, questions remain, especially related to the practical application: How can one handle the potentially large amount of archived operating-history documentation? How to deal with gaps in the documentation? How can the document analysis be effectively combined with forensic measurements? To answer those questions, systematic approaches need to be developed. We explore a real-world scenario with the former nuclear research program from Karlsruhe, Germany, for which we gained access to the archives containing documentation of the operational histories and facility designs. The nuclear research program included a pilot reprocessing plant and the heavy water reactors FR-II and MZFR, which were operated between 1961 and 1984. While the program was used for civilian purposes only, the fact that the reactors were moderated by heavy water makes them ideal candidates for this study as this type of reactor is elsewhere used to produce plutonium. This presentation will show first results on how the documentation of a past nuclear reactor program can be used to develop and test approaches to nuclear archaeology.

1 Introduction

Future agreements that limit or reduce nuclear weapon inventories will require verification measures. For disarmament, it will at some point become essential to verify that declarations of fissile material inventories are correct and complete. This could be done by independently reconstructing how much fissile material was produced in the past and comparing the result to the declared stockpile.

Corresponding approaches are developed within the field of *nuclear archaeology*. Nuclear archaeology research has typically explored analysis techniques based on forensic measurements of samples that have been taken in production facilities; as, *e.g.*, permanent structures within reactor cores are affected by the neutron flux, their isotopic composition can be used to deduce valuable information. Among the methods that have been developed or proposed are approaches for graphite-moderated reactors to deduce neutron fluence [1] or an idea to distinguish whether fluence was used for plutonium or tritium production [2]. Further research explores measurements of produced waste, for instance to determine burnup and cooling times from forensic analyses of reprocessing waste [3].

Another approach has been applied by the IAEA in the context of South Africa's denuclearization, to verify how much highly enriched uranium was produced [4]: There, one focus was on the records created during the operation of the nuclear programs. These records are, however, not public, so the knowledge how exactly they were analyzed is limited. Furthermore, the Democratic People's Republic of Korea (DPRK) handed over documentation on its reactor operations to the US [5]. The first assessment of the potential of this *document-based nuclear archaeology* is provided by Reistad et al. [6], in which archived data from the permanently shut-down civil research reactor JEEP II were analyzed. The authors conclude that "meaningful and difficult-to-spoof information can [be] indeed extracted from these records". Further effort, however, is still needed to develop and demonstrate approaches on how archived operation record can systematically and in practice be used.

This paper aims to contribute to this effort by providing additional first ideas based on an initial 2-day research stay with access to the archived operation records of two former civil reactors in Germany, namely, the Forschungsreaktor 2 (FR-II) and the Mehrzweckforschungsreaktor (MZFR). We take these archives for a testbed of nuclear archaeology, even though the reactors were used for peaceful purposes only; we think that insights on, *e.g.*, what data were typically documented, or how to include large numbers of nuclear-archive paper documents, can lay the basis for an *actual* application of nuclear archaeology in a plutonium-production reactor. Section 2 gives a brief overview on the reactors and the archives, and Section 3 describes initial ideas on how such archived information can be used for nuclear archaeology. Section 4 focusses on practical aspects related to the analogue paper documents, namely, how to digitize and combine the information. A small case study, in which the discussed concepts are applied, is presented in Section 5. Section 6 summarizes the paper and highlights possible next steps.

2 The FR-II and MZFR archives

The research reactor Forschungsreaktor 2 (FR-II) and the demonstration reactor Mehrzweckforschungsreaktor (MZFR) were operated in Germany from the 1960s to the 1980s in Karlsruhe. Both reactors, part of a civil research program, were moderated and cooled with heavy water. The FR-II, a tank reactor, first became critical in 1961 and then operated with a power of 12 MW until mid 1966. After changing the fuel design (among others, changing from natural to low-enriched uranium), its power was increased to 44 MW [7]. In 1981, it was shut down. The reactor was used as a neutron source for basic research, nuclear fuel development, and material research [8]. The MZFR, a pressurized-water reactor, became critical in 1965 and operated with a power of 200 MW, and it was shut down in 1984. The reactor was used to gain experience with heavy-water reactors and as power and heat source for the research campus [9].

Both reactors have been decommissioned, and the dismantlement is currently being carried out by the Kerntechnische Entsorgung Karlsruhe GmbH (KTE) [10]. The FR-II was de-

Figure 1: Example pictures from the KTE archives.

commissioned from 1986 to 1996 by Kernforschungszentrum Karlsruhe (KfK), and now, the reactor block is in secure containment. All auxiliary buildings, released from the controlled-area regime, are either demolished or used for other purposes no longer under German atomic law [11], *e.g.*, the former reactor building (*rotunda*) now hosts an exhibition. The dismantlement of MZFR started in 1987 and is currently ongoing. So far, the reactor core vessel has been dismantled, and the activated areas of the biological shield have been removed [9]. Now, the demolishment of auxiliary buildings is being finished, and the complete dismantlement of all buildings is expected to be completed by 2030 [12].

As legal successor of the former FR-II and MZFR operation company, the KTE obtained the remaining documents of the reactors, which contain information on the past construction and reactor operations. Those documents are preserved in four rooms, two containing FR-II documents (one for folders with text documents, one for large technical drawings), one MZFR documentation, and one additional room with information on both reactors. Example pictures from such rooms are shown in Fig. 1.

The archived documents are preserved mainly for two reasons. First, the detailed technical drawings and documentation on how the reactor facilities were built are used to plan and perform the dismantlement operations. Second, legal obligations require preserving certain documents of such facilities and their dismantlement for a minimum amount of time; typical time scales are 30 years, *e.g.*, for documents on past monitoring of radiation activities. Other documents even need to be preserved until the respective part of the facility is fully dismantled [13], which applies to both the MZFR, which is currently being dismantled, and the FR-II, for which the reactor block is still present.

Those two aspects, however, apply only to part of the documentation that can be found in the archives. Besides the above-mentioned, mainly technical documents, there is also a wide range of other documents, *e.g.*, regarding the personnel management, detailed daily work reports, documentation of the performed experiments, correspondence with authorities, textbooks on nuclear measurement technologies, and more. The documents are kept simply because it would require large financial and personnel effort to examine which documents can be disposed of and which documents are required to be kept for the reasons explained above — so, as a conservative measure, those documents are (for now) preserved, and the archives contain a large number of diverse documents related to various aspects of the past nuclear operations.

3 Using reactor archives for nuclear archaeology

In the following, we assume that inspectors would receive direct archive access, which may be difficult to negotiate, but would provide the best opportunity for confidence-building. To reconstruct how much fissile material was produced in a nuclear reactor, one needs, in principle, three types of information: (1) the reactor and fuel design, (2) its power history, *i.e.*, when the reactor was operating at which power, and (3) – for a more precise assessment – the fuel discharge history. Based on these parameters, the amount of plutonium produced can be determined with neutron transport and burnup calculations. These types of information, in the following referred to as *primary information*, are typically documented during the reactor operation and can therefore be found in archives of past nuclear programs. From our 2-day research stay in the KTE archive, however, we suppose that finding such primary information can be challenging in practice.

Challenges when searching for primary information. One complication relates to the archives being old. This has several consequences: legal requirements on what documents are required to be created and stored might have changed over time, so (1) documents might be missing because they have been disposed of, or they have never been created in the first place. In addition, as some documents themselves are old, (2) they have already become unreadable due to vanishing ink and yellowed paper. It is therefore likely that gaps in such archives occur and not all primary information can be found.

A second complication arises from the fact that some archives may not be actively managed. This is the case for the rooms we visited at KTE. Even though efforts have been made to at least partially sort documents by topic or time period, finding specific information relevant for nuclear archaeology can be challenging under time constraints. Our 2-day visit was hardly sufficient as the number of documents is so large that getting a comprehensive overview of the archive was difficult.

Evaluating secondary information. To build confidence when relevant gaps occur could involve including other, or *secondary*, information. As all documents in the archives were created in connection to the operation of the respective facility, their information should be correlated. This fact could be used to assess the gaps: if some information on when the reactor was operated and not is missing, one could try to find corresponding evidence in, *e.g.*, (a) the worker's shift plans, in (b) the safety reports where reactor incidents are documented, or (c) from reported measurements performed in the context of reactor safety. The details on what information to consider would depend strongly on the context, *i.e.*, scenario, archive content, or missing information; but, with the extent of information available, there might be potential to close gaps when assessing that information from many different angles.

Checking internal and external consistency. Assessing all these information sources can play an important role in building confidence in the correctness and completeness. In addition to re-calculating the past plutonium production based on the records, it should be examined whether an archive in its entirety provides a clear and consistent picture of the past nuclear program. This would mostly be qualitative, but can have quantitative aspects as well. For instance, the KTE records would allow to check whether the loaded reactor fuel is compatible with the declared power output. Nevertheless, one has to be aware that a state seeking to conceal past activities would try to forge or hide all relevant documents. In a comprehensive archive containing information from different origins and authors, this would, however, not be a simple task.

A further step would compare information from the archive with information from external sources. This could include information at other nuclear sites, *e.g.*, to compare fuel element manufacturing and shipments from or to the reactor sites or records at regulator archives, *e.g.*, on safety incidents supporting claims of reactor shut-down. Even local newspaper reports or memories of people who lived in the past in the area could be considered.

Consistency with nuclear-archaeology measurements. Lastly, consistency can be checked between archival information and forensic measurements such as the activation or isotopic compositions in reactor materials. As these quantities are related to the integrated neutron flux (fluence), which is directly connected to how the facility was operated over the full operation history, such measurements can provide information on the whole nuclear past of the facility. Concealing activities, such as declaring a reactor being shut down when it was running, would require a lot of effort: not only would the past documentation have to be forged but also the measurement result, which could have been taken much later. For FR-II and MZFR, some relevant measurement data are available in the archive. They were taken in the context of the facility dismantlement, for which the activity in various parts of the reactor and the auxiliary buildings have been measured before demolishing them. As part of a potential future nuclear-archaeology exercise, such measurement could even be performed today using the remaining FR-II reactor block, which is preserved in secure containment.

4 Extracting and managing the archived information

Using the information preserved in the archive is further related to practical questions, *i.e.*, on how to extract the information from the paper documents and how to systematically collect and combine them. First ideas on those two aspects, (1) bringing the data into a computer-readable format, and (2) designing a framework to collect and collate the data, are discussed in the following.

Digitizing the information. Digitizing information from paper documents is a common challenge in the field of archive preservation, and various projects and approaches for that exist. One example is the work by Correia and Luck [14], which provides a user's guide on the extraction of archival information demonstrated for historic balance sheet data. The authors suggest a data extraction pipeline, which was the starting point for the following considerations.

The first step would be to scan or photograph the relevant documents. To what extent this would be allowed, what technology would be used, and how the data would be stored are relevant points for negotiations between the parties involved. After processing the images, *e.g.*, applying contrast or color corrections, optical character recognition (OCR) and layout detection algorithms could be applied. The results allow quicker searches for keywords or dates among the collected documents, and it simplifies the later treatment of information. OCR software for plain text detection is available from different commercial and non-commercial providers, but which algorithm would give best performance would need to be evaluated on a case-by-case basis. A specific requirement in the context of nuclear archaeology arises from the fact that documents are likely confidential, so the corresponding chosen software should not require any external cloud services.

For plots or graphics which encode relevant primary information such as power or reactor loading, no such automized data extraction algorithms are available. Based on the evaluation of information from the KTE archive, we think that it would further not be feasible to spent effort to develop any fully automated approach; artifacts from hand-drawn graphics, odd type-writer settings, features from background-checked paper, and frequent changes in plot designs would require large amounts of fine-tuning, which would make such approach unfeasible. Instead, we suggest to semi-automatically extract the data from plots with a tool such as from Ref. [15]. This tool provides a graphical-user interface, in which both the coordinate systems and data of the plot can be marked and exported. Two example plots and the corresponding extracted data are shown in Fig. 2. Extracting the data takes roughly 10-15 minutes per plot, depending on the complexity of the data and the practice of the user.

Connecting the information. Using the archived information for reactor simulations or consistency checking requires connecting the various types of extracted information. The following provides a first set of ideas for how this could be done; it should be noted, however, that it is not the goal to design a "one-size-fits-all" solution but rather to provide a collection of ideas for which some could be useful depending on the specific case. In an ideal case, all information would be connected in some type of *framework* that provides the following functionalities: it could (1) return all included information for any requested period of time, (2) export the primary information in a format that can easily be used for reactor simulation codes, and (3) provide functions to perform specific consistency checks.

As explained before, quite different types of information are relevant, which can have quite different properties. On the most abstract level, however, all information from the archive can be associated with a source and one or more timestamps. A further classification could divide the types of information into (a) *numerical and continuous* types, which could be plotted as functions of time, *e.g.*, reactor power, and (b) *discrete* types, *e.g.*, the date of a recurring inspection. This classification might be useful to also include interpolation or integration functions, which would not make sense for the latter category.

The key features would be the functionalities to examine the information. One way to support that would be a *print* function, which would provide all information (or that for a specific time period) sorted by their timestamps; this way, one could directly identify gaps and find time periods where further investigation would be needed. A *plot* function could further provide a visualization of the information, for which continuous and numeric information would be drawn as curves and discrete information indicated at the respective dates; how this could serve for consistency checks is demonstrated in the next section. Many further functions to compare information and check for consistency are possible. Future work

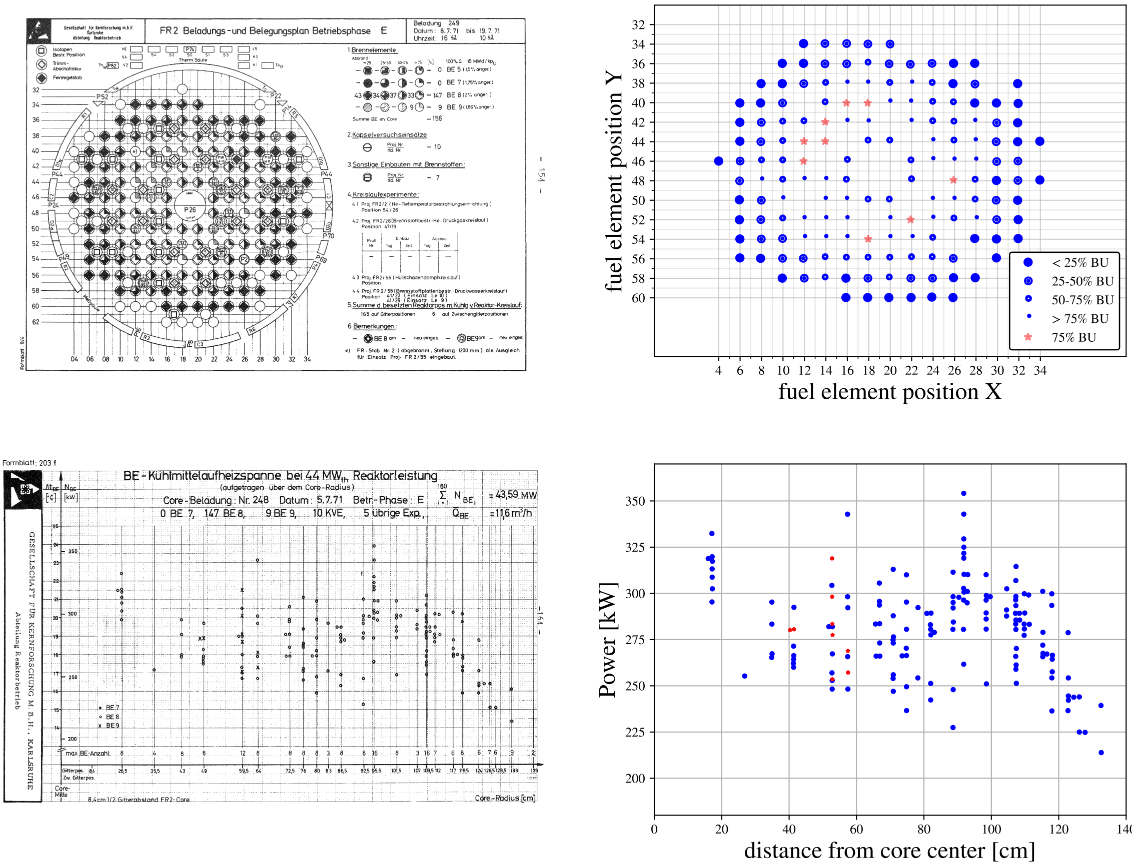

Figure 2: Example plots from Ref. [16] (left) and plots of corresponding extracted information (right). The plots show the fuel elements with corresponding burnup in the reactor (top) and the thermal power for the individual fuel elements at the different distances of the reactor core (bottom). The different colors (red and blue) indicate two different fuel element types.

could evaluate whether reactor codes to compare information from the archive with outputs from the simulation would be possible. How much automatization is possible, however, will depend strongly on the context and the scope of the verification case and will therefore have to be evaluated on a case-by-case basis.

5 Example data from FR-II and consistency checking

The following demonstrates a small check for consistency using a visualization of available information with data from the archived FR-II operation history. The data are taken from the yearly operation record of the FR-II reactor from 1971, which is a document that can be found in the archive, but which is also publicly available under Ref. [16]. This document was chosen for this demonstration since all steps related to scanning, image processing, and running OCR algorithms have already been applied, so the focus can be placed on extracting the information from the document and on combining the information.

We randomly selected the operation phase from June 14th to July 19th in 1971, for which we extract the following types of information: (1) the power, (2) the control rod position within the reactor, and (3) the moderator temperature, all as function of time. In addition to these numerical and continuous types of information, we include (4) the documented unplanned reactor shutdowns. The information is jointly visualized in Fig. 3, and it can directly be seen that for all times of the operation phase, the continuous information is available. Fur-

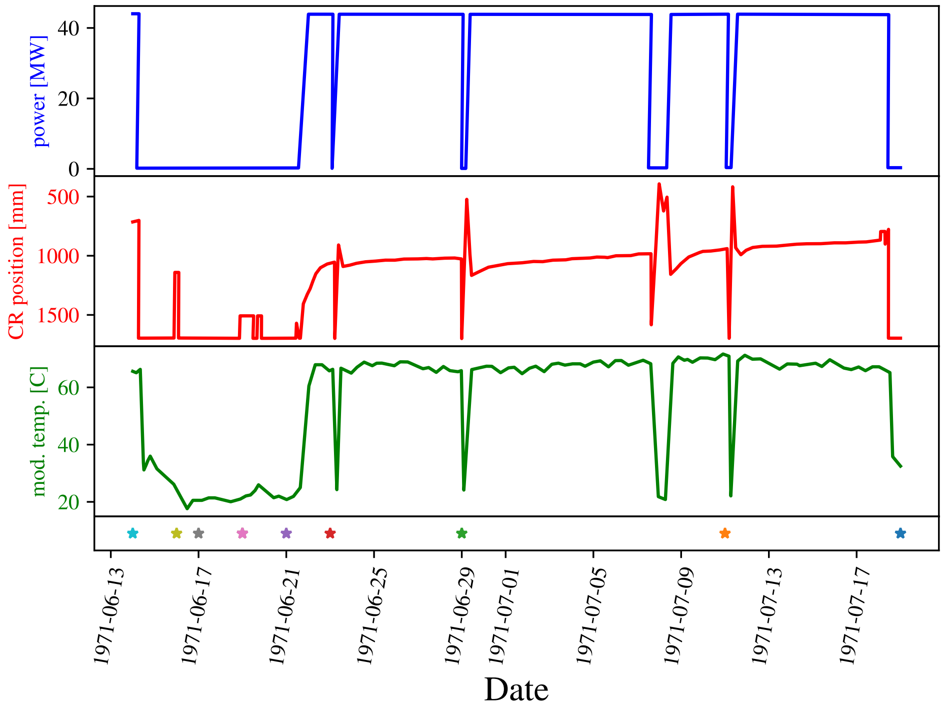

Figure 3: Reactor power (top, blue), control rod positions (middle, red), and moderator temperature (bottom, green) in the FR-II reactor between June 14th and July 19th in 1971. The markers (bottom) indicate events documented in the list of unplanned reactor shutdowns. All data are extracted from Ref. [16].

thermore, the control rod positions, moderator temperature, and power curves are clearly correlated—whenever the control rods are inserted into the reactor, the reactor shuts down, and the moderator temperature decreases. In addition, all reactor shutdowns match either with a documented unplanned reactor shutdown, or, and this shut down lasts longer, for a planned reactor refueling.

This check, however, uses only information from a single document, so other checks would be required. One possibility would be to check more complex relations where forging would be difficult; *e.g.*whether the heat released from the individual fuel elements (shown in Fig.2) is compatible with the reactor core loading with fuel elements (shown also in Fig.2), which could be based on neutron transport and burnup calculations. Further steps could include adding information from external sources or from nuclear-archaeology measurements, as described before. These are currently being investigated.

6 Summary and outlook

This paper presents initial ideas on how confidence in declared fissile material inventories could be built by analyzing documentation of corresponding nuclear facilities. The presented ideas and impressions are based on a 2-day research stay in the archives of the past civil nuclear reactors FR-II and MZFR, which was part of a research project that has recently started.

In the first part of the paper, we conclude from a first assessment of the KTE archive that a large amount of information on the past operation of the facilities is preserved. If a similar amount of information could be found in fissile material production facilities, such archives would provide a good basis to reconstruct their past fissile material production. However, gaps can occur for several reasons. At KTE, many other documents with secondary information are available; if the situation is similar in other facilities, such documents could be used to mitigate the role of those gaps and allow to assess whether they are plausible.

Even without gaps, however, the reconstructed amount of fissile material will always be associated with significant uncertainties. Therefore, we suggest a complementary approach to build confidence in declared fissile material production histories in context of arms control agreements, namely, to assess whether a corresponding archive in its entirety provides a clear and consistent picture of the past nuclear program. In the second part of the paper, we provide first ideas for related practical aspects, such as how to digitize the relevant information and how to include it in a shared framework to connect the different information. A part of these ideas is demonstrated with a small case study on FR-II data.

Currently, our research is ongoing to evaluate what other information could be extracted and used for document-based nuclear archaeology. A particular focus is placed on which external information and which forensic nuclear archaeology measurements could be included; for the former, we investigate whether spent fuel shipments and information from reprocessing plants could be used, and for the latter, how activation measurements, taken in context of the current dismantlement, could be included. Regarding the long-term perspective, we are evaluating whether measurements could be taken from the remaining FR-II reactor core components, which are currently in secure containment, to complement our so-far only document-based nuclear archaeology testbed.

These ideas highlight not only that we see a good potential for using such archives of past civil facilities as testbed to develop approaches for document-based nuclear archaeology but also as potentially valuable tool for verification to support nuclear arms control or disarmament efforts.

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