A technical view on Pakistan's nuclear weapons programme

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Abstract
Pakistan performed at least two nuclear weapons tests in 1998 as a direct response to the Indian nuclear tests earlier the same year. With this act, Pakistan became the seventh country to successfully complete a nuclear weapons programme. The Pakistani nuclear weapons arsenal consists of both uranium and plutonium weapons and the country has an extensive nuclear industry with all facilities necessary for enrichment of uranium, production of plutonium and reprocessing of spent reactor fuel.

Pakistan acquired a Canadian civil heavy water nuclear reactor in 1971; KANUPP-1. In 1976 however, the cooperation with Canada ended as Canada stopped supplying fuel for the reactor. At this point, Pakistan had acquired know-how and experience to manufacture its own fuel and also started building an independent nuclear industry with several unsafeguarded reactors at the Khushab site. With French assistance, a reprocessing plant was constructed and consequently, Pakistan is today in possession of all components necessary for developing and employing both uranium and plutonium nuclear devices.

In this presentation, we will explore technical challenges associated with bringing a country such as Pakistan under the existing or proposed treaty verification following treaties such as the NPT, TPNW and FMCT. Using a simulation framework and estimates based on known physical quantities and derived abilities, we will discuss what conclusions can be drawn with regards to uranium and plutonium stockpiles.

Introduction

Motivated by the hostile competition with India; Pakistan has successfully built and tested nuclear weapons; which was proved by the Chagai bomb tests performed in 1998. Pakistan has not signed the Non-Proliferation Treaty (NPT) and has not declared any intention of doing so. The same is true for the Treaty on the Prohibition of Nuclear Weapons (TPNW), but, interestingly, Pakistan has advocated for the Fissile Material Cut-off Treaty (FMCT), under the condition that also historical production is included [1]. If this proposed form of the treaty would enter into force, not only current enrichment and reprocessing capabilities would need to be quantified; but also historical capabilities leading up to today's stockpiles.

Even if a country does not declare its nuclear weapons stockpiles, it is possible to make estimations, based on capabilities and operation of nuclear facilities. When operational data from these facilities are restricted, as is access to the facilities themselves, a starting point is to develop models resting on data from well-known civilian nuclear facilities under safeguards by the International Atomic Energy Agency (IAEA). One can then successively expand the work to encompass other nuclear facilities such as those expected to be part of a military fuel cycle part of a nuclear weapon programme. As will be discussed below, there are similarities that can be exploited between a civil electricity-producing nuclear fuel cycle and a military cycle producing fissile materials for nuclear weapons.

In this work, we discuss methodologies to estimate a state's capability to produce nuclear weapons, based on openly available information about the nuclear fuel cycle in that state, activities and facilities outside of nuclear safeguards and availability of uranium resources. In relation to nuclear disarmament efforts aiming at reducing or eliminating nuclear weapons arsenals or support verification under treaties such as TPNW and FMCT, such estimates are important.

Background

States that are non-nuclear weapon states (NNWS) and have signed the NPT have already committed to not producing fissile material for use in nuclear weapons, most notably highly enriched uranium and plutonium. The five states recognized as nuclear weapon states (NWS) under the NPT (USA, UK, France, Russia and China) have agreed not to proliferate nuclear weapons or nuclear weapon materials. In addition, there are four additional states that possess nuclear weapons; India, Pakistan, Israel and North Korea.

Estimations of the capability and capacity of states to produce nuclear weapons come from e.g. the SIPRI yearbook [2]. However, for reasons related to nuclear security, states possessing nuclear weapons do not publish information on their weapons programmes and capacities, and reported estimations are rarely commented on or confirmed. For this reason, it is desirable to have a large tool-kit of independent methodologies for making relevant estimates of nuclear activities.

Nuclear weapons and the nuclear fuel cycle

Two types of fission-based nuclear weapons are known to be used; uranium and plutonium weapons. This means that a state dedicated to acquiring nuclear weapons could choose either path or possibly both. The uranium path requires the enrichment of uranium to be drastically increased from the natural level of 0.7% to approximately 90%. The plutonium path requires production of plutonium, which is formed from uranium in the intense neutron flux in a nuclear reactor, as well as reprocessing capabilities for separating the plutonium from the remaining uranium and waste products.

Activities needed for nuclear weapons manufacture have, to some extent, an overlap with activities in civil nuclear power programmes. Many power reactors require uranium enrichment of nuclear fuel (to a level of ca 3-4%) and some states have chosen to reprocess irradiated fuel and recover uranium and plutonium to allow for a more efficient use of natural resources. The nuclear fuel cycle employed for civil purposes is shown in Fig. 1.

States that have signed the NPT have agreed to safeguarding their civil nuclear fuel cycle, meaning that the IAEA is allowed to verify compliance with the NPT by accounting nuclear material in the state. The IAEA also carries out inspections of facilities to ensure that declarations on nuclear material are complete and correct. Many countries that have civil nuclear energy do not have domestic control over all parts of the fuel cycle and instead rely on import of goods produced in nuclear facilities in other parts of the world. Sweden, for instance, does not have active uranium mines, enrichment plants or reprocessing plants. Instead, Sweden imports enriched fuel and plans for a geological storage for spent nuclear fuel.

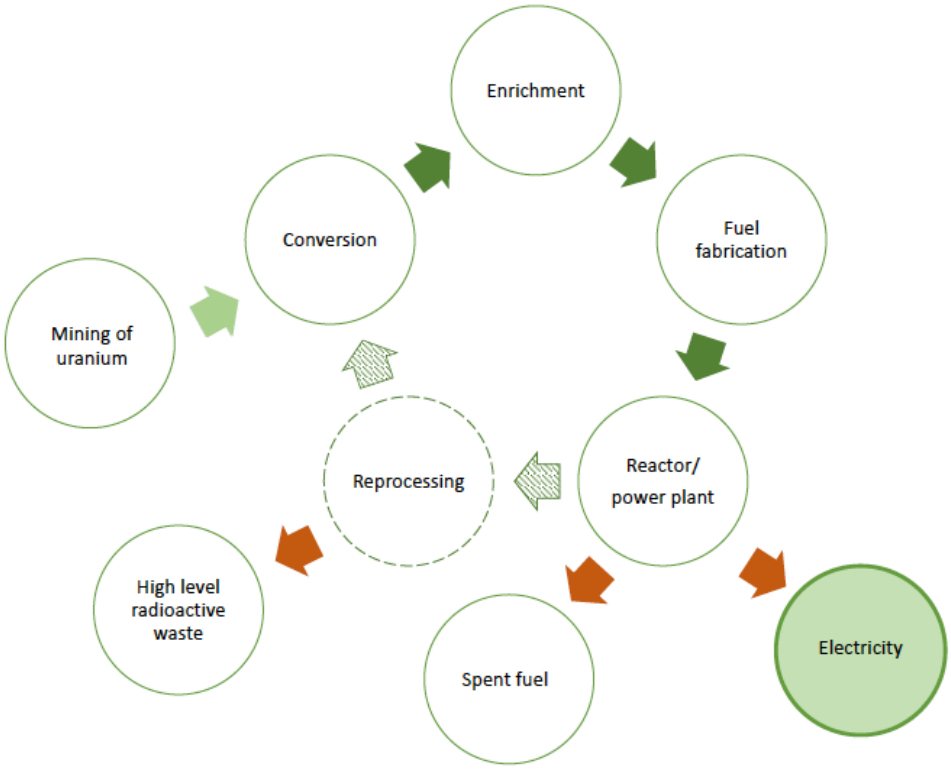

Figure 1: *The closed civil nuclear fuel cycle intended for electricity production. Note that not all states have reprocessing, meaning that they instead employ an open cycle without reprocessing of spent fuel.*

On the other hand, a country dedicated to producing nuclear weapons independently of other countries and actors, needs domestic control of all the activities and facilities needed in a nuclear weapons programme. In order to understand what those facilities are, see Fig 2. In this cycle, uranium is either used for enrichment to produce highly-enriched weapons grade uranium or to fuel a reactor intended to produce not electricity but plutonium. Reprocessing would be employed to recover plutonium for weapons-purposes, and not to produce new civil reactor fuel. By studying such a military fuel cycle, and analysing material production in each step as well as material flows between facilities and activities, it may be possible to estimate quantities of produced weapons-grade uranium and plutonium in a state, and thus also to estimate the number of nuclear weapons in stockpiles.

Studying the facilities in the nuclear fuel cycle is crucial for quantitatively estimating a state's nuclear industry. While nuclear weapons are small and easy to hide; a nuclear programme with an industry on the scale needed for production of nuclear weapons inevitably leaves traces that can be discovered. This is also why nuclear safeguards is such an important tool intended to ensure that facilities and activities intended for civil purposes are not misused to instead produce nuclear weapons. Nuclear safeguards may also provide early indications if the nuclear material accountancy in a state does not appear to balance

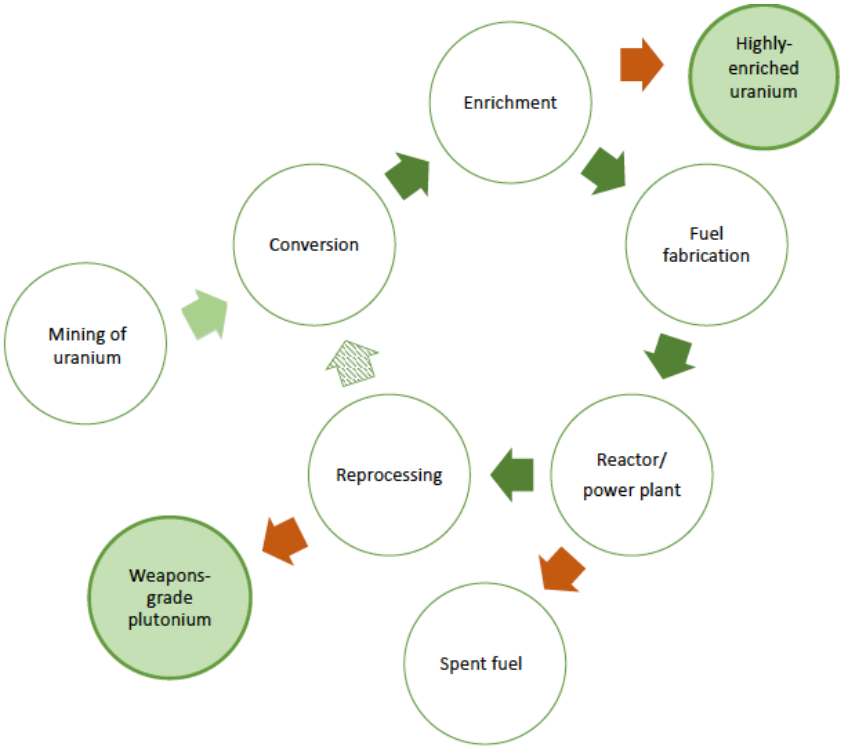

Figure 2: *The military nuclear fuel cycle intended for weapons material production. The reprocessing facility is necessary for extracting plutonium.*

Case study: Pakistan

Using Pakistan as a test case, we can investigate the literature describing the nuclear weapons programme and its associated nuclear fuel cycle. It is stated in e.g., refs [3] that Pakistan has all the necessary production facilities for producing both highly-enriched uranium and weapons-grade plutonium and it is deduced that the Chagai-I test was a uranium device, and the Chagai-II test could have been a plutonium (and possibly also containing uranium) device [4]. It is consequently clear that Pakistan has full control over the military fuel cycle including uranium enrichment facilities, fuel manufacturing facilities, nuclear reactors and reprocessing facilities. When looking at the material flows between various facilities and manufacturing sites a complex picture emerges, where the details on military facilities are scarce.

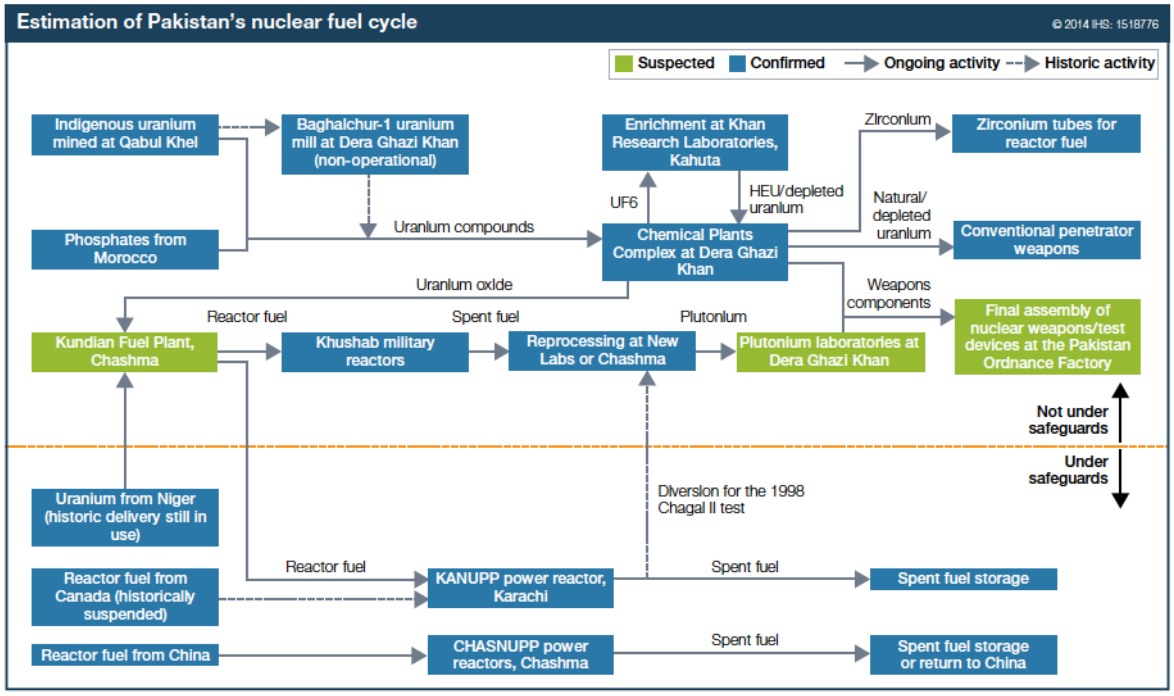

Figure 3: *A detailed picture of Pakistan's nuclear industry, from Janes Intelligence Review [3].*

As can be seen from Fig. 3, Pakistan has both civil facilities under safeguards, and facilities outside of safeguards. For a comprehensive analysis of the military fuel cycle and for accurate assessments of the number of nuclear weapons in a state, it is important to not only paint the right picture including existing facilities and activities in the state (such as seen in Fig. 3), but also to attach numbers on throughput and material production and consumption to each nuclear facility. This is an ongoing work and an ambitious challenge, and needs to be tackled in steps.

So far in this work, we have decided to focus on plutonium production mainly in the Khushab military reactors. To some extent this work however also involves the now decommissioned civil KANUPP reactor, which was under nuclear safeguards. It has been assumed that the building of the military reactors at Khushab rests on the acquired knowledge from the KANUPP reactor.

The arrow pointing from KANUPP to the Chagai-II test in Fig 3. has been contradicted by other sources. I.e. [5] claims that there was no diversion of spent fuel from KANUPP to the military programme. Without certain confirmation either way, the scenario proposed in Fig. 3 is however possible, and reactor calculations (see below) show that the KANUPP reactor theoretically could have been run in such a way that it provided the material for the Chagai-II test. It is also notable that the first military reactor in Khushab went operational in early 1998, and the Chagai tests were performed in May 1998, which is a very short time after start of operation in Khushab.

The KANUPP reactor, operated between 1972 and 2021, was acquired through a cooperation with Canada and is a small CANDU-reactor of the same type as Canada has operated in e.g. Douglas Point. It is a heavy water reactor with a maximum electric output of 137 MWe; corresponding to ca 337 MWt thermal power [6]. The Khushab military site has four reactors operating as of 2022. Their power output is not precisely known, but it has been estimated [7] that Pakistan could only fuel ca 150 MWt of reactors with its domestic uranium resources., i.e., substantially less than the single KANUPP reactor (of 337 MWt).

Being modeled after the Indian CIRUS reactor of 40 MWt [8] a power on the order of 40 MWt (or less) per each reactor at Khushab make sense. However, also in the reference [7] the authors cite sources based on satellite imagery discussing that the sizes of Khushab II and III could be as large as 100 MWt each, which would raise the question of how large Pakistan's uranium resources actually are in order to fuel these reactors. The quoted total capacity to fuel only 150 MWt, does not allow for these sizes of Khushab II and III.

This divergence between the size of the reactors and how much uranium is needed to fuel them versus how much uranium Pakistan is believed to have access to is addressed by Branger et al. in another paper in this conference.

Estimations of plutonium production using simulations

If a reactor design and its reactor power history is known it is possible to use computer simulations to determine the amount of plutonium that can be produced. In this work, reactor simulations have been made with the Monte Carlo code Serpent 2 [9]. This code allows the user to specify reactor geometry and materials present before running the code. The set power history simulates the physical reactions that take place in a true reactor. This is called a burnup calculation meaning that the code calculates the burnup of uranium which results in the neutron flux leading to the production of plutonium and other heavy elements. The output files will contain the isotopic composition of the irradiated fuel and displays the concentration of each isotope in the fuel.

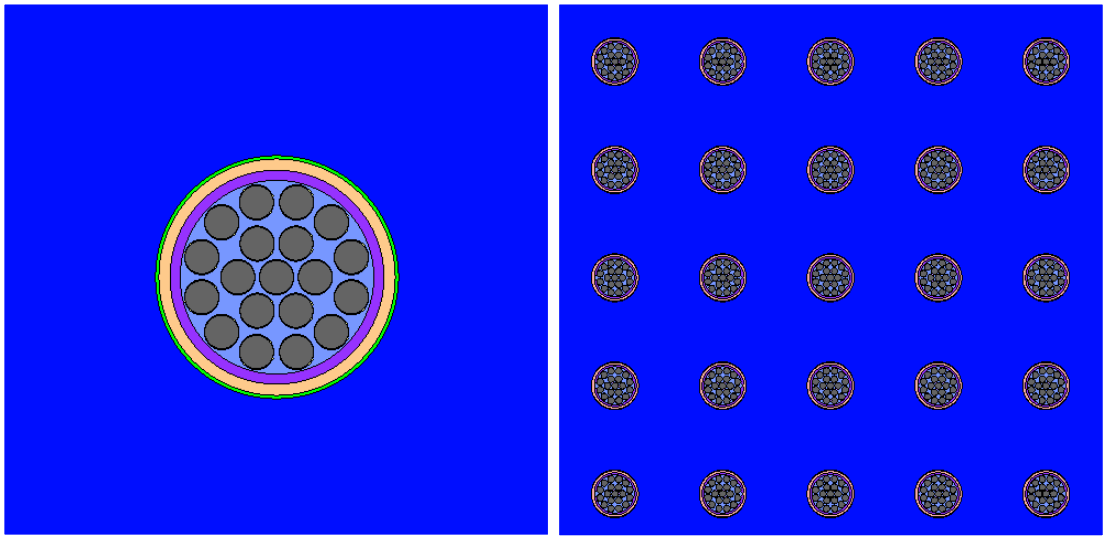

Figure 4: *The KANUPP fuel bundle geometry. The grey elements are cladding-enclosed fuel rods of natural uranium, the purple circle is the pressure tube, the orange circle is CO_2 gas and the green circle is the calandria tube. The blue colours represent coolant and moderator, both heavy water.*

The simulation model shown here represents KANUPP, having a fuel assembly design with 19 fuel rods in a circular arrangement. In the core, each fuel assembly is enclosed by a pressure tube. Each tube is placed inside a calandria shell and these calandria assemblies are placed in a square pattern to make up the reactor core. Both the coolant inside the pressure tubes and the moderator surrounding the calandria assemblies are heavy water. In total there are 208 assemblies and around 35 tons of fuel in the form of uranium dioxide UO_2 in the core. [10]

In the simulations an infinite 2D-lattice model has been used. This means that one assembly has been modelled as an infinite cylinder and then repeated through periodic boundary conditions. In

other words, when a particle exits from the lattice on the right-hand side, it will reappear on the left-hand side, in effect modelling an infinite core.

This approach and the modelled geometry has been benchmarked against two CANDU reactors where the isotopic compositions after irradiation have been determined experimentally. These reactors are the Canadian CANDU reactors NPD (the nuclear power demonstration reactor – a small prototype reactor) and Bruce-1 (a large CANDU-6 reactor) which both have reported isotopic compositions at specified burnups to the NEA database SF-COMPO [11]. The model was applied to these reactor geometries and after simulating the same power histories as the real reactors had experienced, the relative isotopic abundances of uranium and plutonium could be compared between the model and the experimental data sets.

With the model simulating the KANUPP geometry and power it can be shown that 100 g of weapons grade plutonium can theoretically be produced in each assembly of KANUPP, making a total of 20 kg for the whole core of 208 assemblies. (Here, weapons-grade plutonium is defined as an isotopic plutonium composition with less than 7% of the isotope ^{240}Pu.) The optimal production of plutonium is obtained if the fuel is irradiated approximately one month before extraction. A careful study of the official KANUPP power history reveals periodically recurrent drops in power approximately once per month which could be associated with fuel exchanges.

Modelling Khushab is more difficult since neither the exact design, nor the total power or the power history is known. As mentioned before, the design is based on the CIRUS reactor which in turn is modelled after the Canadian NRX reactor [12]. This suggests that the Khushab reactors are heavy water reactors using natural uranium, but of a type where only the moderator is heavy water, while the coolant is light water [8]. Furthermore, the NRX and CIRUS reactors have pressure vessels instead of pressure tubes, as in a classic CANDU design, and these features must be addressed in the simulation model. While the differences in reactor core design will potentially affect the plutonium production, the by far most important uncertain factor is the reactor power. Finding ways to correctly estimate the power of all four Khushab reactors remain the focus of the continuation of this work.

Stockpile of HEU and WG-Pu

Continuing this work towards estimating the total amount of highly-enriched uranium and weapons-grade plutonium a country has produced and can produce, one must start from uranium resources, which are necessary for both paths. The enrichment of uranium is of course dependent on the amount of uranium available, but also the production of plutonium starts with a reactor using uranium as fuel for the breeding process. There is a trade-off between using the uranium in the enrichment stream and to fuel a reactor with it in order to make plutonium

Pakistan has an enrichment facility at Kahuta, see e.g. [13]. It is possible to find data on the estimates of the capabilities of enrichment and stockpiles of already highly-enriched uranium. Ref [14] reports an estimate of more than 1200 kg of HEU in stockpiles in Pakistan (produced 1984-2005). This is based on the yellowcake usage in the enrichment plant and assuming that Pakistan virtually stopped producing HEU in 2005. Ref. [7] reports possible scenarios where the accumulated stockpiles of HEU could reach 6000 kg by 2020.

When it comes to the production of plutonium, the previously reported estimated stockpiles amount to a total production of ca 200 kg at the end of 2014, [14] or 450 kg by 2020 [7]. These figures are based on the assumption that the Khushab reactors are in the order of 50 MWt and use uranium in a simple once-through cycle. What is investigated by Branger et al. in this conference, is that Pakistan may use a more advanced fuel cycle than a once-through cycle, meaning re-using the uranium by reprocessing it for production of new fuel. With such a scheme, it would be possible to use the available uranium

more efficiently and in effect fuel larger reactors and produce more plutonium than has previously been estimated.

Besides looking at uranium resources there are other ways of assessing a reactor's size. One is to look at the consumption of heavy water. There are at least two heavy water production plants in Pakistan; Khushab heavy water plant located at the same site as the four Khushab reactors, and a smaller site called Multan heavy water production facility.

It is well-known that KANUPP had substantial problems with heavy water leaks and this was one of the reasons for the frequent shut-downs and outages [15]. Several measures were taken, and ref [15] states that in the early seventies, the total annual leakage of heavy water from KANUPP amounted to as much as 5000 kg (5 tonnes), and that after introducing several tools and devices to minimize leakage (in the mid-70s), it was cut down to 25% (1250 kg) annually. During the years of operation, the total loss of heavy water from KANUPP must have been in the same order of magnitude as the amount needed for start-up of a small reactor, i.e., up to 50 tonnes. A large CANDU-6 reactor has of the order of 500 tonnes of heavy water in the system whereof approximately half of this amount is used as moderator and the rest as coolant [16,17]. The Khushab reactors are a little bit different from the classic CANDU design, i.e., they are moderated by heavy water but cooled by light water [8], which would make the demand for heavy water approximately halved. They are also substantially smaller in thermal power than at CANDU-6. Pakistan is absent in the international trade statistics of heavy water [18,19], indicating that their yearly consumption of heavy water in Khushab can be met by the country's own production capabilities.

One final way of accurately estimating plutonium production in a nuclear reactor is by investigating the historic neutron fluence. Plutonium production happens through neutron capture in uranium and is dependent on the number of neutrons available. In reactor physics, the neutron flux is defined as the number of neutrons per cm^2 per second, and the neutron fluence is the flux integrated over a certain time period, i.e., the number of neutrons per cm^2. It has been shown [20] that the cumulative neutron fluence can be used to estimate the total amount of plutonium produced, both in graphite-moderated reactors and in heavy water reactors. The idea is to analyse structural material from a reactor and using mass spectrometry measuring the ratio of different isotopes. Since the production of certain isotopes is related to the neutron fluence, a relationship between the isotopic composition of the historic structural material and the experienced neutron fluence of the reactor can be established. In turn, the neutron fluence can be directly linked to the production of plutonium. The method described here belongs to the research field of Nuclear Archaeology. It is a method that requires access to reactor components and it has primarily been used on declassified reactors that have been permanently shut down. It can therefore be a useful tool for estimating plutonium stockpiles from historic nuclear weapons programmes.

Discussion and outlook

In this paper, the challenges associated with quantifying a country's weapons-producing capability have been touched upon. Primarily, focus has been placed on reactor calculations regarding production of plutonium, starting from a well-known reactor design where experimental data on produced amounts of plutonium can be linked to the power history of the reactor. Benchmarking computer simulations against physical data is a valuable tool when developing models, and once a well-described reactor can be confidently simulated, the approach can be extended to encompass other reactor designs.

Being a work in progress, the future research will build on the developed simulations framework with the goal of providing more accurate estimates of capabilities for plutonium production from non-safeguarded reactors. Such estimates could provide a valuable input to the discussion about including

both historic and contemporary fissile-material production in future FMCT, as has been suggested by Pakistan it should be.

Acknowledgements

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