MODELING THE TECHNICAL MEANS TO PRODUCE NUCLEAR WEAPONS FOR PROVIDING ACCURATE DECISION-MAKING TIMETABLES

BY

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THESIS

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Abstract

Government agencies, non-government organizations and academic institutions that focus on nuclear nonproliferation have demonstrated a limited capability to make comprehensive assessments of how far along a state is in the proliferation process. This deficiency exists despite the need to improve programmatic assessments of states that likely pose a risk of developing nuclear weapons. Modeling can help the end-user estimate the probable time required for a given state to complete a nuclear weapons program. This is highly attractive feature for policy makers who – with more accurate assessments – can make informed decisions.

For any given state it is possible to use information on that state's industrial strength, educational strength, and previous experiences with nuclear fuel cycle technology to assess that state's capabilities and estimate a timeframe for that state to complete a nuclear weapons program. This body of research designates a governing equation for the model, discusses the technical attributes that are required for every nuclear weapons program, and discusses the process for designating values to each process variable. Beneficial applications for using this particular model and its limitations are also demonstrated and discussed.

Acknowledgements

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List of Acronyms

AVLIS – Atomic Vapor Laser Isotope Separation
DPRK – Democratic Republic of Korea
EAR – Estimated Additional Resources
ENI – External Neutron Initiator
HEU – Highly Enriched Uranium
INI – Internal Neutron Initiator
ISL – In Situ Leaching
LWR – Light Water Reactor
MLIS – Molecular Laser Isotope Separation
NFC – Nuclear Fuel Cycle
NGO – Nongovernment Organization
NWP – Nuclear Weapons Program
PUREX – Plutonium-Uranium Extraction
RAR – Reasonably Assured Resources
ROK – Republic of Korea
SNM – Special Nuclear Material
SR – Speculative Resources
SWU – Separative Work Units
TBP – Tributyl Phosphate

Chapter 1: Introduction

Nuclear weapons are constructed from the same fundamental elements as a civilian nuclear power program. This fact defines a fundamental problem created by "dual-use" technologies. But technology in itself is not capable of producing nuclear weapons. There must be a collective will amongst the leadership of a state to pursue nuclear weapons. The decision to pursue a nuclear weapon program (NWP) is ultimately a political one. Technology can only dictate how quickly a state can produce a functioning weapon or construct the capability for rapid breakout. A state that is determined to produce nuclear weapons will do so as long as the political will is strong enough to overcome the opposing geopolitical and economic disadvantages from operating a known program. The decision to prevent another state from constructing a NWP is also a political one. Keeping a state from acquiring weapons necessitates a change in the political will in that state. This can be achieved by 1) making the acquisition of nuclear weapons and nuclear weapon technology so challenging that the cost is not worth the perceived benefit, or 2) altering the political composition at the leadership level. Many foreign policy instruments exist to exercise both options, but policymakers trying to determine a proper course of action on either of these two methods need as clear and accurate as possible a timetable to implement an appropriate policy response.

It is reasonable then to place particular importance on assessing the technical progress of a nuclear weapons program in order support and justify policy response options. But there is considerable difficulty in creating an accurate diagnosis of a state's capabilities. Iran is the most recent example, as intelligence agencies and various NGO's still cannot agree on an estimated timeframe to produce a weapon [1]. The purpose of this research is to contribute to the demonstrated need for a better analytical method for determining the length of time necessary for

a given state to produce nuclear weapons. This can be achieved through an examination of technical information related to the nuclear fuel cycle (NFC), the level of prior experience with nuclear facilities, and state-specific metrics.

Understanding the engineering and technical challenges to produce weapons and modeling those challenges based on a given state's scientific, technical, and industrial capabilities will give policymakers a better estimate of their timetable to seek a solution. Using the scientific and engineering knowledge of what is necessary to produce a deliverable nuclear weapon, a set of criteria can be established whereby it is possible to accurately estimate the necessary amount of time for a state to develop a nuclear weapons program based on technical capabilities.

Chapter 2: The Model

2.1 – Scope of the Model

For the purpose of this examination, it is helpful to construct several definite expectations and definitions in order to accurately define the scope of this work. In addressing how quickly a NWP is constructed, it is best to define the scope of the program. What will be considered here is based on a combination of real world considerations while addressing what is the minimum amount of effort needed to develop a NWP. For that reason, the remainder of this section is dedicated to explaining the specifics of those ideas and expectations.

The notion of a state having a "latent" proliferation capability to produce a weapon is an attractive starting point for this research. States with some academic or commercial nuclear facilities are also incrementally more capable of producing a nuclear weapon, as understood by the "dual-use" problem of nuclear technology. The breakout scenario, whereby a state produces a functioning nuclear weapon in three months or less, also then becomes a valid and interesting starting point for discussion. However, the concept of latent proliferation and the breakout can be very vague. Having the capability to produce a single weapon on short notice – which may be desirable for some states – has only limited usefulness. Many states are designated as having latent proliferation capabilities, and this is a subject of considerable study [2, 3]. But this does not signify the true ability to produce a robust apparatus for sustained weapon construction. While having one nuclear weapon maybe enough in a desperate, defensive scenario or as a last minute deterrent, there is limited utility to having only one or two nuclear weapons. Therefore this research will define a NWP as *having the operational capacity to produce at least one deliverable weapon annually*, and a latent proliferation capability will only be described as a possible identifying benchmark to achieve a full NWP.

When looking at the civilian NFC, it is possible to narrow down what is an essential component for weapon production. What is principally essential to construct a nuclear weapon is the special nuclear material (SNM). The type of SNM sought after, either highly enriched uranium (HEU) or plutonium, will dictate a whole series of decisions based on what is required to manufacture that particular type of SNM. In addition to the presence of certain government-controlled NFC facilities, this examination will include state-specific information on: the strength of industry, the strength of the scientific base, current and previous NFC operations experience, and discuss the rate of weapons pursuit. Table 2.1 is a breakdown of NFC processes that are explicitly required for the production of a given SNM.

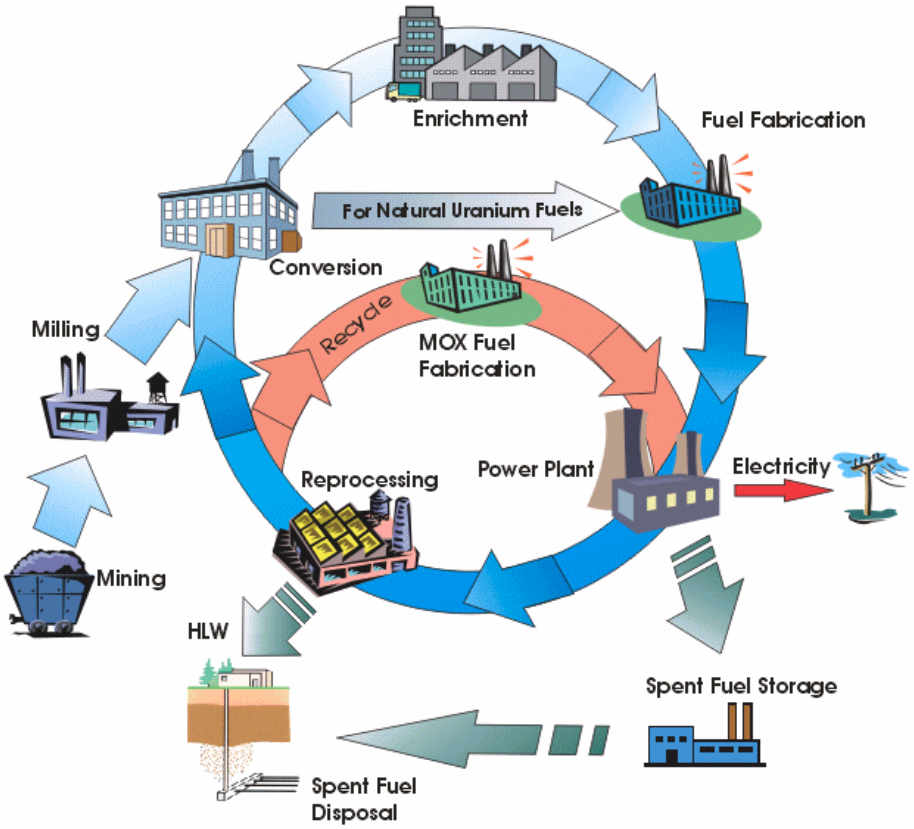


Figure 2-1: Diagram of the nuclear fuel cycle [4]

Table 2.1: Nuclear fuel cycle processes for a NWP

Weapon Material Pursued	Nuclear Fuel Cycle Step
Uranium	Enrichment
Plutonium	Fuel Fabrication
	Irradiation
	Reprocessing
Both	Mining
	Milling
	Conversion

2.2 – Exclusions

In determining what will be the subject of examination, it became apparent that it is equally important to address what will not be considered or represented in the technical model. Because the focus is placed on analyzing the time to produce a NWP based on technical capabilities alone – and because there is simply not enough time to address everything of possible consideration – the model will not address issues related to cost, political or economic conditions in the state (outside of those industries directly involved) or the inclusion of more sophisticated military dimensions in an NWP.

Costs associated with developing a NWP are understandably high, and they serve as an interesting metric for analyzing the intentions of a suspected proliferator. But reasonable estimations are incredibly difficult to calculate without knowing the exact nature of the NFC infrastructure used or current and historical market prices, labor costs, etc. One must also take into consideration the additional costs associated with keeping a NWP clandestine; this can substantially increase the cost of a program because of expenses like building hardening, additional protection assets or dummy buildings [5, p. 99]. This lack of accuracy makes cost an unattractive variable to examine at this time.

Different economic or political systems might make it easier or more difficult to allocate resources towards a state project like a NWP. But the sheer difficulty of analyzing these parameters necessitates the need for an independent study beyond this work. And the possible changes in political and economic conditions during the course of a program add further difficulty. This being the case, it is possible in some sense to describe such changes through the "pursuit rate" (discussed in the next section). Several other possible event parameters like external intervention and technical setbacks are unpredictable by their nature, and cannot be realistically accounted for in this work.

The modern NWP includes many military-specific facets that ensure survivability and increase effectiveness. Such military dimensions are generally related to the deployment of weapons, and these can include: possessing viable delivery vehicles, a command and control structure, basing, storage, and a developed doctrine for use. Having these elements in place is very important for the realistic deployment and operation of nuclear weapons, but developing these elements will take place either in parallel to NWP development or will not directly affect the time to construct a rudimentary weapon. The assumption will be made that a successfully completed weapon would resemble a yield on the same scale as the "Little Boy" or "Fat Man" weapons that were used in World War II and can be deliverable by plane.

2.3 – Governing Equation of the Model

Of course it should be noted that this is not the first exploration on the technical features of what constitutes a NWP. Work has already been conducted to examine the factors that influence proliferation [3, 6]. These works give some categories proliferation indicators, but this meant to address whether or not a state should be categorized as having a latent proliferation

status. These studies are also great starting points for the time-table model because they discuss basic criteria, but there is an over-simplification. Simply having a threshold production-level of steel or a few years of experience in research reactor operation may signify having the basic tools and some measure of experience to make a NWP. But this is like suggesting that a second-year art student with access to paint, brushes, and a blank canvas is only a measure of time away from replicating the Mona Lisa; the statement may be true, but it is not terribly helpful. And if you can deem a state as being capable of developing nuclear weapons because said state has reached a threshold amount of total electrical power production – say 200 MWe installed capacity if using Meyer's model [3, p. 189] – then what can be said about a state with a 1,000 or 10,000 MWe installed capacity? Is such a state able to dedicate more energy to a NWP, and thus produce a weapon more quickly?

This research aims to go a step farther by taking many of these same metrics used in previous studies and using them as a staging point. There is undoubtedly an effective "critical mass" of industrial production and collective experience necessary to produce a NWP[1]. And if the argument can be made that there is a "threshold" level, then there should be a way to express this increased capability. From this idea, Equation (2.1) is proposed as a way of systematically combining the information that will be generated over the next few chapters.

$$T = \frac{R}{I}\left[\sum_{j=1}^{J}\frac{W_j}{S_{w_j}} + \sum_{k=1}^{K}\frac{P_k}{S_{P_k}}\right] \qquad (2.1)$$

Because the ultimate question to be determined is the time, *T*, to complete an NWP, the various NFC process steps, *P*, and weaponization steps, *W*, will have to be expressed individually. The total time is expressed as the aggregate of all the steps. The process steps can be further broken

[1] Meyer partially describes this as a quantitative scientific demand [3, p. 32]

down into construction, *C*, and operation, *O*, steps as show in Equation (2.2). Each of these steps is divided by a scientific knowledge factor, S_w and S_p, as appropriate, and the full summation of the terms is multiplied by the ratio of a rate factor, *R*, and an industrial factor, *I*. Equation (2.3) is the expression that will be used as our modeling equation.

$$P_k = O_k + C_k, \ k = 1, 2, 3, \ldots, K \qquad (2.2)$$

$$T = \frac{R}{I}\left[\sum_{j=1}^{J} \frac{W_j}{S_{w_j}} + \sum_{k=1}^{K} \frac{(O_k + C_k)}{S_{P_k}}\right] \qquad (2.3)$$

C = Incomplete Nuclear Fuel Cycle Step Construction Time
T = Estimated time to Full NWP
I = Industrial Effectiveness Factor
O = Nuclear Fuel Cycle Step Operation Time
P = Nuclear Fuel Cycle Process Time
R = Rate of Pursuit
S_P = Scientific Knowledge Coefficient (Nuclear Fuel Cycle Process)
S_W = Scientific Knowledge Coefficient (Weaponization)
W = Weaponize-Step Operation Time

The final value for the time to NWP completion is based on describing each nuclear process step as a measure of effort that the state must endure. The level of exertion for each step will depend upon the state's knowledge of the technical attributes for that step. This expression is meant to be a simple method for translating qualitative information into quantitative values for evaluation purposes. But it is also clear that describing a state's future NWP efforts as a cumulative effort is not completely satisfactory to real-world conditions or expectations.

Table 2.2: Weapon-Creation (*W*) & knowledge steps (S_w) for chosen SNM

Weapon Material Used	Activity
Uranium	--
Plutonium	Heavy Metal Compression Testing
Both	Design
	Metallurgy
	Fuzing
	Initiation

Equation (2.3) can be interpreted as a methodology through which all of the process steps must proceed in a linear, series fashion. But in actuality the development steps for all large-scale industrial processes will be pursued, to some degree, in parallel. An example is that reactors cannot operate before the fuel is fabricated for that reactor. This parallel process methodology is not captured directly in the proposed model, but it can be indirectly implied – or at least compensated for. Developing multiple nuclear process steps at the same time increases the arbitrary "threshold" value that industry must be able to support. The state's ability to mobilize machines and manpower is a major limiting factor. Therefore a state with a strong industry is more capable of multi-tasking.

The pursuit rate can also help address the issue presented by this model's lack of a parallel process methodology. The rate of weapons pursuit will represent the variable level of effort on the part of the technical community. For example, the dedication of resources and manpower to the Manhattan Project was unprecedented compared to other programs as compared to programs created more subtly to avoid overt detection by modern international nonproliferation regimes. This variable can also be thought of as a level of urgency measurement. These levels are described in Table 2.3. The rate of pursuit of weapons is also predominantly a political decision, but it has great effect on technical developments.

Table 2.3: Nuclear weapons program pursuit rates (R)

Pursuit Rate	Description
Crash	Absolute national priority
Aggressive	Accelerated development; less urgent
Cautious	Slower development to avoid detection
Exploratory	Low interest; keeping the option "open"

2.4 – Model Calibration

The best way to assign values to the program variables is to examine the technical details of each NFC process, the details of weaponization activities, and the NWP's of the non-NPT nuclear weapon states – hereby called "de facto nuclear weapon states." Looking at how long it takes to develop a uranium-based NWP means examining recent historical data on the nuclear programs of states that developed this technology for weapons purposes; the same is true for plutonium-based weapons. The programs that will be examined include those of Israel, Pakistan, India, South Africa and North Korea. These are listed in Table 2.4 along with the understood dates of programmatic development and the type of SNM initially pursued. Because each step is broken down into the fuel cycle processes and weapon-assembly steps, each step will be examined through the lenses of each of these five programs. From the compiled data, the values of each variable and coefficient can reasonably be determined. The limitation on publically accessible data for each of these nuclear programs will play a factor in the analysis described further in this research. There is also a clear problem of separating out external assistance, but the combined information from all of these programs should establish a basic dataset to draw conclusions from.

Table 2.4: De facto nuclear weapons states

State	Weapon Type	Decision-to-Weapon Dates[a]
Israel	Plutonium	1955 – 1967
India	Plutonium	1964 – 1974[b]
North Korea	Plutonium	1982[c] – 2006
Pakistan	Uranium	1972 – 1990
South Africa	Uranium	1974 – 1978

[a]Source: NTI country profiles [7], [b]India's program is considered complete with their first (peaceful) nuclear test, [c]As coded by Jo & Gartzke's data notes [8].

While the ultimate goal of this research is to develop an equation that can be applied to any state, the ability to test the validity of this concept hinges upon an accurate assessment of

several test states. To help facilitate discussion throughout this report, it is important to identify the three states that will be used in the analysis. These states include South Korea, Turkey, and Myanmar. A brief assessment of these states' technical programs is available in Table 2.5. Each state was chosen for the analysis either because they are fairly relevant in recent discussions of nonproliferation or the state represents a major regional actor. These three states also represent an excellent cross-section of different levels of nuclear development.

Table 2.5: States for model analysis

State	Initial Technical Assessment
Myanmar	Startup
South Korea	Advanced Program
Turkey	Knowledgable

Before state-specific data is examined, a technical discussion of each of the NFC processes and weaponization steps is necessary. This information is presented in order to help facilitate discussion and rationalize the values assigned to these steps, as detailed in *Chapter 5*.

Chapter 3: Nuclear Fuel Cycle Steps

The first step is to examine the technical issues involved with each NFC process. Each of the steps discussed in this section corresponds to a specific variable within the overall governing equation – which will be designated in *Chapter 5*. While it is important to provide a comprehensive, detailed look at each process step to determine what difficulties a state encounters, it is beyond the scope of this unclassified research to take on the form of a generic NWP feasibility study.

3.1 – Mining & Processing

The most critical step in making a nuclear weapon is creating the SNM, and this is a process that starts from the ground up. Uranium ore supplies are the major starting point. From a technical standpoint, uranium mining is probably the easiest step to complete. Having domestic uranium supplies is important for sustained weapons development, but not having access to a natural uranium deposit may not necessarily complicate NWP development if access to uranium can be obtained by other means (commercial or illicit trade). Purchasing a base product on the market will bypass this step in weapon acquisition, but a lack of domestic supplies will severely inhibit future growth of a nuclear stockpile after initial capability is achieved. For the purpose of this research, domestic production will be factored into the model.

3.1.1 – Construction

Domestic uranium resource development starts with exploration of known or estimated uranium deposits. Most states will have an understanding of their geography from constant exploration of other resources and commodities. Detailed studies on modern exploration

programs help create more cost-effective mining operations [9]. This analysis will use the more general approach used by the IAEA and the OECD Nuclear Energy Agency in classifying uranium resources.

The distinction between conventional and unconventional resources is drawn based on whether or not the uranium is the primary commodity or a very minor by-product of a given mining operation, respectively [10, p. 261]. Uranium resources are also generally divided into categories based on the certainty of the uranium content in a particular location. What are judged as "reasonably assured resources" (RAR) are deposits with very detailed knowledge and a high confidence in the presence of uranium. RAR are determined to be the easiest resources to exploit with current technology [10, p. 261]. Expressions exist for describing the decreasing certainty of given uranium deposits. These are described by two separate categories of Estimated Additional Resources (EAR-I and EAR-II) and Speculative Resources (SR) [10, p. 261]. The level of initial work to be carried out in mine construction is dependent on the categorization of proposed sites, as additional exploration will be needed for less known/attractive deposits.

Mining is generally divided into open pit or underground operations, and further specifics are dictated by the geological features of the deposit site. Neither of these two methods is technically challenging. Experience is likely to be less important in setting up mining operations, but will contribute to efficiency. Data on the current status of known uranium deposits and mining activities are compiled by the IAEA for public access through several sources, which will be highlighted later.

Once the ore is removed from the ground, it must be processed and separated. Operations are established for this removal and depend on the form of the extracted ore and the anticipated production capacity. Constructing processing operations for the first time will likely require the

setup of pilot-scale operations to gain practical operating experience. Flow sheets and equipment lists have to be made. Equipment includes items needed for crushing, grinding, leaching, solid-liquid separation, uranium recovery, and precipitation and drying [11, p.29]. IAEA TECDOC-314 is an excellent reference for what is necessary to establish a pilot uranium processing plant. Another option to traditional mining and processing is *in situ* leaching (ISL). This process allows the operator to dissolve and mobilize the uranium in the ground, and pump it to the surface where it is then further processed [10, p. 266]. ISL is limited in its application to deposits in sandstone, but can be a more cost-effective alternative to traditional mining techniques [12, p.7]. If the proper situation arises, ISL will be considered in lieu of other mining methods. ISL also eliminates several steps in the milling process.

The OECD reports on uranium mining reinforce the notion that this technology is widely understood. Figure 3.1 is a chart from the OECD that shows that uranium mining development has progressed more slowly in the time period from discovery to the start of operations. Economic, environmental, and regulatory factors are the primary reasons for this trend in commercial uranium development [13, 145]. But considering the ulterior motive for uranium mining, operations can be expected to start at a much earlier time. This work will estimate a period of five years from discovery to development under nominal conditions at the “cautious” rate.

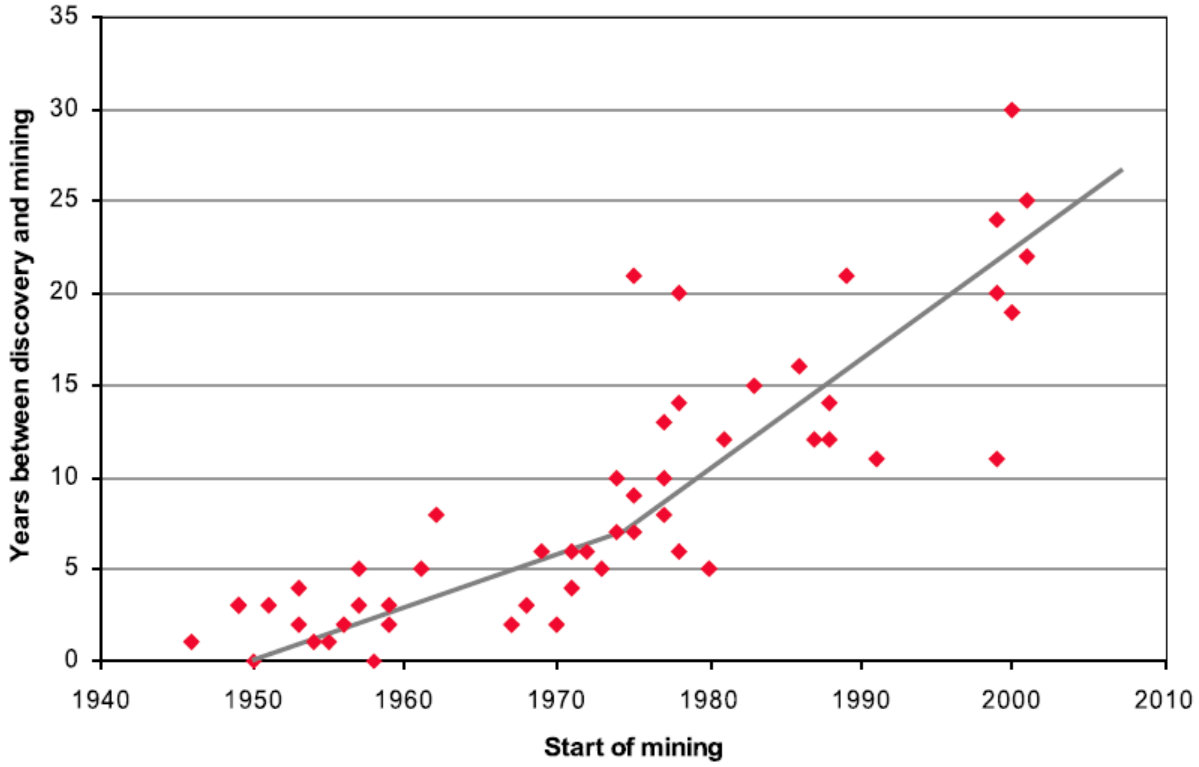


Figure 3.1: Elapsed time between discovery and start of mining for all methods [13]

3.1.2 – Operation

Extracting and processing uranium ore is dependent on the form of the ore and the grade of the uranium. Mining operations are the excavation of the ore, transport to the processing plant, and removal of waste rock. Supporting operations for uranium mining are not terribly different than any other mining operation; radiation monitoring from airborne particles is the only unique safety consideration [9, p. 139].

Many processing operations are very similar. Technology for precipitation is dependent on the choice of the reagent used, and purification is almost always through ion exchange or solvent extraction [9, p. 140]. Several generic process flow sheets are shown in Figure 3.2, and Figure 3.3 is an example of a more specific flow sheet; both figures are adopted from the IAEA. The finished product in mining and milling is U_3O_8, known by the name yellowcake, which is a

widely traded commodity among civilian utilities. Detailed equipment lists can be found in IAEA TECDOC-314. Labor requirements will include work by mining specialists (heavy machinery, explosives experience), logistics, chemists, metallurgists, and construction workers. The work at this stage has unique challenges, but they are not as technically challenging compared to other NFC processes.

In terms of the amount of uranium needed on an annual basis to sustain a NWP as previously defined, there are several determining factors: the type of SNM sought after, the grade of the ore in deposits, and the level of the technology. Plutonium-based weapons produced in a graphite-moderated reactor that use natural uranium will have different demands than a state pursuing uranium-based weapons. And for uranium-based weapons, the choice and operational parameters of the enrichment technology will dictate mining demands.

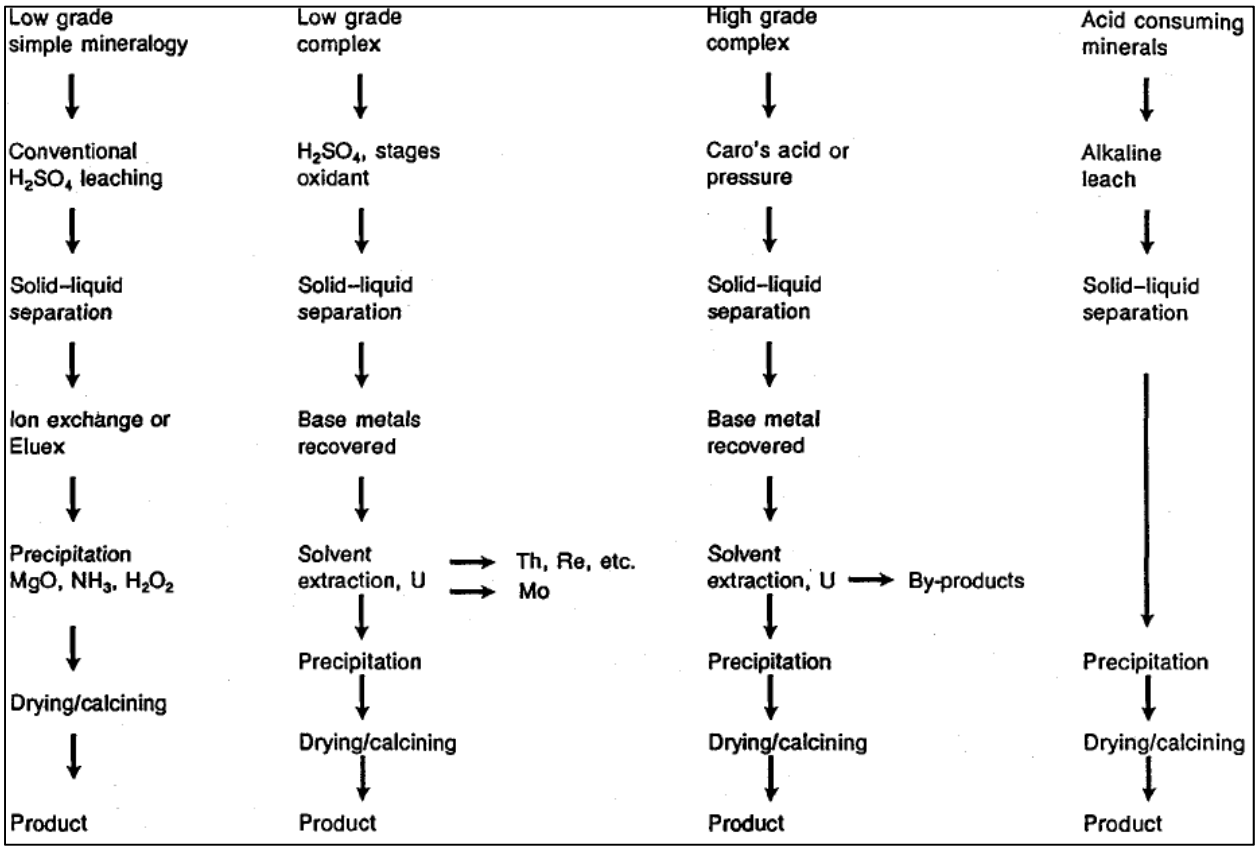


Figure 3.2: Process options for treating various types of ores [14]

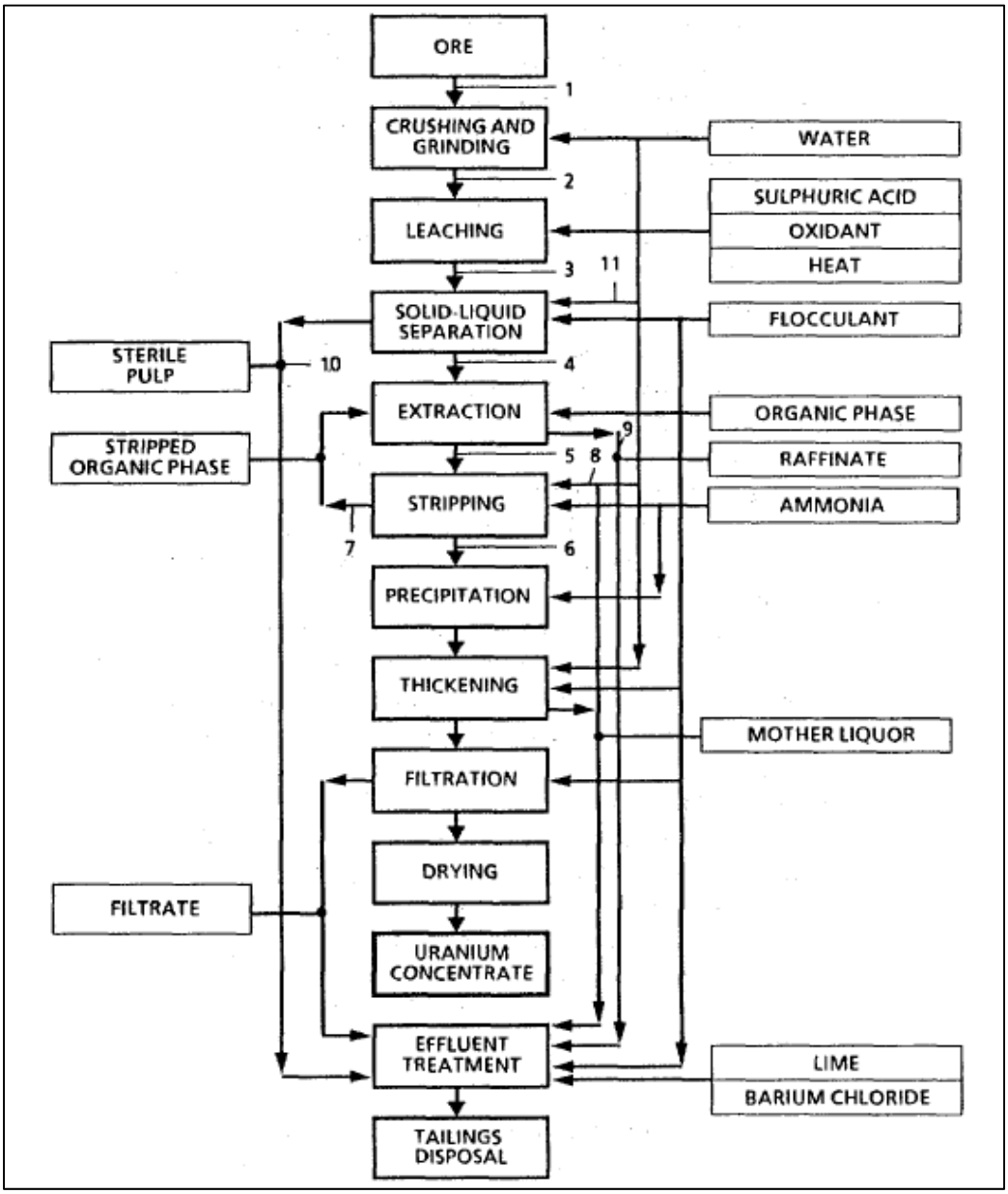


Figure 3.3: Sample diagram of a uranium ore processing plant [11, p. 14]

3.2 – Conversion

Chemical conversion is a critical step regardless of the SNM sought after. Once the uranium yellowcake is produced, it must go through chemical processes to change into a form

that is more suitable for either enrichment or natural uranium fuel fabrication. In the case of enrichment for uranium-based weapons, this process involves conversion from U_3O_8 to UF_6 gas and subsequent storage in canisters. Commercial scale U_3O_8 to UF_6 conversion facilities are operated in Canada, China, the UK, France, Russia, and the USA [15, p. 6]. If producing natural uranium fuels – which are ideal for plutonium production to maintain high concentrations of U-238 – then the conversion from yellowcake to UO_2 or uranium metal is carried out. In either case, conversion is a predominantly chemical process that can be carried out at virtually any scale.

3.2.1 – Construction

The scale of the conversion process will determine the size and scope of facility construction. But the requirements for any radiochemical facility are still demanding to increase cost-effectiveness, minimize process losses, and possibly to reduce the overall environmental footprint to avoid detection. Construction will not have to take into account major shielding requirements, as is necessary for reprocessing operations. Demand will be placed on construction workers and trade specialists as well as chemical, electrical, industrial, and mechanical engineers.

3.2.2 – Operation

The yellowcake uranium is first purified and reduced to UO_2 or UO_3, depending on the process. Purification can take place at the milling stage, but for our purposes we will consider Figure 3.4 as the initial conversion steps. Further conversions to UF_6 for uranium enrichment processes are carried out via fluorination and hydrofluorination processes, as shown in Figure

3.5. At this point, the UF_6 gas is liquefied and shipped in canisters to the enrichment facilities. Reversing this process after the enrichment step is necessary for uranium weapons to convert enriched UF_6 gas to uranium metal, but this process will have a smaller throughput demand. A regular group of process engineers, chemists and operators will be engaged in the day to day operations in the conversion step.

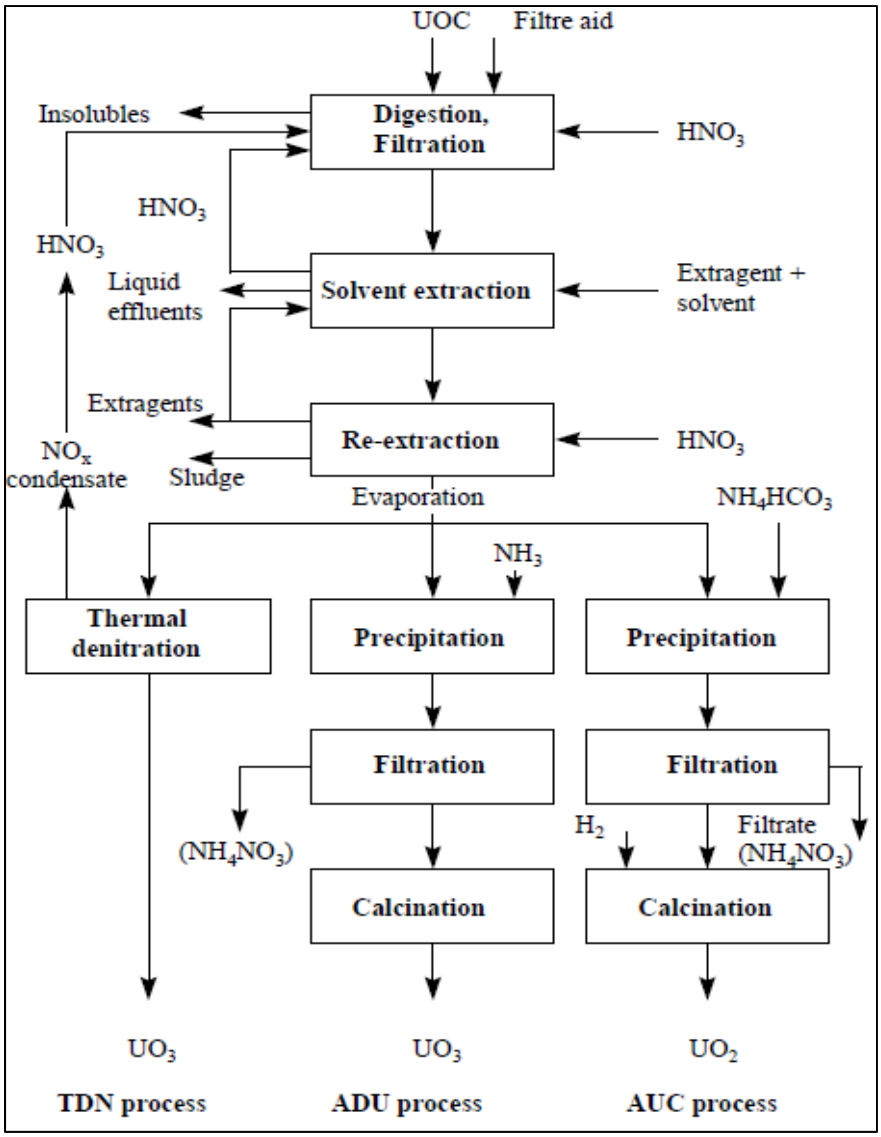


Figure 3.4: UO_2 and UO_3 purifying and reduction [16][2]

[2] Please note Figure 3.3 illustrates three different iterations: thermal denitration (TDN), ammonium diuranate (ADU), and ammonium uranyl carbonate (AUC).

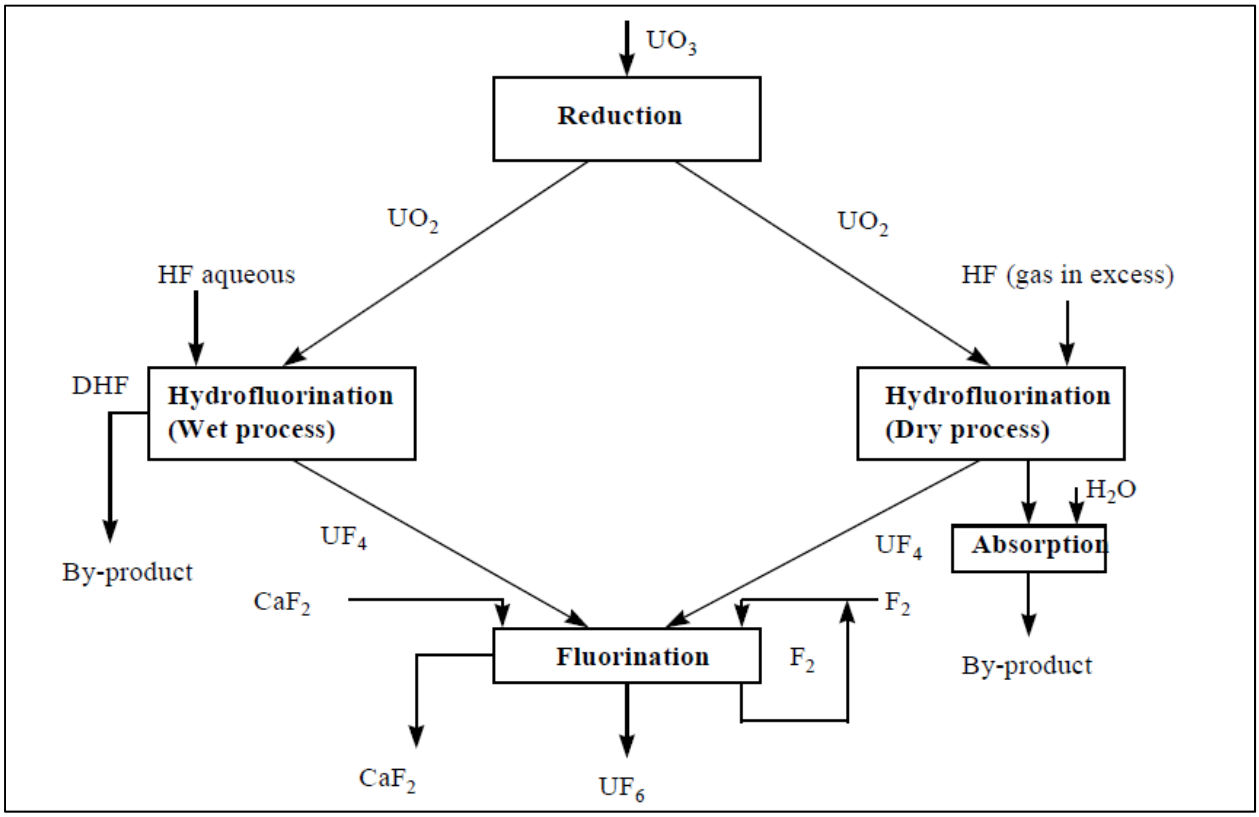


Figure 3.5: Flow sheets of conversion to UF_6 [16]

3.3 – Enrichment

This is by far the most critical and labor intensive step for uranium-based weapons development. The ability to enrich uranium to weapons grade levels (80% U-235 or higher) is absolutely necessary for modern military applications. Enriching to weapons grade is relatively trivial once the capability is established to enrich fuels to levels needed for light water reactors (LWR) – typically 3-5% U-235. Commercial-scale enrichment facilities have enough production capacity to fuel many reactors or – through simple changes in the process stream – can support creating enough HEU for several weapons annually.

Several different methods for uranium enrichment are based on technologies that are decades old and are fairly common. These technologies – while all designed to separate the U-235 isotope from U-238 – are different from one another in size and scope, and this makes a one-size-fits-all approach difficult for this study. A good example of this problem is highlighted in studies of the clandestine Iraqi nuclear program to enrich uranium using multiple technologies [17, p. 317]. But to simplify the overall determination of capabilities, this examination will focus only on gaseous centrifuge technology.

The centrifuge is seen as the best current method for enrichment because of its relatively low energy consumption – compared to gaseous diffusion and electromagnetic isotope separation – and its ease of concealment. It is estimated that centrifuges use only 4% of the electrical power that is used in a diffusion plant of the same capacity [18]. Table 3.1 is a set of additional qualitative ratings to explain why centrifuges will be the main focus of this discussion; it should be noted that molecular laser isotope separation (MLIS) is still not perfected as a technology. While there are many different centrifuge designs, they all operate under the same principals and have the same generic parts and technical obstacles to overcome.

For the stated objective of limiting the NWP scope to the minimum production capacity of one weapon per year, the necessary amount of separative work – expressed as separative work units (SWU) – will be set as 3,000 SWU/year if natural uranium is used as feedstock and a 0.3% tails assay. This amount of separative work will produce 15 kg of weapons-grade uranium, which – in addition to the information provided in Table 3.2 – should be enough for a state with low technical capability to produce a strong yield. Details on how 3,000 SWU/year was determined as the goal are stated below. For simplicity it is a straightforward estimate to understand that a cascade hall with very basic centrifuge (1 SWU/year) work output will require 3,000 centrifuges.

States that can field centrifuges with better performance characteristics will require fewer installed centrifuges to meet the same annual output.

Table 3.1: Important enrichment technique property ratings according to their contribution to proliferation sensitivity

	Separation factor	Equilibrium time and inventory	Size of dedicated facility	Ease of batch recycle	Reflux chemistry and criticality problems
Gaseous diffusion	3	3	3	3	1
Centrifuge	2	1	1	1	1
Aerodynamic					
Nozzle	3	1	2	2	1
Helikon	3	1	2	1	1
Chemical					
Solvent extraction	3	3	3	3	2
Ion exchange	3	3	3	3	2
Laser					
Molecular (MLIS)	1	1	1	1	1
Atomic (AVLIS)	1	1	2	3	3
Electromagnetic					
Calutron	1	1	3	2	3
Ion cyclotron resonance	1	1	2	2	3

[a]Rating 1 implies that the factor presents a low barrier to misuse of the technique; rating 3 a significant obstacle to misuse; and a rating 2 somewhere in between, [b]Reproduced from Krass *et al* [19].

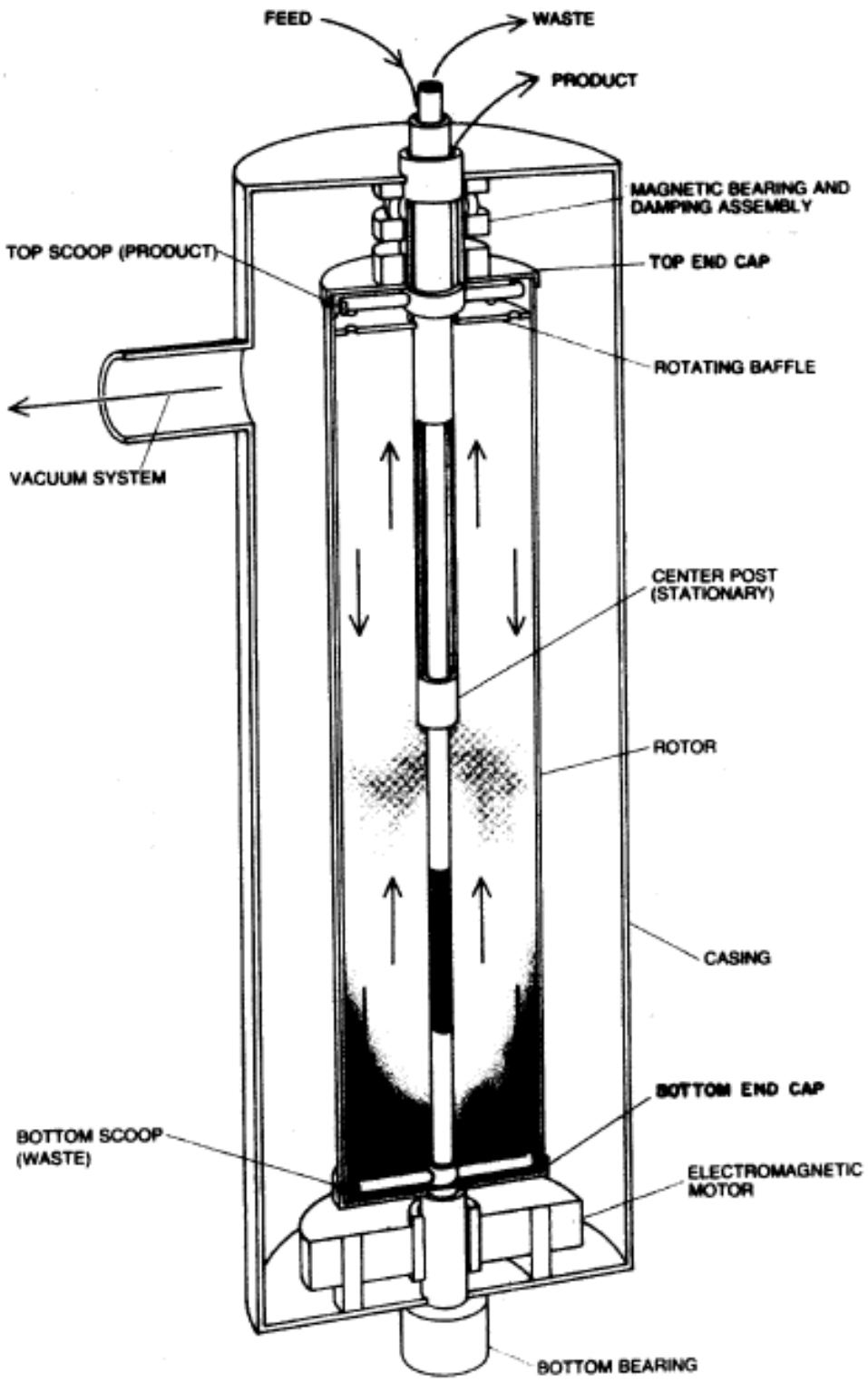


Figure 3.6: Interior of a Uranium Gas Centrifuge [20]

Table 3.2: Approximate fissile material requirements for pure fission nuclear weapons

Technical Capability					Technical Capability			
	Low	Medium	High	Yield (kilotons)	Low	Medium	High	
Weapon-	3	1.5	1	1	8	4	2.5	Highly
Grade	4	2.5	1.5	5	11	6	3.5	Enriched
Plutonium	5	3	2	10	13	7	4.0	Uranium
(kilograms)	6	3.5	3	20	16	9	5.0	(kilograms)

Table reproduced from Norris, Kristensen & Handler [21].

3.3.1 – Construction

Three primary considerations have to be made with respect to developing uranium centrifuge cascades: the design of the centrifuge, the manufacturing of the centrifuges, and the construction of the cascade hall. While information on the basic form of the centrifuge is widely available, specific designs are rare and most are typically classified. Also the materials needed for independent centrifuge development will necessarily depend on the chosen design (either indigenously developed designs or clandestinely procured). The centrifuge design for a state with little or no experience will be fairly basic, but even this can be overcome by the number of deployed centrifuges. Regardless of the design, the same basic parts must be gathered including: rotors, metallic casings, magnets, vacuum equipment (pumps, gauges, gaskets and seals), motor equipment, bearings, composite tubes, and bases.

Drawing from observations of Figure 3.6, it is clear that precision machining is an absolute requirement when manufacturing the centrifuges. The margin for error in the construction of fine parts like the rotor or damping assembly is incredibly small, and poor engineering or installation can cause the centrifuge to crash with significant consequences. The energy released from a crashed centrifuge can be on the order of a mega-joule, and it must be effectively dissipated so that it does not cause failures with other machines nearby [22, p. 32]. Iran's difficulty with its centrifuges provides ample evidence of the technical challenges

associated with proper construction techniques [23]. But because the operational capabilities are so dependent on the design of the centrifuge, it becomes difficult to gauge the true capacity of a state to reach the stated minimum threshold value of 3,000 SWU/year. This is because the separation factor of each rotor is determined by the speed that it operates, and the maximum speed that the rotor can operate at is determined by the material used to construct the rotor. Table 3.3 shows how a given rotor material will coincide with a specific separation factor at a given speed. The separation factor is a method of describing the amount of separative work conducted by a single separation stage.

Table 3.3: Maximum rotor speeds for given rotor material and the total separation factors for given rotor operating speeds

Material	Approximate maximum peripheral speed (m/s)	Rotor speed (m/s)	Total separation factor
Aluminium alloy	*425*	300	*1.056*
Titanium	*440*	400	*1.1*
High-strength steel	*455*	500	*1.16*
Maraging steel	*525*	600	*1.24*
Glass fibre/resin	*600*	700	*1.34*
Carbon fibre/resin	*700*	800	*1.46*

Data taken from Whitley [22].

Once the design of the centrifuges is chosen and a basic laboratory demonstration setup is tested for design flaws and performance, the next step is to link the centrifuges in a cascade. The cascade hall itself can be any sufficiently large industrial building with radiological support and ample power loading. Cascade connections are shown in Figure 3.7 and the "ideal" cascade, the best layout for efficient enrichment, is diagramed in Figure 3.8. Multiple cascades can be produced for a given enrichment facility, and each cascade can be operated in a modular fashion. The exact layout of a cascade is based on six features [24, p. 478]:

1. feed rate per centrifuge
2. separative capacity per centrifuge

3. desired cascade product assay, X_p
4. cascade feed assay, X_f
5. desired cascade tails assay, X_t
6. number of centrifuges per cascade

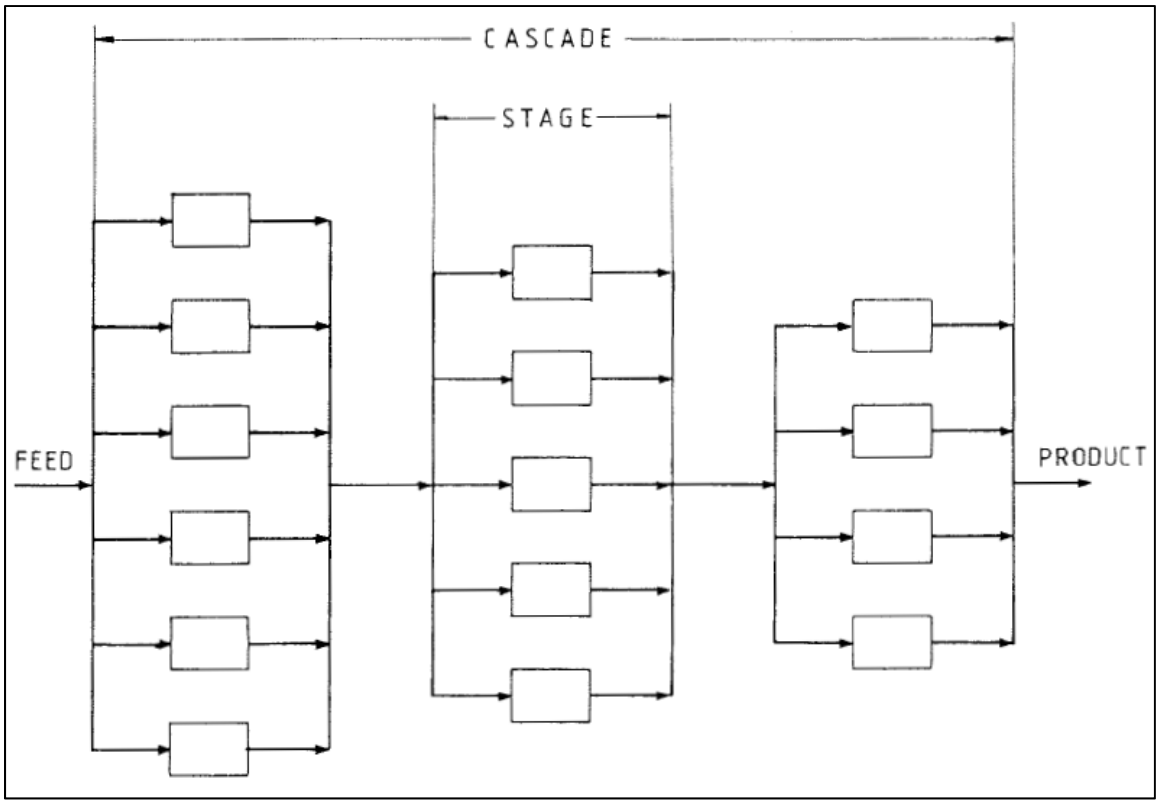


Figure 3.7: Centrifuge cascade diagram [19]

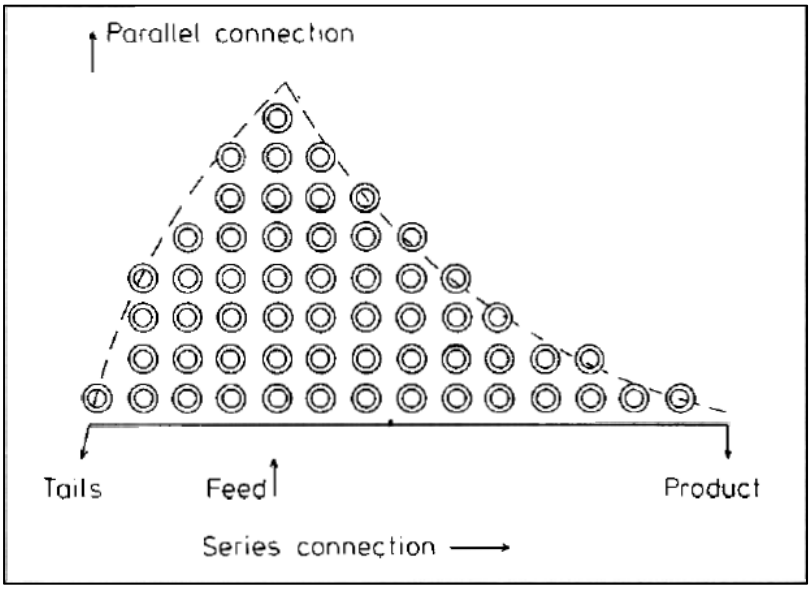


Figure 3.8: Cutaway of the ideal cascade [22]

3.3.2 – Operation

Operating a centrifuge cascade is not as simple as making sure that everything is connected correctly or that there is a steady stream of UF_6 gas entering the cascade. Significant effort has to be made to maintain the integrity of the system. An important design consideration is that ten percent of the centrifuges in a given cascade will crash in a ten year period [22, p. 32]. As discussed earlier, crashes are considerable operational problems, and will put the cascade out of operation until the unit can be replaced. So there needs to be continued manufacturing of replacement centrifuges, parts, and training of available technicians just to maintain regular plant operations.

$$V(N) = (2N - 1)ln[N/(1 - N)] \quad (3.1)$$

$$SWU = pV(x_p) + tV(x_t) - fV(x_f) \quad (3.2)$$

The operational output of a given facility, as dictated by the six aforementioned features, is the largest point of interest for this study. Equations (3.1) and (3.2) are the "value" equation and equation for calculating SWU [19, pp. 97-99]. In (3.2), x is the fraction of the total uranium content that is U-235. The feed assay (x_f), product assay (x_p), and tails assay (x_t) dictate the necessary number of SWU necessary for the specific mass inputs/outputs for the feed (f), product (p), and tails (t). Tables 3.4 and 3.5 illustrate the effects of different input values.

As discussed above, the materials used in the centrifuge greatly affect the number of centrifuges needed to produce a given amount of separative work. But an important operational consideration is how a state might go from a natural uranium feed to a weapons-grade product. This final operational consideration can be explored in multiple ways: batch recycling, cascade interconnection, or final enrichment through a clandestine facility. Batch recycling is when the

cascade that was used for the initial uranium enrichment is pumped down and reused; the enriched product from the first run becomes the feed in the second run.

Table 3.4: Common examples of enriched uranium output

	Product		Feed		
Amount of separative work (SWU)	Amount (kg)	Percentage enrichment	Amount (kg)	Percentage enrichment	Tails assay (%)
200	1	*93*	226	*0.711*	*0.3*
160	1	*93*	440	*0.711*	*0.5*
50	1	*93*	20	*5.0*	*0.5*
40	1	*93*	23	*5.0*	*1.0*
5000	25	*93*	5050	*0.711*	*0.3*
3.9	1	*3.25*	7.2	*0.711*	*0.3*
7.2	1	*5.0*	11.5	*0.711*	*0.3*

Reproduced from Albright, Berkhout & Walker [17]

But besides the obvious safeguards alarms that will be sounded if the residual presence of HEU is detected, the batch recycling requires a significant amount of time to stop, pump down, and restart the process. Krass *et al* describe the limitations of batch recycling best by saying:

> Batch recycling wastes large amounts of ^{235}U because the tails assays increase in every recycling after the first one. So, much more feed material and operating time are needed to produce a kilogram of highly enriched product than in a properly designed cascade. Whether such a waste of time and valuable resources is considered worthwhile depends, of course, on the strength of the motivation to produce highly enriched uranium [19, p. 110].

This last sentence is very true, but quantifying the strength of the state motivation – specific to this particular process step – is a great challenge. Ultimately, it may likely depend on whether or not the initial enrichment cascades are known to the international community, and are under IAEA safeguards. In either case the second option is more likely, where the product from the initial cascade will be enriched to roughly 5% and introduced into a secondary cascade to rapidly increase the enrichment level. This method is cascade interconnection – presumably described by Krass *et al* as the aforementioned, "properly designed cascade." Figure 3.9 and

Table 3.6 – both from Glasser – illustrate the nature and effectiveness of the interconnection system, respectively. Figure 3.9 is particularly interesting because it is a reported cascade configuration proposal adopted by Libya before they elected to abandon their nuclear program. The interconnection method may also be likened to current efforts being undertaken by Iran at enrichment facilities in Natanz and Qom.

Table 3.5: Weapon-grade uranium production (93% enriched)

Capacity (SWU/y)	Uranium feed (% ^{235}U)	Uranium tails (% ^{235}U)	WGU (kg/y)	No. of days to produce 25 kg
5000	*0.71*	*0.2*	21	435
	0.71	*0.3*	24	380
	0.71	*0.5*	31	295
5000	*5.0*	*1.0*	122	75
	5.0	*2.0*	156	60
	5.0	*4.0*	208	45
15000	*0.71*	*0.2*	63	145
	0.71	*0.3*	72	125
	5.0	*1.0*	366	25
70000	*0.71*	*0.2*	294	31
	5.0	*1.0*	17000	5

Reproduced from Albright, Berkhout & Walker [17]

Table 3.6: Summary of the breakout scenario starting from natural uranium; separative capacity of 15,000 SWU/year

	Batch Recycling	Interconnect
Production rate (normalized)	38-40 kg per year (with 6000 machines)	91.0 kg per year (with 6000 machines)
Production rate (real)	35-37 kg per year (with 5576 machines)	88.5 kg per year (with 5832 machines)
SWU requirements	387 SWU per kg HEU	165 SWU per kg HEU
Feed-to-product ratio	33,150 kg per kg	280 kg per kg

Reproduced from Glaser [25]

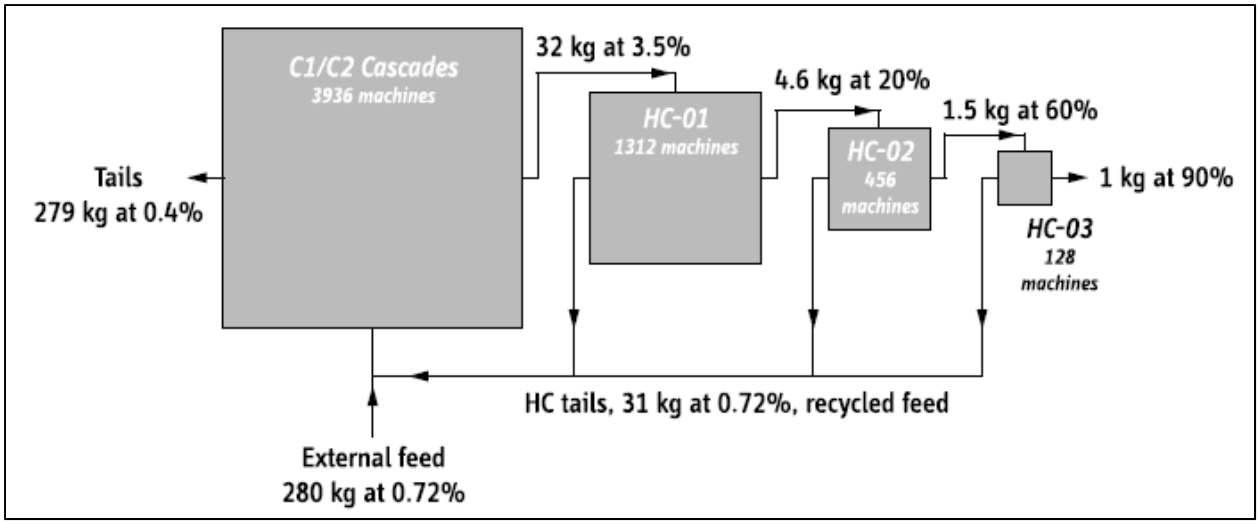


Figure 3.9: Illustration of the cascade as proposed for a Libyan enrichment project [25]

3.4 – Fuel Fabrication

Fuel fabrication is only necessary, in this discussion, for producing plutonium. While having fuel fabrication capabilities is an important step in the legitimate production of fuel for nuclear reactors, it is not a completely necessary step in the fuel cycle for producing uranium-based weapons. The fuel type likely to be used is either natural uranium for heavy water reactors or natural uranium with magnesium cladding – commonly known as Magnox fuel – for use in an air-cooled, graphite moderated production reactor (*Chapter 3.5* provides an explanation choosing a particular reactor design). Magnox fuel is most commonly used by the British nuclear power program. There are some significant material challenges in fabricating Magnox elements, and manufacturing the cladding for Magnox is more complex than other cladding types [26, p. 197]. There is likely sufficient information in open literature and conventional metallurgical experience to assume that magnesium-aluminum alloys can be readily manufactured.

3.4.1 – Construction

Precision machining and quality control will again be necessary in order to construct the fuel elements. Fabricating the fuel elements will mean the construction and operation of a modest metallurgical facility with radiological support. The natural uranium used in the fuel will be in metal form, which necessitates the adoption of design features to minimize the risk of allowing the uranium to oxidize. Uranium metal is very reactive, and is highly susceptible to attack by air and water at room temperature. Finely divided uranium can ignite spontaneously at room temperature [27, p. 233]. It is likely then that the final chemical conversion step from UF_4 to uranium metal will be carried out at the fuel fabrication site to minimize the potential risks from uranium reactivity.

Creating the cladding forms is also an essential step before the final product can be assembled. It is possible to manufacture the fuel cladding at a separate location from the final fuel assembly point, but this may place constraints on the output rate. Taking all of the various factors into account, the fuel fabrication facility will have to be of sufficient size and scope to handle minor chemical conversions, melting and recasting, machining, and welding – all under a strict quality control setting.

3.4.2 – Operation

The fabrication facility scale will have to be in line with the requirements of the reactor. Based on the reactor specifications discussed in the next section, an annual fuel production throughput of about 1,500 fuel elements per year is required for the 1,418 process channels in the core design [28, p. 25]. Having 1,500 elements is a good round number that will compensate for possible unexpected work stoppages or defective products. The fuel assembly operational steps

are shown in Figure 3.10. The UF_4 gas is reduced by magnesium to form uranium billets, which are then vacuum induction melted and alloyed with small amounts of aluminum and iron.

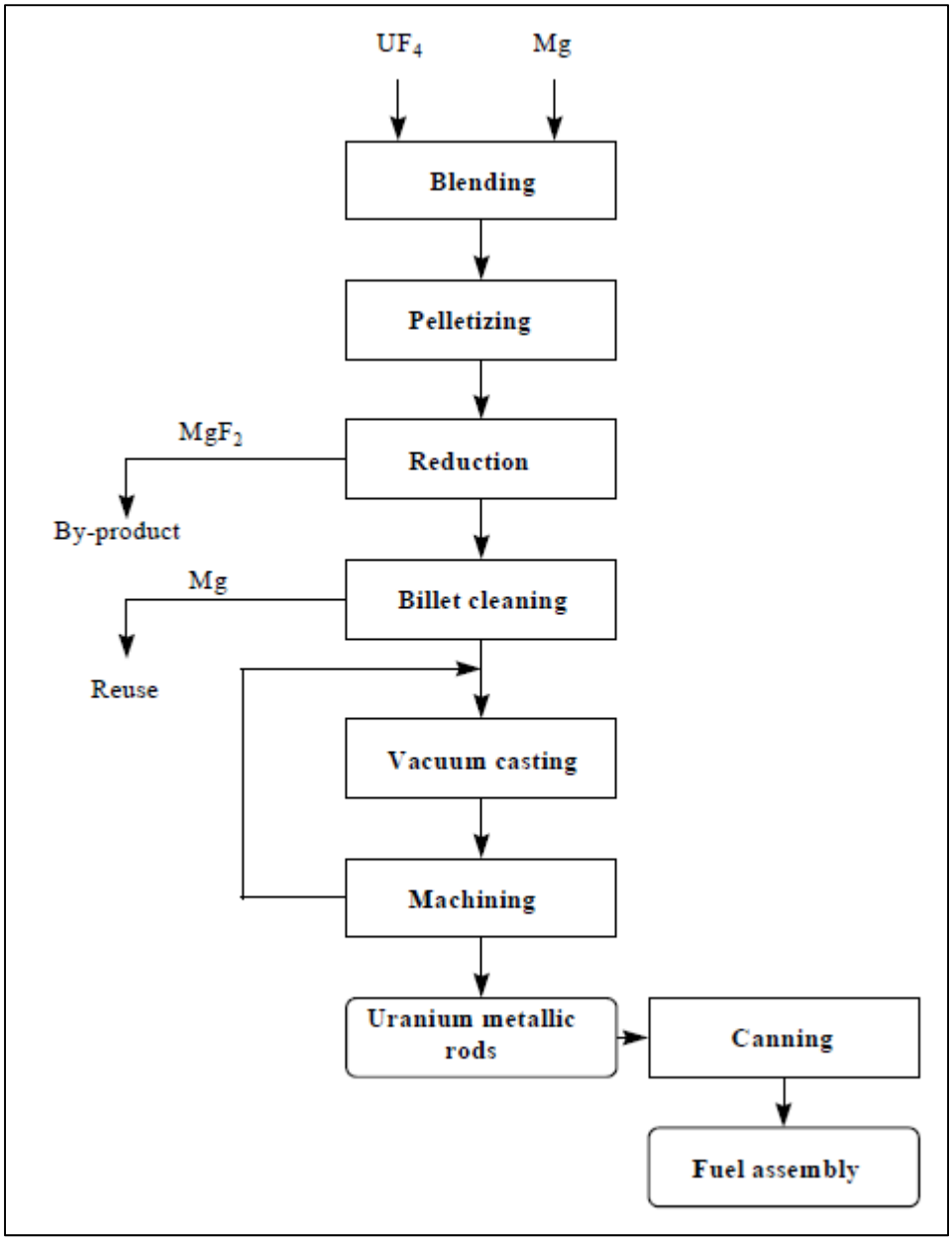


Figure 3.10: Metal uranium fuel fabrication steps [16]

For cladding, the primarily used magnesium alloy is Magnox Al 80, which contains 0.8 wt. % aluminum and 0.005 wt. % beryllium [29, p. 28]. Strong consideration is given to grain size when manufacturing this cladding, requiring the work of materials specialists. Assembling

the Magnox fuel elements is fairly straightforward. One end is sealed and welded shut, the uranium is inserted along with helium fill-gas, and the other end is sealed [26, p. 201]. Several other steps are taken for cleaning and decontaminating.

The greatest operational consideration is from a quality control standpoint. Defective fuel elements will leak when subjected to the conditions in a reactor, and this causes the release of fission gases. These gases will not only increase the radiation dose among the reactor operators, but it will increase the probability that the reactor will be detected by off-gas signatures. A uranium-metal fire may attract unwanted attention. So the quality of the facility operations is paramount to operational secrecy of the entire program; cutting corners is not an option in fuel fabrication.

3.5 – Irradiation

In starting the discussion about plutonium production, it is necessary to list two very important facts: plutonium is produced in some quantity in every reactor and almost all plutonium compositions can be used in the construction of a rudimentary nuclear weapon. On the surface, this means that the ability to assess a state's capacity to produce plutonium for weapons is incredibly complicated. But not all reactors are optimal for producing plutonium that can be used in a weapon, and so not every reactor should be treated with suspicion.

Before characterizing why research and power production reactors are important in generating experience – but not directly considered as a threshold-level process – it is necessary to discuss the basic understanding that not all plutonium is created equal. A first attempt at constructing a plutonium-based weapon will likely involve a relatively simple, low-tech design; any plutonium that does not have the highest possible concentrations of Pu-239 will make an

initial weaponization effort much more challenging. Table 3.7 is a representation of some common isotopic breakdowns of different grades of plutonium, and Table 3.8 shows some characteristics of these isotopes. Super-grade or weapons-grade plutonium (>93% Pu-239) is favored for production of basic nuclear weapons because of the reduced critical mass, spontaneous neutron generation, and decay heat.

Table 3.7: Isotopic composition of various grades of plutonium

	Isotopes				
	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Super-grade		98.0%	2.0%		
Weapons-grade	0.012%	93.8%	5.8%	0.35%	0.022%
Reactor-grade	1.3%	60.3%	24.3%	9.1%	5.0%
MOX-grade	1.9%	40.4%	32.1%	17.8%	7.8%

Reproduced from Herring & MacDonald [30]

Civilian power reactors will produce copious amounts of lower quality reactor-grade plutonium, while research reactors can produce higher quality plutonium but in much smaller quantities. With modern safeguards, neither of these two systems is ideal for producing weapons-grade plutonium at a rate that is sufficient for the needs of a NWP. There are many plausible scenarios whereby plutonium can be diverted and extracted from civilian power plants or research reactors[3]. For simplicity, the assumption is made that known civilian commercial and research reactors that are under safeguards will not be used for military plutonium production[4] [5]. This study assumes a separate, clandestine effort must be undertaken to produce a reactor small enough to stay undetected yet large enough to produce the requisite amount of plutonium needed for our arbitrary weapon-per-year benchmark. Based on values described in Table 3.8 and the

[3] These types of diversion scenarios are more tend to be oriented towards examining "breakout."
[4] Tomanin *et al* give a detailed discussion on Pu-breeding feasibility in research reactors [31].
[5] Dr. Tunc Aldemir of Ohio State University suggests that higher enrichments and frequent refueling in research reactors will prevent their use as a means of plutonium production *while avoiding detection* [32].

SNM material needs described in Table 3.2, it is decided that producing 10 kg/year will be sufficient.

Table 3.8: Properties of dominant plutonium and americium isotopes

Isotope	Halflife years	Bare Crit kg, α-phase	Spontaneous Fission Neutrons neutrons/gm-s	Decay Heat Watts/kg
Pu-238	87.7	10	2600	560
Pu-239	24,100	10	0.022	1.9
Pu-240	6,560	40	910	6.8
Pu-241	14.4	10	0.049	4.2
Pu-242	3.76E+05	100	1700	0.1
Am-241	430	100	1.2	114

Reproduced from Herring & MacDonald [30]

3.5.1 – Construction

Because this is an estimate of technical sophistication, the reactor design chosen for this study will be a gas-cooled, graphite moderated reactor. Larger and more advanced reactor designs can be used by state programs that desire to have an annual plutonium production greater than the 10 kg/year benchmark, but this begins to risk exposure of detection. Studies produced for the now defunct U.S. Arms Control and Disarmament Agency give an excellent comparison of the advantages and disadvantages of different production reactor types. A summary of the different reactor concepts from this study are found in Table 3.9.

The low and medium power reactor options using air and CO_2 as a coolant, respectively, are exactly the reactor designs needed for this examination. A 20-25 MWth variation of the gas-cooled reactor design is what was allegedly created by the Syrians – and allegedly destroyed by the Israelis in September 2007 [33, p. 2]. For simplicity, the air-cooled design will be the basis of this section's discussion. Construction of a graphite reactor is fairly straightforward compared to a modern LWR, but it is still a time consuming process that requires precision engineering and

good quality control measures. The choice of cladding used in fuel fabrication, discussed in the previous section, will influence the pitch of the fuel elements in the core, but the channel and diameters and will be consistent.

Table 3.9: Representative reactor concepts

Thermal power (MW)	30	250	400
Coolant	Air	CO_2	H_2O
Number of fuel channels	1418	1892	2155
Moderator and reflector	Graphite	Graphite	Graphite
Total graphite (mt)	989	1550	2260
Fuel type	Nat. U-metal	Nat. U-metal	Nat. U-metal
Cladding	Mg or Al	Mg	Al
Base plants, previously constructed & operated	Brookhaven, Marcoule G1	Calder Hall, Marcoule G2	Hanford, Soviet production
Appox. Pu production rate (kg/full-power year)[1]	10	80	135
Uranium requirement (mt/full-power year)[1,2]	94	147	274
Fuel burnup (MWd/mtU)[1]	115	620	520
Fissile Pu content (%)[1]	99.2	95.5	96.2

[1]Assuming annual fuel cycle, [2]Also equal to the total loading and to the quantity of U to be reporcessed in recovery of the Pu. Reproduced from Turner *et al* [28]

Heavy-water moderated production reactors are also likely reactor designs for a NWP. One added benefit of using heavy water reactors is the creation of some amount of tritium from neutron capture in the coolant. Tritium can then be used as part of a two-stage or boosted fission weapon design. Heavy-water reactors can also be designed and operated with on-line refueling – increasing the rate of plutonium production. But heavy water reactors require separate heavy water production facilities (discussed in *Chapter 3.7*) and this step requires some additional effort. For the sake of providing a somewhat simpler methodology for determining a timeframe, the graphite moderated reactor concept was adopted as the primary consideration.

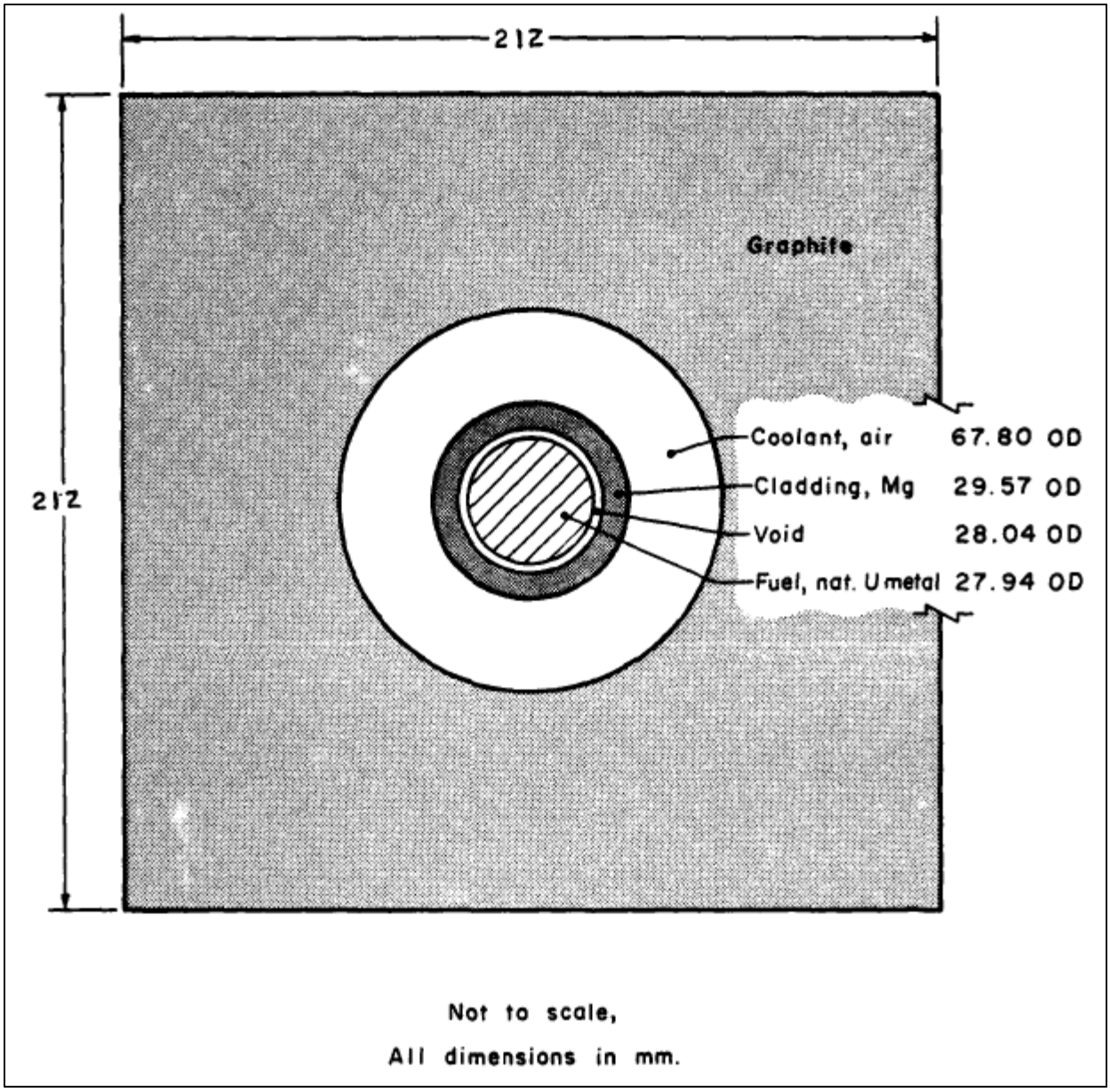


Figure 3.11: Cross-section of air-cooled cell [28]

The graphite used for the reactor will have to be manufactured to very high purities, which is not technically challenging. And any impurities from neutron-absorbing materials in the graphite will be reduced over time while the core is critical. The graphite must be manufactured to a higher quality “nuclear grade” which is a simple, but labor intensive process involving the

constant heating and manipulation of petroleum-based products [28, p. 103]. Figure 3.12 demonstrates the steps of this process.

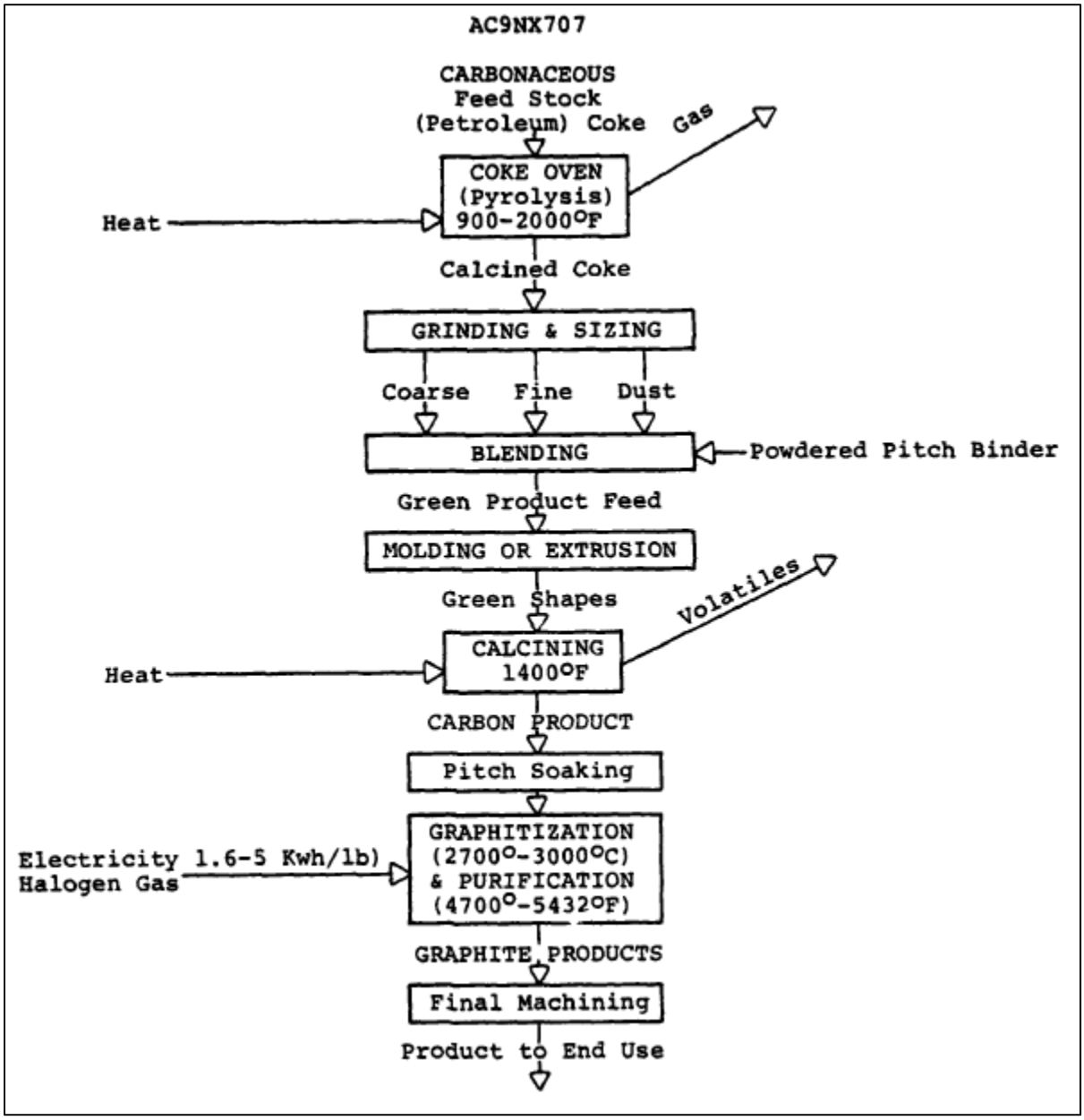


Figure 3.12: Graphite manufacturing process [28]

Constructing the reactor is by far the most labor intensive step requiring copious amounts of concrete for the foundation and walls, a spent-fuel pool, a steel vessel for housing the core, assembly of the graphite pile with fuel and control rods, instrumentation and control systems,

and ventilation. Safety and security systems are also a necessity, and these systems will include shielding, property protection and surveillance assets, and fire suppression equipment. Like any industrial operation, connections to necessary utilities (water, electricity, etc.) are needed at the level commensurate with demand. Assembling a reactor, even one of rudimentary design is a project that takes years to accomplish, and it is reasonable to assume that doing so under a clandestine effort is even more time consuming. The number of people dedicated to reactor construction would be sizeable, ranging from tradesmen of all varieties to mechanical, electrical, and nuclear engineers.

3.5.2 – Operation

Regular operations have a similar demand on engineering specialists, but a reduced number of trade specialists have to be retained for operations. There are significant costs with electricity for systems operation, personnel radiation protection, and security. The operation of the reactor itself is not a technical challenge with competent individuals operating the control systems. Testing of the reactor and its components would be necessary for several months prior to the first fuel loading. Fuel loading/unloading is performed offline with this particular design (to assume the most rudimentary case), and the technical competency of operations personnel will factor into the speed of changing out the fuel in the core. From Table 3.8 it is clear that the target burnup of 115 MWd/mtU will yield slightly larger than one significant quantity of super-grade plutonium per year. Operating a reactor in this way will only require one scheduled outage for fuel reloading per year. At this point, the spent fuel in the core is loaded into a spent fuel pool for cooling before going on to reprocessing.

Another consideration for avoiding detection when using plutonium production reactors is the need to reduce the reactor's thermal signature. Detection of the facility by heat is a real operational factor requiring thermal reduction through heat-exchanges. This will require access to a nearby water source and pumping equipment. Heat removal to reduce the reactor's signature may not necessarily be required if the state determines that the risk of discovery is acceptable.[6]

3.6 – Reprocessing

From a proliferation standpoint, developing the facilities to reprocess spent nuclear fuel for extracting plutonium is a big red flag. Plutonium-uranium extraction (PUREX) is a process that can be done with very small amounts – on the order of grams – of irradiated uranium targets in a radiochemical laboratory setting. But even though reprocessing is simply a chemical separation, the nature of the fission products and transuranics in spent fuel places substantial engineering demands on this process. Constructing and supporting regular PUREX efforts for even a small annual throughput requires a significant initial and sustained resource investment.

The PUREX process starts by receiving spent nuclear fuel – presumably brought to the reprocessing facility in a spent fuel cask from the reactor spent fuel pool. The fuel is prepared by removing it from the transport cask, separating the fuel rods in each element, and chopping them up. The chopped segments can still be jacketed in their cladding with the exception of Magnox fuel, which must be mechanically separated first [18, p. 22]. The fuel is then dissolved in nitric acid and the uranium and plutonium are then separated through multiple solvent extraction cycles using tributyl phosphate (TBP). In this way, the plutonium is chemically separated from the uranium and other transuranics.

[6] See Albright & Brannan for a detailed discussion hiding reactors through process heat-removal [33].

The annual throughput demand will be based on our assumed reactor situation. This will mean an annual throughput of approximately 100 tonnes per year. This is a comparable size to the North Korean reprocessing facility at Yongbyon, which also services Magnox fuel [34]. Because of the high level of attention that a reprocessing facility draws, it is also a safe assumption that there would be tremendous efforts to try to conceal this NFC process step.

3.6.1 – Construction

Design and construction of a reprocessing facility is a major undertaking. While not terribly different from any other basic chemical processing plant, the radioactivity and criticality concerns must be taken into account in the design phase. The structure with all of its shielding requires substantial amounts of concrete. Designers and engineers have to take into account all of the necessary cell operations, exterior wall penetrations for operations systems, ventilation, and waste treatment. Quality assurance in the process equipment manufacturing and installation is very important; minimizing maintenance of the process equipment reduces operational time-losses. The entire process requires large holding tanks (while still being small enough to avoid accidental criticality events), pulsed-air columns, ventilation, piping and valves, pumps, agitators, and steam jets [35, p. 537-538][7]. The sheer size of a reprocessing plant can be appreciated by examining existing facilities. But the technology for such plants dates back to the early 1950's. Construction and design will require effort by civil, mechanical, electrical, nuclear, and chemical engineers.

[7] Refer to Lemon & Reid for a more detailed discussion of individual process equipment demands.

3.6.2 – Operation

Reprocessing runs can continue in a fairly straightforward fashion during normal operating conditions. Many components in PUREX operate in a continuous stream. Chemists, chemical engineers and nuclear engineers will constitute the primary operations staff, with many technicians for operations maintenance. Remote controls in the hot cells will allow the process to continue smoothly, and while limiting exposure to workers. Collective experience operating any remotely complex chemical processing plant will translate effectively to running reprocessing operations. The separated plutonium product will likely be formed into metal ingots for transport to a weapons-pit manufacturing complex.

3.7 – Other Demands & Processes

In addition to all of the other previously described processes, there are some additional demands on nuclear programs that should be factored into the calculations. A good example is that all nuclear processes will produce some amount of waste product that requires treatment and storage. This inescapable requirement is the same for almost every industrial-scale chemical process, but this will be representative as part of the construction and operation of each of the other identified steps.

Plutonium production reactors can also be constructed to use heavy water as the moderator and coolant. But this means the state must either purchase heavy water from another state or produce its own. Because this report focuses on the indigenous efforts of the state, it is assumed that a state pursuing heavy water moderated reactor technology – similar to CANDU reactors – then the state will have to produce its own heavy water to reduce dependence on other states. But the two states that produced SNM for nuclear weapons from heavy water production

reactors, India and Israel, acquired their initial supplies from abroad. Starting a NWP does not necessarily require heavy water production capabilities at the onset or in the initial stages of the program.

3.7.1 – Heavy Water Production: Construction & Operation

Heavy water production is a technology that dates back to the 1930's, but still requires a fairly sizable industrial process. There are many different methods, but overwhelming majority of the world's heavy water production is carried out through the hydrogen sulfide-water vapor exchange process [36, p. 841]. This process is based on the exchange between hydrogen sulfide and water:

$$H_20(l) + HDS(g) \leftrightarrow HDO(l) + H_2S(g) \qquad (3.3)$$

The exchange process carries out between a cold and hot tower with temperatures around 32 and 138°C, respectively [27, p. 767-768]. The hydrogen sulfide is recycled in the system, and the overall process can reach very high throughputs. Figure 3.13 shows an example of this process.

The overall process design, construction, and operation can be conducted as a fairly routine processing facility. As for most of the previous steps, mechanical, electrical and chemical engineers will be involved in the construction phase, but chemical process engineers and technicians will be the main requirements among educated specialists during operations. There is no unique radiation or criticality hazard that necessitates shielding or special controls and procedures.

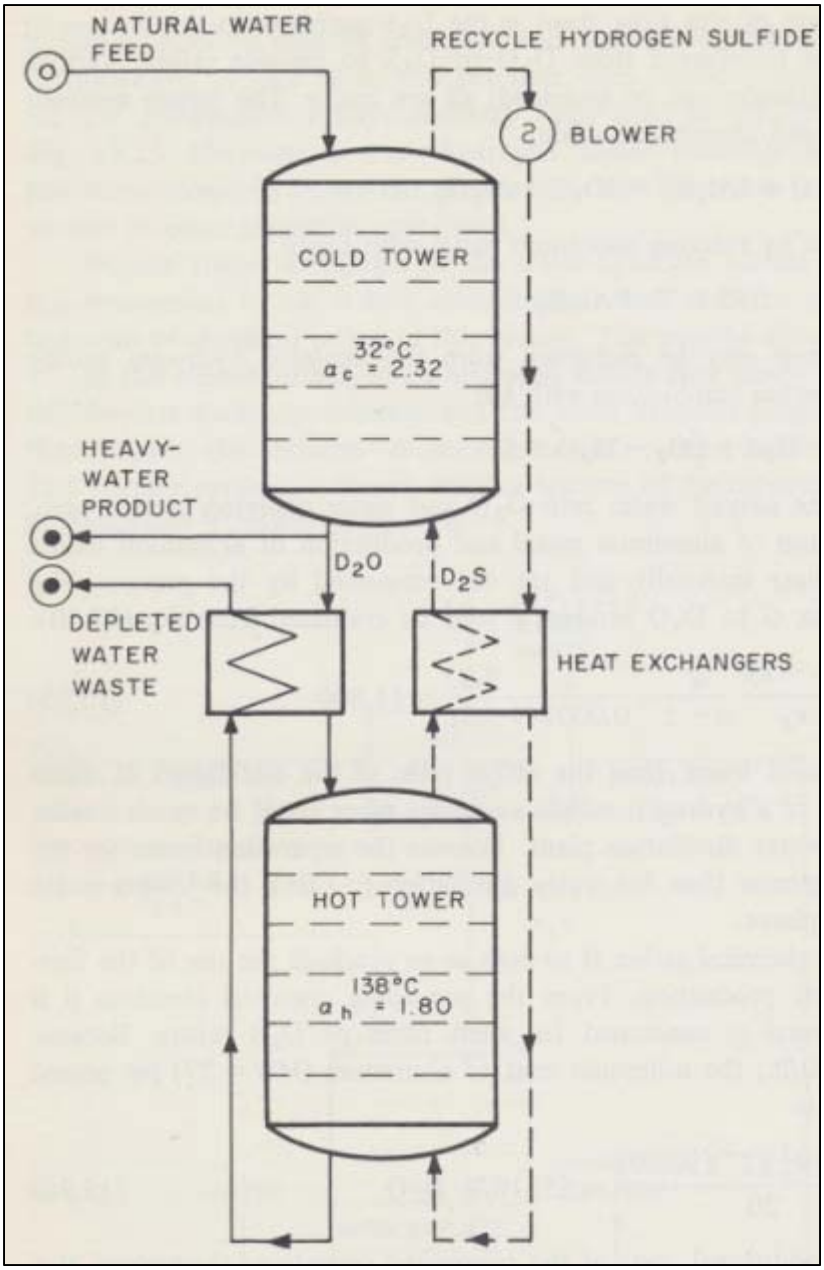


Figure 3.13: Dual-Temperature reflux for water-hydrogen sulfide process [27]

3.8 – Process Summary

These industrial processes are completely necessary for the formation of nuclear weapons, but the type and number of nuclear facilities is dependent on the state's needs and desires. Not every NFC process discussed above is necessary for a NWP, and so discussion in *Chapter 5* will focus on the minimum process requirements needed for an initial uranium-based

or plutonium-based program. A state might also elect to have all NFC processes in order to have a fully-developed NFC; possibly to create the illusion of a peaceful, civilian dimension. This theory requires a decision-making analysis to determine a true proliferation pathway, but this is beyond the scope of this research. Despite this fact, the SNM-production technologies described here are necessary and relevant to assign appropriate values to the NFC process (P) development time.

Chapter 4: Weaponization Steps

Forming a functioning nuclear weapon, something that was not curtain to even be possible seventy years ago, is still a highly technical endeavor. The majority of the work spent accomplishing this is in the manufacture of the NEM used in nuclear weapons. But the ability to construct a rudimentary weapon is so trivial that graduate students at various DOE national laboratories are sometimes tested to see if they can design a functioning weapon [37]. A simple gun-type weapon design assembled with HEU, as was used against Hiroshima in 1945, is often discussed as the principle nuclear weapon design for sub-state groups. While a rudimentary gun-type weapon is a viable, deliverable weapon, what is described in this section is meant to go beyond the discussion of the simplest case. A more modern implosion design – ideally made for future incorporation with a two-stage thermonuclear design – will be examined. All six of the technical steps discussed in *Chapter 2* will be described here regardless of the SNM used in the weapon design. There is no viable nuclear weapon if a state cannot overcome these technical challenges.

4.1 – Design

It may be the opinion of some that a basic nuclear weapon design is not very hard to come by. There are many plans and schematics that people can find on the internet, but like most information on the internet, there is a question of reliability. Many publicly available designs may lack in critical dimensions or may be missing important elements, but it takes a limited amount of engineering experience to determine what those shortcomings are. That being said, the level of detail expected for a modern weapon design is extraordinary, and there are still many design secrets and engineering secrets relating to specific dimensions, switches and electronics,

and other parts related to proper function. This is especially true when it becomes important to miniaturize weapons for delivery vehicles.

It is also important to point out that a militarily useful weapon is one designed to function *as intended*, and not one with a highly unpredictable yield. The design must come first because it is the basis of all other testing, modeling and procurement efforts related to weaponization. Nuclear engineers and physicists with expertise in stochastic neutronics[8], neutronics in a moving medium, and hydrodynamics are essential. A proper calculation of the stochastic neutronics requires some experimental data for neutron/fission calculations[9]. Technical support is also necessary from materials specialists, explosives specialists, and electrical engineers. More complex designs based on miniaturization, boosted fission or two-stage thermonuclear reactions are derived from achieving confidence in more basic designs. The requirements here include human capital, testing facilities, and having individuals with the highly specialized experience necessary for developing full design details.

4.2 – Metallurgy

A dedicated facility, likely positioned within a military complex, must be constructed to assemble the HEU or plutonium pits. The NEM must be converted to a metal product (which may or may not be carried out at a separate conversion facility or as part of the reprocessing effort). Material properties of the NEM will require adjustment to the specified design. An example of this is to transition the allotropic phase of plutonium metal from the α-phase to the less dense δ-phase. The main engineering challenge from assembling the pits will be to do so without causing a criticality accident or radioactive exposure to the principle workers.

[8] More detailed information on stochastic theories of neutron transport and stochastic point kinetics can be found through Ramsey, Axford and Hutchens [38].
[9] See Ramsey and Axford [39].

Describing state experience on this topic is very difficult, and it is not known if there are any real distinctions between efforts undertaken by states that have produced nuclear weapons. This particular step will be gauged as minimal in its difficulty assessment.

4.3 – Fuzing & Arming

Fuzing a weapon for detonation is not a trivial matter when you consider that is equally important, if not more so, to design a fuzing system that prevents the weapon from detonating before it is supposed to. This also helps to reinforce the point that timing is everything with nuclear weapons. It is for this reason that fuzing and arming are somewhat in tandem. Modern instruments and signal processing make it easier to design a simple fuzing system. Any military establishment will have a large pool of competent individuals with the skills necessary to construct a simple fuzing system. And as stated in *Chapter 2*, there will be minimal consideration for design aspects that go beyond making it functional and deliverable. It is reasonable to relate this aspect of weapons development with the design phase for consideration of quantifying time and capital invested in this step.

4.4 – Initiation

Forcing a subcritical configuration of SNM to become prompt supercritical is the first main step in detonating a nuclear device, but while this increases the neutron multiplication factor, the initial number of fast neutrons in the system will ultimately determine the number of initial fissions that take place in the first generation. Hence, all mildly-sophisticated weapon designs need some form of neutron initiator to flood the supercritical assembly.

The only rational for developing initiator technology is for production of a weapon. This specific weaponization element has emergence in recent news bulletins as additional evidence of a NWP in Iran: IAEA inspectors have requested access to a military site in Iran because of a suspected test on a neutron initiator conducted there [40]. This particular example likely illustrates the development of a chemical, internal neutron initiator (INI). The INI is located in the center of the implosion device, and it usually consists of two different elements which are kept separated until the weapon is detonated. An example of an INI is the combination of polonium and Li-7 or beryllium foil. When the two elements are combined, the alpha particles emitted from the polonium decay, principally from the Po-210 isotope, will interact with the lithium or beryllium to produce copious amounts of fast neutrons that will start fission reactions in the SNM [41, p. 187]. Another type of initiator is the external neutron initiator (ENI). The more complex ENI uses a miniature particle accelerator to produce (p, n) reactions in a target material. The resulting neutrons are released into the NEM to start fissions.

Initial efforts at producing an implosion device during the Manhattan Project hinged upon the construction of the initiator. As Richard Rhodes describes the initial efforts at implosion design, “Initiator design, significantly was one of the most difficult aspects of implosion development and effectively paced the plutonium implosion project” [41, p. 188] But with the level of open literature available on initiators and shaped charges, it is reasonable to assume that initiators are no longer the pace-setters for implosion-weapon construction and development. Creating initiators is not a major industrial undertaking, especially at a pace of one weapon per year.

4.5 – Heavy Metal Compression Testing

Isotropically imploding SNM is still a technically challenging endeavor, but it is far from being the most difficult step in weaponization. Sophisticated militaries and arms manufacturers have plenty of experience with creating shaped charges for conventional munitions – most notably in anti-tank weapons. But equal compression from simultaneously detonating the explosive charges around the SNM is a bit more complicated. Hydrodynamics is used to describe the compression of the pit, but it is also used to describe the next all-important step in weapons development, the compression of the fusion packet in a two-stage thermonuclear weapon. While this body of work focuses exclusively on efforts to create single-stage weapons, it is helpful to mention the added benefits of experience in hydrodynamics when considering the next step forward to two-stage thermonuclear weapons. If the hydrodynamics calculations are incorrect, the resulting outcome will likely be a nuclear explosion, but one of substantially degraded yield.

The compression testing is likely the most important step in verifying the validity of the initial design. Testing can be carried out on a depleted uranium surrogate or another appropriate heavy metal in place of the SNM. Figure 4.1 is the basic design drawn by Klaus Fuchs for the FBI 1950 [41]. The high explosive lenses surrounding the SNM are interweaving segments of "fast" and "slow" explosive lenses. This is one design that allows the energy of the high explosives to be focused inward on the pit. These variations of sub-critical testing are also strong external indicators of an active weaponization effort.

When considering all of the necessary weaponization steps, the only realistic way to judge the amount of time to go from the possession of SNM to a functioning, fairly sophisticated implosion weapon is to assess the education and industry metrics of the state. For weapon designs that are less sophisticated, thus requiring greater amounts of SNM for a comparable

yield, the burden on weaponization activities is reduced. This concept means that the operational demands for SNM production will be increased. An inverse relationship between the sophistication of the weapon design and the SNM demand is established. Because this body of research assumes that a definite annual SNM production rate provides approximately one weapon per year, the efforts to weaponize this material will also be fixed to a particular value. Assigning a set of reasonable weaponization values to the model will be described in detail in the next chapter.

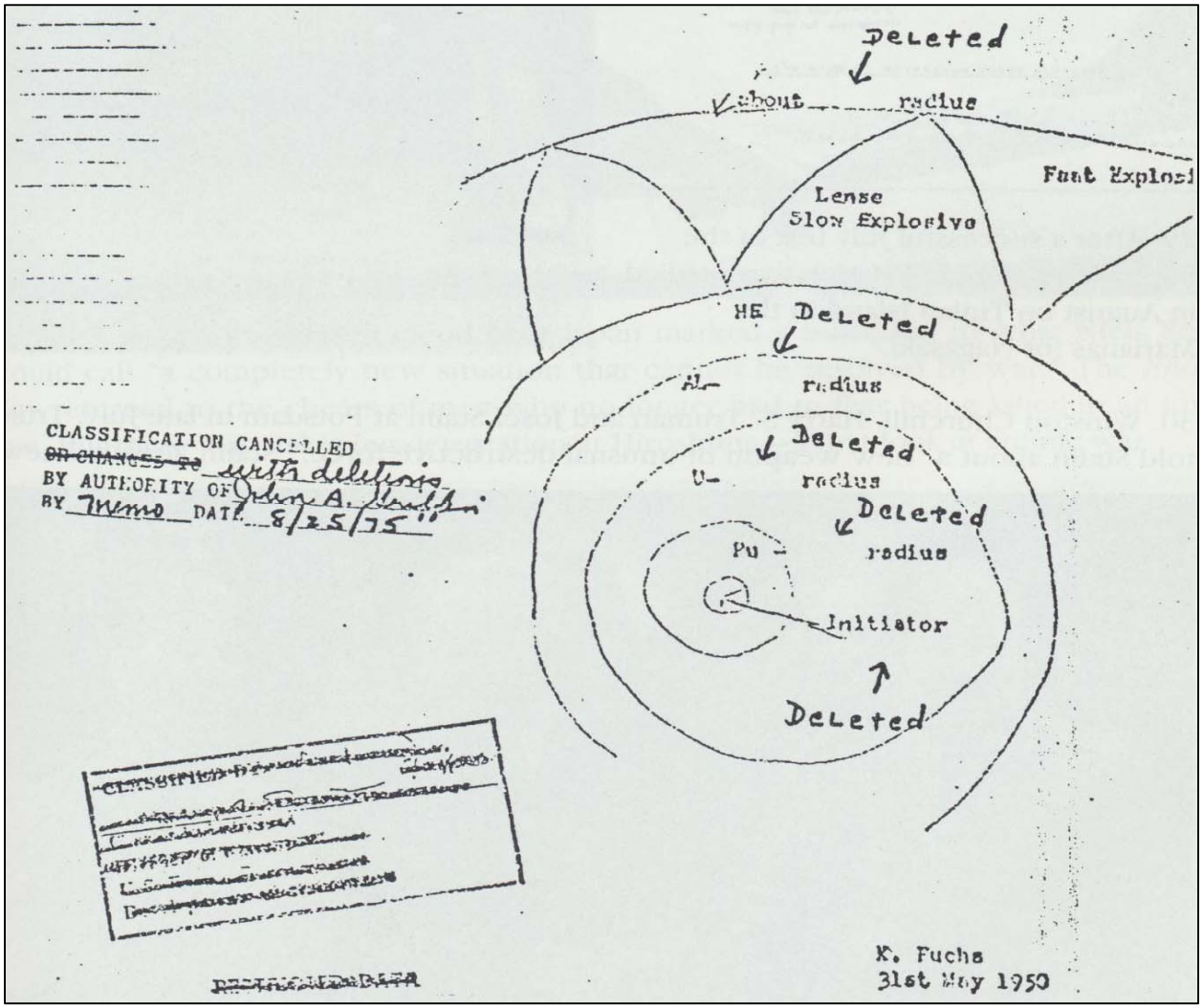


Figure 4.1: Diagram of the Fat Man bomb with measurements deleted[10]

[10] Photo credit: The Federal Bureau of Investigation. Reproduced from Richard Rhodes [41]

Chapter 5: Data Accumulation & Assessment

A deeper understanding of how the de facto nuclear weapon states (see Table 2.4) achieved their capabilities is based on dissecting the steps that were taken to get there. But each state's history nuclear weapons acquisition is complicated in some way by secrecy, uncertainty of present information, espionage efforts, international pressures, and developmental rate changes and freezes. These complications also restrict the accuracy and depth of information in open source literature regarding any given NWP. The information that was gathered on each state represents a large cross-section of open literature. It is compiled in this chapter to assign appropriate values to the amount of effort required to complete each process, while balancing the unique considerations faced by each of the discussed NWP's.

The model requires an expression for the industrial robustness of the state, knowledge of NFC processes prior to engaging in weaponization work, the level of urgency given to completing the program, and the efforts to weaponize. But the first step is to identify the amount of time that each state required to go from political decision to full NWP. The timeframes for each de facto weapon state to complete at full NWP is listed in Table 5.1.

Table 5.1: Time to acquire nuclear weapons

	DPRK	India	Israel	Pakistan	S. Africa
Program Start	1982[a]	1964	1955	1972	1971
Acquisition[b]	2006	1974[c]	1967[d]	1990[c]	1978
Time to Acquire (*T*)	24	10	12	18	7

[a]Coded from Jo & Gartzke, [b]Year when full weapon capability is demonstrated through testing or otherwise assumed, [c]India's first test, designated as a PNE, [d]Israel is believed to have rapidly assembled a weapon prior to the Six Days War, [e]Date assumed the first weapon was assembled. First test was not until 1998.

5.1 – Pursuit Rate

Comparing the efforts between de facto weapon states will start with an understanding of the pursuit rates that each nation undertook. The circumstances that drove each of these five states to develop nuclear weapons are entirely unique, but there is one element that is common throughout: all of these states received some form of outside assistance. The level of assistance from foreign sources varies between states and varies in time. This introduces an incredible set of complexities that cannot be taken into account in this document. However, it is reasonably possible to express the level of urgency that each state gave its nuclear program at any given point in development. These rates, which were first discussed in Table 2.3, are assigned values in Table 5.2 to help determine the overall programmatic pursuit rate of each state in Table 5.3.

Table 5.2: Development rate coefficient values

Rate Type	Category	Coefficient Value
Crash	1	0.5
Aggressive	2	0.8
Cautious	3	1
Exploratory	4	1.5

Some comments can be made regarding the final values of each assigned rate in Table 5.3. A category 2 value is given to India and South Africa – both states pursued an aggressive path because of geopolitical considerations and neither of these states experienced much resistance in the form of international pressure. A similar case is developed for Israel with the exception of a hurried effort to develop a functioning weapon at the onset of the Six-Days War 1967. Pakistan's urgency to develop nuclear weapons became significantly enhanced after India's "peaceful nuclear explosive" test and this can be seen in the final rate value that it was assigned. The North Korean NWP is substantially more complicated than the others. After starting off with Soviet assistance in the early 1980's, the program became the focus of Western

suspicion later in the decade. This focus led to a crisis in 1994 that was temporarily contained with the Agreed Framework between the DPRK and the United States. The plutonium-based weapons program was on a virtual freeze until the Agreed Framework was abandoned in 2003, after which the DPRK worked feverishly to complete the project.

Table 5.3: Rate of pursuit coefficient assessments

	Pursuit Rate	Category	Explanation
DPRK			
1982-1994	Cautious	3	Steady development
1994-2003	Exploratory	4	Near freeze after Agreed Framework
2003-2006	Crash	1	NPT withdrawal; rush to weaponize
Assigned Coefficient		**1.13**	
India			
1964-1974	Aggressive	2	Steady development until first test
Assigned Coefficient		**0.80**	
Israel			
1955-1956	Cautious	3	Development sought
1957-1966	Aggressive	2	Suez Crisis leads to increased intent
1967	Crash	1	Outbreak of Six-Days War
Assigned Coefficient		**0.81**	
Pakistan			
1972-1974	Cautious	3	Initial development
1974-1990	Aggressive	2	Increased urgency after India test
Assigned Coefficient		**0.82**	
S. Africa			
1971-1978	Aggressive	2	Steady development
Assigned Coefficient		**0.80**	

A case can be made that each of these NWP's had some variation of an "exploratory phase" prior to any political decision to pursue a full-scope NWP. But this judgment will complicate the assessment because then it can be said that if all programs had an exploratory phase, it could date back to the time of the first nuclear weapons use at the end of WWII, and this

is not particularly insightful. Additionally, the level of each state's experience at the onset of the NWP can be characterized by the experience level of the technical community at the time the political decision is made.

5.2 – Industry Metrics

The strength of industry that can be brought to bear on a NWP is the strongest determining factor beyond the core competency that is necessary to construct and operate a nuclear weapons complex. But determining the strength of industry is not terribly straightforward. When Meyer first proposed industrial metrics for determining the "latent" proliferation capability of a state, it was done by asking whether or not the state had a minimum capability in that given category[11]. The difficulty with this approach, as expressed earlier, is that it does not help us determine the potential added benefit of having industry beyond a set threshold. While more detailed studies of these possible correlations are necessary, a basic examination of historical data can shed some light for this research to proceed. Table 5.4 is a listing of some industrial factors compiled through several different editions of the United Nations *Statistical Yearbook*. A normalized comparison of the per capita rate of the date in Table 5.4 is offered in Figure 5.1, along with the per capita vocational education rates (presented in table-form in the next section). The data for each state is given for the time closest to the start of their respective NWP.

The individual industrial metrics were chosen for their importance in NFC process construction and operation, and also because these values were identified by Meyer as being key metrics [3, p. 186]. From this information we can see that a state like South Africa has a much greater advantage over the other states in consideration. Israel also has fairly decent industrial

[11] See "Appendix B: The Technical Model," [3, pp. 173-193]

numbers, but these are highly limited by their comparatively small population in 1955. Conversely, India's industrial numbers appear very large until the population size is taken into account. But the per capita comparison may not be as important for India because a "sufficiently large" industry is what is being gauged.

Table 5.4: Comparative industrial metrics at the onset of the respective state's NWP

	DPRK[c]	India	Israel	Pakistan	S. Africa
Year of Program Start	1982	1964	1955	1972	1971
Population (million people)	15.9	472	1.77	65.3	23.1
Installed Electric Capacity (MW)	7,500 (1983)	8,397 (1966)	239	1,820	13,435
Nitric Acid Production (1,000 t)[a]		12	1.6 (1960)[b]		
Cement Production (1,000 t)	8,000	9,690	664	2,605	7,296
Crude Steel Production (1,000 t)	3,500	6,032	24 (1959)[b]		5,832
Source: UN Statistical Yearbook Year	1983/84	1966	1958	1975	1975

Parenthesis denote the year of closest available data, [a]In terms of 100% nitric acid, [b]values for DPRK are entirely estimated, [c]1966 yearbook.

What is not reflected in this study – for several reasons – is the change in industry over the course of the program. This is especially important for the DPRK. At the start of the program, the DPRK enjoyed tremendous economic benefits as a client state of the USSR. It should also be noted that the numbers for the DPRK are listed as estimates in the *Statistical Yearbook*. Rendering a final judgment on the industry coefficient (*I*) for each state will be deferred until after the scientific and process-step values are determined.

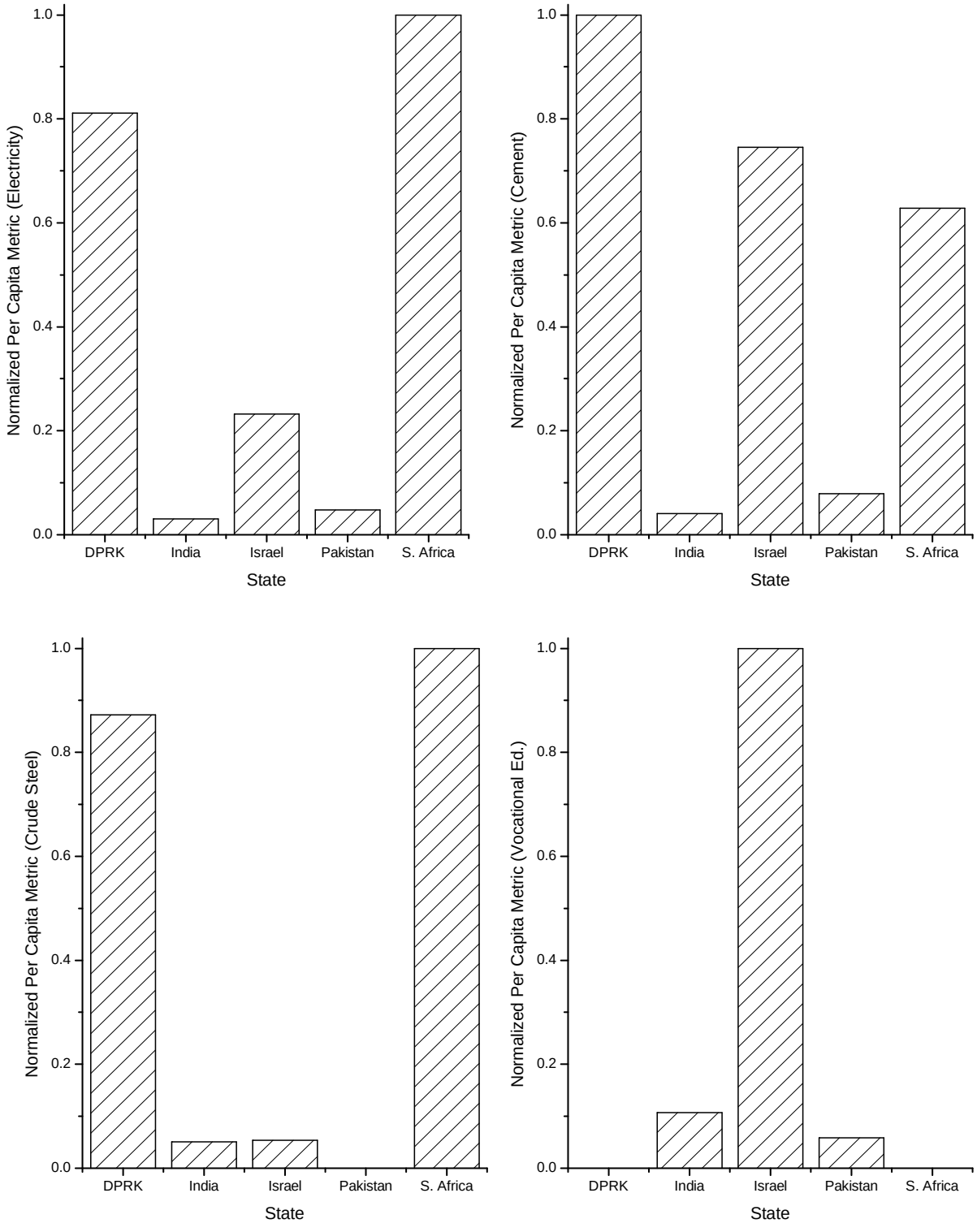


Figure 5.1: Per capita industry metric comparisons[12]

[12] Information on steel production in Pakistan and vocational education is DPRK and South Africa was not available.

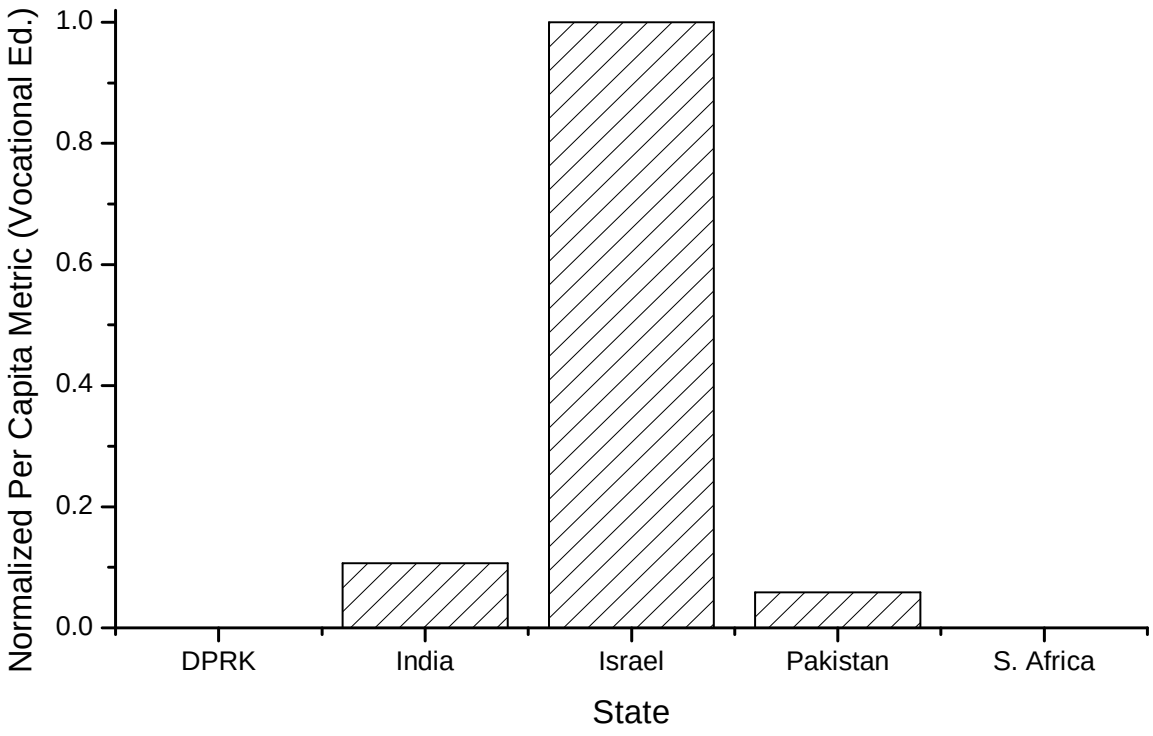
5.3 – Knowledge Metrics

In much the same way that industry plays a part in developing a NWP, education metrics can be used to help assign values to knowledge coefficients. Human capital is as important as having a requisite level of industrial strength, if not more. Modern technological connectivity has become an enhancing factor regarding access to basic scientific resources and knowledge; a fact that will allow a state to better train, educate, and recruit knowledgeable individuals. But there is no substitute for direct scientific and engineering experience. The strength of the education base does not just apply to the strength of upper educational institutions. It is also important to have a knowledgeable base of educated professionals to carry out the more regular tasks in a NWP. Access has to be given to a sufficiently large labor market in a given state for competent tradesmen such as electricians, plumbers, construction workers, and office works. For this reason, Table 5.5 and Figure 5.2 also list the numbers of individuals in the education system and the normalized per capita comparison, respectively.

Table 5.5: Comparative educational metrics at NWP onset

	DPRK	India	Israel	Pakistan	S. Africa
Year of Program Start	1982	1964	1955	1972	1971
Population (million people)	15.9	472	1.77	65.3	23.1
Vocational Institutions		*(1963)*		*(1973)*	
Instructors	--	21,396	999	1,810	--
Enrolled	--	340,000	11,922	25,798	--
Higher Education Institutions				*(1972)*	*(1973)*
Instructors	--	80,247	--	3,790	--
Enrolled	--	1,310,000	7,500	107,757	98,577[a]
Source: UN Statistical Yearbook Year	1983/84	1966	1958	1975	1975

Data in parenthesis denote the year of closest available data, [a]from 1976 Statistical Yearbook [46]



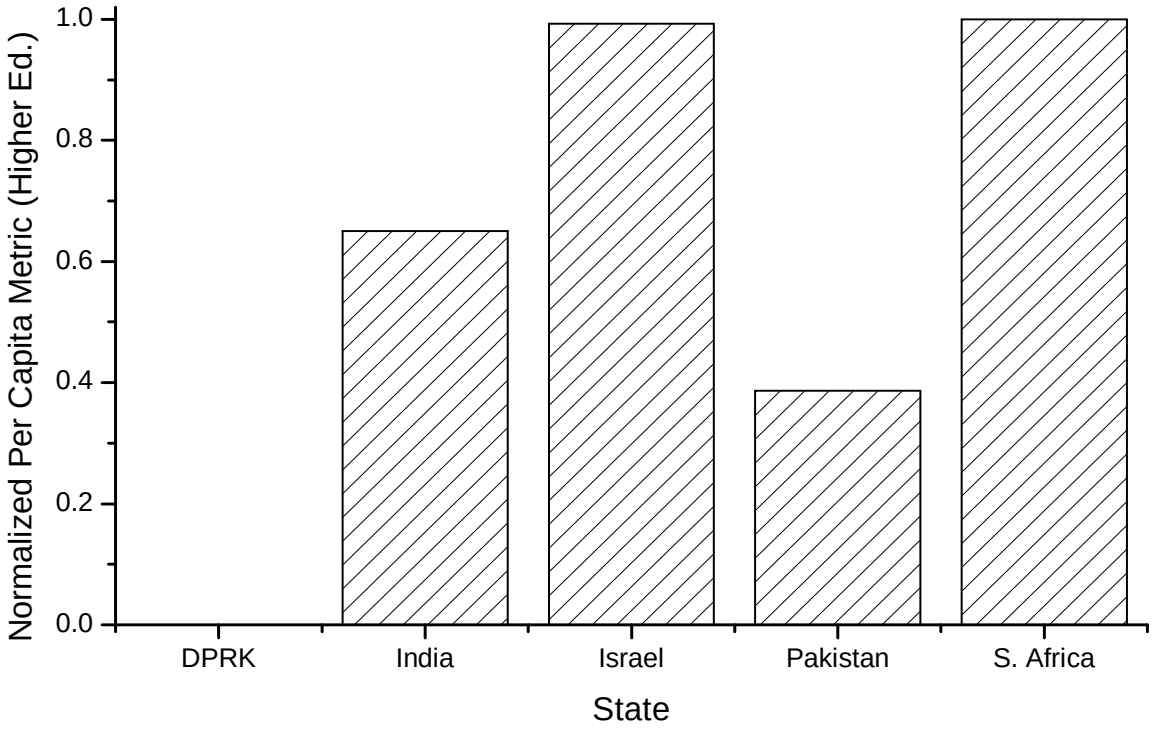


Figure 5.2: Per capita education metrics[13]

[13] Information on vocational education in South Africa and education information on the DPRK was unavailable.

Regrettably, the lack of education-based numbers from some states is glaring and unfortunate, but it is interesting to note the strength of the Israeli and South African upper education systems, as well as the vocational system in Israel. It is on the latter point that a competitive edge can be given to Israel. India also shows an education base that, when multiplied out to its population size, demonstrates a significant human capital pool.

Prior experience in nuclear fuel cycle operations is another principle education factor. A state with a commercial or research reactor will have more collective knowledge on constructing and operating a future project. The same is true for any of the fuel cycle operations. Cataloging this knowledge, as displayed below in Table 5.6, is important to show which steps can be given the benefit of additional operating knowledge. Only the highlighted fields represent known or suspected operations that predate weapons programs. With data on pursuit rates, industry and education, it is now possible to start assigning values to each countries process steps.

Table 5.6: Process experience prior to NWP initiation

	DPRK[c]	India	Israel	Pakistan	S. Africa
Mining/Milling	--	--	--	--	--
Conversion		1968[c]		Early 1980's[d]	
Enrichment	--	1985[c]	--	1981[e]	Early 1960's[f]
Fuel Fab.		1971		1975[c]	--
Irradiation	1965[a]	1956[a]	1960[a]	1965[a]	1965[a]
PUREX	1975[b]	1964		--	--
Heavy Water	--	1962[c]		--	--

Hightlighted times indicate known experience prior to achieving a NWP threshold. Sources: [a]IAEA "Nuclear Research Reactors in the world" [47], [b]Albright *et al* [17], [c]Cirincione *et al* [48], [d]Risk Report [49], [e]CNS "Pakistan's Nuclear Related Facilities" [50], [f]Albright [51].

5.4 – Establishing the Values

The final step in determining the timetables of future at-risk proliferation states is to determine the value of each step in achieving the whole. Reverse engineering these programs and fitting the knowledge of each one will yield an analytical method for determining future timetables of full weapons-program acquisition. Based on the discussion of each step in *Chapter 3* and *Chapter 4*, values for the construction and operation of the NFC and weaponization processes can be expressed; these values are set in Table 5.7 and Table 5.8, respectively. These numbers increase with the perceived level of required effort, and designate a comparable standard. Because these values represent the standard set, it should not change from one state program to the next with the exception of steps that were already completed or partially completed prior to the weapon program decision being made.

Table 5.7: Standard process variable values

	Construction (*C*)	Operation (*O*)
Mining/Milling	5	3
Conversion	3	3
Enrichment	5	10
Fuel Fab.	2	2
Irradiation	5	5
PUREX	4	3
Heavy Water	2	2

Table 5.8: Standard weaponization effort values

	Weaponization (*W*)
Design	3
Metallurgy	1
Fuzing	1
Initiation	1
Compression	1.5

Table 5.9 is the combined listing of each state's NWP-level construction and operation steps. This information is also presented graphically in Figure 5.3 (plutonium-based NWP's) and

Figure 5.4 (uranium-based NWP's). The procedure for assigning values will also rely on making some determinations and special considerations for each state. These considerations are based upon the unique circumstances of each program. Each state will be evaluated individually.

Table 5.9: Time NFC process construction and operation reached NWP levels

	DPRK	India	Israel	Pakistan	S. Africa
Program Start	1982	1964	1955	1972	1971
Acquisition	2006	1974	1967	1990	1978
Threshold-level process construction start/end dates					
Mining/Milling	1960's[a]	-1967[c]			-1955[h]
Conversion	-1984[a]		1957-[k]	-1980	
Enrichment	--	--	--	1976-1981[g]	1969-1974[i]
Fuel Fab.	-1974[a]	-1970[c]	1957-[k]	--	--
Irradiation	1980-1986[b]	1955-1960[d]	-1963[d]	--	--
PUREX	1985-1989?[a]	1961-1964[c]	1957-[k]	--	--
Heavy Water	--	-1962[e]		--	--
Threshold-level process operation started					
Mining/Milling	Early 1960's[a]	1967[c]		1977-1978[e]	1955[h]
Conversion	1984[a]	1972[f]		1980[c]	
Enrichment	--	--	--	1981[g]	1974[j]
Fuel Fab.	1974[a]	1971[c]		--	--
Irradiation	1986[b]	1960[c]	1963[d]	--	--
PUREX	1989[b]	1964[c]	Before 1967	--	--
Heavy Water	--	1962[e]		--	--

[a]FAS North Korean Special Weapons Facilities [52], [b]Albright *et al* [17], [c]NTI Country Profiles [7], [d]IAEA "Nuclear Research Reactors in the World" [47], [e]Benedict, Pigford, Levi [27, p. 711], [f]NFCIS-IAEA [4], [g]Pakistan's Nuclear Related Facilities [50], [h]Ford [53, p 37], [i]Albright [51], [j]Cirincione *et al* [48], [k]Date estimated based on signing of Dimona agreement with France on 10/03/1957 [54].

5.4.1 – DPRK

As described earlier in this chapter, the DPRK went through several changes in its pursuit rate because of its unique geopolitical interactions with the United States in the early 1990's and 2000's. In addition to these changes, the collapse of the Soviet Union – the primary economic

and military backer of the DPRK – coincided with a major downshift in the industrial and educational prowess of that state. These factors can be observed very prominently in Figure 5.3, where a significant stretch of time takes hold between the establishment of PUREX operations before the collapse of the Soviet Union in 1991 and the first weapon test in 2006. The change in rate is already numerically factored into the equation, but the decline in industrial capabilities is difficult to gauge. It is also difficult to gauge the education metrics – as no numerical data was available.

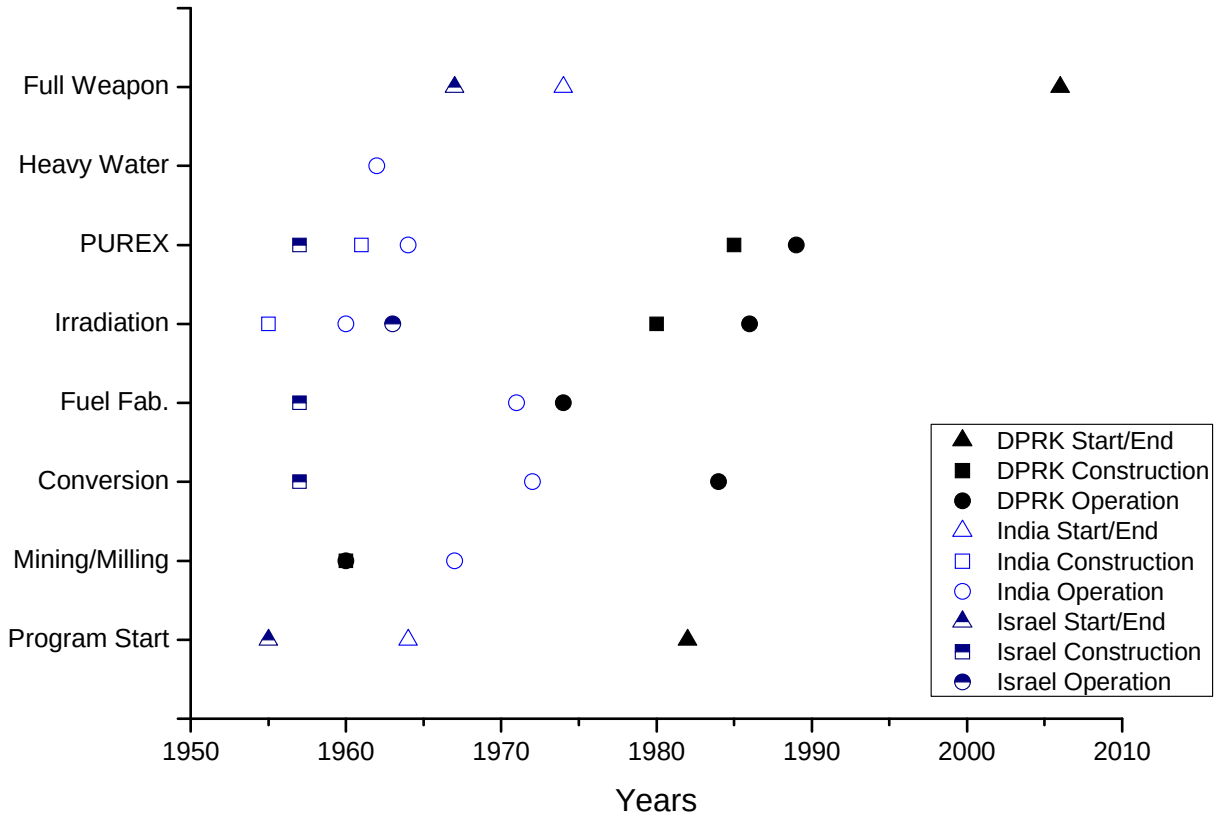


Figure 5.3: Plutonium program time-steps

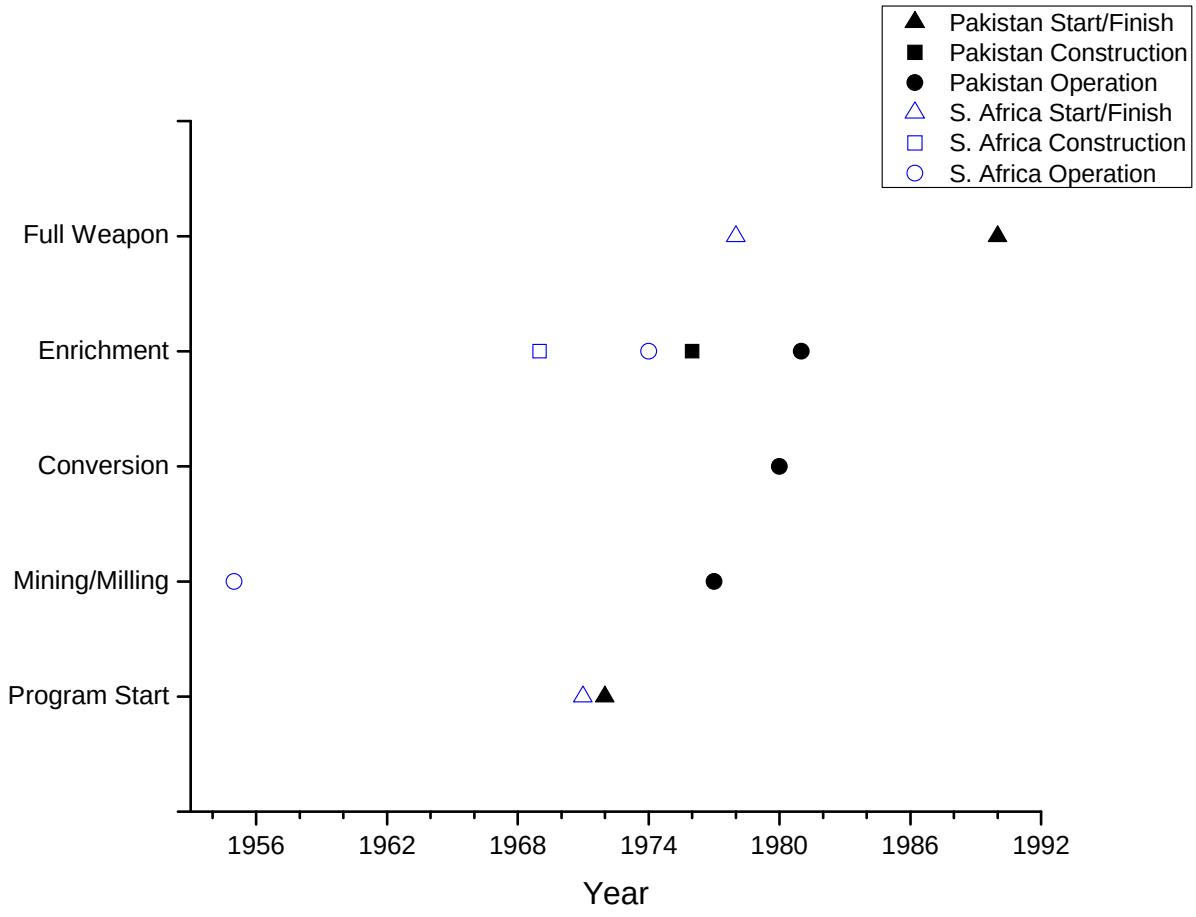


Figure 5.4: HEU program time-steps

Despite these issues, the DPRK has a significant nuclear training complex, and many engineers and technicians were sent to Soviet institutions for education throughout the second half of the twentieth century. Also, the absolute control that the government exercises over the economy gives the DPRK the latitude to focus a disproportionately higher level of resources towards a nuclear project as compared to other states. Table 5.10 is the full variable calibration performed on the DPRK with values assigned to every applicable field. Construction on the mining/milling and fuel fabrication steps was reduced to zero because those elements of the fuel cycle were in place prior the decision to pursue a weapon. The DPRK reactors also do not use heavy water, and some measure of confidence can be given to their knowledge of fuel cycle

operations. The most difficult area to correctly assign values is the weaponization knowledge, hence these values were given a conservative, equal weighting. Rough breakdowns of the effort undertaken by the state are also shown. Discussion of the calculated results, the validity of the values assigned to each element in the table, and what it means going forward will be discussed at the end of this chapter.

Table 5.10: DPRK – values and timetable calibration

	Construction (*C*)	Operation (*O*)	Knowledge (S_p)
Mining/Milling	0	3	1.2
Conversion	3	3	1.2
Enrichment	--	--	--
Fuel Fab.	0	2	1.1
Irradiation	5	5	1.3
PUREX	4	3	1.3
Heavy Water	--	--	--
Effort	12	16	**78.87%**
	Weaponization (*W*)	Knowledge (S_w)	
Design	3.0	1.0	
Metallurgy	1.0	1.0	
Fuzing	1.0	1.0	
Initiation	1.0	1.0	
Compression	1.5	1.0	
Effort	7.5		**21.13%**
Industry (*I*)	1.40		
Rate (*R*)	1.13	Actual Completion	24 Years
Calculated Time (*T*)			**24.1**

5.4.2 – India

India received a head-start in its nuclear program through collaborative efforts on nuclear technology through the United States and Canada. These efforts gave India several facilities and many years of experience that were used in its initial program to construct and detonate a PNE in

1974. It is for this reason that several fuel cycle construction values are zeroed out in the value breakdown given for India in Table 5.11.

Table 5.11: India – values and timetable calibration

	Construction (*C*)	Operation (*O*)	Knowledge (*Sp*)
Mining/Milling	5	3	1.2
Conversion	3	3	1.1
Enrichment	--	--	--
Fuel Fab.	2	2	1.1
Irradiation	0	5	1.3
PUREX	0	3	1.3
Heavy Water	0	2	1.2
Total Effort	10	18	**78.87%**
	Weaponization (*W*)	Knowledge (*Sw*)	
Design	3	1.2	
Metallurgy	1.0	1.1	
Fuzing	1.0	1.0	
Initiation	1.0	1.0	
Compression	1.5	1.0	
Total Effort	7.5		**21.13%**
Industry (*I*)	2.25		
Rate (*R*)	0.80	Actual Completion	10
Calculated Time (*T*)			**10.8**

India's industrial value is elevated because of the size of the advantages granted to it by its large population; per capita values are low, but the raw production values are competitive. Education is slightly elevated for the same reason, and because of its previous fuel cycle experience. The calculated time for an Indian program is slightly greater than the actual completion time, despite the belief that the assigned programmatic values are reasonable. It is possible that this is reflected in the fact that India's first nuclear detonation was a PNE, principally not a deliverable weapon for military use. This may seem like a subtle distinction, but it is an important to note that some significant time was spent to further advance the Indian program to field a deliverable weapon. It could be very interesting if this fact is playing out in some way with the final calculated time.

5.4.3 – Israel

The level of secrecy surrounding the Israeli weapons program makes analysis very difficult. Based on what is generally understood, the Israeli program was mainly an indigenous effort, but the scientific and technical communities are advanced. This is not just based on high enrollment numbers in upper education, but the contributions from vocational and trade schools are very important for a state with a comparatively small population. Coupled with a strong industrial base and an accelerated program rate, it is believed that the Israel program came to fruition 1967 after twelve years. When compared to the Indian program, the Israeli numbers in Table 5.12 show that increased education and industry factors have compensated for the lack of initial fuel cycle infrastructure.

Table 5.12: Israel – values and timetable calibration

	Construction (*C*)	Operation (*O*)	Knowledge (*Sp*)
Mining/Milling	5	3	1.2
Conversion	3	3	1.3
Enrichment	--	--	--
Fuel Fab.	2	2	1.2
Irradiation	5	5	1.3
PUREX	4	3	1.2
Heavy Water	2	2	1.2
Total Effort	21	18	**83.87%**
	Weaponization (*W*)	Knowledge (*Sw*)	
Design	3.0	1.2	
Metallurgy	1.0	1.1	
Fuzing	1.0	1.1	
Initiation	1.0	1.1	
Compression	1.5	1.1	
Total Effort	7.5		**16.13%**
Industry (*I*)	2.50		
Rate (*R*)	0.81	Actual Completion	12
Calculated Time (*T*)			**12.3**

5.4.4 – Pakistan

The Pakistani program – which was accelerated in the wake of the Indian nuclear test in 1974 and benefited substantially from illicit nuclear technology transfers – is an example of how a state of fairly low technical capability can achieve a viable program. Reflected in Pakistan's numbers – in Table 5.13 – is the enhanced knowledge on enrichment through gaseous centrifuge technology. A.Q. Khan provided Pakistan with centrifuge blueprints and a list of parts suppliers. Pakistan also received assistance in their nuclear program in the form of a detailed weapon design provided by China [55, p. 3].

Table 5.13: Pakistan – values and timetable calibration

	Construction (*C*)	Operation (*O*)	Knowledge (*Sp*)
Mining/Milling	5	3	1.1
Conversion	3	3	1.0
Enrichment	5	10	1.4
Fuel Fab.	--	--	--
Irradiation	--	--	--
PUREX	--	--	--
Heavy Water	--	--	--
Total Effort	13	16	**86.57%**
	Weaponization (*W*)	Knowledge (*Sw*)	
Design	0	1.0	
Metallurgy	1.0	1.0	
Fuzing	1.0	1.1	
Initiation	1.0	1.1	
Compression	1.5	1.0	
Total Effort	4.5		**13.43%**
Industry (*I*)	1.25		
Rate (*R*)	0.82	Years to complete	18
Calculated Time (*T*)			**18.6**

When assigning values it was determined that the assistance from the Chinese could also increase the knowledge coefficients in other weaponization activities, such as initiation and fuzing. Industry and education are significantly reduced compared to other states. Assistance in

key areas helped the Pakistani program become what it is, although the clandestine tech imports and procurement efforts cannot be expressed directly.

5.4.5 – South Africa

At the time their nuclear program was started, South Africa already had a fully developed mining industry. South Africa has vast uranium ore deposits and uranium mining efforts in this country date back to the Manhattan Project [53, p. 38]. It can be assumed from this information that when South Africa's government sought nuclear weapons in 1971, there was considerable knowledge in extracting, processing, and handling uranium.

Table 5.14: South Africa – values and timetable calibration

	Construction (*C*)	Operation (*O*)	Knowledge (*Sp*)
Mining/Milling	0	3	1.2
Conversion	3	3	1.2
Enrichment	3	10	1.3
Fuel Fab.	--	--	--
Irradiation	--	--	--
PUREX	--	--	--
Heavy Water	--	--	--
Total Effort	6	16	**74.58%**
	Weaponization (*W*)	Knowledge (*Sw*)	
Design	3.0	1.1	
Metallurgy	1.0	1.1	
Fuzing	1.0	1.1	
Initiation	1.0	1.1	
Compression	1.5	1.1	
Total Effort	7.5		**25.42%**
Industry (*I*)	2.75		
Rate (*R*)	0.80	Years to complete	7
	Calculated Time (*T*)		**7.07**

South Africa is coded as having the strongest industry compared to the other four states discussed in this chapter. Despite the lack of numbers available for South Africa's vocational

school enrollment, it is reasonable to assume that these numbers are elevated based on the strong industrial numbers, and upper education metrics.

5.5 – Assessments

The purpose of assigning the values in this way is to generate a comfortable range of values that can be translated to future test cases and evaluations. Each of these states described above has unique characteristics and circumstances that were appropriately programmed into their respective data tables. This is a great benefit of this method; assumptions about a program based on high-confidence information can be expressed appropriately by this model.

It is also necessary to state that some of the values assigned in this portion are based on conjecture, but they are assigned values with a significant level of qualitative justification. This is not an unreasonable method of assessment for such a complex system where large portions of usable numerical data are either unknown or unavailable to the public. In going forward with the test cases in the next chapter, there is a sufficient scope of appropriate numerical values to make reasonable judgments. But because the level of potential error that is intrinsic to this form of methodology, a detailed sensitivity analysis is carried out on a test case and can be found in Appendix-A.

Chapter 6: Model Testing & Analysis

Using the accumulated information from all of the previous chapters, we are now able to test the validity, accuracy, and utility of the model equations. The three states that are being examined – Myanmar, the Republic of Korea (ROK), and Turkey – were chosen because they are interesting from a geopolitical standpoint and they all have very different levels of experience with nuclear technology. Myanmar, which has recently been in the spotlight for a possible illicit trade relationship with the DPRK, has no nuclear facilities, and a comparatively weak industry and educational base. Turkey has some experience with nuclear facilities but this is not a very large program. The ROK is a very interesting case because it is very experienced with nuclear technology, has very strong industry and education, and is in a geopolitical hot-zone in the Far East. In testing these cases, it is necessary to provide similar information on industrial production, education, and previous NFC experience. Tables 6.1 and 6.2 are the industrial and education metrics, respectively. The ROK is very dominant in all categories, despite Turkey having a population advantage.

Table 6.1: 2006 Industry metrics for test states

	Myanmar	ROK	Turkey
Population (million people)	48.7	47.8	72.1
Electricity Production (1,000 TOE)	286	13,262	3,823
Calculated Equivalent (MW)	380	17,607	5,076
Cement Production (1,000 t)	552	55,021	47,906
Crude Steel Production (1,000 t)	25	48,259	23,308

Data from the 2009 U.N. *Statistical Yearbook* [56]. Electricity production converted from TOE to MW

Because of changes made to the United Nations *Statistical Yearbooks*, current information is not necessarily presented in the same way as in older editions. This creates a problem for comparison purposes between the data provided for the de facto weapon states and the data presented here. The education metrics are categorized differently, with “vocational

education" and "installed electrical capacity" being eliminated as outright categories. The installed capacity is replaced with "electrical production" – which is not equivalent, but still provides useful data – and education is expressed as "secondary" and "tertiary" levels to cover all of the pertinent areas of education. Newer editions of the *Statistical Yearbook* also include information on research and development activities. Because of these changes, a strong comparison to the numerical data supplied for the de facto weapon states were not attempted.

Table 6.2: 2007 Education metrics for test states

	Myanmar	ROK	Turkey
Population (million people)	48.7	47.8	72.1
Secondary Education - Enrolled	2,686,198	3,917,400	5,527,208
Tertiary Education - Enrolled	507,660	3,208,591	2,453,664
Research & Development			
Researchers	837 (2002)	289,098	49,668
Technicians	6,499 (2002)	94,319	7,420

Data from the 2009 U.N. *Statistical Yearbook* [56]. Parenthesis indicate year of closest available data.

When industry and education information was examined for the de facto weapon states, it was based on the information that was closest to the starting time of the NWP for that particular state. This current information, ranging from 2002-2007, is expected to be substantially elevated compared to state values that are thirty or more years old. When factored against population as part of the per capita comparison and total production values – see Figures 6.1 and 6.2 – this trend is very clear. It is expected that the modern, industrialized state is more capable of completing NWP on a faster timetable. Access to better computing power and the internet also decreases the negative impact of diminished educational values. Nuclear fuel cycle experience data in Table 6.3 is the last piece of information needed to make a series of reasonable assessments in how long it is likely to take a state to produce a full NWP. Myanmar has no nuclear experience, while Turkey and the ROK have proficiency in this area.

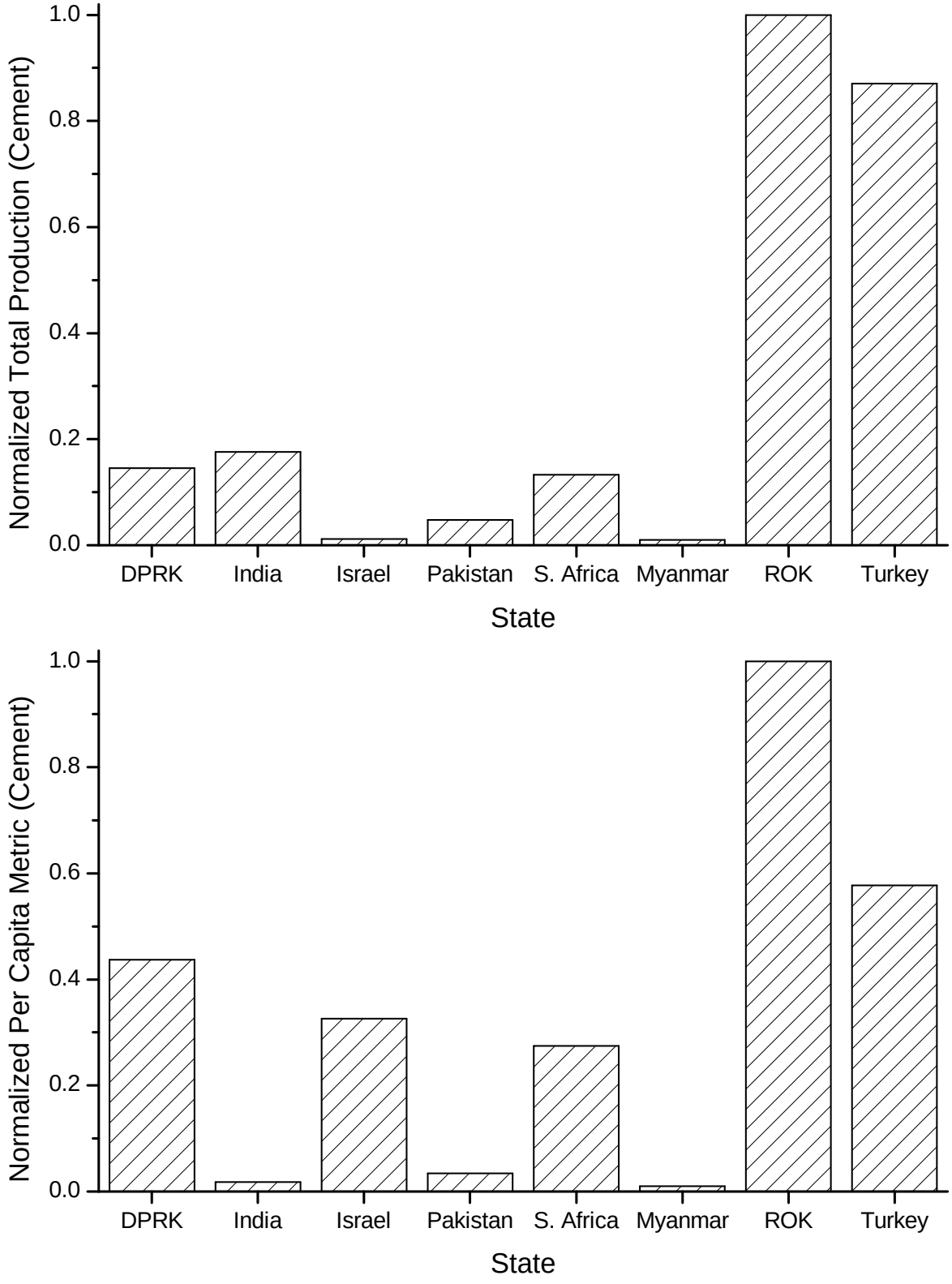


Figure 6.1: Annual cement production comparisons (per capita and total)

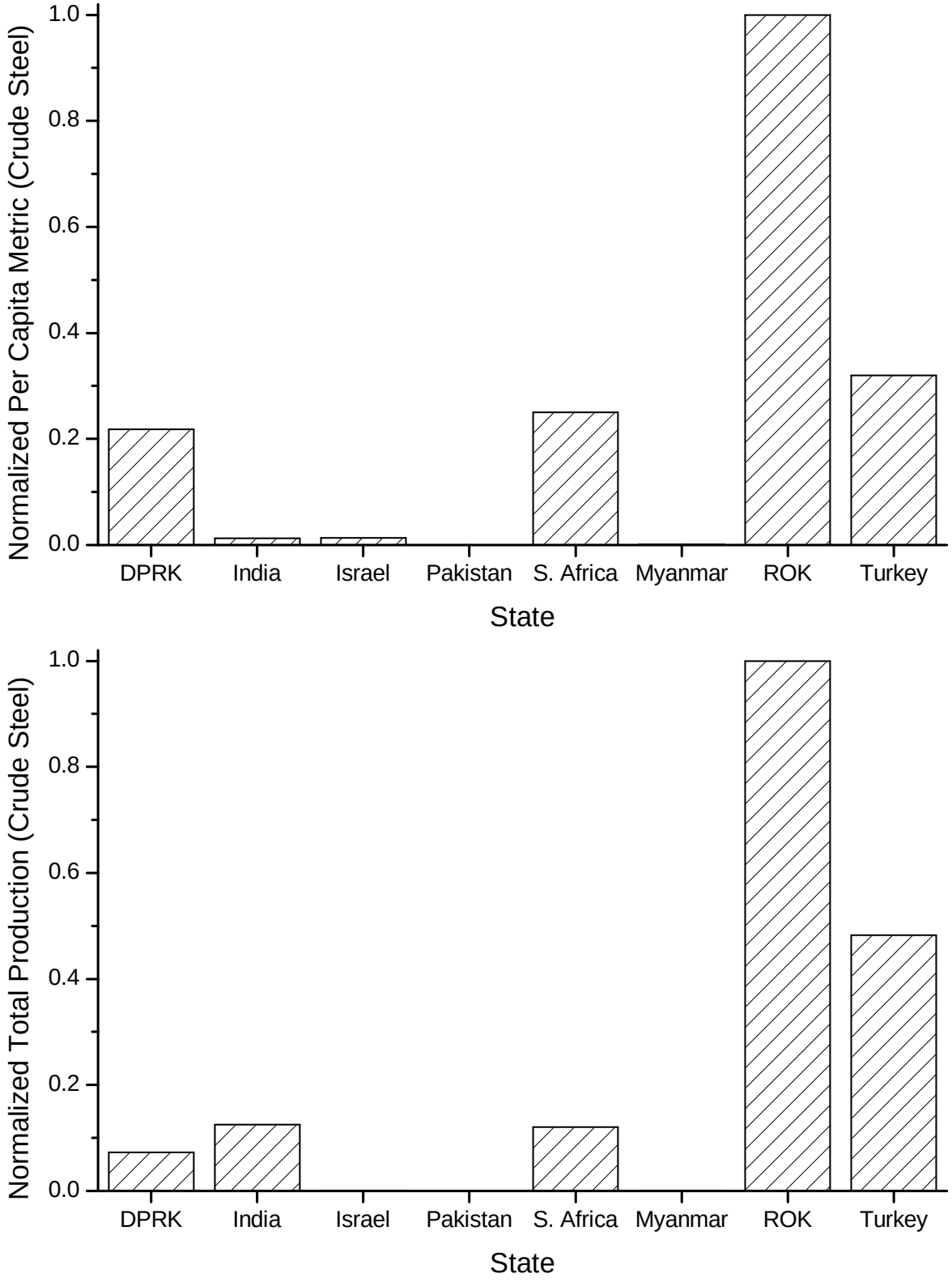


Figure 6.2: Annual steel production comparisons (per capita and total)

Table 6.3: Nuclear process information for test cases

	Myanmar	ROK	Turkey
		Time of Initial Operating Experience	
Mining/Milling	--	--	1974[ab]
Conversion	--	1989[ab]	1986[b]
Enrichment	--	--	--
Fuel Fab.	--	1987[b]	1986[b]
Irradiation	--	1962[c]	1962[c]
PUREX	--	--	--
Heavy Water	--	--	--
		Present Effort/Experience	
Mining/Milling	None	No Domestic Production	Ore Processing: shutdown[b]
Conversion	None	Pilot-Decommissioned[d]	Pilot plant[b]
Enrichment	None	Experimented[e]	None
Fuel Fab.	None	800 t U/a capacity[d]	Pilot plant[b]
Irradiation	None	15,700 MW(e) installed[d]	Two research reactors[e]
PUREX	None	Experimented[e]	Limited experience[e]
Heavy Water	--	--	--

[a]Listed facility is being decommissioned. A new one will require construction, [b]IAEA NFCIS [4], [c]IAEA "Nuclear Research Reactors in the world" [47], [d]TRS-425-IAEA [15], [e]NTI Country Profiles [7].

6.1 – Myanmar

For each of the three test-cases, the values will be programed two show both uranium and plutonium-based weapons as two different tracks. Each state will also be tested through the four different pursuit rates. For Myanmar, the lack of experience in nuclear energy and the weak industry makes this a very difficult challenge. Without any help from other states, Myanmar could be expected to take on the order of decades to achieve a weapon capability, even under crash-rate conditions. While independent confirmation of this estimate is unlikely to be available, the values expressed in Table 6.4 are not unreasonable. Error values in the measurements are not assessed here, but the sensitivity analysis in Appendix A can help address possible uncertainty issues.

Table 6.4: Myanmar - values and timetable calibration

	Construction (*C*)	Operation (*O*)	Knowledge (*Sp*)
Mining/Milling	5	3	1
Conversion	3	3	1
Enrichment	5	10	1
Fuel Fab.	2	2	1
Irradiation	5	5	1
PUREX	4	3	1
Heavy Water	--	--	--
Effort	24	26	**86.96%**
	Weaponization (*W*)	Knowledge (*Sw*)	
Design	3.0	1.0	
Metallurgy	1.0	1.0	
Fuzing	1.0	1.0	
Initiation	1.0	1.0	
Compression	1.5	1.0	
Effort	7.5		**13.04%**
Industry (*I*)	1.20		
Rate		Uranium-Weapon Time (*T*)	Plutonium Weapon Time (*T*)
Crash	0.5	**15.2**	**17.7**
Aggressive	0.8	**24.3**	**28.3**
Cautious	1.0	**30.4**	**35.4**
Exploratory	1.5	**45.6**	**53.1**

6.2 – Republic of Korea

Excellent knowledge from considerable levels of operating experience helps the ROK nuclear program considerably. It is reasonable to assess that a plutonium-based weapon can be fielded in five years with its current capabilities, if it elects to pursue weapons regardless of the consequences. There are however several issues with the ROK assessment, in Table 6.5, that must be pointed out. South Korea does not have domestic uranium deposits of any kind. The assumption that can be substituted in place of mining considerations is an effort at either slow accumulation or diversion of uranium yellowcake or UF_6. And despite the fact that the ROK has a large number of reactors, it is assumed that the state will likely opt to independently produce

some form of production reactor – likely to attempt to circumvent IAEA safeguards or to prevent its civilian power reactors from becoming legitimate military targets.

Table 6.5: ROK - values and timetable calibration

	Construction (*C*)	Operation (*O*)	Knowledge (*Sp*)
Mining/Milling	5	3	1
Conversion	3	3	1.3
Enrichment	5	10	1.1
Fuel Fab.	2	2	1.4
Irradiation	5	5	1.5
PUREX	4	3	1.1
Heavy Water	--	--	--
Total Effort	24	26	**86.96%**
	Weaponization (*W*)	Knowledge (*Sw*)	
Design	3	1.2	
Metallurgy	1.0	1.2	
Fuzing	1.0	1.1	
Initiation	1.0	1.1	
Compression	1.5	1.2	
Total Effort	7.5		**13.04%**
Industry (*I*)	3.5		
Rate		Uranium-Weapon Time (*T*)	Plutonium Weapon Time (*T*)
Crash	0.5	**4.66**	**4.99**
Aggressive	0.8	**7.46**	**7.98**
Cautious	1.0	**9.33**	**9.97**
Exploratory	1.5	**13.99**	**15.0**

6.3 – Turkey

The thought of a Turkish NWP is likely to stem from an arms race scenario developing in the Middle East, should Iran acquire a nuclear capability. However likely or remote this possibility is, it is worth studying the possible creation of a NWP in a state with good industry and some level of nuclear experience. As Table 6.6 indicates, Turkey's efforts are likely to take a decade or longer to produce a program based on the information previously described. Again this assumption is reasonable, but all of these values have to be accepted with an understanding that –

as explained in the previous chapter – the values assigned to each variable are based on qualitative findings. For Turkey, Myanmar and the ROK, the values expressed are meant to serve as a guide, and not necessarily as a prediction.

Table 6.6: Turkey - values and timetable calibration

	Construction (*C*)	Operation (*O*)	Knowledge (*Sp*)
Mining/Milling	5	3	1.1
Conversion	3	3	1.1
Enrichment	5	10	1
Fuel Fab.	2	2	1.1
Irradiation	5	5	1.1
PUREX	4	3	1
Heavy Water	--	--	--
Total Effort	24	26	**86.96%**
	Weaponization (*W*)	Knowledge (*Sw*)	
Design	3.0	1	
Metallurgy	1.0	1	
Fuzing	1.0	1	
Initiation	1.0	1	
Compression	1.5	1	
Total Effort	7.5		**13.04%**
Industry (*I*)	2.80		
Rate		Uranium-Weapon Time (*T*)	Plutonium Weapon Time (*T*)
Crash	0.5	**6.29**	**7.1**
Aggressive	0.8	**10.06**	**11.4**
Cautious	1.0	**12.58**	**14.3**
Exploratory	1.5	**18.87**	**21.4**

Chapter 7: Conclusions & Future Work

The research presented in this work is meant to support nuclear nonproliferation efforts by demonstrating that timeframes for developing a nuclear weapon program, in any given state, can be effectively estimated based on quantitative metrics and qualitative analysis. This method of modeling helps prospective users focus attention on specific NFC processes, technical steps that allow a state to go from the creation of SNM to the development of a deployable nuclear weapon, and how the unique circumstances of a state can impact its ability to complete a program. There are some clear disadvantages to this particular method. It is limited in its ability to correctly explain the order of progression through the various NWP-creation steps; some creation steps must commence in a particular series and some can be worked out in parallel. The industry can compensate for this by showing that a state with a sufficiently sized industry can engage in multiple areas at once – and hence is operating in parallel by some measure. But this is not a satisfactory way of handling this problem.

Another disadvantage of this model is that assigning appropriate values to each variable is not based on a straightforward process. That in itself seems to suggest that there is an "unscientific" methodology with this approach, but like all matters that involve intelligence assessment, there is some intrinsic level of uncertainty. The model is meant to be a framework through which known facts and assumptions made by the user can be combined to answer meaningful nonproliferation questions:

1. If the political decision is made to ready a NWP, approximately how long will it take?
2. Based on information from two different points in time, is a state proliferating?
3. What sequence of values in the model – and by extension, what level of real world values – does a state need to achieve in order to have a "latent" capability?

There is not a completely straightforward approach to modeling a system as complex as nuclear weapons development, but this work is an important support step for those analytical efforts.

Future work in this area is likely to consist primarily of two parts: 1) efforts to improve accuracy and functionality and 2) efforts to incorporate political and economic dimensions. Improving the effectiveness can be done partially by introducing a more scientific or statistically-motivated method of determining input values. Addressing the specifics of how well a state may be able to produce – or acquire by various other means – the parts that it needs may lead to better estimations of the total process step. Political and economic factors can include assumptions on the effects of market conditions or the level of democratization in a state.

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Appendix A – Sensitivity Analysis

A straightforward sensitivity analysis is performed in this section to demonstrate the system response to changes in an equation constant. The purpose of this exercise is to demonstrate the effect on the equation outcome from a change in the value of each variable. Data taken from programmatic information on the Israeli nuclear program was used for this purpose. Table A.1 is a reproduction of those values originally used in Table 5.12 with changes of ten percent ($\delta = 0.1$). The change in variable response is shown in Table A.2.

Table A.1: 10% Change in values of Israeli program test numbers

	Construction (C)	$C+\delta C$	Operation (O)	$O+\delta O$	Knowledge (S_p)
Mining/Milling	5	5.5	3	3.3	1.2
Conversion	3	3.3	3	3.3	1.3
Fuel Fab.	2	2.2	2	2.2	1.2
Irradiation	5	5.5	5	5.5	1.3
PUREX	4	4.4	3	3.3	1.2
Heavy Water	2	2.2	2	2.2	1.2

	Weaponization (W)	$W+\delta W$	Knowledge (S_w)	$S_w+\delta S_w$	$S_p+\delta S_p$ 1.32
Design	3.0	3.3	1.2	1.32	1.43
Metallurgy	1.0	1.1	1.1	1.21	1.32
Fuzing	1.0	1.1	1.1	1.21	1.43
Initiation	1.0	1.1	1.1	1.21	1.32
Compression	1.5	1.65	1.1	1.21	1.32
Industry (I)	2.50	$I+\delta I$	2.75		
Rate (R)	0.81	$R+\delta R$	0.89		

Table A.2: Changes in time T for given value adjustments

	Calculated Time (T)	Change in T	Percent Change
Original	12.33	--	--
$C+\delta C$	12.88	0.55	4.46%
$O+\delta O$	12.80	0.47	3.81%
$S_p+\delta S_p$	11.41	-0.93	-7.52%
$W+\delta W$	12.55	0.21	1.73%
$S_w+\delta S_w$	12.14	-0.19	-1.57%
$I+\delta I$	11.21	-1.12	-9.09%
$R+\delta R$	13.57	1.23	10.00%

The construction (C) and operation (O) constants are set fairly rigorously and there is a low level of change from adjusting this value. The same is true for the weaponization (W) constants. However, the effects from the process knowledge (S_p), industry (I) and rate (R) values are much more pronounced. This is not terribly unreasonable or unexpected, as these three elements are the primary determinations for the rate that a program can be assembled. This analysis does place some additional level of emphasis on the need to better streamline the process for assigning these coefficients.

Because the rate values are the most sensitive, an effort was made to reexamine the pursuit rates of the de facto states. This reevaluation is shown in Table A.3, where a slight change in the rate values is made to demonstrate the change between the calculated and programmed completion times. Because the programmed completion time values are rounded to the nearest year, the accuracy of the newly recalculated rate values is questionable, but the methodology points to a way of reevaluating all of the data in this study in the future.

Table A.3: Rate value reevaluation

	Assigned	Time to Completion		Recalculated
	Rate	Programmed	Calculated	Rate
DPRK	1.13	24	24.1	**1.13**
India	0.80	10	10.8	**0.74**
Israel	0.81	12	12.3	**0.79**
Pakistan	0.82	18	18.6	**0.79**
S. Africa	0.80	7	7.07	**0.79**