Science and Global Security, 14:163–182, 2006
Copyright © Taylor & Francis Group, LLC
ISSN: 0892-9882 print / 1547-7800 online
DOI: 10.1080/08929880600993105

Anatomy of a Project to Produce a First Nuclear Weapon

Robert Harney,[1] Gerald Brown,[2] Matthew Carlyle,[2]
Eric Skroch,[2] and Kevin Wood[2]

[1]Department of Systems Engineering, Naval Postgraduate School, Monterey, CA, USA
[2]Operations Research Department, Naval Postgraduate School, Monterey, CA, USA

We describe the industrial project that a "proliferator" would conduct to produce a first, small batch of nuclear weapons. From refining yellowcake ore to final weapons assembly, we highlight the project's tasks and their interactions. The proliferator can choose alternative production technologies that offer quicker completion, but at higher cost in terms of limited resources. The proliferator can also expedite his project by devoting more resources to critical tasks. From physics and chemistry, we determine raw material requirements. From industrial engineering and materials science, we convert these requirements into estimates of the time, manpower, energy, and money required to complete each task under normal and expedited conditions. Using generalized project-management analysis tools, we then estimate the earliest possible completion time of the project, assuming two different levels of resource availability. We also estimate the time required to complete a weapon if some of the project's steps can be skipped; for example, if the proliferator acquires stolen, highly enriched uranium metal.

INTRODUCTION

This article documents the component tasks of a major industrial project that a "proliferator" must complete, or may need to complete, to produce "a first nuclear weapon." By this last phrase, we mean a first small batch of crude nuclear weapons. We integrate details from physics, chemistry, industrial engineering, and materials science to create a generalized critical-path network model of the project.[1] We also derive estimates of raw-material, manpower, energy, and

---

Received 30 January 2006; accepted 15 March 2006.
For sustained research support, the authors thank the Air Force Office of Scientific Research, and the Office of Naval Research.

Address correspondence to Robert C. Harney, Associate Professor, Department of Systems Engineering, Naval Postgraduate School, Monterey, CA 93943, USA. E-mail: harney@nps.edu

time requirements for task completions under normal or expedited conditions. With this information and the model, we then show how to estimate the earliest possible completion time for such a project given different assumed levels of resources. An extended model in a follow-on article[2] shows how one might delay the project's overall completion time by disrupting certain tasks through, for example, embargoes on key materials. The current article should provide policymakers with a sound quantitative basis for devising technologically oriented policies regarding nonproliferation.[3]

The details of the proliferator's nuclear-weapons program depend on too many factors to consider in a single article, so we make the following simplifying assumptions in a case study: (a) The program is covert, (b) the proliferator already produces yellowcake uranium for use in civilian reactors or for sale to others, (c) he will pursue a simple fission weapon, and (d) he has signed the Non-Proliferation Treaty (NPT).

A nuclear-weapons program is complex, but the basics of nuclear-weapon design are now well known and publicly available:[4] The acquisition of weapons-grade uranium or plutonium is the proliferator's main hurdle to creating a nuclear weapon, not theoretical physics. But, (a) neither uranium nor plutonium are available on the open market, (b) NPT inspections preclude the reprocessing of spent nuclear fuel into weapons-grade plutonium, and (c) we shall initially assume that stolen materials are unavailable. Consequently, the key to creating a nuclear weapon covertly will be the proliferator's development of an organic manufacturing infrastructure for weapons-grade uranium and/or plutonium. A plutonium-based weapon would require the covert construction of a nuclear reactor, and plutonium is difficult to handle, so it is reasonable to assume that the proliferator would choose a simpler, uranium-based weapon. Yellowcake uranium oxide, diverted from civilian use, will constitute the raw material. (For context, see Spears[5] who traces the lifecycle of nuclear materials from raw ore to waste disposal.)

Yellowcake can be diverted from civilian use even if the proliferator does not operate a nuclear fuel cycle. For example, controlling a uranium mine suffices because yellowcake can be diverted from the ore-processing facilities near such a mine. More than 30 countries have proven uranium reserves, and surely others have uranium-ore deposits that have not been discovered, or at least not reported. Uranium oxide can also be extracted from certain ores that are sold in international commerce for their scandium, vanadium, or other metal content. This offers another means to obtain yellowcake, or a substitute for it, without operating a nuclear fuel cycle.

The proliferator will need to commit a great deal of material, manpower, and technology to all parts of his nuclear-weapons project, from constructing manufacturing infrastructure for uranium metal, to the acquisition of a weapons-delivery method, for example ballistic missiles. Managing such a complex and expensive project is difficult without some sort of project-management protocol, especially if the project is to remain covert. Since the late 1950s, governments and industry have widely employed techniques of operations research to the scheduling and coordination of complex projects. In particular, the basic methods of the Program Evaluation Review Technique/Critical Path Method (PERT/CPM) have been extended over the years to manage the complexities that arise in real-world projects.[6]

Moder, Phillips, and Davis define a *project* as "a set of tasks or activities related to the achievement of some planned objective, normally where the objective is unique or non-repetitive."[7] The proliferator's program to develop a first nuclear weapon fits this definition well. We can therefore reasonably expect him to employ standard project-management tools such as Microsoft Project to plan, organize, and schedule the project's tasks efficiently.[8] In any case, we will use these tools to estimate the project's completion time, and should the proliferator choose to act suboptimally by not using such tools, the resulting estimate will be appropriately conservative for our purposes. That is, the project will take longer to complete than we estimate.

Project-management models are universally represented as networks. In the now-standard *activity-on-node* version of a project network, *nodes* represent important (sub)tasks that must be completed to finish the project, whereas *arcs* represent precedence relationships between tasks. In the basic model, a task-i node is connected to a task-j node with a directed arc (i, j) if task i must be completed before task j is begun. Each node i possesses a "length" that represents task i's nominal duration; arcs have zero length. The overall duration of the project, from an artificial "start task" to an artificial "finish task," is the total length of the longest, directed path through the network, also known as the *critical path*.

We must generalize the basic project model, as follows:

1. Completion of any task in a "normal" amount of time consumes a fixed amount of one or more resources that are in limited supply.[9] In particular, we model consumption of energy, raw materials, and three types of manpower, and through these, the consumption of money.
2. The duration of an individual task may be expedited, that is, shortened, by allocation of additional quantities of required resources.[10,11] We assume a linear relationship between the amount of each additional resource provided and the duration of the task: More resources accelerate progress. However, each task requires some minimum amount of time to complete, below which additional resources have no effect.
3. When one or more tasks are expedited to minimize project completion time, the project has been "crashed." Crashing is limited by resource availability, including a monetary budget.

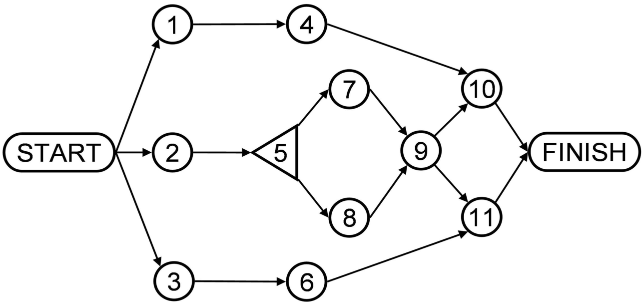

Figure 1: An activity-on-node project network with one decision node. Tasks represented by nodes 1 through 6, and 9 through 11, must be completed to complete the project. A triangular node represents a "decision task"[14]: After Task 5 is complete, either Task 7 or Task 8 must be completed. Arcs represent precedence relationships.

4. Standard finish-to-start (FS) precedence relationships between pairs of tasks are generalized to include start-to-start (SS), finish-to-finish (FF), or start-to-finish (SF). Given this generality, it is easy to accommodate a lag- or lead-time between pairs of tasks.[12]

5. Certain milestone events, most importantly the stockpiling of adequate supplies of highly enriched uranium metal (HEU), can be achieved via alternative courses of action. When one such alternative is chosen, the tasks in the other alternative(s) need not be completed. Alternative courses of action diverge at *decision nodes*;[13] see Figure 1. In our case study, the decision node chooses one of three uranium-enrichment technologies.

Within the limits of his resources, the proliferator wishes to minimize the completion time of his weapons project, that is, crash the project, by expediting "critical tasks" (i.e., tasks on the critical path), and tasks that become critical as other task durations are reduced.

ASSUMPTIONS

Given the proliferator's goal of completing a first weapon as soon as possible, we assume he will pursue a gun-type fission weapon, the same design used in the "Little Boy" bomb dropped on Hiroshima, Japan in 1945. That design is simple but reliable: Little Boy was relatively crude, but its designers were so confident that Hiroshima was its first full-scale test.[15] The gun-type weapon requires more HEU than the alternative, an implosion weapon, but the latter design would require high-visibility, high-energy testing to ensure its reliability and it seems likely that a covert proliferator would prefer to avoid such testing.

"The first nuclear weapon" will really be a small number of weapons, the most that can be manufactured without undue risk of detection. We assume a production of six weapons per year, which we estimate will require an annual input of 300 kilograms (kg) of HEU. In turn, this will require the inputs estimated by the chemistry of Appendices A and B, which include about 120 metric tons of yellowcake each year.

The main tasks in the project are:

1. Covert diversion of 120 metric tons of yellowcake annually (this quantity amounts to only one medium truckload per month, is likely to go undetected, and is the key reason for assuming a production of at most six weapons per year);
2. Production of enrichment-plant feed material (uranium hexafluoride, UF_6) from yellowcake;
3. Uranium enrichment, including the choice of method to employ;
4. Conversion of highly enriched UF_6 to HEU metal; and
5. Design and construction of the actual weapons.

Appendix C displays the tasks included in our case study, and the Gantt chart in Figure 2 shows a small part of a complete production plan from that study.

We assess the requirements for specialized equipment from the chemical processes described in Appendix A. The project network comprises

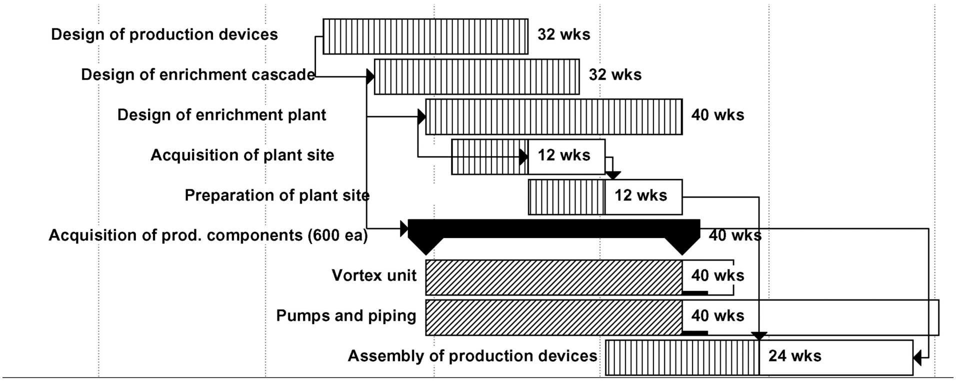

Figure 2: Gantt chart, from Microsoft Project, depicting 9 out of about 200 tasks in the case-study project. (Created using Microsoft Project.) The solid horizontal bar for "Acquisition of production components" indicates a summary task. (A "summary task" is a feature of Microsoft Project, not a fundamental component of a standard project network.) This summary task comprises two (sub)tasks, the acquisition of a "Vortex unit" and of "Pumps and piping." The "forward" hashing on their corresponding bars indicates that they do not lie on the critical path. The task "Acquisition of plant site" is represented by two adjacent bars. The first bars "backward" hashing indicates that this task is critical, and its left and right endpoints represent the tasks planned, expedited start and completion dates, respectively. The tasks planned duration of 12 weeks is displayed to the right of the first bar. The second bars vertical hashing signals that the task has been expedited by an amount proportional to the bars length, which also happens to be 12 weeks. (The nominal, unexpedited duration of this task is 24 weeks.) The figure uses arrows to indicate precedence relationships between tasks. For example, there is an "SS" (start-to-start) relationship, including an 8-week lag, between "Design of production devices" and "Design of enrichment cascade."

Table 1: Efficiency of uranium-enrichment technologies.

Technology	Separation factor	Number of stages for 90% HEU	kWh/SWU	Kilowatts for 60,000 SWU/Yr
Gaseous diffusion	1.0040–1.0045	3,500–4,000	2,500	17,120
Gas centrifuge	1.2–1.5	40–90	100–200	685–1,370
Aerodynamic	1.015–1.030	540–1100	3,600–4,000	24,660–27,400

Regardless of the technology used, producing HEU from natural uranium requires multiple equipment stages arranged in a progressive enrichment cascade. The *separation factor* is the ratio of the relative enrichment (U_{235} to U_{238}) of the concentrated product to that of the depleted tails in the output of any single stage of the cascade. The number of stages required to produce HEU assumes the final tails contain less than 0.3% U_{235}. "kWh per SWU" measures the kilowatt-hours of energy required to produce approximately 5 grams of HEU. The final column gives the average power consumption (rate) of an enrichment cascade producing about 300 kg of HEU a year. Source: U.S. Congress, Office of Technology Assessment (OTA), 1993. "Technologies Underlying Weapons of Mass Destruction," OTA-BP-ISC-115, U.S. Government Printing Office, December, p. 143.

approximately 200 tasks (nodes) and 600 precedence relationships (arcs). The proliferator must manage five key resources in addition to money: energy, materials, professional labor (e.g., scientists and engineers), skilled labor (e.g., machinists), and unskilled labor.

If the proliferator chooses to expedite a given task, he must expend more of each resource required for that task. The amount of resource r consumed, given task duration T, is assumed to be $b_r(1 + (a_r - 1)(\bar{T} - T)/(\bar{T} - \underline{T}))$, where $\bar{T}$ denotes the task's nominal duration, $\underline{T}$ denotes its minimum duration, T must satisfy $\underline{T} \leq T \leq \bar{T}$, b_r is the nominal consumption of that resource (i.e., when the task's duration is $\bar{T}$), and a_r is an "acceleration factor" that depends only on the resource. See Appendix C for the values of $\bar{T}$ and $\underline{T}$ used in the case study; Table 2 lists the acceleration factors.

The proliferator can choose one of any number of enrichment technologies to pursue: In our case study his options are gas centrifuges, gaseous diffusion, or aerodynamic enrichment. Other enrichment technologies exist, but they are expensive and/or technically demanding, and therefore seem unlikely options.[16] However, any optional enrichment technique can be modeled with our methods. Table 1 shows how to estimate the required number of enrichment machines

Table 2: Acceleration factors for the five non-monetary resources tracked in our case study.

Resource	Acceleration Factor
Energy	2.0
Professional labor	1.2
Skilled labor	1.5
Unskilled labor	2.0
Materials	1.2

Each value is a multiplicative factor on total resource consumption for the fastest possible completion time of any task. For example, if 10 professional laborers are needed to complete a task its nominal time $\bar{T}$, then it would require 12 professional laborers ($12 = 1.2 \times 10$) to complete the task in the shortest possible time $\underline{T}$.

Table 3: National cost and availability of resources in our case study. The project is further constrained by a budget of $190 million.

Name	Units	Unit cost ($/Unit)	Units available
Energy	MWhr	100	3,100,000
Materials	$K	1,000	190,000
Professional labor	Mmo	48,000	10,000
Skilled labor	Mmo	24,000	10,000
Unskilled labor	Mmo	6,000	6,000

MWhr = megawatt-hours. Mmo = man-months

and the energy consumption for each technology. A separative work unit (SWU) measures the effort required to separate U_{235} and U_{238} isotopes during enrichment. Production of 1 kg of HEU from natural uranium requires approximately 200 SWUs, and therefore anywhere from 570 to 23,000 kilowatts of power, depending on the technology used.[17] Appendix C lists case-study data, including nominal costs.

RESULTS AND CONCLUSIONS

Using the amounts of energy, materials, manpower, and labor listed in Table 3, and a budget of $190 million, the proliferator uses aerodynamic enrichment to complete his project in 338 weeks (six and a half years).

If all resource availability is doubled, including that for dollars, crashing allows the proliferator to complete the project in 260 weeks (just under 5 years).

If we relax our initial assumption that stolen HEU is unavailable, and suppose the proliferator obtains 300 kg of stolen HEU directly from a third party, we have a scenario viewed by some as nearly equivalent to having a deliverable weapon.[18] Our model, appropriately modified and using nominal resource levels, shows that the proliferator will still need 208 weeks (4 years) to complete a first batch of 6 weapons. (With no organic source of HEU, that may also be the only batch of weapons he will ever be able to produce.) If the proliferator has access to unenriched uranium hexafluoride (UF_6), and has also developed a prototypic gas-centrifuge process (as Iran has), the model predicts that he will remain committed to gas-centrifuge enrichment, and will need an additional 216 weeks to complete his first weapon.

Even with 300 kg of HEU, the proliferator could be delayed in completing his project by limiting access to certain manufacturing components. “Acquire hafnia crucibles,” task 127, is not a critical task—we estimate 24 weeks of slack here—but if we could delay this task in excess of 24 weeks, by any means, then we could delay a finished weapon by that excess. Furthermore, an instance of this task occurs in all alternative enrichment technologies, so the proliferator cannot avoid this delay by switching technologies.

The International Atomic Energy Agency[19] has recently declared that more than 40 countries do not fully comply with the NPT, and lists several nations that are capable of, or are suspected of engaging in, nuclear-weapons development. This article has shown how any one of them could proceed in this development.

NOTES AND REFERENCES

1. Chapter 1 of this book provides a good overview of this topic: J. J. Moder, C. R. Phillips, and E. W. Davis, *Project Management with CPM, PERT and Precedence Diagramming*, 3rd ed. (Van Nostrand Reinhold Company Inc., New York, 1983)

2. G. Brown, M. Carlyle, R. Harney, E. Skroch, and K. Wood, 2006. "Interdicting a nuclear weapons project," Technical Report NPS-OR-06-003, Naval Postgraduate School, Monterey, CA.

3. We find many books, papers, and reports that promote technology-based policies for nonproliferation, but, typically, the analysis of that technology is limited. For example, see: G. Perkovich, J. T. Mathews, J. Cirincione, R. Gottemoeller, and J. Wolfsthal, *Universal Compliance: A Strategy for Nuclear Security* (Carnegie Endowment for International Peace, 2005), J. Spector, "Strategic Planning for U.S. Nonproliferation Initiatives in Russia," in Occasional Paper No. 6, *WMD Threats 2001: Critical Choices for the Bush Administration*, M. Marletta, ed. (Monterey Institute of International Studies, 2001) 38–40; Counterproliferation Program Review Committee, 1997. "Report on Activities and Programs for Countering Proliferation and NBC Terrorism," Report Number A468823, U.S. Congress, Washington, DC, May.

4. In fact, many of the details from the early weapons programs in the United States and elsewhere have been declassified and appear in the open literature; see: U.S. Department of Energy, Office of Declassification, 2001. "Restricted Data Declassification Decisions 1946 to the Present," (RDD-7), January 1, 2001.

5. D. Spears, ed., "Technology R&D for arms control," *Arms Control and Nonproliferation Technologies* (Lawrence Livermore National Laboratory, Spring 2001).

6. D. G. Malcolm, J. H. Roseboom, C. E. Clark, and W. Fazar, "Application of a technique for research and development program evaluation," *Operations Research*, 7 (1959): 646–669.

7. Moder, Phillips, and Davis, *op. cit.*, 3.

8. Microsoft Corporation, 2004. "Microsoft Office." http://office.microsoft.com/home/office.aspx?assetid=FX01085795, 10 February, 2004.

9. D. G. Malcolm, J. H. Roseboom, C. E. Clark, and W. Fazar, *op. cit.*

10. See this article and its references: J. E. Kelley, Jr., "Critical path planning and scheduling: Mathematical basis," *Operations Research*, 9 (1961): 296–320.

11. A. Charnes and W. W. Cooper, "A network interpretation and a directed subdual algorithm for critical path scheduling," *Journal of Industrial Engineering*, 13 (1961): 213–218.

12. Early work on project networks required that a "successor task" not begin until after all its "predecessor tasks" had been completed; for example, see: D. G. Malcolm, J. H. Roseboom, C. E. Clark, and W. Fazar, *op. cit.* This was later generalized in a model called "precedence diagramming" that permits every combination of pairwise partial

orders between the start or finish of a predecessor-task and those of a successor-task; for example, see: Moder, Phillips, and Davis 1983, *op. cit.*, chapter 4.

13. W. Crowston and G. L. Thompson, "Decision CPM: A method for simultaneous planning, scheduling, and control of projects," *Operations Research*, 15 (1967): 407–426.

14. *Ibid.*

15. For example, see: R. Rhodes, *The Making of the Atomic Bomb* (Simon & Schuster Inc., New York, 1986) and R. Rhodes, *Dark Sun: The Making of the Hydrogen Bomb* (Simon & Schuster Inc., New York, 1995).

16. M. Benedict, T. H. Pigford, and H. W. Levi, *Nuclear Chemical Engineering*, 2nd ed. (McGraw Hill, Boston, MA, 1985) chapter 14.

17. Nonproliferation Policy Education Center (NPEC), "Iran: Breaking Out Without Quite Breaking the Rules?" http://www.npec-web.org/projects/iranswu2.htm, 30 April 2004.

18. For example, see: C. D. Ferguson, 2004, "Can Bush or Kerry prevent nuclear terrorism," *Arms Control Today*, 34 (7): 13, 3 pgs.

19. International Atomic Energy Agency, 2004. Annual Report, http://www.iaea.org/Publications/Reports/Anrep2003/index.html, 6 October, 2004.

APPENDIX A. URANIUM-ENRICHMENT CHEMISTRY

We study these chemical processes to deduce the facilities and equipment required to produce enriched uranium metal from yellowcake. The numbers beneath the chemical reaction formulas are molecular weights.

Source: For example, see M. Benedict, T. Pigford, and H. Levi, 1981. *Nuclear Chemical Engineering*, 2nd ed. (McGraw-Hill, New York), 129–160.

Feedstock Preparation (Yellowcake to Uranium Hexafluoride)

Stainless steel vessel (dissolution of yellowcake in nitric acid):

$$U_3O_8 + 6HNO_3 \rightarrow 3UO_2(NO_3)_2 + 2H_2O + H_2$$

$$842 + 6 \times 63 = 3 \times 394 + 2 \times 18 + 2$$

Stainless steel boiler (boil down of nitrate solution):

$$UO_2(NO_3)_2 + 6H_2O \xrightarrow{\text{boil}} UO_2(NO_3)_2^{*}6H_2O$$

$$394 + 6 \times 18 = 502$$

High-temperature stainless steel boiler (thermal decomposition of nitrate into uranium trioxide):

$$UO_2(NO_3)^{2^*}6H_2O \xrightarrow{300^\circ C} UO_3 + 6H_2O + 2NO_x$$

$$502 = 286 + 6 \times 18 + 108$$

Gas-solid reactor vessel (reduction of uranium trioxide to uranium dioxide):

$$UO_3 + H_2 \xrightarrow{650^\circ\text{—}800^\circ C} UO_2 + H_2O \quad \text{or} \quad 3UO_3 + 2NH_3$$

$$\xrightarrow{650^\circ\text{—}800^\circ C} 3UO_2 + N_2 + 3H_2O$$

$$286 + 2 = 270 + 18 \quad \text{or} \quad 3 \times 286 + 2 \times 17 = 3 \times 270 + 28 + 3 \times 18$$

Stainless steel reaction vessel (use hydrogen fluoride to convert uranium dioxide into uranium tetrafluoride):

$$UO_2 + 4HF \xrightarrow{300^\circ\text{—}500^\circ C} UF_4 + 2H_2O$$

$$270 + 4 \times 20 = 314 + 2 \times 18$$

Ultrahigh-temperature gas-solid reactor vessel (production of uranium hexafluoride gas):

$$UF_4 + F_2 \xrightarrow{1700^\circ\text{—}1800^\circ C} UF_6$$

$$314 + 38 = 352$$

Conversion of Uranium Hexafluoride to Uranium metal

Gas-phase reactor with particulate separation; uranium hexafluoride to uranium fluoride solid:

$$UF_6 + H_2 \xrightarrow{375^\circ C} UF_4 + 2HF$$

$$352 + 2 = 314 + 2 \times 20$$

High-temperature metallurgical furnace; uranium fluoride to liquid uranium to be cast into weapon components:

$$UF_4 + 2Ca \xrightarrow{\text{low heat}} U + 2CaF_2 \quad \text{or} \quad UF_4 + 2Mg \xrightarrow{550^\circ\text{—}700^\circ C} U + 2MgF_2$$

$$314 + 2 \times 40 = 238 + 2 \times 78 \quad \text{or} \quad 314 + 2 \times 24.3 = 238 + 2 \times 62.3$$

APPENDIX B. CALCULATION OF RAW-MATERIAL REQUIREMENTS FOR SIX GUN-TYPE FISSION WEAPONS

This appendix assesses the quantity of key raw materials required to produce six fission weapons, each of which requires 50 kg of HEU. Theoretical requirements are computed from the chemical reactions and molecular weights specified in Appendix A. We show inputs needed to create one kilogram of each intermediate material or one kilogram of the final HEU metal. The reader can then easily compute the theoretical requirements to manufacture the full 300 kg of HEU. However, our final values multiply the theoretical requirements by 1.5 to account for imperfect conversions in real-world industrial processes.

Source: the authors.

1 kg of UNH(uranyl nitrate hexahydrate) requires 0.559 kg yellowcake and 0.251 kg HNO_3

1 kg UO_3 requires 1.755 kg of UNH

1 kg UO_2 requires 1.059 kg$UO_3$and 0.0074 kg H_2

(hydrogen is ubiquitous, so we do not computed its final consumption)

1 kg UF_4 requires 0.860 kg $UO_2$and 0.255 kg HF

1 kg UF_6 requires 0.892 kg UF_4 and 0.108 kg F_2

1 kg $HEUF_6$ requires 232 kg UF_6

1 kg $HEUF_4$ requires 1.122 kg $HEUF_6$ and 0.0064 kg H_2

1 kg HEU metal requires 1.302 kg $HEUF_4$, and 0.336 kg Ca or 0.204 kg Mg

Each weapon requires 50 kg 93% HEU metal, so six weapons require 300 kg HEU metal.

Using the theoretical conversion listed earlier, and multiplying by 1.5 to account for imperfect production processes, we estimate that 300 kg HEU requires:

120,000 kg yellowcake

54,000 kg HNO_3

35,000 kg HF

16,500 kg F_2

150 kg Ca or 90 kg Mg

These numbers are assumed when making the estimates in Appendix C.

APPENDIX C. TASKS INVOLVED IN A NUCLEAR WEAPONS PROGRAM

The data described here reflect standard engineering analyses, and are based on one author's experience in weapon-systems development and production. However, we have made no attempt to obtain actual costs from vendors or to extract detailed development-and-production data from specific programs; such data would almost certainly be classified or proprietary. Consequently, individual cost estimates may be accurate only to within a factor of two, up or down.

A bold task name indicates a summary task, which is feature of Microsoft Project, not a standard component of a project network. (Note: For technical reasons, summary tasks are split into “summary-task start” and “summary-task finish.”) “Task” 28 is the decision node: Exactly one course of action must be chosen at this point. A component name by itself, for example, “Stainless steel boiler,” implies that the corresponding task is “acquire this component.” Column 1 gives task identifier or “ID”; column 2 gives the task’s name; column 3 is a “Code” not used in this article; column 4 gives the nominal task duration in weeks (wks); column 5 gives the minimum task duration if additional resources are applied; column 6 gives the task’s direct predecessors, which must be completed before the task can commence (“FS,” “FF,” and “SS” denote finish-to-start, finish-to-finish and start-to-start precedence relationships, respectively. Each such relationship can have a lead (−) or lag (+), measured in weeks, associated with it. For instance “7SS + 24” in row 9 indicates that task 8 cannot begin until 24 weeks after task 7 begins); column 7 specifies the energy, in megawatt-hours (MWhr), required to complete the task; column 8 specifies the millions of dollars ($M) in materials required to complete the task; column 9 gives the man-months (mm) of professional labor required to complete the project; columns 10 and 11 are similar, but for skilled labor and unskilled labor, respectively.

Tasks involved in a nuclear weapons program.

ID	Name	Code	Normal duration (wks)	Crashed duration (wks)	Predecessors	Energy (MWhr)	Materials ($M)	Professional labor (mm)	Skilled labor (mm)	Unskilled labor (mm)
1_s	**Nuclear Weapons Program [start]** (tasks 2_s–177_f)	—	—	—	None	—	—	—	—	—
2_s	**Diversion of commercial yellowcake [start]** (tasks 3–5)	—	1_s	—	—	—	—	—	—	—
3	Design yellowcake plant modifications	Fb	48	24	2_s	2.4	0.01	6	6	—
4	Modify yellowcake plant	Fc	48	24	3	—	0.1	6	6	12
5	Divert yellowcake	Lc	120	60	4	—	45	48	48	—
2_f	**Diversion of commercial yellowcake [finish]**	—	—	—	5	—	—	—	—	—
6_s	**Produce enrichment plant feed material [start] (uranium hexafluoride, UF6, tasks 7–10,25,26)**	—	—	—	1_s	—	—	—	—	—
7	Design fluoridation plant (FP)	Ib	80	40	6_s	20	0.13	50	50	—
8	Acquire FP site	Ca	24	12	7SS + 24	0.6	0.15	3	—	—
9	Prepare FP site (internal modifications)	Cc	24	12	8	6.6	0.07	3	15	15
6_s	**Produce enrichment plant feed material [finish]**	—	—	—	1_s					
10_s	**Acquire FP components [start] (tasks 11–24)**	—	—	—	7SS + 12	—	—	—	—	—
11	Stainless steel mixing vessel	Ha	72	36	10_s	1.8	0.03	—	9	—
12	Distilled water system	Ha	72	36	10_s	1.8	0.03	—	9	—
13	Nitric acid storage tank	Ha	72	36	10_s	1.8	0.1	—	9	—
14	Stainless steel boiler	Ha	72	36	10_s	1.8	0.1	—	9	—
15	Thermal decomposition vessel	Ha	72	36	10_s	1.8	0.25	—	9	—
16	Drying kiln	Ha	72	36	10_s	1.8	0.05	—	9	—
17	Gas/solid high-temperature reaction vessel	Ha	72	36	10_s	1.8	0.5	—	9	—
18	Hydrogen gas (or ammonia) storage tank	Ha	72	36	10_s	1.8	0.01	—	9	—
19	Stainless steel reaction vessel	Ha	72	36	10_s	1.8	0.5	—	9	—
20	Hydrogen fluoride storage tank	Ha	72	36	10_s	1.8	0.2	—	9	—
21	Gas/solid ultrahigh temperature reaction vessel	Ha	72	36	10_s	1.8	0.5	—	9	—
22	Fluorine storage tank	Ha	72	36	10_s	1.8	0.15	—	9	—
23	Hexafluoride condensing vessel	Ha	72	36	10_s	1.8	0.1	—	9	—
24	Pumps and piping	Ha	72	36	10_s	1.8	0.1	—	9	—
10_f	**Acquire FP components [finish]**	—	—		11–24	—	—	—	—	—
25	Assemble and integrate FP	Fb	48	24	9, 10FF + 12	27.6	—	18	30	90
26	Operate FP	Lc	120	60	5SS + 0, 25	590	4.0	42	240	—
6_f	**Produce enrichment plant feed material [finish]**	—	—	—	10_f, 26	—		—	—	—

(Continued on next page)

Tasks involved in a nuclear weapons program. *(Continued)*

ID	Name	Code	Normal duration (wks)	Crashed duration (wks)	Predecessors	Energy (MWhr)	Materials ($M)	Professional labor (mm)	Skilled labor (mm)	Unskilled labor (mm)
27_s	**Enrich uranium [start] (some subset of tasks 28--89)**	—	—	—	1_s	—	—	—	—	—
28	*Choose enrichment process* (decision node)	—	0	0	27_s	—	—	—	—	—
29_s	**Gas centrifuge enrich-ment process (CP) [start] (tasks 30–53)**	—	—	—	28	—	—	—	—	—
30	Design basic GC	Fb	48	24	29_s	13.2	0.2	36	30	—
31_s	**Acquire research components for CP [start] (5 ea, tasks 32–37)**	—	—	—	30SS + 12	—	—	—	—	—
32	Rotor tubes	Fa	48	24	31	2.4	0.08	6	6	—
33	Air bearing systems	Ea	40	20	31	1	0.08	—	5	—
34	Motors	Ea	40	20	31	1	0.03	—	5	—
35	End caps	Ca	24	12	31	0.6	0.03	—	3	—
36	Centrifuge cases	Ca	24	12	31	0.6	0.05	—	3	—
37	Pumps and piping	Ca	24	12	31	0.6	0.05	—	3	—
31_f	**Acquire research components for CP [finish]**	—	—	—	32–37	—	—	—	—	—
38	Assemble research centrifuges	Cb	24	12	29_sSS, 31_f	9.6	0.1	18	30	—
39	Test and evaluate research centrifuges	Cb	24	12	38	9.6	0.1	18	30	—
40	Design production centrifuges	Db	32	16	29_sSS, 39FS−4	8.8	0.07	24	20	—
41	Design enrichment cascade	Db	32	16	40SS + 8	12.8	0.07	24	40	—
42	Design enrichment plant (EP)	Eb	40	20	41SS + 8	16	0.08	30	50	—
43	Acquire EP site	Ca	24	12	42SS + 4	0.6	2.5	3	—	—
44	Prepare EP site	Cc	24	12	43	13.2	0.3	3	30	30
45_s	**Acquire production CP components [start] (1000 ea, tasks 46–51)**	—	—	—	41SS + 8	—	—	—	—	—
46	Rotor tubes	Ja	96	48	45_s	4.8	4.8	12	12	—
47	Air bearing systems	Ja	96	48	45_s	2.4	1.6	—	12	—
48	Motors	Ja	96	48	45_s	2.4	1.6	—	12	—
49	End caps	Ia	80	40	45_s	2.4	1.6	—	12	—
50	Centrifuge cases	Ia	80	40	45_s	2.4	3.2	—	12	—
51	Pumps and piping	Ia	80	40	45_s	2.4	3.2	—	12	—
45_f	**Acquire production CP components [finish]**	—	—	—	46–51	—	—	—	—	—
52	Assemble production centrifuges	Fb	48	24	29_sSS, 44, 45_fFF + 8	315	—	42	1536	—
53	Integrate centrifuges	Db	32	16	52SS + 8	44	—	20	200	—
54	Cascade loading	Kb	112	56	26SS + 8, 52, 53	65	—	54	288	—
55	Produce enriched and depleted material	Cc	24	12	54	45,000	—	54	432	—
29_f	**Gas centrifuge enrichment process (CP) [finish]**	—	—	—	55, 45_f, 44, 42, 41, 40,31_f	—	—	—	—	—

Tasks involved in a nuclear weapons program.

ID	Name	Code	Normal duration (wks)	Crashed duration (wks)	Predecessors	Energy (MWhr)	Materials ($M)	Professional labor (mm)	Skilled labor (mm)	Unskilled labor (mm)
56_s	**Gas-diffusion enrichment process (DP) [start] (tasks 57–76)**	—	0	0	28	—	—	—	—	—
57	Design basic DP system	Fb	48	24	56_s	13.2	0.2	36	30	—
58_s	**Acquire research components for DP [start] (5 ea, tasks 59–61)**	—	—	—	57SS + 12	—	—	—	—	—
59	Diffusion barriers	Fa	48	24	58_s	2.4	0.05	6	6	—
60	Heat exchangers	Ea	40	20	58_s	1	0.03	—	5	—
61	Pumps and piping	Ca	24	12	58_s	0.6	0.07	—	3	—
58_f	**Acquire research components for DP [finish]**	—	—	—	59–61	—	—	—	—	—
62	Assemble research devices	Cb	24	12	58_fFF, 56_s	9.6	0.1	18	30	—
63	Test and evaluate research devices	Cb	24	12	62	9.6	0.1	18	30	—
64	Design production gas-diffusion devices	Db	32	16	63FS–4	8.8	0.07	24	20	—
65	Design enrichment cascade	Db	32	16	64SS + 8	12.8	0.07	24	40	—
66	Design enrichment plant (EP)	Eb	40	20	65SS + 8	16	0.08	30	50	—
67	Acquire EP site	Ca	24	12	66SS + 4	0.6	5	3	—	—
68	Prepare EP site	Cc	24	12	67	13.2	0.55	3	30	30
69_s	**Acquire production components for DP [start] (4000 ea, tasks 70–72)**	—	—	—	65SS + 8	—	—	—	—	—
70	Diffusion barriers	Fa	48	24	69	2.4	40	6	6	—
71	Heat exchangers	Ea	40	20	69	1	20	—	5	—
72	Pumps and piping	Ca	24	12	69	0.8	60	—	4	—
69_f	**Acquire production components for DP [finish]**	—	—	—	70–72	—	—	—	—	—
73	Assemble production devices for DP	Fb	48	24	68, 69_fFF + 8	126	—	30	600	—
74	Integrate enrichment cascade	Db	32	16	73SS + 8	84	—	20	400	—
75	Cascade loading	Kb	112	56	26SS + 8, 73, 74	65	—	36	288	—
76	Produce enriched and depleted material	Cc	24	12	75	600,000	—	54	432	—
56_f	**Gas-diffusion enrichment process (DP) [finish]**	—	—	—	76,64–66, 58_f, 57	—	—	—	—	—
77_s	**Aerodynamic enrichment process (AP) [start] (tasks 78–95)**	—	0	0	28	—	—	—	—	—
78	Design basic AP enrichment device	Fb	48	24	77_s	13.2	0.2	36	30	—
79_s	**Acquire research components for AP [start] (5 ea, tasks 80–81)**	—	—	—	78SS + 12	—	—	—	—	—
80	Vortex unit	Fa	48	24	79_s	2.4	0.25	6	6	—
81	Pumps and piping	Ca	24	12	79_s	0.6	0.08	—	3	—
79_f	**Acquire research components for AP [finish]**	—	—	—	80, 81	—	—	—	—	—
82	Assemble research devices	Cb	24	12	79_f	9.6	0.1	18	30	—

(Continued on next page)

Tasks involved in a nuclear weapons program. *(Continued)*

ID	Name	Code	Normal duration (wks)	Crashed duration (wks)	Predecessors	Energy (MWhr)	Materials ($M)	Professional labor (mm)	Skilled labor (mm)	Unskilled labor (mm)
83	Test and evaluate research devices	Cb	24	12	82	9.6	0.1	18	30	—
84	Design production devices	Db	32	16	83FS–4	8.8	0.07	24	20	—
85	Design enrichment cascade	Db	32	16	84SS + 8	12.8	0.07	24	40	—
86	Design of enrichment plant (EP)	Eb	40	20	85SS + 8	16	0.08	30	50	—
87	Acquire EP site	Ca	24	12	86SS + 4	0.6	2	3	—	—
88	Prepare EP site	Cc	24	12	87	12.6	0.25	3	30	30
89_s	**Acquire production components for AP [start] (600 ea, tasks 90–91)**	—	—	—	85SS + 8	—	—	—	—	—
90	Vortex unit	Fa	48	24	89_s	2.4	30	6	6	—
91	Pumps and piping	Ia	80	40	89_s	1.2	9	—	6	—
89_f	**Acquire production components for AP [finish]**	—	—	—	90, 91	—	—	—	—	—
92	Assemble production devices	Fb	48	24	88, 89_fFF + 8	126	—	30	600	—
93	Integrate enrichment cascade	Db	32	16	92SS + 8	84	—	20	400	—
94	Cascade loading	Kb	112	56	26SS + 8, 92, 93	65	—	36	288	—
95	Produce enriched and depleted material	Cc	24	12	94	900,000	—	54	432	—
77_f	**Aerodynamic enrichment process (AP) [finish]**	—	—	—	93, 92, 84–86, 79_f, 78	—	—	—	—	—
27_f	**Enrich uranium [finish]**	—	—	—	28, 95	—	—	—	—	—
96_s	**Prepare uranium metal [start] (tasks 97–112)**	—	—	—	1_s	—	—	—	—	—
97	Design metal plant (MP)	Gb	56	28	96_S	19.6	0.12	28	70	—
98	Acquire MP site	Ca	24	12	97SS + 12	0.6	0.1	3	—	—
99	Prepare MP site	Cc	24	12	98	6.6	0.06	3	15	15
100_s	**Acquire metal plant components [start] (enriched metal, tasks 101–104)**	—	—	—	96_s	—	—	—	—	—
101	Gas-phase reactor with particulate collection	Fa	48	24	96_s	1.8	0.25	6	3	—
102	Hydrogen storage tank	Fa	48	24	96_s	0.6	0.001	—	3	—
103	Metallurgical furnace	Fa	48	24	96_s	0.6	0.1	—	3	—
104	Hafnia crucibles	Fa	48	24	96_s	0.6	0.03	—	3	—
100_f	**Acquire metal plant components, enriched metal [finish]**	—	—	—	101–104	—	—	—	—	—
105_s	**Acquire metal plant components, depleted metal [start] (tasks 104–109)**	—	—	—	96_s	—	—	—	—	—
106	Gas-phase reactor with particulate collection	Fa	48	24	105_s	0.6	0.25	—	3	—
107	Hydrogen storage tank	Fa	48	24	105_s	0.6	0.001	—	3	—

Tasks involved in a nuclear weapons program.

ID	Name	Code	Normal duration (wks)	Crashed duration (wks)	Predecessors	Energy (MWhr)	Materials ($M)	Professional labor (mm)	Skilled labor (mm)	Unskilled labor (mm)
108	Metallurgical furnace	Fa	48	24	105_s	0.6	0.1	—	3	—
109	Hafnia crucibles	Fa	48	24	105_s	0.6	0.03	—	3	—
105_f	**Acquire metal plant components, depleted metal [finish]**	—	—	—	106–109	—	—	—	—	—
110	Integrate components	Db	32	16	99, 100FF + 12, 105FF + 12	20.8	—	24	40	40
111	Produce natural uranium metal	Fc	48	24	110	80	0.01	6	18	—
112	Produce depleted/enriched uranium metal	Cc	24	12	27_fFF	160	0.02	12	36	—
96_f	**Prepare uranium metal [finish]**	—	—	—	97, 112	—	—	—	—	—
113_s	**Prepare nuclear explosive devices [start] (tasks 114s–196)**	—	—	—	1_s	—	—	—	—	—
114_s	**Design gun device components [start] (tasks 115–123)**	—	—	—	113_s	—	—	—	—	—
115	Gun	Fb	48	24	114_s	9.6	0.2	18	30	—
116	Propellant	Fb	48	24	114_s	3.6	0.03	6	12	—
117_s	**Critical core [start] (tasks 118–121)**	—	—	—	114_s	—	—	—	—	—
118	Fissionable receiver	Fb	48	24	117_s	9.6	0.07	18	30	—
119	Fissionable projectile	Fb	48	24	117_s	9.6	0.05	18	30	—
120	Tamper	Fb	48	24	117_s	9.6	0.05	18	30	—
121	Initiator	Fb	48	24	117_s	1.2	0.01	6	—	—
117_f	**Critical core [finish]**	—	—	—	118–121	—	—	—	—	—
122	Safety and arming devices	Fb	48	24	114_s	2.4	0.01	6	6	—
123	Fuse	Fb	48	24	114_s	2.4	0.01	6	6	—
114_f	**Design gun device components [finish]**	—	—	—	115, 116, 117_f, 122, 123	—	—	—	—	—
124	Design weapon assembly plant (AP)	Cb	24	12	114_f	12	0.07	30	30	—
125	Acquire AP site	Ba	16	8	124	0.6	0.8	3	—	—
126	Prepare AP site	Cc	24	12	125	6.6	0.15	3	15	15
127_s	**Acquire fabrication devices [start] (tasks 128–132)**	—	—	—	114_f	—	—	—	—	—
128	Large-diameter precision lathe	Fa	48	24	126FF + 12	2.4	0.1	6	6	—
129	Inert-gas environment precision milling machine	Fa	48	24	126FF + 12	1.2	0.25	—	6	—
130	Metallurgical furnace	Fa	48	24	126FF + 12	1.2	0.25	—	6	—
131	Hafnia crucibles	Fa	48	24	126FF + 12	1.2	0.05	—	6	—
132	Inert-gas environment casting system	Fa	48	24	126FF + 12	1.2	0.05	—	6	—

(Continued on next page)

Tasks involved in a nuclear weapons program. *(Continued)*

ID	Name	Code	Normal duration (wks)	Crashed duration (wks)	Predecessors	Energy (MWhr)	Materials ($M)	Professional labor (mm)	Skilled labor (mm)	Unskilled labor (mm)
127_f	**Acquire fabrication devices [finish]**	—	—	—	128–132	—	—	—	—	—
133_s	**Acquire research device components [start] (natural uranium prototype, tasks 134–138)**	—	—	—	114	—	—	—	—	—
134	High-strength steel cylinder	Ca	24	12	133_s	0.6	0.01	—	3	—
135	Double-base propellant powder	Ca	24	12	133_s	0.6	0.01	—	3	—
136	Polonium	Ca	24	12	133_s	0.6	0.05	—	3	—
137	Beryllium powder	Ca	24	12	133_s	0.6	0.01	—	3	—
138	Detonator and explosive train components	Ca	24	12	133_s	0.6	0.01	—	3	—
133_f	**Acquire research device components [finish] (natural uranium prototype)**	—	—	—	134–138	—	—	—	—	—
139_s	**Fabricate research device components [start] (natural uranium prototype, tasks 140–149)**	—	—	—	133_f,139_s	—	—	—	—	—
140	Gun barrel	Fc	48	24	128, 135, 139_s	3.6	—	9	9	—
141	Breech mechanism	Fc	48	24	128, 135, 139_s	1.8	—	—	9	—
142	Cast uranium components	Dc	32	16	111, 130, 139_s	16	—	—	6	—
143	Cast uranium tamper	Dc	32	16	111, 130, 139_s	16	—	—	6	—
144	Machine uranium receiver	Dc	32	16	129, 142FF + 8,139_s	1.2	—	—	6	—
145	Machine uranium projectile	Dc	32	16	129, 142FF + 8,139_s	1.2	—	—	6	—
146	Machine uranium tamper	Dc	32	16	129, 142FF + 8,139_s	1.2	—	—	6	—
147	Initiator	Dc	32	16	131, 136, 137, 139_s	2.4	—	6	6	—
148	Propellant charge	Dc	32	16	132, 135, 139_s	1.2	—	—	6	—
149	Detonator and explosive train	Db	32	16	138, 139_s	1.2	—	—	6	—
139_f	**Fabricate research device components [finish]**	—	—	—	140–149	—	—	—	—	—
150	Assemble research devices (natural uranium prototype)	Dc	32	16	133_fFF + 4, 139_fFF + 4	3.6	—	6	12	—
151_s	**Acquire research device components [start] (enriched uranium prototype, tasks 152--157)**	—	0	0	172	—	—	—	—	—
152	High-strength steel cylinder	Ca	24	12	151_s	0.6	0.01	—	3	—
153	Double-base propellant powder	Ca	24	12	151_s	0.6	0.01	—	3	—
154	Polonium	Ca	24	12	151_s	0.6	0.05	—	3	—
155	Beryllium powder	Ca	24	12	151_s	0.6	0.01	—	3	—
156	Detonator and explosive train components	Ca	24	12	151_s	0.6	0.01	—	3	—
151_f	**Acquire research device components [finish]**	—	—	—	152–156	—	—	—	—	—

Tasks involved in a nuclear weapons program.

ID	Name	Code	Normal duration (wks)	Crashed duration (wks)	Predecessors	Energy (MWhr)	Materials ($M)	Professional labor (mm)	Skilled labor (mm)	Unskilled labor (mm)
157_s	**Fabricate research device components, enriched uranium prototype [start] (tasks 158–167)**	—	0	0	172	—	—	—	—	—
158	Gun barrel	Cc	24	12	128, 152, 157_s	3.6	—	9	9	—
159	Breech mechanism	Cc	24	12	128, 129, 157_s	1.8	—	—	9	—
160	Casting of enriched uranium components	Ac	8	4	112, 130, 157_s	16	—	—	6	—
161	Cast depleted uranium tamper	Ac	8	4	112, 130, 157_s	16	—	—	6	—
162	Machine enriched uranium receiver	Bc	16	8	129, 160, 157_s	1.2	—	—	6	—
163	Machine enriched uranium projectile	Bc	16	8	129, 160, 157_s	1.2	—	—	6	—
164	Machine depleted uranium tamper	Bc	16	8	129, 161, 157_s	1.2	—	—	6	—
165	Initiator	Ac	8	4	131, 154, 155, 157_s	2.4	—	6	6	—
166	Propellant charge	Ac	8	4	132, 153, 157_s	1.2	—	—	6	—
167	Detonator and explosive train	Ac	8	4	156, 157_s	1.2	—	—	6	—
157_f	**Fabricate research device components, enriched uranium prototype [finish]**	—	—	—	158–167	—	—	—	—	—
168	Assemble research devices (enriched uranium prototype)	Ab	16	8	151FF + 4,	3.6	—	6	12	—
169_s	**Sub-critical testing of research devices [start] (tasks 170–174)**	—	—	—	170–172	—	—	—	—	—
170	Verify critical mass	Cb	24	12	170FF + 4	2.4	—	6	6	—
171	Verify gun velocity	Cb	24	12	160	3.6	0.1	6	12	—
172	Delivery vehicle compatibility mock-up	Cb	24	12	171	3.6	0.1	6	12	—
169_f	**Sub-critical testing of research devices [finish]**	—	—	—	170, 172	—	—	—	—	—
173	Test full-scale device (not required)	Fb	48	24	170	80	1	36	360	—
174	Finalize production-weapon design	Eb	40	20	170FF + 12	18	0.1	30	60	—
175	**Acquire weapon components [start] (6 weapons; tasks 172–176)**	—	—	—	174SS + 8	—	—	—	—	—
176	High-strength steel cylinder	Ca	24	12	175_s	1.2	0.06	—	6	—
177	Double-base propellant powder	Ca	24	12	175_s	1.2	0.06	—	6	—
178	Polonium	Ca	24	12	175_s	1.2	0.3	—	6	—
179	Beryllium powder	Ca	24	12	175_s	1.2	0.06	—	6	—
180	Detonator and explosive train components	Ca	24	12	175_s	1.2	0.06	—	6	—
175_f	**Acquire weapon components [finish]**	—	—	—	176–180	—	—	—	—	—
181_s	**Fabricate weapon components [start] (tasks 182–194)**	—	—	—	174	—	—	—	—	—

(Continued on next page)

Tasks involved in a nuclear weapons program. *(Continued)*

ID	Name	Code	Normal duration (wks)	Crashed duration (wks)	Predecessors	Energy (MWhr)	Materials ($M)	Professional labor (mm)	Skilled labor (mm)	Unskilled labor (mm)
182	Gun barrel	Cc	24	12	128, 176, 181_s	4.8	—	12	12	—
183	Breech mechanism	Cc	24	12	128, 129, 181_s	2.4	—	—	12	—
184	Cast enriched uranium components	Cc	24	12	112, 130, 181_s	93	—	—	12	—
185	Cast depleted uranium tamper	Cc	24	12	112, 130	93	—	—	12	—
186	Machine enriched uranium receiver	Cc	24	12	D	2.4	—	—	12	—
187	Machine enriched uranium projectile	Cc	24	12	125, 180	2.4	—	—	12	—
188	Machine depleted uranium tamper	Cc	24	12	129, 185	2.4	—	—	12	—
189	Initiator	Cc	24	12	131, 178, 179, 181_s	4.8	—	12	12	—
190	Propellant charge	Cc	24	12	132, 177, 181_s	2.4	—	—	12	—
191	Detonator and explosive train	Cc	24	12	180, 181_s	2.4	—	—	12	—
192	Fuse	Cc	24	12	181_s	2.4	—	—	12	—
193	Safety and arming device	Cc	24	12	181_s	2.4	—	—	12	—
194	Weapon case and structure	Cc	24	12	172, 181_s	2.4	—	—	12	—
181_f	**Fabricate weapon components [finish]**	—	—	—	182–183, 186–194	—	—	—	—	—
195	Assemble weapon components	Cc	24	12	181_f	7.2	0.1	12	24	—
196	Production weapons deliveries	—	0	0	195	—	—	—	—	—
113_f	**Prepare nuclear explosive devices [finish]**	—	—	—	196	—	—	—	—	—
1_f	NUCLEAR WEAPONS PROGRAM (finish)	—	0	0	113_f	—	—	—	—	—

Source: the authors.