ISIS Course

Introduction to Reactors and Fuel Cycle:

Small Yongbyon Nuclear Reactor

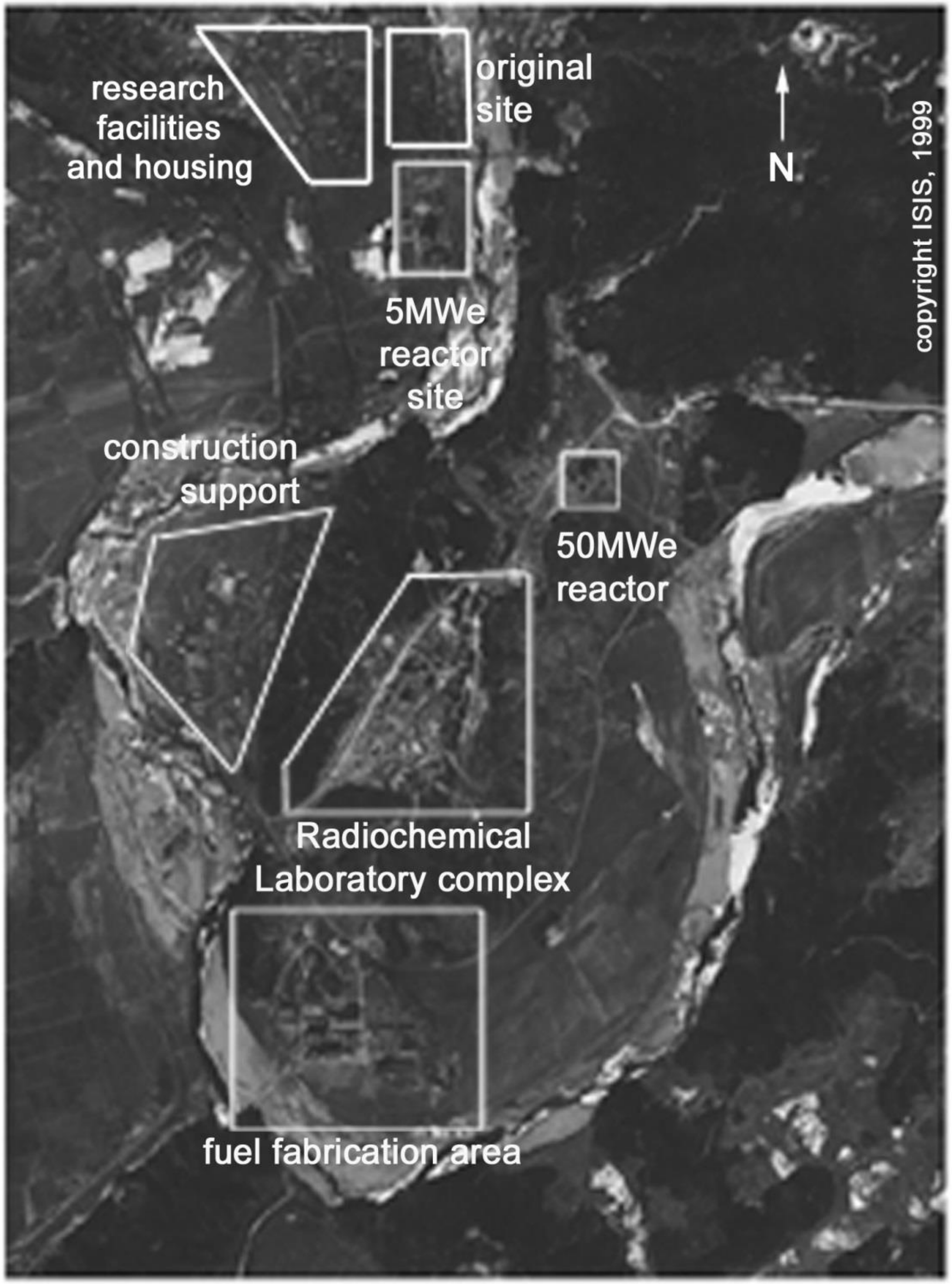
Important Non-Proliferation Example: North Korean Yongbyon Reactor

- North Korea started operating a small reactor at the Yongbyon nuclear research center in 1986. When it was revealed officially, North Korea said it was for civilian purposes.
- It has a nominal power of up to 25 megawatt-thermal, although actual power is less. North Korea often discusses this reactor in terms of its output of electricity, namely 5 megawatts electrical
- In the electric power industry, megawatt-**electrical** (abbreviation: MWe or MWe) is a term that refers to electric power, while megawatt-**thermal** (abbreviations: MWt, MWth) refers to **thermal** power produced and is typically 3 to 5 times greater than the electrical power.
- North Korea started calling the reactor a 5MWe reactor during the early 1990s when it denied that plutonium from this reactor was for nuclear weapons. It no longer denies that the plutonium is for weapons.
- So far, the plutonium produced in this reactor has been North Korea's principal source of nuclear explosive materials for its nuclear weapons.

5MWe Reactor’s Fuel Cycle

- Uranium mine and mills outside Yongbyon produce natural uranium
- Fuel fabrication complex converts the uranium from the mills into reactor fuel
- The 5MWe reactor irradiates the uranium 238 in the fuel making plutonium
- The “Radiochemical Laboratory” chemically separates plutonium from highly radioactive irradiated or spent fuel, resulting in plutonium metal.
- The plutonium metal is shipped off-site to other entities, evidently under the control of the military.
- Waste sites store leftover uranium and radioactive materials

Overview of Yongbyon Site, 1989 (KVR image)



Yongbyon Overview May 16, 2006


May 16, 2006 (DG)

Yongbyon 5 MWe Reactor

A 2008 file photo shows the 5 MWe reactor at the Yongbyon nuclear complex.
Picture credit: Reuters

Yongbyon 5 MWe Reactor

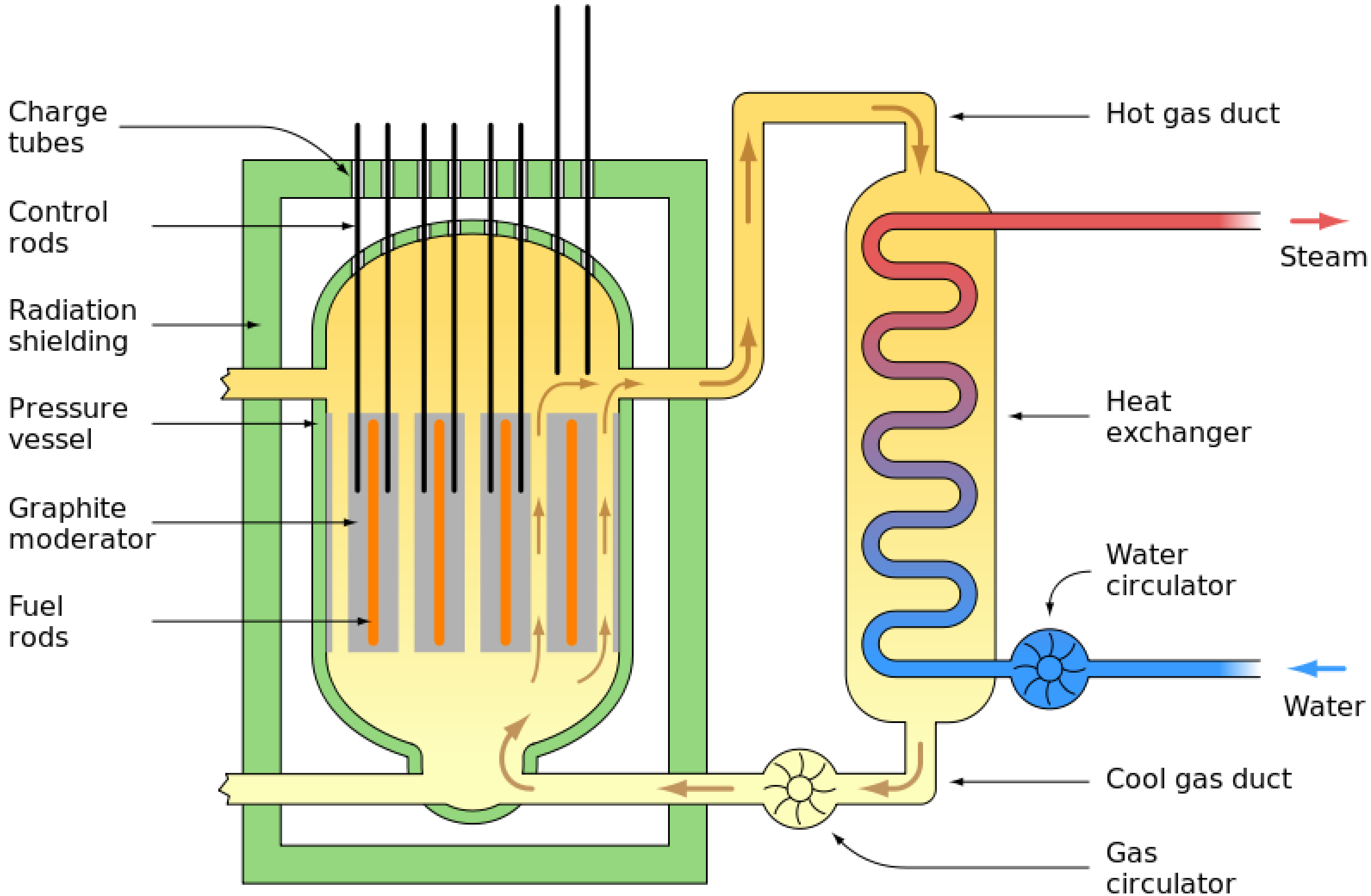
A 2008 file photo showing the cooling tower of the Yongbyon nuclear complex being demolished. The cooling tower was demolished as part of an agreement under the Six Party Talks to disable Yongbyon plutonium production facilities. The reactor without a cooling tower has since restarted. Picture credit: AP

Yongbyon Gas-Graphite Reactor

- The 5 MWe reactor is based on an old reactor design that is comparatively simple to duplicate. This technology is also straightforward to scale up. But despite its simplicity, North Korea acquired many goods abroad for this reactor and associated fuel cycle facilities.
- The reactor is similar in design to a larger British gas-graphite reactor built in the 1950s.
- The 5MWe reactor is moderated by graphite. Three hundred tonnes of graphite are used in the core for moderation, or the slowing down of the neutrons produced by the fissioning of uranium 235.
- It is cooled by carbon dioxide in a primary cooling circuit.
- The carbon dioxide in turn is cooled by water in a secondary cooling circuit. The water is drawn from an adjacent river.

Schematic of a Gas-Graphite Reactor

http://en.wikipedia.org/wiki/Magnox



Recent Commercial Satellite Image (no cooling tower)

5MWe Reactor at Yongbyon, October 15, 2003, before cooling tower destroyed

Front End of Fuel Cycle

- The starting material in the Yongbyon fuel cycle is natural uranium that must be extracted from the earth.
- North Korea extracts uranium-bearing ore at several mines.
- The ore is processed in special facilities called mills in order to concentrate the uranium.
- Each tonne of ore is estimated to contain about one kilogram of uranium
- The product of the mills is called yellowcake, typically U_3O_8
- The yellowcake is shipped to the Fuel Fabrication Complex at the Yongbyon site.

Fuel Fabrication Complex

Fuel Manufacturing Steps

- The yellowcake is converted into a pure uranium oxide form, UO_2, or uranium dioxide
- The uranium dioxide is further processed into uranium tetrafluoride, UF_4.
- The uranium tetrafluoride is turned into uranium metal, which is the form of uranium used in the fuel

Unclad Uranium Metal Fuel Rods

- The uranium metal is extruded into rods.
- When finished, the rods are about 60 centimeters in length (see photo).
- The uranium is then “clad”, or inserted into, a magnesium alloy tube and sealed.

Fuel in Core

- The core contains 50 tonnes of natural uranium in about 8,000 fuel rods.
- Each fuel rod contains a uranium rod with a mass of 6.2 kilograms. It is contained in a water-tight magnesium tube.
- The fuel rod's dimensions are 60 centimeters in length and 3 centimeters in diameter

Top of Core of 5 MWe reactor, 2008:

http://edition.cnn.com/2008/WORLD/asiapcf/06/26/nkorea.nuclear/index.html?eref=edition_asia&utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+rss%2Fedition_asia+(RSS%3A+Asia)

- The rods are loaded into about 800 vertical channels or tubes from the top of the reactor, via a fueling/refueling machine.
- Each channel contains up to 10 fuel rods.

Banner translation: “Let us defend with our lives the Beloved and Respected General Kim Jong Il”

Fuel for 5 MWe reactor

- The fuel rods typically will remain in the reactor for at least a few years before being discharged. Typically, the entire core is discharged and replaced by a fresh core of fuel.
- The irradiated or spent fuel is transferred remotely to a cooling pond in a building adjacent to the reactor.
- The rods are left there until enough of the radioactive elements have decayed so as to allow for their safe chemical processing.
- The irradiated rods are then sent for plutonium separation.

Spent Fuel Pond Yongbyon 2008:

http://www.abc15.com/news/national/north-korea-says-it-plans-to-restart-shuttered-nuclear-reactor

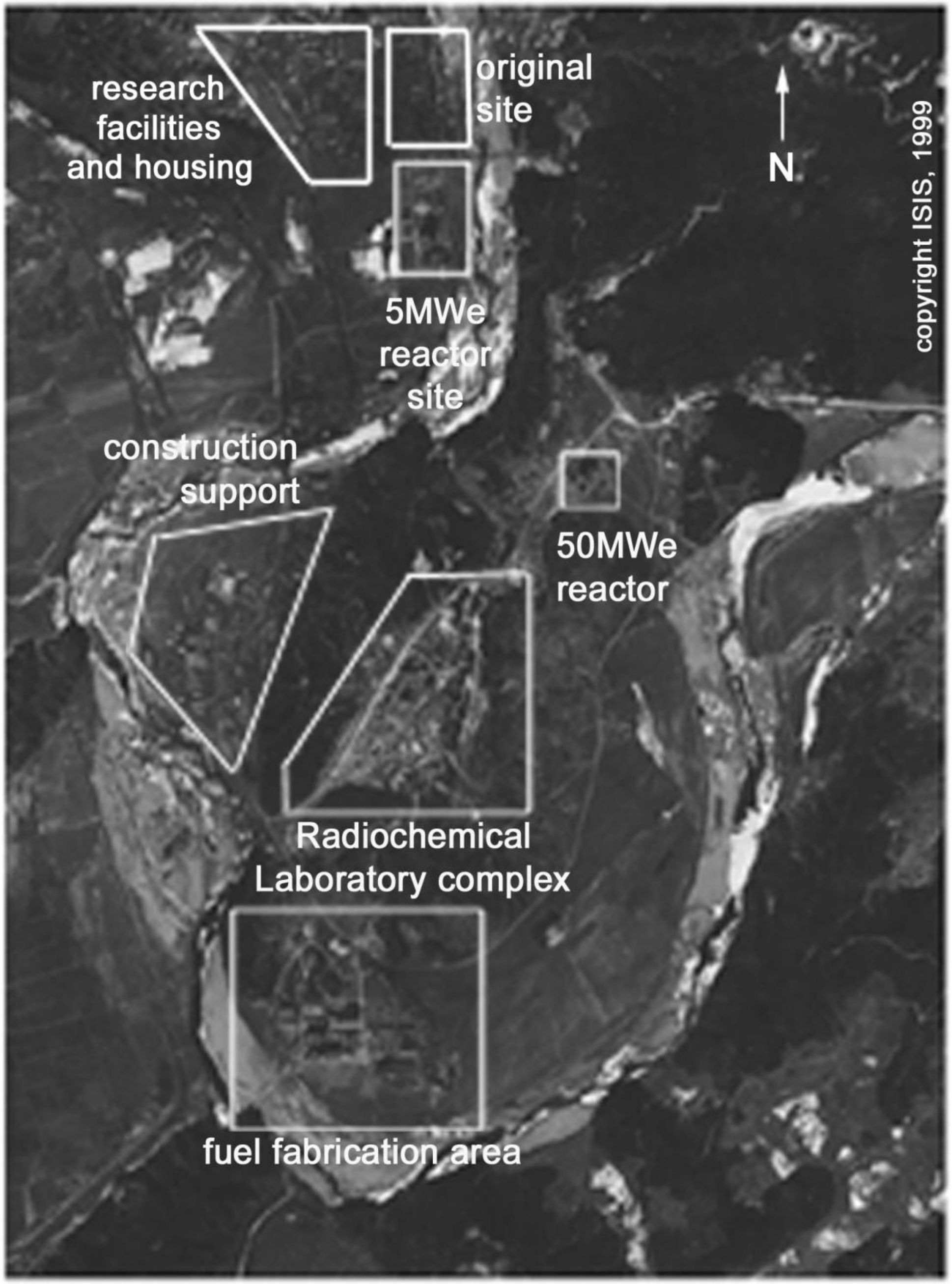
Radiochemical Laboratory

- The irradiated, or spent fuel, is sent in special containers by truck to a nearby chemical processing plant, the Radiochemical Laboratory. Here, the plutonium is separated from the irradiated rods.
- The 200 meter “canyon” where plutonium separation occurs is in a multi-story building on the right.

Plutonium Metal Production

- The final step is the conversion of the separated plutonium into metal discs or pucks
  - In this step, pure plutonium oxide is converted into plutonium tetrafluoride and then into plutonium metal.
- This process takes place in the product area of the Radiochemical Laboratory.
- Prior to the IAEA inspection visits in 1992, North Korea removed this section of the plant, claiming that the final product was plutonium oxide.

1989 (KVR)


research
facilities
and housing
original
site
N
copyright ISIS, 1999
5MWe
reactor
site
construction
support
50MWe
reactor
Radiochemical
Laboratory complex
fuel fabrication area

1992 Video of Initial Visit by IAEA to Yongbyon

- Go to video at http://isis-online.org/conferences/detail/iaea-director-general-hans-blix-tours-north-korean-nuclear-sites/10

Plutonium Production

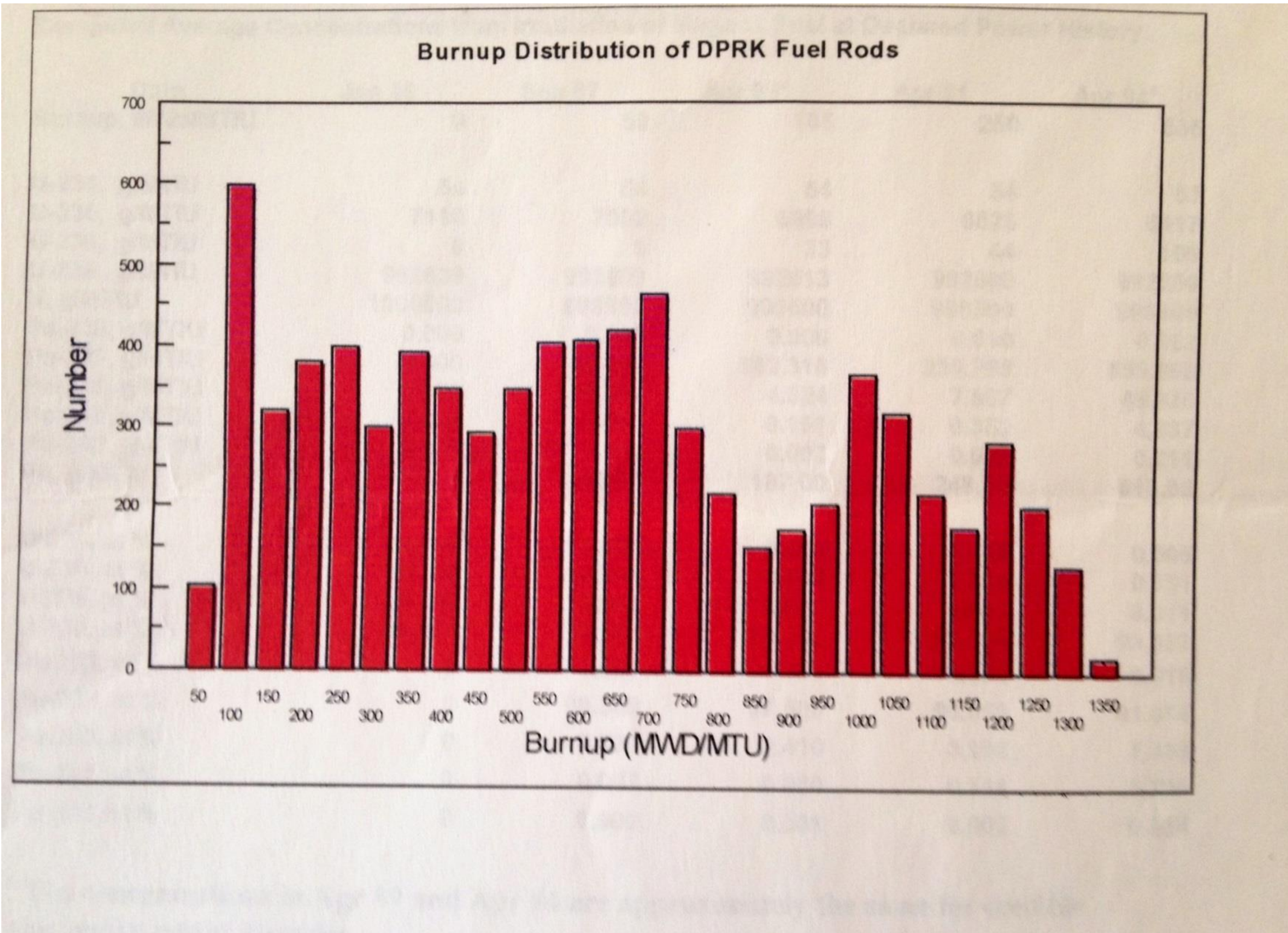
- The 5 MWe reactor produces plutonium rather slowly.
- Typically, after a few to several years, the core is unloaded, and all the irradiated fuel is chemically processed at the Radiochemical Laboratory , producing separated plutonium metal.
- North Korea is estimated to currently have a stock of about 30-34 kg of separated plutonium.
- This is enough for 6 to 17 nuclear weapons, where each weapon has between 2 and 5 kg of plutonium.

Table VIII.5

Calculated average properties of the 5 MWe reactor fuel during irradiation with the power history declared by North Korea.

Date	Jan. 1986	Sept. 1987	April 1989[a]	April 1991	April 1994[a]
Burnup, MWth-d/t	0	50	185	250	635
^{234}U, g/tU	54	54	54	54	53
^{235}U, g/tU	7,110	7,052	6,898	6,825	6,417
^{236}U, g/tU	0	9	33	44	106
^{238}U, g/tU	992,836	992,800	992,613	992,600	992,200
U, g/tU	***1,000,000***	***999,900***	***999,600***	***999,500***	***998,800***
^{238}Pu, g/tU	0.000	0.000	0.006	0.010	0.062
^{239}Pu, g/tU	0.000	55.452	182.318	239.769	559.868
^{240}Pu, g/tU	0.000	0.387	4.524	7.967	45.920
^{241}Pu, g/tU	0.000	0.004	0.151	0.352	4.887
^{242}Pu, g/tU	0.000	0.000	0.002	0.006	0.211
Pu, g/tU	***0.00***	***55.84***	***187.00***	***248.10***	***610.95***
^{234}U, at %	0.005	0.005	0.005	0.005	0.005
^{235}U, at %	0.720	0.714	0.699	0.691	0.651
^{236}U, at %	0.000	0.001	0.003	0.004	0.011
^{238}U, at %	99.274	99.279	99.292	99.299	99.333
^{238}Pu, at %	0	0.001	0.003	0.004	0.010
^{239}Pu, at %	0	99.302	97.506	96.655	91.674
^{240}Pu, at %	0	0.690	2.410	3.198	7.488
^{241}Pu, at %	0	0.007	0.080	0.141	0.794
^{242}Pu, at %	0	0.000	0.001	0.002	0.034

1994 Discharge of Irradiated Fuel, Distribution of almost 8,000 fuel rods



This book uses two main approaches to estimating the amount of weapon-grade plutonium produced in production reactors. The first approach involves a simple approximation of average annual weapon-grade plutonium production. It can be represented by the following equation:

$$Pu_{\text{yearly total}} = P_{\text{thermal power}} \times C \times (365 \text{ days}) \times F$$

where *P* is the nominal thermal power of the reactor and *C*, often called the capacity or 'innage' factor, represents the ratio of the total annual heat output to the annual heat output based on continual full-power operation. This ratio is often stated to be the fraction of the year the reactor operates at full power. The last factor in the equation, *F*, represents a plutonium conversion factor which gives the amount of plutonium produced per megawatt-day of thermal output (MWth-d) from the reactor. For weapon-grade plutonium produced in a graphite-moderated, natural uranium reactor, the factor is about 0.9 g weapon-grade plutonium per MWth-d (g/MWth-d).[1] Because weapon-grade plutonium includes all plutonium with more than 93 per cent ^{239}Pu, this conversion factor can vary by up to 10 per cent (ignoring the uncertainty of the estimate itself). This variation reflects the range of burnup for irradiated fuel containing weapon-grade plutonium. Table A.1 contains typical conversion factors for several types of reactor.

[1] Turner, S. E., *et al.*, *Criticality Studies of Graphite-Moderated Production Reactors*, Report prepared for the US Arms Control and Disarmament Agency, SSA-125, Southern Sciences Applications, Washington, DC, Jan. 1980.

Have a nice evening and goodbye from DPRK
Next week—A more detailed discussion of reactors and plutonium production