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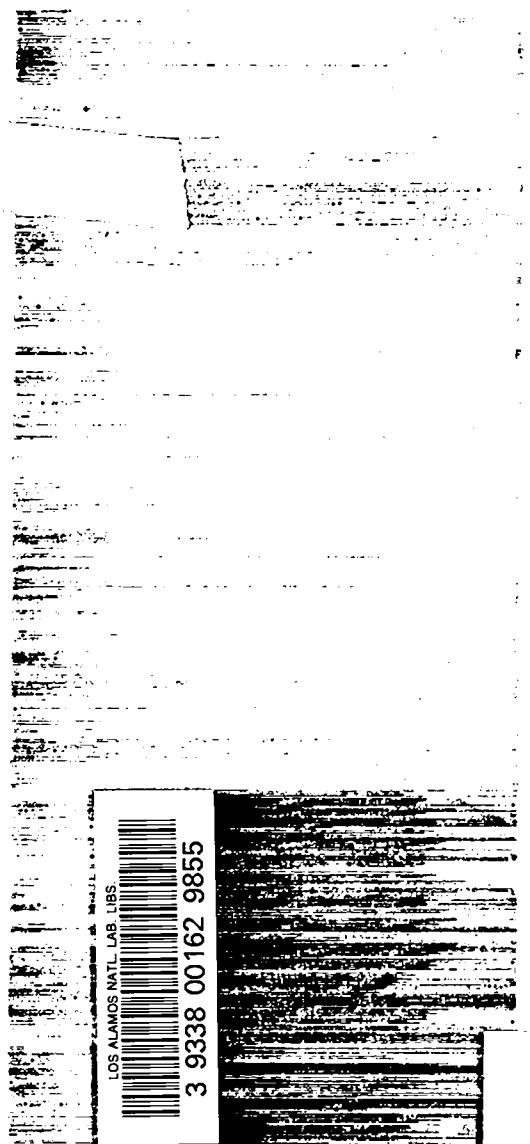

Nuclear Weapon Proliferation Indicators and Observables

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Edited by Gerry Edwards, Group IS-11
Composition and Layout by Randi Bagley, Group IS-11

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LA-12430-MS

UC-700
Issued: December 1992

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GLOSSARY

calutron - Califomia University cyclotron

CANDU - Canadian deuterium-uranium reactor

EBW - exploding bridge wire

g - gram

HE - high explosive

HEPA - high-efficiency particulate air filters

HEU - highly-enriched uranium

IAEA - International Atomic Energy Agency

kg - kilogram

kt - kiloton

kW - kilowatt

L - liter

LEU - low-enrichment-uranium

MDF - mild detonating fuse

MeV - megaelectronvolt

MOX - mixed-oxide

MPa - megapascals

MUF - material unaccounted for

MW - megawatt

NDA - non-destructive assay

psi - pounds per square inch

SNM - special nuclear material

tonne - metric ton

NUCLEAR WEAPON PROLIFERATION INDICATORS AND OBSERVABLES

by

Richard R. Paternoster

ABSTRACT

This report discusses indicators and observables that might be present from various phases of a nuclear weapon development effort. The indicators themselves are accompanied by some general discussions of what is likely to be observable by inspection or sampling techniques. The areas discussed include nuclear materials production, materials fabrication, related technology development, testing, and scientific personnel. Brief discussions of on-site inspections, sampling techniques, and evasion of safeguards are also included.

I. INTRODUCTION

The development of nuclear explosives requires simultaneous technology development in several broad areas. Work done to fulfill these goals will be accompanied by technological observables that may be broadly classified into a limited number of categories. A program to develop nuclear weapons would include the following elements:

- Nuclear Materials Production
- Extraction and Chemical Processing
- Fabrication Processes
- Technology Development Programs
- Nuclear Laboratory Experiments
- Physics Design
- Nuclear Testing

Among other factors, the program will depend upon the planned source of nuclear materials, some details of the design itself, the amount of money that can be spent, and the country's political motivation. At the same time, in a less detailed sense, technological goals must be fulfilled that do not differ greatly from one approach to another.

The state of progress for these program categories also determines which of the indicators might be present. Initial efforts will be laboratory-scale programs dedicated to developing the basic technology infrastructure for materials production, extraction, and fabrication. Laboratory-scale (that is, small-scale) production efforts might be expected to work with gram quantities of special nuclear materials (SNM) in glove-box processes. While these efforts are underway, high-explosives (HE) technology development and physics design efforts might begin.

Prototype-scale programs would follow, with SNM production efforts geared toward kilogram quantities. During this stage, hydrodynamic testing of HE/metal systems might begin in earnest. A prototype device could be built during this phase; however, it is likely that prior to testing, the first critical mass quantity ("crit") of material would be used for research into fabrication techniques and criticality properties of weapons mockups. Production-scale efforts would follow to enable annual production and handling of tens of kilogram quantities of SNM.

Indicators provide technology watch points for significant developments in nuclear weapons technology. These indicators must be used with caution as they are not infallible. Individually, they may be misleading and must be viewed in the context of a total program. Furthermore, the uncertainty in estimating a nation's nuclear capabilities is inversely related to the degree of access to their facilities and technology. Clearly, inspection and sampling provide the greatest degree of confidence, but may prove unacceptably intrusive.

Within the broad categories, the detailed differences among the observables for different kinds of programs may then be noted. In a previous work [1] a variety of hypothetical Nth country nuclear weapon development programs were discussed, and detailed observables, or indicators, were drawn from those programs and grouped into broad categories. In this report the list of detailed indicators has been expanded and updated to include explanatory comments to help the readers understand what the indicators show. The material is outlined for convenience and brevity.

II. NUCLEAR MATERIALS PRODUCTION

Plutonium and highly enriched uranium (HEU) are the most commonly used nuclear weapon materials. For the immediate future, plutonium and HEU will be the only nuclear materials of importance to nuclear proliferation. ^{233}U made in the thorium fuel cycle, is fissile and can be used for nuclear explosives, but its use is limited to breeder research and development activities. Produced this way, it has an isotopic impurity, ^{232}U, whose decay product is ^{208}Tl, which produces a high gamma-ray output. Consequently, it makes ^{233}U an undesirable choice for use in explosives manufacturing.

A. Plutonium Production

Plutonium is made in a reactor by the absorption of neutrons in ^{238}U that is in the fuel. Nuclear power reactors using natural-uranium or low-enrichment-uranium (LEU) fuel have a great deal of ^{238}U in the core. Run for long periods of time with a high neutron flux, they produce large amounts of plutonium. Research reactors fueled with HEU are generally unsuitable for producing large quantities of plutonium. However, they may make enough plutonium for developing chemical extraction technology. In general terms, HEU-fueled reactors trade one atom of U^{235} for one atom of ^{239}Pu.

Plutonium left in a reactor accumulates by neutron capture the isotopes ^{240}Pu, ^{241}Pu, ^{242}Pu, and higher actinides. To be isotopically pure in ^{239}Pu, the reactor fuel must be "changed out" often - typically with burnup rates < 2,000 MW-days/metric ton (tonne) of uranium. The production rate for plutonium isotopes by natural-uranium or LEU fuel in graphite and heavy-water-moderated reactors is ~ 0.9 - 1.1 g/MW-day. A 30-MW_t graphite-moderated research reactor fueled by 50 tonnes of natural uranium operated for one year (80% capacity factor) would produce ~ 8.7 kg

of plutonium. If the fuel remained in the reactor for one year, the extracted plutonium would contain over 95% purity in ^{239}Pu.

The used fuel contains almost isotopically pure ^{239}Pu, mixed, of course, with unburned uranium and fission fragments. If the fuel in a light-water power reactor is changed at a rate most economical for power production, it will contain a mixture of plutonium isotopes: ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, etc. Although this "reactor-grade" plutonium is somewhat more radioactive than the more isotopically pure material, it is still useful for nuclear explosives manufacturing.

Two pathways might be considered for reactor production of weapons-grade ^{239}Pu: (1) construction of a "research" reactor that could then be used for production; and (2) diversion of fuel material (irradiated or unirradiated) from a power reactor fuel cycle. A variation of the second pathway is the purchase by a country of irradiated power reactor fuel for reprocessing and extracting plutonium. Each of these paths is considered separately below.

1. Research Reactor. The design of a research reactor provides basic information conceming the purpose of the reactor. Furthermore, production of kilogram quantities of ^{239}Pu involves operating a reactor in a different manner than one typically operated for research purposes.

Some of the differences between research and production reactors are amplified below.

Research Reactor	Production Reactor
Research reactors acquired from advanced nuclear nations use HEU in a high-power density configuration (> 5-10 kW/L) to produce high in-core neutron fluxes. A country developing an indigenous uranium-mining industry might build natural uranium reactors, such as CANDU (heavy-water-moderated), or graphite-moderated types.	Production reactors typically use natural uranium or LEU in low-power-density (0.01-1.0 kW/L) configurations. Natural uranium, graphite-moderated, air-cooled reactors have been used by most nuclear weapon states for ^{239}Pu production.
Research reactors are low power (typically < 10 MW).	Production reactors are typically 30-50 MW and above. **Note**: High-power-density reactor cores (> 10 kW/L) fueled by HEU could be used only for limited production capability before the core would need replacement.
Research reactors operate intermittently to accomplish some research program initiatives, e.g., neutron radiography, fuel-element research, and operator or student training.	Production reactors operate on continuous, three-shifts-per-day schedules.
Research reactors operated intermittently require infrequent refueling (annually or less often). Frequent shutdown of research reactors may indicate weapons-grade plutonium manufacturing.	Production of low-irradiation plutonium requires abnormally high fuel throughput. Typically 25-30% of the fuel would be changed out periodically, with the remaining fuel repositioned toward the outside of the core.

Research Reactor (cont)	Production Reactor (cont)
Fuel elements for research reactors are static, specifically designed, custom-fabricated units integrated into the reactor core. Typically, only one spare core and one spent core are stored on-site.	Production-reactor fuel elements are designed for simple placement and removal and must be fabricated and designed for easy dissolution in fuel reprocessing. Abnormally large spent-fuel storage pools or numerous fuel-shipping casks could indicate a capability to store and ship large numbers of fuel/target elements.
Typical research reactors have several specialized beam ports for experimental irradiations.	Production reactors use several hundred identical fuel channels, accessible for hand-loading or machine-loading of fuel/target elements.
Research reactor fuel is typically acquired from advanced nuclear countries.	The indigenous capability to manufacture low-tech natural uranium fuel/target elements is required to produce ^{239}Pu in volume.

2. Power Reactor. Diverting fuel material from a power-reactor fuel cycle could be accomplished before or after irradiating the fuel. A country with a developing nuclear power economy might attempt to divert unirradiated fuel for use in a covertly operated production reactor. In addition, irradiated fuel might be diverted to a laboratory-scale reprocessing operation to extract plutonium.

Production of weapons-grade plutonium requires low fuel bumup and abnormally high fuel throughput. Monitoring operation logbooks or using tamper-proof power monitors provides information about the reactor duty cycle.

The following items are indicators pertinent to power reactors.

If there are...	it may indicate...
nuclear power plants in operation, under construction, or planned,	a potential source of nuclear material. **Note:** Material accountability procedures should be established prior to receiving the first fuel shipments.
frequent shutdowns of power reactor,	production of weapons-grade plutonium.
partial replacements of the fuel core,	diversion attempts.
reactors operating with on-line refueling systems (for example, CANDU),	a plutonium diversion that is difficult to detect. **Note:** These remotely operated machines employ sophisticated positioning or alignment systems in conjunction with video monitoring to allow charging and discharging of fuel elements while the reactor is operating.
placements of unnecessary ^{238}U in or around a reactor core (as in-core gamma shields or replacement of reflector materials),	attempts at plutonium production (although the amount might be small if care is not exercised in the location).

If there are...	it may indicate...
increased movements of material in and out of the spent-fuel pool, in conjunction with frequent shutdowns,	attempts to divert material. **Note:** Spent-fuel elements or production-target elements would be stored, at least temporarily, in spent-fuel pools adjacent to the reactor.

B. Uranium Enrichment

The second pathway to weapons-grade material is through production of enriched uranium. Enriched uranium for nuclear explosives must be produced by an enrichment plant. These processes increase the fraction of ^{235}U in uranium from the natural value of 0.7% to various higher percentages. Nuclear explosive devices based on the implosion principle can be made with either plutonium or HEU ($\geq$ 90% ^{235}U); however, the "gun-assembled" device uses HEU.

Some research reactors use HEU in their cores. The uranium could be diverted from several unused cores for a nuclear device development program. Some "critical assemblies" (Godiva, for example) used for research purposes contain substantial amounts of HEU, and these assemblies could be used either in nuclear weapons development or as the source of nuclear material for a live nuclear test program.

Methods of uranium enrichment include gaseous diffusion, electromagnetic separation, gaseous centrifuge, the jet-nozzle process, and laser-isotope-separation schemes. The critical details of gaseous diffusion technology, gaseous centrifuges, and laser isotope enrichment remain classified. A country wishing to develop these technologies would require trained technologists, access to advanced technology components, vast sums of money, and several years of devoted effort.

Some indicators of developing-uranium-enrichment technology would arise from these activities:

(1) **carrying out any uranium enrichment (isotope separation) program, with or without foreign assistance and with or without safeguards commitments;**

(2) **importing high-tech enrichment technology coupled with attempts to circumvent import-export controls** (which might be accomplished through multi-national intermediaries or adopting of dual-purpose technologies);

(3) **assembling clusters of trained personnel with specialties in associated technologies required for known enrichment schemes** (for example, large power supplies, high-speed bearing design, etc.) ;

(4) **attempting to enlist foreign consultants with known backgrounds in enrichment technology;**

(5) **developing chemical processing for uranium conversion to a form suitable for enrichment feedstock** [UF_6 for gaseous diffusion, nozzle enrichment, or gas centrifuge; UCl_4 for calutrons (*Cal*ifomia *U*niversity cyclo*tron*)];

(6) **importing materials and components with the ability to resist corrosive attack by UF_6** (these would include high-alloy stainless-steel sheet and tubing, storage vessels, gas valves, and pressure or vacuum fittings); and

(7) **building facilities with design features, such as large power inputs and large cooling systems, inconsistent with their purported use.**

The calutron is basically a production-type mass spectrometer designed to process large volumes of material. It employs single- or multiple-ion sources to ionize and accelerate the uranium atoms through a magnetic field. Some of its key components include ion sources; high-voltage; high-current (300-800 V and 1-1.4 kA) stabilized dc power supplies; high-capacity vacuum diffusion pumps; and large water-cooled magnetic coils.

Calutrons were used by the U.S. to produce the first enriched uranium used in the Little Boy device. Abandoned by the U.S. after WWII because of its intrinsic inefficiency, the calutron was totally declassified. Two calutron models were developed: the alpha calutron, with a 48-in. radius of separation used to enrich uranium to 10-30%; and the beta unit, with a 24-in. radius for enrichment from 30-90% in ^{235}U.

The following are indicators for developing calutron technology.

Indicator	Explanation
Large stabilized power supplies (tens of megawatts) and large, water-cooled magnet systems	Water chillers would be an integral part of any prototype-scale calutron facility.
Large amounts of copper wire for the production of "racetrack"-type magnets	Several source-collector units can be ganged within one large racetrack-type magnet coil.
Location of a nearby chemical processing plant for collecting enriched uranium and for cleaning source collector units.	^{235}U atoms are deposited on graphite targets that are later bumed to collect the uranium. Any indications of graphite contaminated with enriched uranium may indicate calutron activity.
Extensive manpower for operating and maintaining a facility.	Calutrons require extensive manpower because the ion source, the vacuum chamber, and the collector chamber must be routinely cleaned of the uranium that is deposited on the inside surfaces. Uranium-contaminated nitric acid solutions would be present in waste tanks at the facility.

Early nuclear development efforts with gaseous centrifuge technology were published in both the U.S and Germany. In the gaseous centrifuge, rotors of carbon fiber composite are spun in a vacuum at high speed (upwards of 36,000 rpm) on magnetic suspension bearings. However, design details of rotors, bearings, seals, and drive systems used in modem uranium centrifuges have remained classified. The development of production centrifuge technology would require significant development effort.

Some potential indicators of developing production centrifuge technology are

(1) attempts to import, purchase, or fabricate carbon composite cylinders with precision tolerances and balance specifications;

(2) attempts to import or purchase magnetic suspension bearings, high-speed motors, or inverter power supplies; and

(3) the purchase or construction of uranium-to-UF_6 and UF_6-to-metal chemical conversion plants.

III. EXTRACTION AND CHEMICAL CONVERSION

After irradiation in a reactor, the fuel/target elements must be cooled in water storage pools to allow for the decay of short-lived fission products. Typically, this cooling time may be from 100-150 days and may take place at the reactor facility or at a holding facility adjacent to the chemical extraction plant. Shipping casks would be required to transport the irradiated elements.

A. Plutonium

Plutonium may be obtained from spent reactor fuel elements by chopping up and dissolving the elements; processing the solution using solvent extraction or ion-exchange processes; and chemically converting the resulting liquids to desired forms: plutonium metal, PuO_2, etc. The following indicate these operations.

(1) Several connected glove boxes would be sufficient to demonstrate basic processes of fuel-element chopping, dissolution, and chemical extraction. Therefore so-called "laboratory facilities" or "pilot-plant facilities" are more than likely large enough to process plutonium in significant quantities in the context of early nuclear device development work.

(2) Construction of or attempts to purchase irradiated-fuel-element-chopping machines could indicate interest in fuel reprocessing. These machines, typically remotely operated, are designed to cut, chop, or shear irradiated nuclear-fuel assemblies, bundles, or rods.

(3) A laboratory-scale operation would need 500 to 1000 gal. of TBP solvents (kerosene, carbon tetrachloride, or normal dodecane) to start up, then 50 to 100 gal. per six months of operation.

(4) Effluents from such plants or facilities as described will contain radioactive fission products, including iodine, xenon, and krypton gas. These noble gases could, however, be adsorbed on carbon or silica gel at low temperature and stored to eliminate their release. **In general, process effluents will also contain uranium, plutonium, and the chemicals characteristic of the processes themselves:**

Process	Chemical Ingredients and Effluents
Dissolution	nitric acid, uranium, plutonium, and fission products in solution
Solvent Extraction	nitric acid, TBP (n-tri-butyl phosphate), ferrous sulfamate, hydroxylamine, ascorbic acid, sodium nitrite, kerosene, carbon tetrachloride, normal dodecane, plutonium, and uranium

Process (cont)	Chemical Ingredients and Effluents (cont)
Chemical Conversions	hydrogen peroxide, oxalic acid, carbon dioxide, hydrofluoric acid, calcium, iodine, magnesium oxide, potassium hydroxide, magnesium fluoride, hydrogen, and plutonium

(5) Critically safe vessels (for example, small-diameter cylinders, annular tanks, or slab tanks) would be required if quantities of ^{239}Pu exceeding a few hundred grams are present in solution. Process vessels of special alloy steels are required to withstand the hot, highly corrosive solutions used in the fuel-element dissolution process (usually done with 70% nitric acid at boiling temperature). Dissolver vessels might use electrical heating elements and insulation wrapping.

(6) Plutonium compounds, such as PuO_2 and PuC, may be used to produce an explosion, but it is more likely that the metallic form (plutonium metal) would be used. The chemicals listed in the table above are those required to convert the plutonium found in nitric acid solution from the solvent extraction process to plutonium metal.

(7) Analysis of the plutonium from some of the above operations will show the irradiation level of the reactor fuel. Low irradiation would be a strong indicator of weapon activities.

As noted above, some critical assemblies and research reactors for mixed-oxide (MOX) fuel research contain large amounts (measured in metric tons) of plutonium and uranium in metallic form. These assemblies are usually purchased from a nuclear weapon state. Separating the plutonium from the uranium (if alloyed) could be accomplished by dissolving the alloy in nitric acid, and then using either solvent extraction, as before, or oxalic acid precipitation. The latter may have to be done twice to get plutonium with < 1% uranium in it.

Indicators for this diversion would have much in common with those for spent-fuel-element processing, except that there would be little or no fission products present. **The following operations and materials would characterize the MOX processing.**

Process	Chemical Ingredients and Possible Effluents
Dissolution	nitric acid, plutonium, and uranium
Solvent extraction	nitric acid, TBP, ferrous sulfamate, hydroxylamine, ascorbic acid, sodium nitrite, kerosene, carbon tetrachloride, normal dodecane, uranium, and plutonium
Precipitation	oxalic acid, plutonium oxalate, carbon dioxide or hydrogen peroxide, and plutonium peroxide
Conversion to metal	plutonium, plutonium oxide, hydrofluoric acid, calcium, iodine, magnesium oxide, potassium or sodium hydroxide, magnesium fluoride, calcium fluoride, and hydrogen

The dissolution of metals or oxides in nitric acid is accompanied by considerable quantities of red-brown fumes. These fumes may be sent via a stack to the atmosphere. There would also be present in the stacked gas some small, but detectable, amount of the materials being dissolved, unless extreme measures were used to remove them.

B. Enriched Uranium

To reclaim enriched uranium from research reactor cores, the most straightforward method would be dissolution in nitric acid and solvent extraction as described earlier for spent-fuel processing. The same process would probably be used whether or not the research reactor core elements had been used in a reactor, because the chemistry of solvent extraction is relatively well understood.

Chemicals and materials characteristic of reclaiming enriched uranium would be the following:

Process	Chemical Ingredients and Possible Effluents
Dissolution	nitric acid, uranium, and aluminum (plus fission products and a small fraction of plutonium if fuel has been exposed)
Solvent extraction	nitric acid, TBP, ferrous sulfamate, hydroxylamine, ascorbic acid, sodium nitrite, kerosene, carbon tetrachloride, normal dodecane, uranium (and possibly a small fraction of plutonium)
Precipitation	hydrogen peroxide and uranium
Conversion to metal	uranium, uranium oxide, hydrofluoric acid, calcium, iodine, magnesium , potassium or sodium hydroxide, magnesium fluoride, calcium fluoride and hydrogen

If the country has obtained enriched uranium in the form of uranium tetrafluoride (a green powder), the reduction of UF_4 to the metallic form would involve the following chemicals and materials: calcium, iodine, magnesium oxide, and calcium fluoride. The crucible containing the reactants is a magnesium-oxide ceramic cylinder. The reactants are uranium tetrafluoride, calcium, and iodine; and the products are uranium and calcium fluoride, with the iodine going into the calcium fluoride slag.

IV. FABRICATION PROCESSES

A. Plutonium

The metal "buttons" from the precipitation process must then be cast into raw shapes and machined. These operations must be performed in a glove box or hot cave to protect workers. Glove-box or hot-cave operations are usually indicated by special ventilation and air filtration systems (HEPA filters). The installation of remotely loaded electrical fumaces and numerically controlled, multi-axis milling machines under these circumstances would be especially noteworthy.

If casting and machining are taking place in a facility, some or all of the following materials would probably be found in effluents.

Process	Chemical Ingredients and Possible Effluents
Casting	tantalum, magnesium oxide, aluminum, graphite, calcium fluoride, plutonium, and plutonium oxide
Machining	plutonium and plutonium oxide

B. Enriched Uranium

The casting and machining of natural uranium and enriched uranium are done in exactly the same way except that there is a limit on the amount of enriched uranium that can be melted and poured into a mold because of nuclear criticality. Casting and machining uranium can be done in any modem foundry and machine shop. No part of these operations is beyond the capabilities of equipment and tools normally used in such a facility.

Since melting and pouring are done in graphite crucibles and molds coated with a zirconium silicate and magnesium silicate mix, there will be stocks of these materials in or around the shop. Foundry sand is not likely to be used for uranium fabrication. The scrap from molds and crucibles will be contaminated with uranium.

A great deal of casting and machining of natural uranium will probably be done as part of the device development program, resulting in the following effluents.

Process	Chemical Ingredients and Possible Effluents
Casting and machining	uranium, uranium oxide, graphite, zirconium silicate and magnesium silicate

V. TECHNOLOGY DEVELOPMENT PROGRAM

A. HE Implosion Program

An extensive HE development effort is necessary. Some of the tests done are on the explosive itself, and others involve driving metal shapes with explosives. Almost all of the tests require electronic or optical instrumentation to observe what is occurring. **The following indicators would characterize an HE development program.**

Indicator	Significance
Expansion of facilities and/or personnel at or near an existing ordnance plant	This operation could be done in an HE-loading plant that produces standard ammunition and bombs. Some minor modification of equipment might be needed.

Indicator (cont)	Significance (cont)
Purchase or production of energetic HE; that is, something better than pure TNT	More probable materials are baratol, cyclotol, RDX, HMX, or PETN--any of which may be mixed with TNT.
Equipment for melting and casting HE	Early fabrication processes used steam to melt the HE prior to casting.
As an altemative to casting, facilities for pressing explosives into shapes could be used. Presses are large, weigh many tons, and are probably remotely operated.	Such facilities are not normally needed in conventional HE-loading plants. However, production of shaped charges for anti-tank ammunition may be done this way.
Facilities for precise machining of HE	Tools for machining spherical contours, such as multi-axis numerically controlled milling machines, would be especially noteworthy.
Waste and scrap from operations listed above	• Effluent waste water systems involving filters or catch basins • Pronounced red coloration in waste water caused by dissolved TNT • Solid scrap periodically destroyed by buming or detonation
Purchase or development of exploding bridge wire (EBW) detonators	
Purchase of certain types of linear detonation cord	Example: mild detonating fuse (MDF)

B. Hydrodynamic Testing

Implosion testing would be preceded by construction of an instrumented firing point for testing HE and HE/metal systems. Charges up to hundreds of pounds need to be fired on asphalt or concrete pads. Usually the charges would be set on simple wooden tables, with cables that run to a control bunker or underground room to the firing system and data recording equipment.

Exclusion zones with warning indicators (klaxons and beacons) would be in evidence. The control room might be several-hundred meters away for electronic data recording, but probably would be within a few meters if optical instrumentation is used.

Instrumentation may be a combination of the following equipment:

- High-speed oscilloscopes (a few dozen might be required)
- High-speed rotating mirror "streak" camera
- Electronic image converter camera
- High-speed framing camera
- Pulsed x-ray generator

Test firing of HE/metal systems with uranium (probably natural uranium) will have the following observables.

Observable	Significance
Bright streamers radiating from the test shot	Caused by buming fragments of uranium, these streamers can be recorded by a camera and may be visible to the eye.
People associated with the firing crew who carry portable radiation monitoring equipment, especially after the shot is fired	Radiation monitoring equipment would be used to map the extent of contamination from α-emitting natural or enriched uranium.
Fire trucks and/or fire extinguishers	Fires often started by the buming uranium fragments are associated with a test containing uranium.
Some advanced non-nuclear munitions may involve natural or depleted-uranium tests	Indicators are similar to those listed above.
Permanently installed air-sampling-type radiation monitors around the firing point.	Samples of dust, debris, or vegetation from the firing point will be contaminated with uranium.

C. Gun Weapon Development Program

Gun-type nuclear devices do not involve HE, but they do require propellants similar to those used in artillery shells. The nuclear explosive material must be enriched uranium because of the neutron preinitiation problem associated with using ^{239}Pu. **There would probably be a neutron-reflecting material, surrounding the enriched uranium, that could be any one of the following:**

- **natural uranium**
- **tungsten or a tungsten alloy**
- **beryllium (metal)**
- **beryllium oxide (ceramic)**

A development program for a gun-type nuclear explosive would probably use thousands of pounds of natural uranium, tungsten or tungsten, alloy, or hundreds of pounds of beryllium or beryllium oxide for the neutron reflector alone. Imports of these materials in substantial quantity might indicate such work. Modifications to naval gun or artillery barrels would be especially noteworthy.

The following additional indicators apply to a gun-type device development program:

(1) **Firing points used for "gun" programs would not show the effects of HE blast.** The area would probably not be cleared of ground cover in a circular pattem, but possibly in one direction only. Exclusion areas with waming indicators would be in evidence.

(2) **A firing point for gun work is likely to have a concrete pad** on which to mount test devices and to eliminate dust clouds that obscure photographing early portions of the test.

(3) **Photographing test devices requires only medium-speed framing cameras such as "Fastax" or possibly "Mitchell" cameras.**

(4) **Photographing projectiles is conveniently done with a shutterless moving film camera incorporating a slit in the optical path.** Such cameras can be bought or made in a modem machine shop.

(5) **Recording pressures in the gun breech is usually performed with a quartz-type pressure gage working in the pressure range of 70 MPa to 300 MPa (10000 to 45000 psi).** Gages need 10- to 100-μs response times. In the U.S. gages are manufactured by Kistler Instruments.

(6) **Fewer cables are probably needed for data recording for most gun tests compared to implosion tests;** however, there may be individual cases in which the reverse is true.

(7) **Gun tests that contain natural uranium as a mockup for enriched uranium will also produce bright streamers of hot metal.** The streamers will not be produced uniformly in all directions, as they are from an implosion, but will be contained mostly in a conical volume coaxial, corresponding to the direction of motion of the uranium projectile of the gun assembly.

(8) **Fire trucks, or at least fire extinguishers, will probably be associated with gun tests containing uranium.**

(9) **The noise from a gun shot is easy to distinguish from an HE detonation** with a little practice.

(10) **There is very little visible flash from a gun shot compared to an implosion test.**

VI. NUCLEAR LABORATORY EXPERIMENTS

A. Criticality Tests

It is very likely that the first critical mass quantity of weapons-grade nuclear material obtained would be used to study the criticality aspects of fabrication and assembly before a nuclear yield test was devised. Gun-type nuclear devices can be operated as critical assemblies by incrementally adjusting the separation distance of the HEU components. The "pits" of implosion devices might be tested to determine the amount of surrounding tamping/reflecting material that is critically safe. In addition, criticality measurements might be performed to give the scientists confidence in their computer codes and may help avoid criticality accidents in final assembly operations with live nuclear materials.

The following indicators might be associated with criticality measurements.

Indicator	Significance
The experiment is remotely operated, probably in a separate building, perhaps a quarter of a mile from a control room.	Typical critical assembly machines are hydraulically or electrically activated platforms on which are mounted fissile material and other components.
Experiments may be conducted in a large room underground	Evidence of massive radiation shielding composed of a few to several feet of concrete or earth
Live nuclear material neutron sources, and neutron counters present	Live nuclear material (plutonium or enriched uranium) is required. Pieces are brought into proximity by precise, step-wise increments. Neutron counters (pulse-mode BF_3 and current-mode ion chambers) are used to measure the neutron multiplication of the assembly.
Closed-circuit television	Used to observe the experiments in such facilities. A facility used for neutron irradiation research (agriculture or biology) might be modified rather easily to do the required experiments.
Criticality accident (inadvertent assembly of nuclear material parts resulting in a near prompt-critical or prompt-critical excursion) suspected or verified	This occurrence would probably be covered up. If it is known that one occurred in a suspect facility, there is a high probability that weapon R&D was going on. Requests for information on criticality accident dosimetry would be of interest.

B. Neutron Diagnostics

For a gun-weapon development program, one has to be assured that there will be a minimum of "background" neutrons at the time of detonation. This requirement places some restrictions on the purity of the enriched uranium to be used. It is likely that some measurement of spontaneous neutron emission from nuclear materials and other possible sources of neutrons would be undertaken.

In early U.S. programs, the nuclear initiator (a "modulated" neutron source) employed radioactive polonium and metallic beryllium. Even when not "tumed on," these initiators produce a certain number of neutrons. A country using such initiators would have to measure how many neutrons were being emitted both before and after turning the source on. **Neutron measurements of this type would be characterized by the following indicators:**

- neutron counters of either the scintillation or gas-filled variety connected to electronic recording devices (gases used in counters might be $^{10}BF_3$ or ^3He); and
- an experimental area with thick [~0.3 m (~1 ft) of water or polyethylene] shielding that is well away from any sources of radiation except that being measured.

C. Development and Testing of Nuclear Initiators

Nuclear initiators may be of the (α,n) type or the particle accelerator type; implosions or gun-type weapons may employ either. An (α,n) initiator produces neutrons from the physical mixing of

a radioactive alpha emitter (such as ^{210}Po) with a light element (such as beryllium). Various nuclide materials can be used as alpha emitters (for example, ^{238}Pu, ^{208}Po, ^{210}Po, ^{227}Ac, or ^{226}Ra).

A country that decides to develop (α,n) initiators must first produce or import the alpha-emitting material. Plutonium-238 is produced in a reactor by the irradiation of ^{237}Np, which is a by-product of irradiating ^{238}U and must be chemically extracted. Polonium-210 is made from high-purity bismuth (100% ^{209}Bi). There must be considerable testing of designs to insure the device turns on at the proper time and achieves the required intensity.

Particle accelerator initiators use a neutron generator vacuum tube (for example, zetatrons) that is electrically pulsed to accelerate deuterium or tritium ions from a source into a target containing deuterium or tritium to produce a pulse of neutrons. Specialized power supplies are required to produce the necessary filament and accelerating voltages. Neutron sources using the particle accelerator principle have been produced commercially for oil-well logging and various laboratory uses. Imports of such sources to be adapted for use in nuclear programs may indicate weapon development activity.

Experimental work on either type of initiator requires electronic instrumentation to detect neutrons. For the radioactive type, neutron background data must be taken as described above. In addition, experimental work with the radioactive type requires hot cell and glove-box facilities resembling those for plutonium processing. A few "proof" tests of the radioactive type would probably be done in underground chambers containing a mockup of the nuclear device and many neutron counters. Such chambers need only be 15-30 m (50-100 ft) underground, because no nuclear explosion is involved.

D. Nuclear Assay Laboratory

The production of high-quality SNM requires establishment of a nuclear assay laboratory. The assay laboratory would be needed (1) to assure high-purity uranium feed material for production reactors; (2) to assay isotopic content of irradiated fuel target elements; (3) to verify completeness of chemical extraction processes; and (4) to assay purity of metal stock prior to fabrication.

The assay of chemical composition and isotopic content of process nuclear materials would require some of the following instrumentation:

- **Mass spectrograph**
- **Gas chromatographic analyzer**
- **Neutron-count-rate analyzer**
- **Multichannel gamma-ray spectrometer**

VII. PHYSICS DESIGN

A. Computational Physics Models

Nuclear-device design calculations are performed on special-purpose computer codes incorporating several physics models that use numerical-differencing schemes to solve the required equations. The nuclear device is modeled by a spatial mesh and calculated over a series of discrete time intervals, covering the time of nuclear yield. Many physical variables (such as velocity, density, energy, etc.) are tracked over the computational mesh.

Computational physics models developed for inertially confined fusion research would be closely applicable to nuclear device modeling. **Interest in the following areas of computational physics might indicate nuclear-device-design activities:**

(1) **numerical hydrodynamics models incorporating shock propagation physics in a variety of materials;**

(2) **equation-of-state properties for greater than standard metal density conditions in uranium and plutonium;**

(3) **time-dependent neutron transport methods in one or more dimensional symmetry;**

(4) **neutron cross sections (particularly for fast-neutron assemblies and variation of neutron cross sections with temperature); and**

(5) **explosive burn models.**

B. Computing Systems

Many aspects of nuclear device design are performed on computers. Initial device design might be performed using data available in the open literature, but by their very nature, nuclear device calculations are computer-intensive. Large-memory, fast computers are used to calculate device performance and optimize device design. **In addition, several attributes of nuclear device design require special computing system features:**

- **High-security features to protect the installation**
- **Computer-security features to protect design data**
- **Large arrays of disk or tape drives to store restart dumps and past calculations**
- **Film-plotting or pen-plotting capabilities to visually display vast amounts of generated data**

VIII. NUCLEAR TESTING

A. Preliminary Tests

Hydronuclear testing refers to the use of very low-yield (< 1-lb equivalent of HE yield) nuclear tests to verify computer code calculations. These experiments were conducted at Los Alamos[2] during the Nuclear Testing Moratorium from 1958-61 to test safety design of stockpile devices. Thirty-five tests were conducted in 50- to 100-ft-deep holes, using complete HE systems and neutron sources. An "approach to critical" methodology used incremental loading of fissile material in depleted uranium to obtain neutron multiplication within the device.

Another possible approach would be through the containment of very low-yield nuclear tests in steel containment vessels. Steel spheres capable of containing 50-100 lb of HE yield would be useful for hydronuclear tests described above or for small-scale hydrodynamic tests of proposed designs. Such containment would allow SNM to be collected and reused.

These approaches do not provide a substitute for full-yield testing, but could provide much useful information on the quality of the design, while maintaining the covert nature of the program. **Preparation of a site for an underground nuclear test would probably be characterized by the following kinds of observables:**

- **drilling rigs, mining operations, road construction, or other signs of activity in a "new" location, isolated or otherwise suitable for an underground test;**
- **sections of large-diameter (up to about 1.2 m, or about 4 ft) pipe for casing laid out near drilling rig; and**
- **contacts (possibly through their embassy in the U.S.) with large drilling companies in the U.S. who know "large-hole" drilling technology by virtue of experience with the U.S. testing program.**

B. Yield Testing

Assuming that some kind of diagnostic information is to be recorded during the live nuclear test, cabling and electronic recording stations would be needed. The extent and sophistication of such an effort is difficult to predict, but the electronic skills needed for good diagnostics are believed to be widespread in the world. Good equipment can be bought from several countries, and some data acquisition schemes used by the U.S. have been published in open literature.

The following indicators relate to instrumentation of a live nuclear test.

Indicator	Purpose
Importing or developing computer codes for "unfolding" data	To remove system response effects from the recorded signals
A few to a dozen cable reels, 1.8-2.4 m (6-8 ft) in diameter and 1.2-1.5 m (4-5 ft) wide	To transport air dielectric or foam dielectric coaxial cables from 7/8-in. diam to 1-5/8-in. diam for recording fast signals
Both of the above items coupled with the purchase of plastic scintillators, photodiodes, photomultipliers, and 10- to 50-MHz bandwidth oscilloscopes (such as Tektronix) with cameras	To produce neutron and gamma-ray diagnostics

IX. PERSONNEL AND PUBLICATIONS

A. Personnel

It is to be expected that a group of technically proficient people will be formed to organize and help conduct the nuclear weapons program. **One might judge whether this has taken place by the following activities:**

- **Movement of top scientists from former positions into undisclosed or inaccessible locations**
- **Sudden decline or cessation of published papers by top scientists**

- **Extensive technological training or exchange programs in advanced countries**
- **Recall of trained scientists from other countries**
- **Close association of several top scientists of diversified backgrounds (for example, hydrodynamicists associated with nuclear physicists)**

B. Publications

One can also expect that the scientists working in any country on nuclear programs would be allowed to publish some of their work and would be anxious to read what others had done in the same fields. They would also probably obtain computer codes already developed by others for related kinds of calculations, notably for nuclear reactor studies and shock-wave hydrodynamics. **This facet of the theoretical and experimental work attendant to a weapons program would probably include some of the following specifics and possibly others:**

- **Papers published on calculations of nuclear reactor "excursions," especially energy release and the reactor core "neutronics"**
- **Requests by foreign scientists for neutron calculational codes**
- **Correspondence between the code user and the code originator (possibly in the U.S.) about the application of the code to higher pressure or temperature regimes**
- **Publications of critical mass data using weapons-grade materials or weapons-like configurations**
- **Papers published on experiments with HE using pin or optical instrumentation techniques**
- **Purchase of formerly secret, weapon laboratory reports recently declassified**

X. INSPECTIONS

A. Sampling

An important aspect of inspections of suspect nuclear facilities is sampling materials for later analysis, using passive or active non-destructive assay (NDA) techniques.[3,4] These techniques can provide further evidence of covert weapons-grade plutonium production, fuel processing for plutonium extraction, uranium enrichment, or other weapons activities.

Typically, inspections will be limited in duration, so analysis would be performed at a later time at an NDA laboratory. **In general, samples may take a variety of forms:**

- **swipes of surfaces or samples of solid materials or solutions from process areas**
- **water or soil samples from waste-handling areas**
- **air samples from process stacks**

Sample strategies and logistics require advance planning to properly cover a facility adequately. Samples will generally be radioactive, and health physics arrangements for transport of such

material should be made ahead of time. Milligram-to-gram quantity samples would be adequate for multichannel gamma-ray spectrometry; and multiple samples (at least two) will help reduce uncertainty. Samples should be sealed (double bagged) to eliminate any possibility of stray contamination. Location of acquired samples should be recorded for later reference.

Ideally, one would like to sample everything of interest, but the degree of intrusiveness that is tolerated and the level of risk that can be assumed will determine what samples are allowed. **Some of the samples that might be considered would include the following.**

Samples taken from...	**could provide information...**
fresh fuel material	on fuel composition and indicate any plutonium recycle.
dissolver operations material	through NDA analysis, on fuel bumup and plutonium isotopic composition and indicate if fuel-reprocessing operations are present.
process waste streams from waste or holdup tanks	on reprocessing operations. **Note:** Samples near waste tanks or any discolored pools near waste tanks may be from tank leakage or spills during transfer operations.
soil at suspected HE firing sites	on the composition of implosion systems being tested. The top layer of soil may be removed and covered with a thin layer of uncontaminated earth. **Note:** Fragments of metals used in experiments may be retrieved with metal detectors.

B. Inspection Games to Evade Safeguards

Some possible indications of diversion of nuclear materials for undisclosed uses might tum up. Because the IAEA (International Atomic Energy Agency) can only enter a country on an "invited" basis, there are a number of "foot-dragging" techniques that might be employed to prevent admission. They essentially involve politics and bookkeeping. **Among them might be**

(1) stalling tactics against IAEA inspections, such as repeated objections to agency-designated inspector (this may take the form of purported discrepancies in credentials, access visas, or other paperwork);

(2) refusing IAEA inspectors access to certain portions of the plant for a variety of reasons, for example, an accidental spill;

(3) refusing to admit IAEA inspectors to verify oralloy inventory;

(4) declaring "pilot" fuel-fabrication facility unsafe;

(5) substantial MUF (material unaccounted for) at the processing plant; and

(6) bookkeeping tricks to hide MUF.

Finally, of course, a country may achieve nuclear independence and withdraw from all safeguards agreements.

XI. ADVANCED PROLIFERATION

Once a country has developed the basic infrastructure necessary to produce a nuclear device, research would probably continue toward producing smaller and lighter devices. The first device produced might be deliverable only by truck or ship. **Efforts to enhance the yield-to-weight ratio would try to capitalize on the known development paths of the major nuclear weapon states. These efforts might include the following production and development efforts.**

Goal	Technology Developments	Indicators/Observables
1. Reducing the amount of HE necessary in implosion devices	Use of computer simulations in conjunction with hydrodynamic testing	• Increased activity in computer simulation technology • Frequent HE detonations would be evident to local populations
2. Development of "boosting" technology for nuclear devices	• Developing technologies for handling high-pressure deuterium and tritium gas • Research interest in hydride reactions in uranium and plutonium	Purchase or production of heavy water (large amounts would not be necessary, unless it were to be used in a production reactor)
3. Purchase of isotopically enriched ^{6}Li or development of lithium enrichment technology. ^{6}Li is required to produce tritium and thermonuclear devices.	The Colex process involves enrichment of natural lithium (nominally, 7.5 % ^{6}Li and 92.5% ^{7}Li) by exchange between lithium amalgam and an aqueous solution of lithium hydroxide in a tall, packed column. Lithium-6 concentrates in the amalgam phase and is recovered by decomposing the amalgam with pure water in the presence of a graphite catalyst.	Purchase or use of quantities of mercury and disposal of lithium-contaminated mercury or graphite, hydrochloric acid, and lithium chloride
4. Purchase of tritium (^{3}H) or reactor production of tritium. Tritium is used to produce boosted devices and thermonuclear components of nuclear devices.	Tritium is produced by irradiating lithium (natural or enriched in ^{6}Li) targets in production reactors. After irradiation, the targets are heated in a vacuum to extract the tritium gas. Tritium beta decays with a half-life of 12.3 years, and, unless sophisticated measures are taken, it finds its way to the outside world where it is readily absorbed in the ecosystem.	• Tritium production or a release of tritium into the atmosphere (other indicators of tritium production would include release of ^{3}He or ^{4}He) • Presence of tritium in surrounding vegetation

Goal	Technology Developments	Indicators/Observables
5. Production of both plutonium and ^{235}U (many nuclear devices use both plutonium and ^{235}U)	Reactor production of plutonium or development of uranium-enrichment technology	After an initial weapons infrastructure is established, efforts toward producing both weapons materials might commence.
6. Development of boosted nuclear fission devices [boosted devices use 14-MeV neutrons from the D(T,α)n reaction to increase the device yield from fast fission]	Boosted devices could not be developed without multiple nuclear yield testing.	Indicators include those from technology items (1) through (4) above, combined with theoretical/computational activity in thermonuclear fusion.
7. Development of thermonuclear devices	Multiple tests in the 10-kt range and the technologies of 2-6 are necessary for success.	Test of 10-kt and higher yield devices

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