The most recent NWSMs include:

- FY 1979-81, approved by Carter, 11 January 1978 (PD-26,)
- FY 1980-82, approved by Carter, 5 January 1979 (PD-44),
- FY 1981-83, approved by Carter, 24 October 1980 (PD-?),
- FY 1983-87, approved by Reagan, 17 March 1982 (NSDD-?),
- FY 1983-88, approved by Reagan, 18 November 1982 (NSDD-68),
- FY 1984-89, approved by Reagan, 16 February 1984 (NSDD-?),
- FY 1985-90, approved by Reagan, mid-February 1985 (NSDD-?), and
- FY 1986-91, approved by Reagan, 4 March 1986 (NSDD-?)

Nuclear Weapons Development Guidance

Biennially, the Defense Nuclear Agency prepares a Nuclear Weapons Development Guidance (NWDG) document in coordination with DOE This states *qualitative* requirements for the development of nuclear warheads It identifies potential qualitative requirements for nuclear weapon systems for which the DOD envisions a requirement over the next ten to fifteen years The NWDG also contains a number of technological objectives to guide DOD and DOE research and development These objectives include, increasing the yield-to-weight ratio of a weapon; decreasing the use of special nuclear material; achieving tailored effects such as enhanced or reduced radiation; and developing better command control and disable techniques for protection against possible terrorist threats [22]

Materials Management Plan

The Materials Management Plan (MMP) serves as the annual Department of Energy nuclear materials planning document for producing and using nuclear materials over the ensuing sixteen-year planning period [23] This document is sent to the Office of Management and Budget (OMB) as background information for reviewing the DOE budget The Department of Defense and the National Security Council also use it for nuclear materials planning activities

The basic input to the MMP is from individual MMPs of DOE field offices The enriched uranium analysis is prepared primarily by the Office of Uranium Enrichment and Assessment The MMP is published after issuance of the NWSM [24]

Warhead Development, Stockpiling, and Retirement

DOD and DOE Agreements

The NWDG and military planning documents described above lay the groundwork for research, devlopment, stockpiling, and retirement of specific nuclear warheads This formal process is highly structured and includes seven distinct phases A number of agreements between the DOD or DOE specify the responsibilities of the two agencies during these seven phases Two of the most important agreements date from 1953 and 1983 The 1953 agreement—titled *An Agreement Between the AEC and the DOD for the Development, Production and Standardization of Atomic Weapons*, and dated 21 March 1953—divides responsiblities between the two departments

As set forth in this Agreement the DOD is responsible for the military characteristics, development priority, suitability, and acceptability of nuclear weapons; custody and maintenance of the stockpile; development and production of delivery systems and support equipment for nuclear weapons; and the training and deployment of forces for their use DOD also directs some nuclear-effects and vulnerability tests and evaluation programs It establishes threat assessments, in response to which nuclear weapons are developed

The agreement makes DOE responsible for the design, development, testing, and production of special nuclear materials for weapons, surveillance and certification of the technical quality of stockpiled weapons; provisioning of limited-life components (e g , tritium); and budgeting for the annual appropriation required to conduct these activities DOD and DOE jointly review the safety, handling, and operating procedures for each weapon The separate and joint functions and procedures of each agency are defined for each warhead phase

Supplements to the 1953 Agreement further define responsibilities A 1977 supplement delineates Phase 2 activities in more detail requiring a Major Impact Report and a Weapon Design and Cost Report "for investigating weapons design/military characteristics trade-offs, identifying baseline designs, determining the development schedule and reporting nuclear weapon costs and other resource requirements "[25] A 1984 supplement delineates more specific DOE and DOD responsibilities during Phase 2, Phase 2A (design definition and cost studies) and Phase 3 [26]

A 1983 Memoradum of Understanding reaffirms DOE and DOD objectives, which are to "provide a safe,

22 SASC F 1979 DUR, pp 28-29
23 The nuclear materials include: (1) enriched uranium; (2) weapon grade plutonium; (3) fuel grade plutonium; (4) power-grade plutonium; (5) tritium; (6) plutonium-238; (7) uranium-233; and (8) heavy water
24 General Accounting Office Federal Information Sources and Systems GAO/AFMD-85 1 p 532
25 Supplement to the 1953 Agreement for the Development Production and Standardization of Atomic Weapons Between U S Energy Research and Development Administration and Department of Defense dated 31 May 1977
26 Supplement to the 1953 Agreement for the Development Production and Standardization of Atomic Weapons Between the Department of Energy and the Department of Defense dated 5 September 1984 See also Department of Defense Directive 3150 1 Joint Nuclear Weapons Development Studies and Engineering Projects 27 December 1983

secure, and militarily effective nuclear weapon stockpile, and conduct an aggressive research and development effort to ensure technological superiority and meet future national security needs " Other objectives mentioned are "to improve nuclear weapon stockpile planning and acquisition"; and "ensure continued high-level attention to nuclear weapon safety, security, control and classification "[27]

Phase 1—Concept Definition Studies[28]

Phase 1 consists of continuing studies by DOE laboratories and offices to develop new ideas for a warhead or component to warrant a program study Any DOD office (with the cooperation of other military services and the DOE, as desired) or the DOE may conduct their own Phase 1 study to define a new nuclear warhead concept This study assists DOE laboratories and the Under Secretary of Defense Research and Engineering (USDRE) in deciding whether to proceed with a joint Phase 2 study In Phase 1 DOE compares the practicability of modifying existing warheads or developing new ones

When a Phase 1 study involves a nuclear warhead associated with a major delivery system acquisition, it is coordinated with the DOE Development Concept Paper (DCP), a key document in the approval of a weapon system

A Phase 1 study includes the following information about proposed warhead characteristics and parameters: performance parameters, transportability, employment concepts, delivery techniques, yield and/or effect selection, fuzing options, typical targets, safety considerations, and command and control requirements

Phase 2—Joint Feasibility Studies

A Phase 2 study determines the technical feasibility of developing a nuclear warhead to meet the stated Phase 1 requirement The study presents proposed warhead/delivery system trade-offs and preferred warhead designs It lists warhead parameters (maximum/minimum values) and specific requirements such as yield selectability, warhead interchangeability, and command and control systems A statement of first production unit (FPU) and initial operational capability (IOC) dates with the number of weapons desired is also included

Any military department may submit to the USDRE for approval a request for a joint Phase 2 study If the request is approved, the USDRE designates a military department as the "cognizant Military Department" to chair the study and requests formally, through the MLC, DOE participation In addition to the joint Phase 2 report, the DOE produces a Major Impact Report (MIR) identifying those aspects of the development, design, testing, and production processes perceived as likely determining factors in meeting program objectives The Military Departments annually review Phase 2 studies that have not progressed to Phase 2A or Phase 3 and recommend to the USDRE their disposition The USDRE then informs the DOE through the MLC of any changes in Phase 2 plans

Phase 2A—Joint Design Definition and Cost Studies

After completing a Phase 2 report and before deciding to request a Phase 3 project, the USDR&E also may request, through the MLC, that DOE join the DOD in forming a Project Officers Group (POG) This group conducts a Phase 2A study The DOD request designates a military department to provide the lead Project Officer and includes a projected start date for Phase 3, a projected IOC for the weapons system, and a proposed production schedule The DOE Phase 2A study estimates costs, production schedules, options It also analyzes trade-offs involving safety, security, survivability, and control features for the weapon Cost information is included in a Weapon Design and Cost Report (WDCR) provided by the DOE

Phase 3—Development Engineering Project

Phase 3 launches the warhead's development, at a DOE weapon laboratory It culminates with a proposed warhead design Warhead testing by the laboratories is conducted throughout all phases, including Phase 3 Physics experiments and tests of new weapon design concepts, in fact, are conducted independently of the life cycle, defined by the phases, of a particular warhead

Based upon favorable evaluation of a Phase 2 or 2A study, and with agreement of the JCS, the military service desiring a new warhead requests a Phase 3 project to the USDRE After review within DOD, a Phase 3 request for DOE warhead development is discussed and approved in the MLC The same military service is designated to lead the project for the DOD

In some cases, Phase 3 development on two or more warhead candidates continues to resolve uncertainties During this Phase all options are identified and evaluated These include technological feasibility and risk assessment, costs, nuclear materials availability, test objectives, and stockpile projections The designated military service (see above) designs, develops, and produces those components of the weapon (e g , parachute, bombcasing, reentry vehicle) that are the responsibility of the DOD Issues of design and characteristics of the warhead are then coordinated between the DOE and the DOD at the working level through the POG The lead project officer is responsible for the warhead throughout its stockpile life

Project Officers, in coordination with the DOE, prepare reports defining the new weapon in terms of Military Characteristics (MCs) and Stockpile-to-Target Sequence (STS) (see page 120)

27 Memorandum of Understanding Between the Department of Defense and the Department of Energy on Objectives and Responsibilities for Joint Nuclear Weapon Activities dated 17 January 1983

28 DOD Directive 3150 1 Joint Nuclear Weapons Development Studies and Engineering 27 December 1983

Phase 4—Production Engineering

Phase 4 covers the adaptation of the design developed during Phase 3 into a manufacturing system that can mass produce warheads and components

Testing of developmental prototypes continues during this phase Once the warhead design is approved, the basic tooling, layout, and fundamental assembly procedures are completed

Phase 5—Initial Production

Phase 5 comprises the delivery of the first warhead, called the First Production Unit (FPU) The production during this phase is limited but increases as the various production facilities come into operation The "final review" of the warhead design culminates in acceptance by the MLC of the warhead, termination of Phase 5 and approval of quantity production

Phase 6—Quantity Production

During Phase 6, the DOE and DOD undertake quantity production of warheads for the stockpile Modifications to the warhead may also take place during Phase 6

Phase 7—Retirement

Phase 7 begins when a coordinated program of physical removal of warheads from the stockpile begins Retirement of a warhead (Phase 7) may overlap production of a new modification of the same warhead (Phase 6)

Organizations

The Executive Office of the President

The President makes all final decisions involving the acquisition of nuclear weapons Within the Executive Office of the President two principal bodies—the National Security Council (NSC) and the Office of Management and Budget (OMB)—advise and assist the President They help with major policy and budgetary decisions involving nuclear weapons and warheads

National Security Council

The National Security Council is the principal Executive Branch forum making policy decisions about nuclear weapon acquisition The NSC was created by the National Security Act of 1947 The Act states that "the function of the Council shall be to advise the President with respect to the integration of domestic, foreign, and military policies relating to the national security so as to enable the military services and the other departments and agencies of the Government to cooperate more effectively in matters involving national security " The President, Vice President, Secretary of State, and Secretary of Defense are statutory members The Chairman of the Joint Chiefs of Staff and the Director of Central Intelligence advise and attend meetings of the NSC Other officials—for example, the Secretary of Energy—may attend when nuclear weapons acquisition issues are discussed

The Assistant to the President for National Security Affairs, also called the National Security Advisor, coordinates National Security Council activities In recent years especially, the National Security Advisor and NSC Staff have become influential in the making of policy

Each President since 1947 has used the Council, the National Security Advisor, and the NSC Staff in ways reflecting their preferences and personalities The policy is formulated in part by using Staff structured by regional or functional areas Directors or Special Assistants head smaller office staffs that attempt to coordinate, integrate, and centralize issues from other federal departments and agencies Offices with nuclear weapons responsibilities include Political-Military Affairs, Defense Programs and Arms Control, and Intelligence Programs These offices prepare studies and reports, coordinate and serve on interagency committees, and write key policy guidance In the Nixon and Ford administrations this guidance was known as National Security Decision Memoranda; in the Carter administration Presidential Directives; and in the Reagan administration National Security Decision Directives

The most important acquisition policy document forwarded to the President through the NSC is the Nuclear Weapons Stockpile Memorandum Approved by the President each year, the NWSM authorizes precise numbers of warheads to be built, modified, and retired, as well as special nuclear material requirements over short-, middle-, and long-range periods Other key Presidential nuclear weapons-related documents include the annual Nuclear Weapon Test Program, the annual Nuclear Weapon Deployment Plan, and the periodic Nuclear Weapon Employment Policy

Office of Management and Budget

The Office of Management and Budget coordinates and prepares the budget for the entire Executive Branch A section of the Office devoted to national security affairs oversees the Department of Defense budget and the Atomic Energy Defense Activities portion of the Department of Energy budget

Office of Science and Technology Policy

The Science Advisor to the President heads the Office of Science and Technology Policy This office advises the President and the NSC on all scientific matters, including nuclear weapon technologies

Department of State

The Department of State's primary nuclear weapons responsibility concerns foreign policy implications The Department assesses issues of deployment of weapons abroad, Programs of Cooperation with allies, proliferation, arms control, and testing The Bureau of Politico-Military Affairs is the key office that represents Department views on acquisition policy

The Arms Control and Disarmament Agency also reviews and analyzes the arms control implications of U S nuclear weapons during the acquisition process through its annual volume, the Arms Control Impact Statements

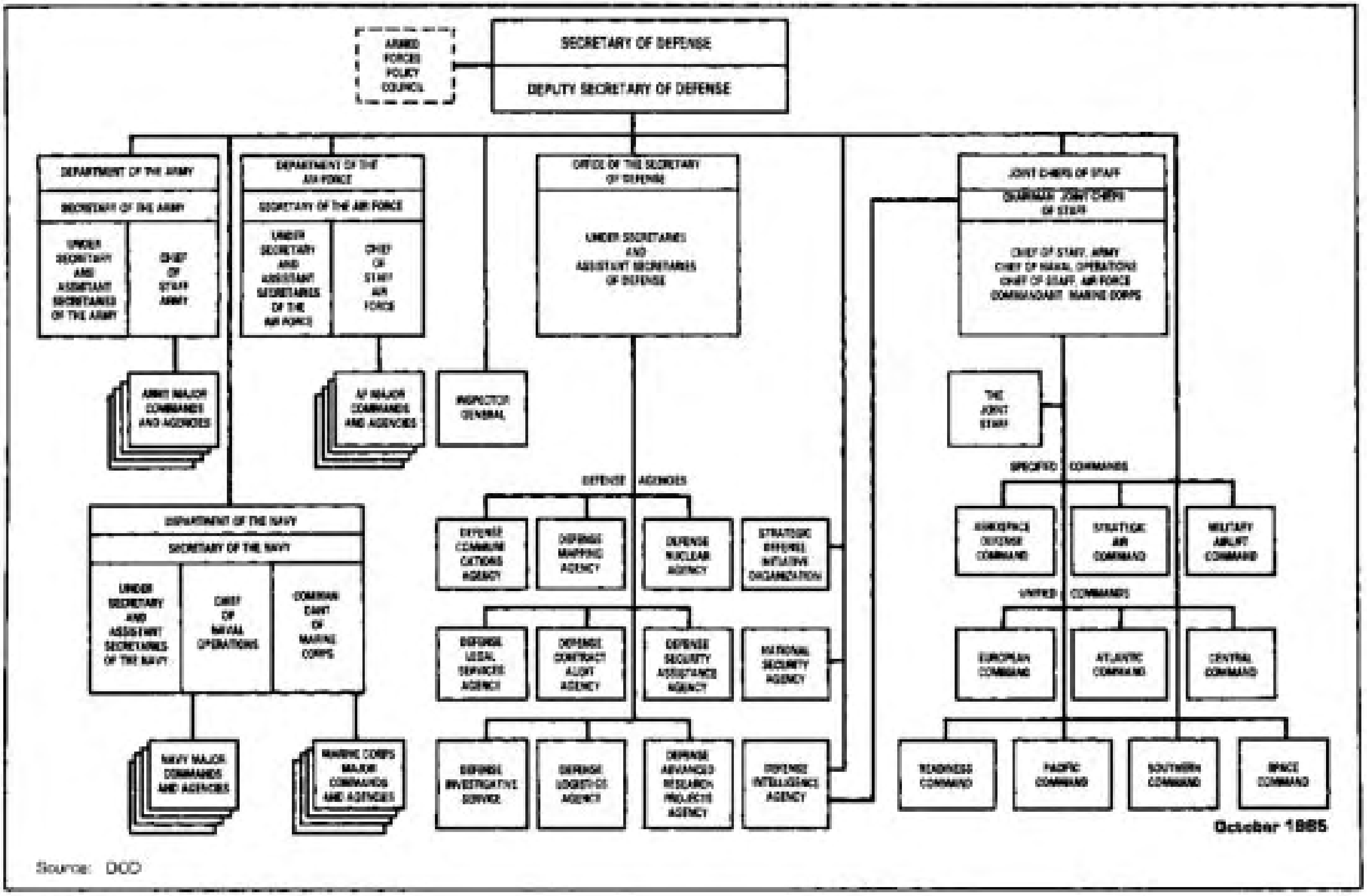


Figure 4 2 Department of Defense

Department of Defense

The decision to acquire nuclear weapons begins with a requirement identified by the Department of Defense [29] As the principal assistant to the President in all matters relating to the Department, the Secretary of Defense (SECDEF) has "direction, authority and control" over all nuclear weapons-related decisions

The major subdivisions within the Department of Defense are: the Office of the Secretary of Defense; the Joint Chiefs of Staff; the three military departments and the military services within those departments; the unified and specified commands; and the defense agencies (see Figure 4 2) [30] Each reports to the Secretary of Defense

Office of the Secretary of Defense

The Office of the Secretary of Defense (OSD), primarily a civilian staff, exercises control over policy development, planning, resource management, and fiscal and program evaluation for the entire department (see Figure 4 3) The Under Secretary of Defense, Research and Engineering (USDRE), was established in 1977 as one of two third-level deputies to the SECDEF It has responsibility for the entire range of matters concerning weapon systems acquisition, including nuclear weapons [31]

As the principal advisor to the SECDEF on scientific and technical matters, the USDRE oversees the military application of atomic energy, nuclear weapons development and acquisition, security, safety, research and development (R&D), deployment, employment and targeting, and theater nuclear force modernization The USDRE also directs the Assistant to the Secretary of Defense, (Atomic Energy) (ATSD(AE)) and the Defense Nuclear Agency It plays a major role in the Defense Systems Acquisition Review Council (DSARC), which advises the SECDEF on major systems acquisitions

The Under Secretary of Defense, Policy (USD(P))

29 The ultimate users (operational commands and units) of nuclear weapons participate indirectly in the development and acquisition process but feed their requirements through the military services or the Joint Chiefs of Staff They are not specifically addressed in this volume See *Nuclear Weapons Databook* Volume I Chapter Three

30 Defense Organization: The Need for Change Staff Report to the SASC Senate Print 99 86 16 October 1985

31 DOD Directive 5129 1

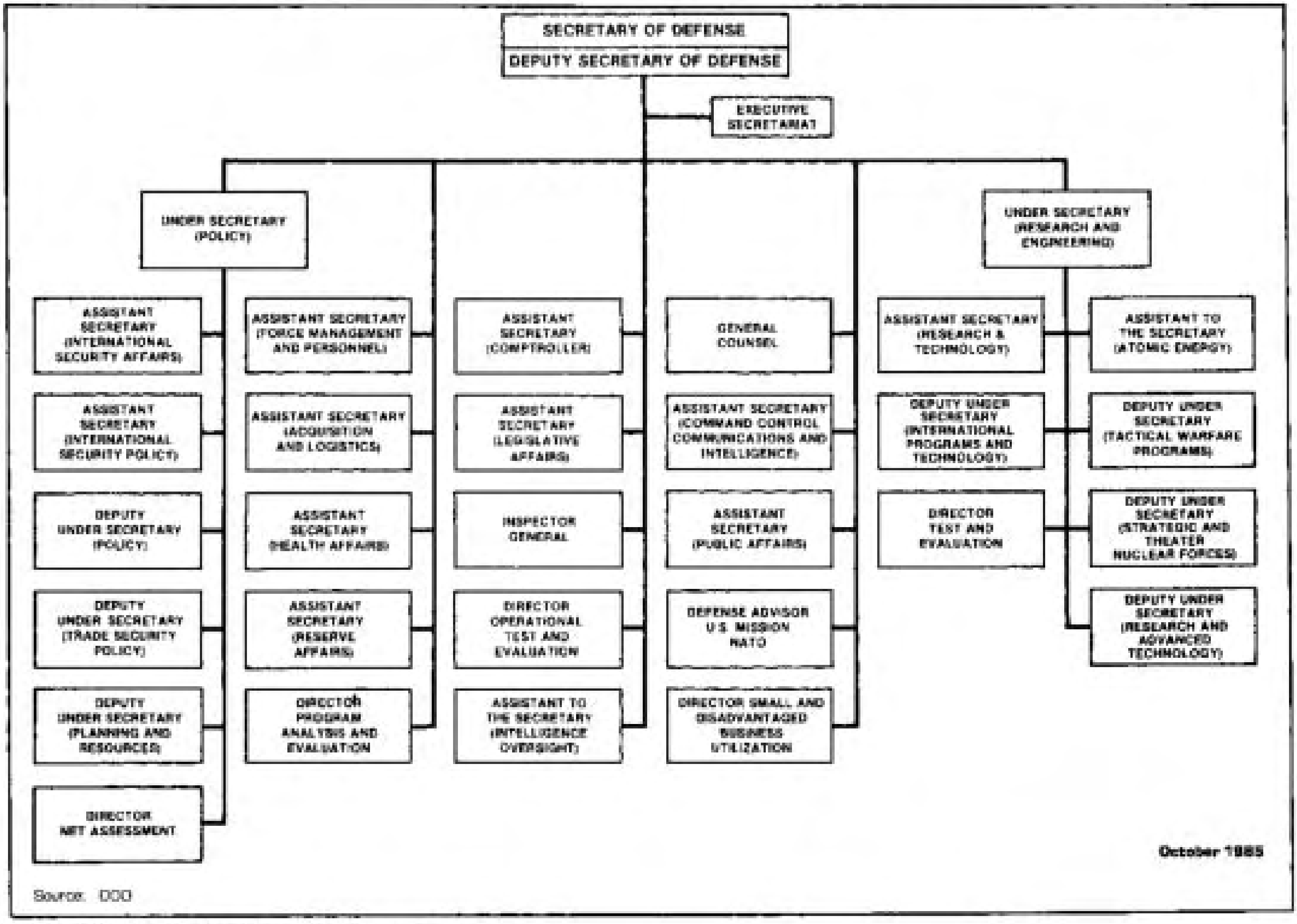


Figure 4.3 Office of the Secretary of Defense

oversees and coordinates formulation and implementation of DOD planning and policy concerning nuclear weapons.[32] As such, he is responsible for nuclear weapons contingency planning and nuclear weapons employment guidance to the Joint Chiefs of Staff and the military departments.

Assistant to the Secretary of Defense (Atomic Energy) The Assistant to the Secretary of Defense (Atomic Energy) (ATSD(AE)) is the principal staff assistant to the SECDEF for nuclear weapons matters.[33] The ATSD(AE) serves under the direction and authority of the USDRE and as the principal staff assistant for DOD atomic energy matters is chairman of the Military Liaison Committee (MLC) to the DOE. ASTD(AE) responsibilities include:

- supervision of nuclear wepaons research and engineering;
- nuclear weapons long-range resource planning, including review and drafting of policy, planning and programming documents on the military applications of nuclear energy;
- logistics aspects of nuclear stockpile management, including stockpile-to-target sequences; and
- technical analyses and support to arms control negotiations.

More specifically, the ATSD(AE) is responsible for policies, plans, and programs in such areas as nuclear weapon development and production; military effectiveness and nuclear warhead characteristics, reliability, security, safety, survivability and endurance; command and control; modernization and status of nuclear materials production; foreign nuclear weapons activities and testing; nuclear weapons accident and incident control

32 DOD Directive 5111.1.
33 DOD Directive 5148.2, 10 August 1978.

measures; and Programs of Cooperation and information exchanges with foreign nations The ATSD(AE) also develops policies and procedures for DOD communications to Congress, as required by the Atomic Energy Act

Military Liaison Committee The Military Liaison Committee (MLC) to the DOE, acting for DOD, is the point of contact for all nuclear weapons matters "that the DOD determines relate to the military applications of nuclear weapons or nuclear energy "[34] These matters include the development, use, and storage of nuclear weapons, the allocation of special nuclear materials, nuclear weapons and military research, and the control of information relating to the manufacture or use of nuclear weapons [35] The MLC serves as the formal channel of communications between DOE and DOD, approves the Military Characteristics (MCs) of nuclear warheads desired by the military services, and transmits Phase 3 requests to DOE for development engineering ("weaponization") of nuclear warheads

The Atomic Energy Act established the MLC as consisting of a chairman appointed by the President and confirmed by the Senate, and an equal number of members from the Army, Navy, and Air Force Additional observers from the JCS, DOE, DNA, and Marine Corps also participate in MLC deliberations (see Table 4 1) Traditionally the Assistant to the Secretary of Defense (Atomic Energy) chairs the MLC In accordance with Section 202 of the Atomic Energy Act of 1954, as amended, the MLC keeps Congress informed on all DOD matters relating to the "development, use, or application of atomic energy "[36]

Joint Chiefs of Staff

The Organization of the Joint Chiefs of Staff (JCS) serves as the principal advisors to the SECDEF and the President on all military matters and specifically the military adequacy of nuclear weapons They state military requirements and prepare strategic and joint war plans, as well as short-, middle-, and long-range projections for nuclear warhead research and development programs The Organization also supervises the operational aspects of the Defense Nuclear Agency—composition of the nuclear stockpile, allocation and deployment of nuclear weapons to military services and Unified and Specified Commands, military participation and support of nuclear testing, and frequency and standards of inspections of nuclear capable units and weapons While not a statutory member of the MLC, the JCS sends an observer [the Assistant Deputy Director for Force Development and Strategic Plans, J-5 Directorate (Plans and Policy)] so that JCS views may be presented [37] The JCS also participates, either as a member or by coordination, in many formal elements of the weapon system acquisition process—for example, development of the Mission Element Needs Statement (MENS) or DSARC deliberations

Defense Nuclear Agency

The Defense Nuclear Agency (DNA) is a designated agency of the DOD It provides support to the SECDEF, the military services, the JCS, and other DOD components in matters concerning nuclear weapons It consolidates management and control of DOD nuclear weapons development, effects research, and the nuclear testing program It is the central coordinating agency with the DOE on matters relating to the research, development, production, stockpiling, and testing of nuclear weapons DNA operates in four key areas:[38]

- central management of the DOD nuclear weapons stockpile, including coordination of specialized technical publications, standardization and certification inspections (inspections of military units having responsibilities for assembling, maintaining, or storing nuclear warheads), production, composition, allocation, deployment, movement, storage, maintenance, quality assurance and reliability assessments, reporting procedures and retirement;
- management and coordination of DOD nuclear weapons testing and nuclear weapons effects research programs, including underground nuclear tests, high explosives tests, simulation experiments, pulse power machines, radiobiology research, and maintaining the "national nuclear test readiness program" at Johnston Island;
- staff advice to the Secretary of Defense, the JCS, the military services, the Unified and Specified Commands, other DOD agencies and non-DOD agencies, on the effectiveness of nuclear weapons, vulnerability to nuclear weapons effects; and nuclear-related problems, including strategy and tactics for weapons-use, -design, and -targeting procedures; and
- oversees DOD nuclear weapons security, including preparation of the DOD *Nuclear Weapons Security Manual*, nuclear surety inspections, management of physical security, survivability, and security of Theater Nuclear Forces, disable/destruct systems, and the Overseas Nuclear Emergency Search Team (ONEST)

The DNA is the oldest of the Defense Agencies It began as the Manhattan Project in 1942, which in turn became the Armed Forces Special Weapons Project on 1 January 1947, the Defense Atomic Support Agency on 6 May 1959 and DNA on 1 July 1971 The Director of DNA is a Lieutenant General or Vice Admiral and reports to the USDRE and JCS DNA reports to the JCS for all activities relating to operational aspects of the nuclear weap-

34 Memorandum for the Special Assistant to the Secretary of Defense concerning Briefing Materials for Incoming Officials (ATSD(AE)) 21 November 1980 p 5

35 DOD Directive 5030 2 4 January 1974; DOD Directive 5148 1

36 DOD Defense Nuclear Agency DOD Directive 5105 31 3 November 1971 pp 2-3

37 For mission and functions see Organization and Functions of the Joint Chiefs of Staff JCS Pub 4 1 July 1980, pp III 8-37-40

38 Defense Nuclear Agency DOD Directive 5105 31 3 November 1971

ons stockpile The USDRE supervises DNA activities relating to nuclear weapons development and effects research and test programs The ATSD(AE) supervises DNA activities associated with nuclear safety, logistics of nuclear weapons, information management, and liaison with the DOE

DNA Headquarters are located in Alexandria, Virginia It operates five major activities for the DOD:

- the DNA Field Command, Kirtland Air Force Base, New Mexico;
- the Armed Forces Radiobiology Research Insititute (AFRRI), Bethesda, Maryland;
- the Joint Nuclear Accident Coordinating Center (JNACC), Kirtland Air Force Base, New Mexico (jointly operated with DOE);
- the Joint Atomic Information Exchange Group (JAIEG), Washington, D C ; and
- the Enewetak radiological cleanup

The agency has 1,150 personnel assigned (44% military, 56% civilian), including 550 at its Field Command at Kirtland Air Force Base, New Mexico

Military Services

The military services—the Air Force, Army, Navy, and Marine Corps[39]—are the ultimate customers for the nuclear weapons produced by the DOE They develop requirements for a particular warhead to satisfy the operational needs and designate its required "Military Characteristics " They then fund, manage, and support the DOD-furnished portions of the nuclear warhead in the development stage and take custody of the completed nuclear weapon upon delivery by DOE During the life of the nuclear warhead the Services provide logistics support, transportation, security, and maintenance, under the guidance and standards of the OSD, JCS, and DNA

The Air Force. The Air Force is the youngest military service and includes the U S strategic aviation and aerospace forces Nuclear warheads currently developed under Air Force guidances and for Air Force use include intercontinental ballistic missiles (TITAN II, MINUTEMAN II and III, MX, Small ICBM), air- and ground-launched cruise missiles, air-to-surface missiles (SRAM and SRAM II), and nuclear bombs (B28, B43, B53, B57, B61, B83) The Air Force also has primary responsibility for developing and procuring nuclear bombs used by Navy and Marine Corps aviation It also serves as custodian for nuclear bombs allocated to allied Air Forces

The Assistant Secretary of the Air Force (Research, Development, and Logistics) is the primary staff officer of the Secretary of the Air Force responsible for overseeing the development and acquisition of Air Force nuclear weapons The Chief of Staff of the Air Force is the senior military officer of the department and a member of the Joint Chiefs of Staff He is the principal Air Force advisor to the President, SECDEF, and Secretary of the Air Force, while supervising and commanding the Air Force

Under the Chief of Staff, the Deputy Chief of Staff, Operations, Plans and Readiness (DCSOPS) sets requirements for nuclear weapons within the Air Force The Director of Plans (AF/XOX) within DCSOPS is the responsible officer for nuclear requirements and one of two Air Force members of the MLC The Deputy Chief of Staff, Research, Development, and Acquisition (DCSRDA) develops Air Force plans, policies and programs for R&D of weapon systems and directs their execution The Directorate of Operational Requirements (AF/RDQ) within the DCSRDA is the responsible office for the development and acquisition of nuclear weapons The Director of the Directorate serves as the second Air Force member of the MLC Also under the DCSRDA is the Special Assistant for ICBM Modernization and the Special Assistant for Strategic Defense Initiative

All matters relating to nuclear safety and security for the Air Force come under command of the Air Force Inspector General (IG) Two agencies of the IG, the Director of Nuclear Security and the Office of Security Police, perform safety and security missions, with worldwide responsibilities in these areas The Directorate of Nuclear Surety of the Air Force Inspection and Safety Center at Kirtland Air Force Base, New Mexico, inspects nuclear units and assures nuclear safety and compliance with security regulations

The functions of research, development, testing, and production within the Air Force are centralized within the Air Force Systems Command (AFSC), with headquarters at Andrews Air Force Base, Maryland Through laboratories, research centers, and operating divisions, the AFSC conducts basic research, exploratory and advanced development, and acquisition of Air Force nuclear delivery systems and warhead components

The Air Force Weapons Laboratory, an AFSC subordinate organization, is the lead Air Force agency for nuclear weapons R&D (see Chapter Two) AFWL functions include:

- preparation of Phase 1 studies;
- participation with DOE and other DOD agencies in Phase 2 studies;
- origination of Military Characteristics and Stockpile-to-Target Sequences for Air Force nuclear warheads; and
- participation in safety studies, Project Officer meetings, Design Review and Acceptance Group (DRAAG) meetings

Three divisions of AFSC and one office also act as product subcommands: Aeronautical Systems Division, Electronics Systems Division, Space Division, and the Ballistic Missile Office The Aeronautical Systems Divi-

39 The Coast Guard is also a military service

sion (ASD), at Wright-Patterson Air Force Base, Ohio, develops and acquires aircraft and subsystems ASD work includes such programs as B-52 offensive avionics and integration of the air-launched cruise missile with the B-52, B-1B, and the Advanced Technology Bomber (ATB) ("Stealth") The Air Force Wright Aeronautical Laboratories of ASD supervises the work of the Air Force Avionics Laboratory, the Flight Dynamics Laboratory, and the Air Force Materials Laboratory All of these work on nuclear weapons components and delivery systems

Electronic Systems Division (ESD), located at Hanscom Air Force Base, Massachusetts, manages electronics and command and control systems Space Division, at Los Angeles Air Force Station, California, manages all space-related activities Its Space Technology Center at Kirtland Air Force Base, New Mexico supervises the work of AFWL (described above) and other laboratories Among these are the Air Force Geophysics Laboratory, Hanscom Air Force Base, Massachusetts, which conducts research and advanced development in geophysics, including nuclear modeling for the DNA The Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, California conducts research, and exploratory and advanced development of rocket propulsion technology, including work on the MX, air-launched missiles, SRAM, TITAN, and MINUTEMAN

The Ballistic Missile Office, at Norton Air Force Base, California, handles all Air Force design, development, and acquisition of ballistic missile systems, including the MX, Small ICBM, and new reentry vehicles It also operates the Space and Missile Test Organization (SAMTO) (see Chapter Two)

The Directorate of Special Weapons of the Air Force Logistics Command, located at the San Antonio Air Logistics Center at Kelly Air Force Base, Texas, provides day-to-day management and logistics support to the nuclear warheads under the operational control of the Air Force [40] In addition, the Directorate supervises three Air Force Aviation Depot Squadrons These, in turn, operate central nuclear weapons depots and provide maintenance services at Barksdale Air Force Base, Louisiana; Nellis Air Force Base, Nevada; and Kirtland Air Force Base, New Mexico

The Army. The Department of the Army is DOD's senior service It is responsible for the support and preparation of land forces Nuclear warheads currently developed under Army guidance and for Army use include 155mm and 8-inch nuclear artillery projectiles, NIKE-HERCULES surface-to-air missiles, surface-to-surface missiles (HONEST JOHN, LANCE, PERSHING 1a, PERSHING II), and atomic demolition munitions The Army maintains custody of its nuclear warheads used by allied forces, including two nuclear weapons (NIKE-HERCULES and HONEST JOHN) that are no longer used by U S forces Nuclear artillery projectiles and atomic demolition munitions (ADMs) are also developed for use by the Marine Corps, and ADMs for the Navy

The Assistant Secretary of the Army (Research, Development, and Acquisition) is the Secretary of the Army's principal advisor on development and acquisition of Army weapon systems The Chief of Staff, through his direction over the Army staff (also called the General Staff), coordinates Army decisions relating to nuclear weapons

The Chief of Staff of the Army ranks as the senior military officer of the Department of the Army He sits under the Joint Chiefs of Staff and is the principal advisor to the President on Army matters, SECDEF, and Secretary of the Army Finally, he supervises and commands Army forces

Within the Army staff, the Nuclear and Chemical Directorate (DAMO-NC) in the Office of the Deputy Chief of Staff for Operations and Plans (ODCSOPS) is the "focal point for nuclear and chemical warfare and NBC [Nuclear, Biological, Chemical] matters and shall act as the principal adviser to the SA [Secretary of the Army], CSA [Chief of Staff of the Army], and ARSTAF [Army Staff] for these matters "[41] The Director of DAMO-NC acts for the DCSOPS on most nuclear matters, is one of two Army members on the MLC, and also commands the U S Army Nuclear and Chemical Agency

> He is responsible for monitoring, coordinating, and integrating Department of the Army efforts in all matters involving nuclear and chemical weapon operations and NBC defense including, but not limited to, weapon system and equipment development; weapon system design; reliability, safety, and security; employment and deployment policy; nuclear and chemical weapon system operational testing; and force survivability His responsibilities do not include nuclear reactors [42]

The Directorate has broad responsibilities relative to employment, deployment, operations, training, safety, and arms control policy It coordinates Army views and positions within the DOD relating to "material needs for theater nuclear [weapons] "[43] DAMO-NC compiles Army contributions to the nonstrategic nuclear forces sections of key planning documents The Directorate also determines Army requirements for nuclear forces and resources, prepares joint DOE-DOD Phase 1 studies, approves Army nuclear weapons Stockpile-to-Target documents, and coordinates the Army stockpile reliability program In addition, the Directorate is responsible for "developing and expressing Army policy for achieving national weapon BMD [Ballistic Missile Defense] in coordination with the BMD Program Manager and in consonance with military objectives "[44]

40 AFLC Directorate of Special Weapons AFLC Regulation 23-46 8 July 1977
41 Army CSR 5 14 p 1
42 Ibid
43 Ibid p 2
44 Ibid

Decisionmakers—DOD/Army

The Army Nuclear and Chemical Agency (ANCA) (see Chapter Two) is the staff agency of the DCSOPS that conducts research and development activities dealing with nuclear weapons It is also responsible for the safety and security of nuclear weapons The Director of the ANCA is also the Director of Strategy Plans and Policy within the DCSOPS Like the Air Force Weapons Laboratory of the Air Force, ANCA prepares most nuclear warhead requirements documents (Military Characteristics, Stockpile-to-Target Sequences), and participates in Program Officer Groups during warhead development

Whereas the DCSOPS formulates overall Army requirements for nuclear weapons, the Deputy Chief of Staff for Research, Development and Acquisition (DCSRDA) is the principal staff office responsible for nuclear hardware issues and programs The office monitors

> research, development, testing, evaluation, acquisition, and maintenance engineering of nuclear and chemical projectiles, warhead sections, replacement items, delivery systems (less ABM), nuclear cratering and demolition devices, and nuclear, chemical, and radiological defensive hardware and equipment [45]

Within the DCSRDA, the Director of Combat Support Systems (DAMA-CS) is the principal nuclear weapons-related staff officer and the second Army member of the MLC The Director develops procurement plans and budgets, and provides guidance to materiel developers In coordination with DOE, the Director manages Army nuclear warhead programs "from exploratory development through operational system development and acquisition phase" and prepares joint DOE-DOD Phase 2 and Phase 3 studies and projects This Directorate is also responsible for testing the quality assurance and reliability of Army nuclear warheads

As the primary Army staff logistics agent, the Deputy Chief of Staff for Logistics (DCSLOG) is responsible for developing policy and funding requirements for the maintenance, supply, and logistical aspects of nuclear warheads, including stockpile surveillance and reliability programs In addition, all materiel management of Army nuclear weapons, including the custody and accountability of nuclear warheads, repair and supply parts, and nuclear materials falls under the DCSLOG [46]

The Chief of Engineers (COE) is also responsible for some nuclear matters, including the Army Nuclear Power Program, and nuclear reactor research and development, construction, and operations [47]

Army Materiel Command The functions of research, development, test and evaluation, procurement and production, and logistics support of Army weapons system are under the Army Materiel Command (AMC) [48] With headquarters in Alexandria, Virginia, AMC controls Army development of nuclear weapons through product subcommands, laboratories, proving grounds, and testing ranges The Deputy Commanding General for Research, Development, and Acquisition also serves as the Executive Director for Chemical and Nuclear Matters An AMC Field Office at Kirtland Air Force Base, New Mexico performs liaison with the DNA Field Command, AFWL, NWEF, and other nuclear weapons organizations in New Mexico

The major subcommand of AMC responsible for nuclear weapons is the Army Armament Munitions and Chemical Command (AMCCOM), headquartered at Rock Island Arsenal, Illinois AMCCOM is the Army manager and developer of nuclear weapons including nuclear artillery, rocket and missile warhead sections, atomic demolition munitions, and fire control systems The Army Armament Research and Development Center, in Dover, New Jersey, is the armament R&D arm of AMCCOM

Within AMC, a program, project, or product manager is designated to supervise the total development of major weapons systems Currently, there are three managers involved in the development of nuclear weapons: Joint Tactical Missile Systems (JTACMS), Nuclear Munitions, and PERSHING

The Nuclear Munitions Project Office within AMC has responsibility for life-cycle management of nuclear weapons in the custody of the Army Specific responsibilities of the Project Office include:

- life-cycle management, to include development, procurement, production, product improvement, product assurance, safety, stockpile reliability, integrated logistics support, and new equipment training;
- serving as lead project officer for Army nuclear weapon systems;
- chairing Phase 2 feasibility studies;
- chairing Design Review and Acceptance Group (DRAAG);
- providing chairmen for joint test working groups and nuclear weapons subsystems; and
- providing the principal Army members for configuration control groups and Joint Task Groups

Other subcommands of AMC with nuclear weapons responsibilities include:

- the Depot Systems Command in Chambersburg, Pennsylvania, which operates the Army's two central nuclear storage and maintenance depots: Sierra Army Depot in Herlong, California, and Seneca Army Depot in Romulus, New York;

45 CSR 5 14 p 7
46 CSR 5 14 pp 8-9
47 CSR 5 14 p 11
48 AMC was formerly the Army Materiel Development and Readiness Command (DARCOM) which was redesignated Army Materiel Command on 1 August 1986

- the Test and Evaluation Command at Aberdeen Proving Ground, Maryland, which operates the Army testing grounds (see Chapter Two); and
- the Army Missile Command at Redstone Arsenal in Huntsville, Alabama, which manages the research, development, acquisition, and logistic support of tactical nuclear missiles (including PERSHING 1a & II, NIKE-HERCULES, JTACMS, LANCE, and HONEST JOHN)

The laboratories of AMC involved in nuclear weapons work include:[49]

- Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, which performs R&D on propulsion dynamics, launch and flight dynamics, warhead dynamics, terminal and nuclear weapons effects, primary laboratory for design of nuclear artillery;
- Harry Diamond Laboratories, Adelphi, Maryland performs R&D on fire control, fuzing (PERSHING II, 8-inch and 155mm nuclear artillery projectiles), warhead electronics, nuclear weapons effects; and
- Belvoir R&D Center, Fort Belvoir, Virginia, which is responsible for physical security and mobility equipment

The Training and Doctrine Command (TRADOC), headquartered at Fort Monroe, Virginia, trains personnel to employ nuclear weapons, and develops Army nuclear doctrine and requirements

The Navy and Marine Corps. The Department of the Navy includes both the Navy and Marine Corps services Navy nuclear warheads in use or currently being developed include submarine-launched ballistic missiles (POSEIDON, TRIDENT I, TRIDENT II), the TOMAHAWK sea-launched cruise missile, TERRIER and STANDARD 2 surface-to-air missiles, and anti-submarine rockets [SUBROC, ASROC, vertical launch ASROC (VLA), SEA LANCE ASW Standoff Weapon] Nuclear bombs used by Navy and Marine Corps aviation components, as well as marine nuclear artillery and atomic demolition munitions, are the primary development responsibility of the Air Force and Army, respectively The Navy maintains custody of nuclear depth bombs for allied forces

All matters related to research, development, engineering, test and evaluation within the Navy come under the purview of the Assistant Secretary of the Navy (Research, Engineering, and Systems) [ASN(R,E&S)], who operates through four program Directors: Strategic Programs, Air Programs, Surface Programs, and Submarine/Anti-submarine Programs

The Chief of Naval Operations (CNO) is the senior military officer of the Department of the Navy and a member of the Joint Chiefs of Staff He is the principal Navy advisor to the President, SECDEF, and Secretary of the Navy He supervises and commands the Navy and Marine Corps Under the CNO, the Office of Naval Warfare (OP-095) coordinates doctrine, strategy, and force levels, while the Office of Research, Development, Test, and Evaluation (OP-098) coordinates weapons development The Undersea & Strategic Warfare and Nuclear Energy Development Division (OP-981) of the Office is the principal Navy hardware staff office involved in the development of nuclear weapons The Director of OP-981 is one of two Navy members on the MLC

The Deputy Chiefs of Naval Operations (DCNOs) act as principal advisors to the CNO with respect to force levels and characteristics of weapon systems DCNOs responsible for nuclear weapons include: DCNO (Submarine Warfare) (OP-02); DCNO (Surface Warfare)(OP-03); DCNO (Air Warfare) (OP-05); and DCNO (Plans, Policy, and Operations) (OP-06) The Director, Anti-submarine Warfare (ASW) and Ocean Surveillance Program (OP-095), also coordinates requirements for ASW weapons

Within the office of the DCNO (Plans, Policy, and Operations) is the Strategic and Theater Nuclear Warfare Division (OP-65), the main Navy office coordinating operational requirements and plans related to nuclear weapons The Director of the Division is the second Navy member of the MLC He coordinates Navy requirements in a similar fashion to the work of the DCSOPS of the Air Force and Army

The Commandant of the Marine Corps is also a designated observer on the MLC His Deputy Chief of Staff for Research, Development and Systems in HQ, Marine Corps (HQMC) is the principal staff officer responsible for acquisition of new systems Marine Corps staff representation is found in all Navy organizations which deal with Marine Corps nuclear weapons

The Naval Weapons Evaluation Facility advises, assists, and provides technical support to the CNO on all matters related to naval nuclear weapons (see Chapter Two) It conducts feasibility studies on new concepts and design criteria for future naval nuclear weapons (Phase 1 and 2 studies) and prepares Military Characteristics and Stockpile-to-Target Sequences for new Naval nuclear weapons

The Chief of Naval Materiel, under the CNO, supervises and commands all Navy research, development, test and evaluation The Office of Naval Materiel consists of the five systems commands—Air Systems Command, Space and Naval Warfare Systems Command, Sea Systems Command, Facilities Engineering Command, and Supply Systems Command—project management offices

49 These laboratories are under the supervision of the Army Laboratory Command in Adelphi, Maryland, which was activated on 1 October 1985 of the former Army Electronics R&D Command

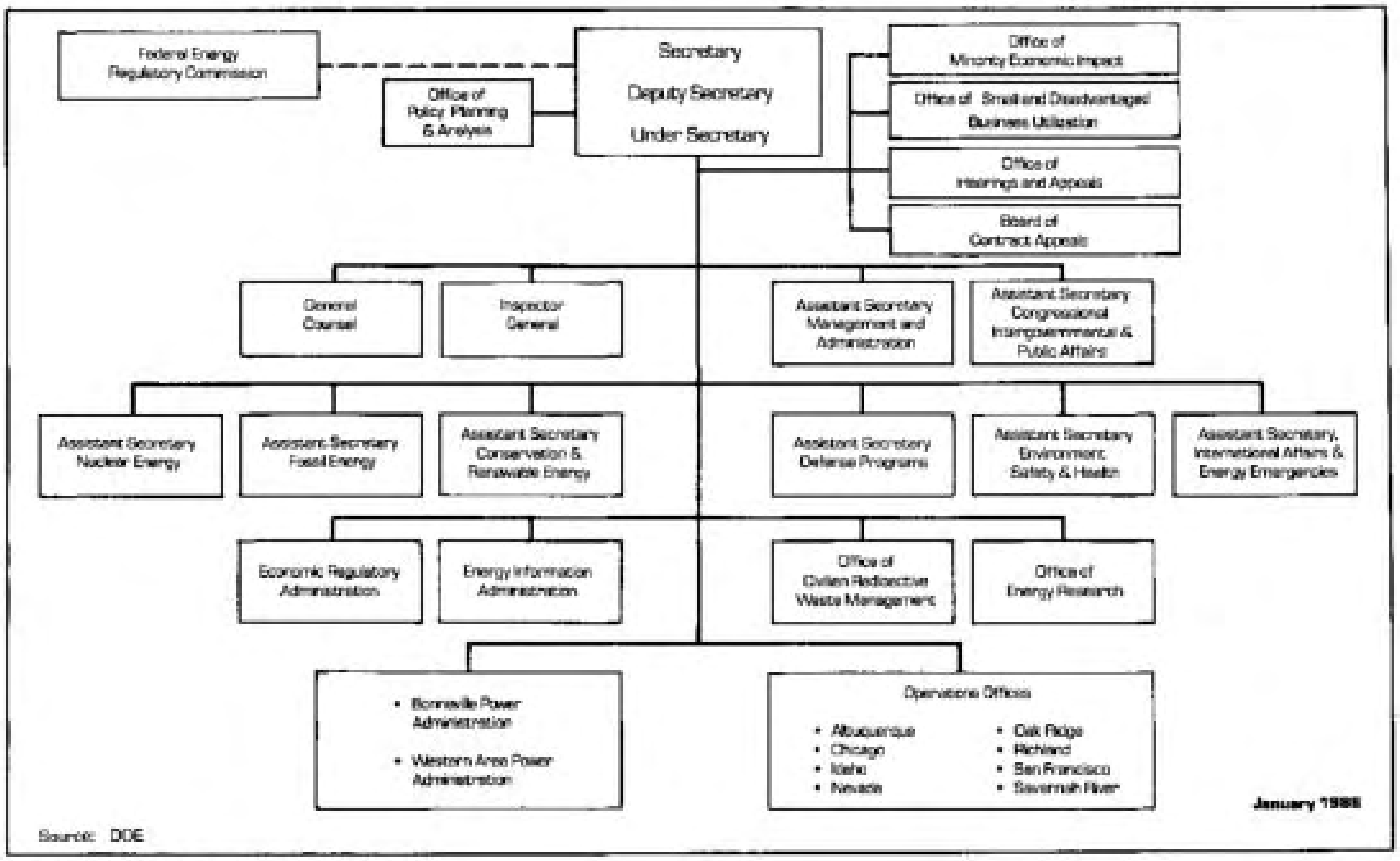


Figure 4 4 The Department of Energy

(and Joint project offices), and research and development centers and laboratories The Naval Space and Naval Warfare Systems Command develops all air- and shipboard-delivered nuclear weapons The Naval Sea Systems Command is responsible for nuclear weapons safety studies, and nuclear storage and security Stockpile evaluation and reliability management for all Navy and Marine nuclear warheads is provided by the NMC through the Naval Weapons Station, Seal Beach, California

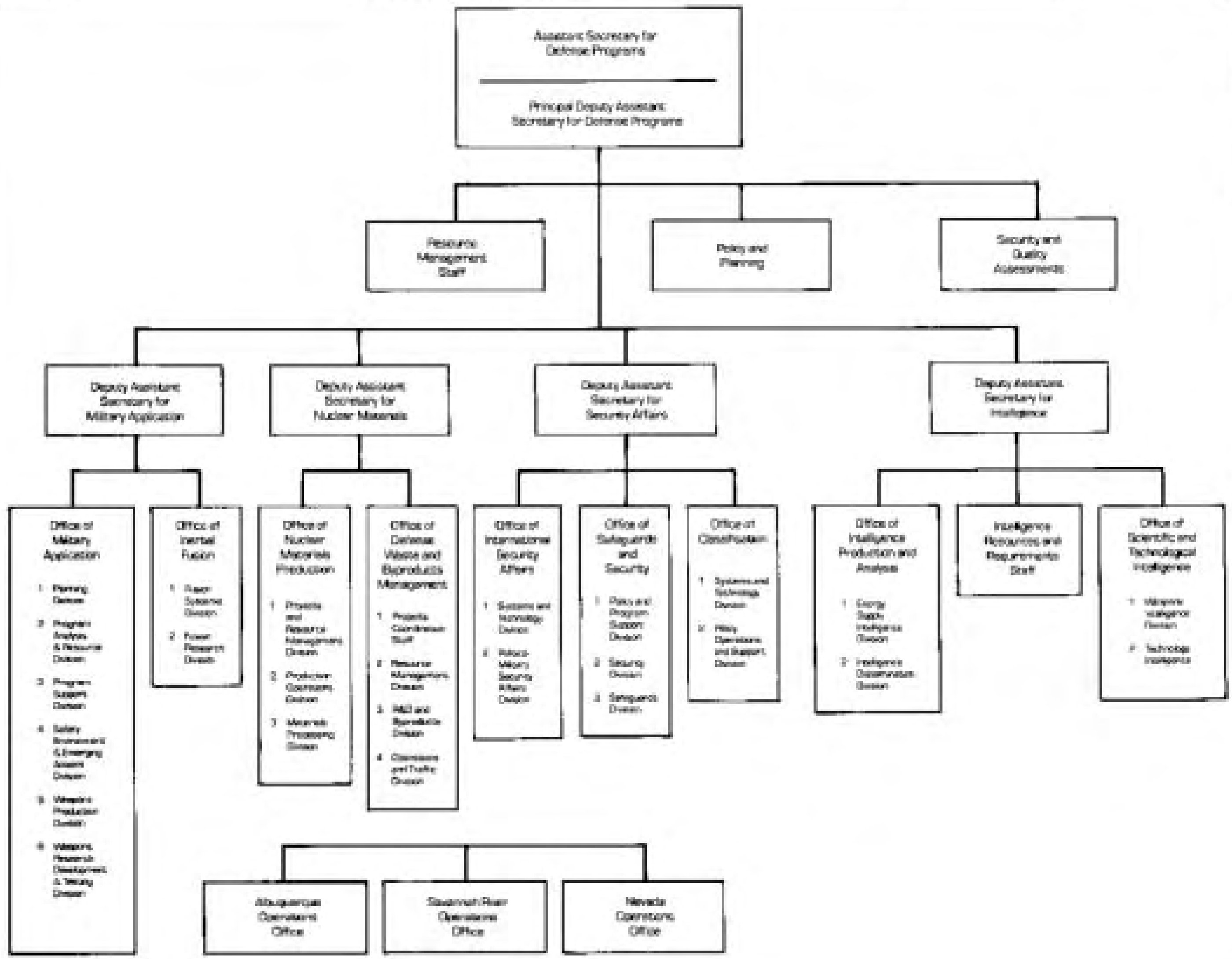
Currently there are four project offices of the Office of Naval Materiel that oversee the life-cycles of nuclear weapons and delivery systems:

- Strategic Systems Project Office (PM1): responsible for the development, acquisition, and operational support of Fleet Ballistic Missile (FBM) systems;
- TRIDENT System Project Office (PM2): responsible for the development and deployment of the TRIDENT submarine and missile systems;
- Joint Cruise Missile Project Office (JPM3): responsible for the development of all long-range sea and ground cruise missiles; and
- Theater Nuclear Warfare Project (PM23): responsible for the management of the development, procurement, and life-cycle support of theater nuclear warheads [50]

Under the Space and Naval Warfare Systems Command, there are a number of R&D centers and laboratories that also perform work related to nuclear weapons and delivery systems:

- David W Taylor Naval Ships R&D Center, Carderock, Maryland: RDT&E for naval vehicles, ships, and logistics;
- Naval Ocean Systems Center, San Diego, California: R&D on ASW nuclear weapons;
- Naval Surface Weapons Center, Dahlgren, Virginia: the principle Navy RDT&E center for surface-ship weapon systems, ordnance, mines, and strategic systems support including nuclear warhead fuzing and anti-submarine warfare development (through its White Oak, Maryland laboratory);
- Naval Undersea Warfare Engineering Station Key-

50 Naval Material Command "Designation of Theater Nuclear Warfare (TNW) Project NAVMAT INSTRUCTION 5430 62 24 June 1981 p 1



Source DOE

Figure 4 5 Defense Programs Organization

port, Washington: conducts RDT&E of nuclear-capable ASW weapons through its detachment at Barking Sands, Hawaii;

- Naval Underwater Systems Center, Newport, Rhode Island: RDT&E of submarine weapon systems; and
- Naval Weapons Center, China Lake, California: principal Navy RDT&E center for air warfare, missile systems, cruise missiles, and anti-submarine rockets and missiles

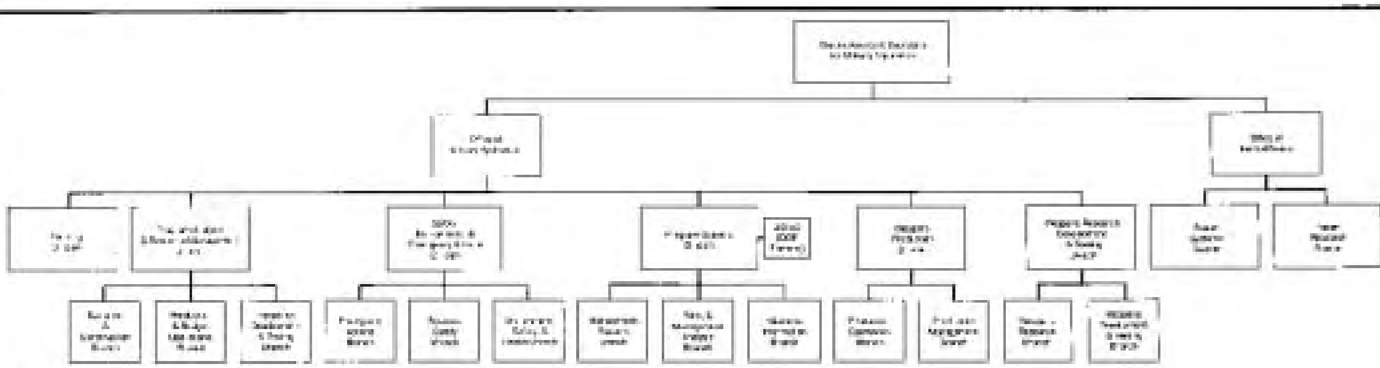
The Naval Explosive Ordnance Disposal Facility, at Indian Head, Maryland, is responsible for joint RDT&E and training of explosive ordnance disposal (EOD) and establishes safe procedures for nuclear warheads within the DOD

Department of Energy

The Department of Energy, like other federal departments, is organized hierarchically Headquarters and offices are located at the Forrestal Building in Washington, D C and in Germantown, Maryland The senior official is the Secretary of Energy, who together with his Deputy and Under Secretaries supervises eight Assistant Secretaries (see Figure 4 4) Below the assistant level come Deputy Assistant Secretaries, Office Directors, Division Directors, and Branch Chiefs The principal office responsible for nuclear warheads is the Assistant Secretary for Defense Programs

Assistant Secretary Defense Programs

The Assistant Secretary for Defense Programs (ASDP) is the principal advisor to the Secretary on national security matters and the manager of the nuclear



Source: DOE

Figure 4 6 Military Application

weapon program and weapon complex He also manages programs for: nuclear materials production, international security affairs, safeguards and security, classification, defense nuclear waste, inertial confinement fusion, and intelligence To help carry out these responsibilities, a principal Deputy and four Deputy Assistant Secretaries oversee nine program offices (see Figure 4 5)

Deputy Assistant Secretary for Military Application. Within the Office of Military Application (OMA) are divisions and branches that formulate plans and policies and direct the nuclear weapon research, development, testing, and production programs (see Figure 4 6) The Deputy Assistant Secretary for Military Application also serves in a dual capacity as Director of the Office of Military Application and is responsible for the Office of Inertial Fusion By statute the Director of Military Application must be a military officer

Some specific responsibilities of the various Branches are:

Production Operations

- Direct and monitor nuclear weapon production, modifications, retirement, disposal, quality assurance, and reliability assessment programs;
- Develop, publish, distribute, and maintain the currency of the DOE Nuclear Weapons Production and Planning Directive; and
- Coordinate MLC matters

Production Management

- Develop planning for the design, development, testing, and production of new nuclear weapons and components;
- Monitor the weapons complex quality assurance program;
- Maintain liaison between DOD program offices and DOE laboratories and the warhead production complex; and
- Monitor material sources and availability necessary for nuclear warhead production

Weapons Information

- Control access and authorize communication of weapon data in oral or written form; and
- Assist the United Kingdom in nuclear weapons design, development, and fabrication activities

Weapons Development and Testing

- Participate in the development of policy and guidance on nuclear weapons research, development, and testing programs; and
- Develop, for Presidential approval, guidance to field activities for the conduct of the annual underground testing program and prepare for the ASDP the underground nuclear tests planning directive

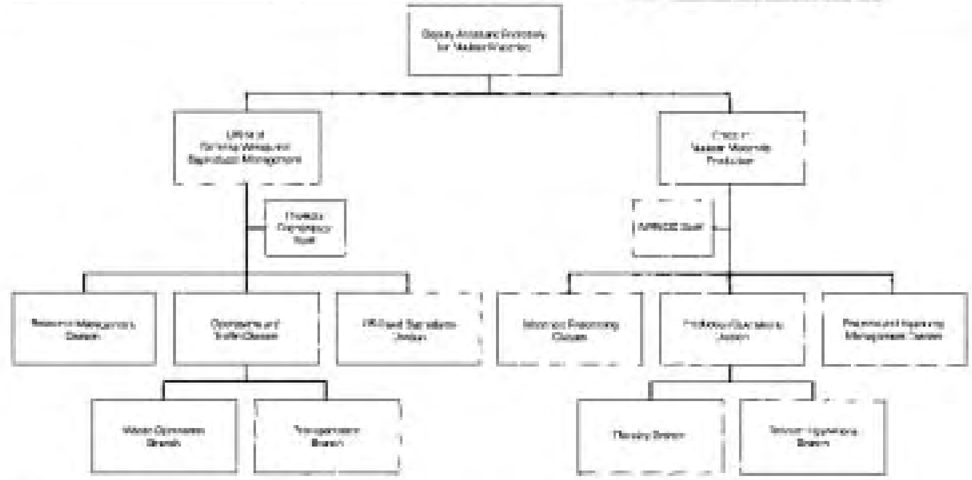
Systems Safety

- Serve as the DOE contact with the DOD and the Services for all matters concerned with the safety and security of nuclear warheads; and
- Coodinate the development of the joint *DOD/DOE Annual Report to the President on Nuclear Weapons Surety*

The Division of Planning prepares, with the DOD, the annual NWSM for Presidential approval, the Nuclear Weapon Program Plan, and prepares and distributes *A History of the Nuclear Weapons Stockpile* The Division also provides OMA input to nuclear material planning documents The DOE is represented on the Joint (DOD/DOE) Atomic Information Exchange Group, which transmits nuclear weapon information (Restricted Data/Formerly Restricted Data) to foreign governments

The Office of Inertial Fusion is responsible for planning, developing, coordinating, and supervising the programs for research, development, demonstration, and utilization of laser and particle beam initiated inertial fusion for military and domestic energy application

Deputy Assistant Secretary for Nuclear Materials. The Deputy Assistant Secretary for Nuclear Materials



Source DOE

Figure 4 7 Deputy Assistant Secretary for Nuclear Materials

oversees two offices—Nuclear Materials, and Defense Waste and Byproducts Management—each with three divisions (see Figure 4 7) Responsibilities of the divisions are:

The Materials Processing Division
- Manages the processing of production reactor fuel and targets;
- Manages tritium production and the recovery of Pu-238 and transplutonium materials from special reactor targets; and
- Develops technology for new and improved chemical processing capabilities

The Production Operations Division
- Provides program management for the operations of the production reactors, fuel fabrication facilities, reactor feed plants, and other facilities to produce nuclear materials for warheads;
- Directs program to develop new and improved technology for nuclear materials production: and
- Provides near- and long-term planning with DOD and the Planning Division of OMA to develop the annual NWSM

The Office of Defense Waste and Byproducts Management is responsible for the storage, transportation, and disposal of nuclear wastes generated from the material production facilities, the naval propulsion reactor and test reactor programs, and the warhead component facilities Byproduct management includes the use of tritium, cesium, krypton, strontium, and noble metals recovered from nuclear waste for military and civilian application

Deputy Assistant Secretary for Security Affairs. The Deputy Assistant Secretary for Security oversees three offices dealing with Classification, International Security, and Safeguards and Security (see Figure 4 8)

The International Security Office
- Develops and produces the sensors and devices to monitor foreign nuclear explosions conducted underground, in the atmosphere, and in space, and to monitor compliance with nuclear weapons related treaties;
- Controls exports of nuclear and energy-related materials, equipment, and technology to ensure they are consistent with U S national security and with nonproliferation policy; and
- Provides technical and analytical support for DOE's role in nuclear arms control negotiations, policy formulation, and implementation

The Office of Safeguards and Security
- Develops measures to protect DOE nuclear warheads, nuclear materials, facilities, and classified information against theft and sabotage by "terrorists, criminals, psychotics, disgruntled employees, and anti-nuclear extremists "[51]

The Office of Classification
- Executes the DOE classification program, developing criteria for the classification and declassification of Restricted Data, Formerly Restricted Data, and National Security Information within DOE's jurisdiction in accordance with requirements of the Atomic Energy Act of 1954, as amended, Executive Order 12065 and successor laws and statutes

51 HAC FY 1985 EWDA Part 6, p 676

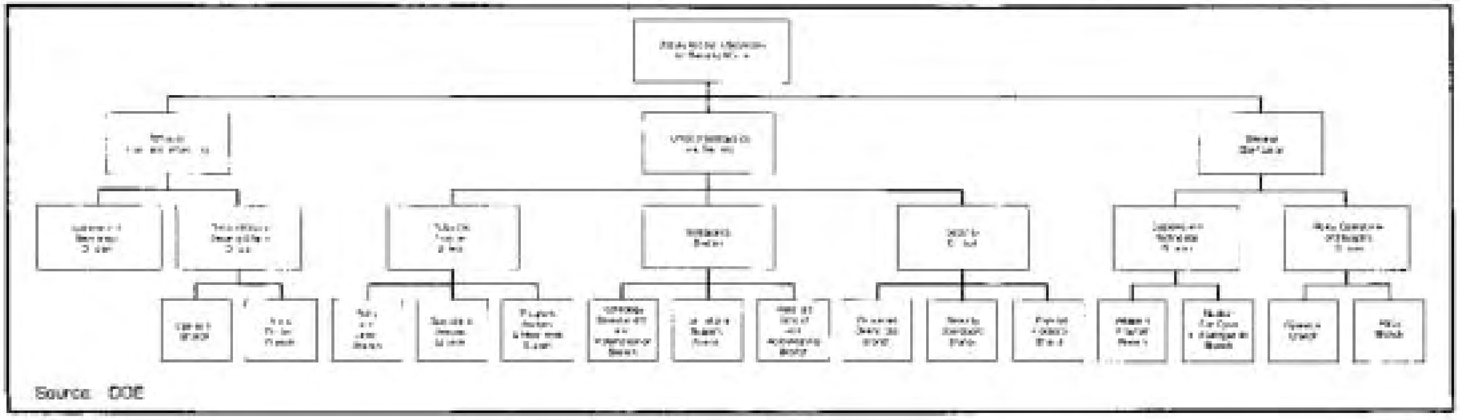


Figure 4 8 Deputy Assistant Secretary for Security Affairs

Deputy Assistant Secretary for Intelligence. In January of 1984 the Secretary of Energy decided to upgrade the importance of the intelligence function within DOE and created the post of Deputy Assistant Secretary for Intelligence within Defense Programs The Secretary transferred to him the Division of Intelligence that had been under the Office of International Security Affairs This Deputy Assistant Secretary also acts as DOE's Senior Intelligence Officer, reporting directly to the Secretary (see Figure 4 9)

While the Department of Energy has no intelligence-gathering functions,[52] relying for information on the CIA and DOD, it conducts technical analyses of nuclear weapons developments

The *Division of Weapons Intelligence*

- Identifies the threat to U S weapons from foreign capability;
- Determines and assesses the differences between U S and Soviet weapon design practices Maintains programs to insure that a future Comprehensive Test Ban does not place the United States at a disadvantage;
- Characterizes and assesses past and present Soviet and Chinese nuclear weapon design technologies and philosophies; and
- Monitors the Soviet and Chinese weapons complex

The *Division of Technology Intelligence*

- Prepares intelligence studies for the purpose of developing national estimates regarding nuclear proliferation

The Office of the Deputy Assistant Secretary for Intelligence also represents the DOE on the Signals Intelligence (SIGINT), Photographic Intelligence (PHOTINT), and Human Intelligence (HUMINT) Committees of the Director of Central Intelligence Additional responsibilities include the representation of DOE on other intelligence and counterintelligence collection related subcommittees and working groups within the Intelligence Community and on selected National Intelligence Estimate panels

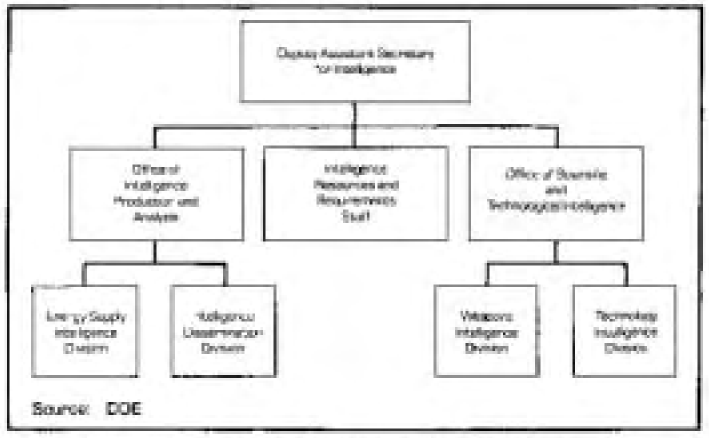


Figure 4 9 Deputy Assistant Secretary for Intelligence

Assistant Secretary for Nuclear Energy

Three programs under the Assistant Secretary for Nuclear Energy (ASNE) are weapon-related The Naval Nuclear Propulsion Program (NNPP) is a joint program of the DOE and the Department of the Navy The Director of NNPP (in the Office of the Chief of Naval Operations) also serves as Deputy Assistant Secretary for Naval Reactors (DOE) and Deputy Commander for Nuclear Propulsion, Naval Sea Systems Command [53]

The NNPP commands all matters concerning the nuclear propulsion of naval ships and submarines This includes the design, development, and testing of propulsion plants and reactor cores Development work is carried out at Knolls Atomic Power Laboratory, Schenectady, New York, and Bettis Atomic Power Laboratory, Pittsburgh, Pennsylvania, operated for DOE by Westinghouse Electric Corporation and General Electric Company respectively The NFS Erwin (Tennessee) plant (see Chapter Three) fabricates naval nuclear fuel

52 Executive Order 12333 U S Intelligence Activities

53 See Executive Order 12344 1 February 1982 in HASC FY 1982 DOE p 10-12

The ASNE is also responsible for research in space power systems that would supply prime power for a number of Strategic Defense Initiative platforms and other systems These applications include multimegawatt power for non-Nuclear-Driven Directed Energy Weapons (NDEW); space-based radar systems; communications, command, control, and intelligence; cryogenic cooling of non-reactor power sources; tracking systems; and sensing systems Specific space power activities include: the SP-100 program, whose R&D focus is on a 300 kilowatt electric reactor to satisfy onboard space electrical power requirements; the Dynamic Isotope Power System program, whose R&D focus is on power systems in the one to ten kilowatt range for a surveillance and tracking system; and a multimegawatt power program, whose R&D focus is on steady state and burst power requirements greater than one megawatt, which could be used for space or ground power applications

The Deputy Assistant Secretary for Uranium Enrichment is responsible for uranium enrichment at the gaseous diffusion plants, development of new enrichment technology, and assessing of U S and foreign uranium resources

Operations Offices

DOE follows a decentralized management approach Operations Offices and their subsidiary Area Offices are charged with ensuring execution of the programs that are, in large measure, defined by the program offices at DOE Headquarters Headquarters' role is to develop program goals, formulate plans and budgets, provide management and direction, and assure accomplishment The Operations Offices and other field offices report formally to the Secretary through the Undersecretary

The establishment of the field office system began with the first General Manager of the Atomic Energy Commission Initially there were Operations Offices at New York, Chicago, Hanford, Santa Fe, and Oak Ridge By 1971 four more had been added— Savannah River, Idaho Falls, Nevada, and San Francisco The New York office was later closed, and the Albuquerque office replaced Santa Fe

The Albuquerque Operations Office (ALO) oversees plans and schedules for warhead production at all seven facilities in the warhead production complex The Nevada Operations Office (NVO) manages the Nevada Test Site and oversees engineering, construction, and logistical support activities The national laboratories report directly to the ASDP and the ASDP program directors (primarily OMA), while field offices provide their contract administration

The Savannah River Operations Office (SRO) is responsible to the ASDP for management oversight of all Savannah River facilities and laboratories The Oak Ridge Operations office manages facilities at the Oak Ridge Reservation, the Paducah and Portsmouth Gaseous Diffusion Plants, and the Fernald and Ashtabula Plants The Chicago, Oak Ridge, and San Francisco Operations offices report to the Undersecretary primarily through the Director of the Office of Energy Research The Idaho and Richland offices report through the Assistant Secretary for Nuclear Energy However, each of these field offices provides support and contract management services to the ASDP For instance, the San Francisco office manages the Lawrence Livermore National Laboratory, while Chicago manages the New Brunswick Laboratory in Argonne, Illinois Only three operations offices—Albuquerque, Nevada, and Savannah River—report exclusively through the ASDP

Table 4 1
Military Liaison Committee

Chairman—Assistant to the Secretary of Defense (Atomic Energy)

Executive Secretary

Department of Army
- Director, Combat Support Systems, Deputy Chief of Staff for Research, Development & Acquisition (DAMA-CSZ-A)
- Director, Nuclear and Chemical Directorate, Deputy Chief of Staff for Operations & Plans (DAMO-NC)

Department of Navy
- Director, Undersea and Strategic Warfare & Nuclear Energy Development Division, CNO, Office of Research, Development, Test and Evaluation (NOP-981)
- Director, Strategic & Theater Nuclear Warfare Division, Deputy Chief of Naval Operation, Plans, Policy and Operations (OP-65)

Department of the Air Force
- Director, Directorate of Operational Requirements, Deputy Chief of Staff Research Development & Acquisition (AF/RDQ)
- Director, Directorate of Plans, Deputy Chief of Staff Plans & Operations (AF/XOX)

Observers
- Commandant, U S Marine Corps
- Director, Defense Nuclear Agency
- Assistant Deputy Director for Force Development & Strategic Plans, J-5 Plans and Policy, Joint Chiefs of Staff
- Director of Military Application, Deputy Assistant Secretary for Military Application, Assistant Secretary for Defense Programs, Department of Energy

Congressional Committees

The Congress exercises its constitutional control over the military forces by the enactment of legislation, including that involving appropriations, and by other actions that are incident to the enactment of legislation, such as hearings and investigations Long-established congressional procedure requires that the appropriation of money be preceded by separate authorizing legislation

More than half of the committees in each house may consider legislation of interest to the military services However, the committees with major oversight and legislative responsibility for nuclear weapons are the House and Senate Armed Services Committees and the House and Senate Appropriations Committees and their subcommittees (see Table 4 2) A number of other committees address DOD activities and nuclear weapons, although they have less impact upon acquisition matters They can demand Reports and conduct Hearings Among the more important Senate and House Committees are:

- Budget;
- Energy and Natural Resources/Energy and Commerce: nuclear materials and nuclear proliferation;
- Senate Governmental Affairs/House Government Operations: operations in general, the handling and sale of property;
- Foreign Relations/Foreign Affairs: arms control and regional policy; and
- Science and Technology

Table 4 2

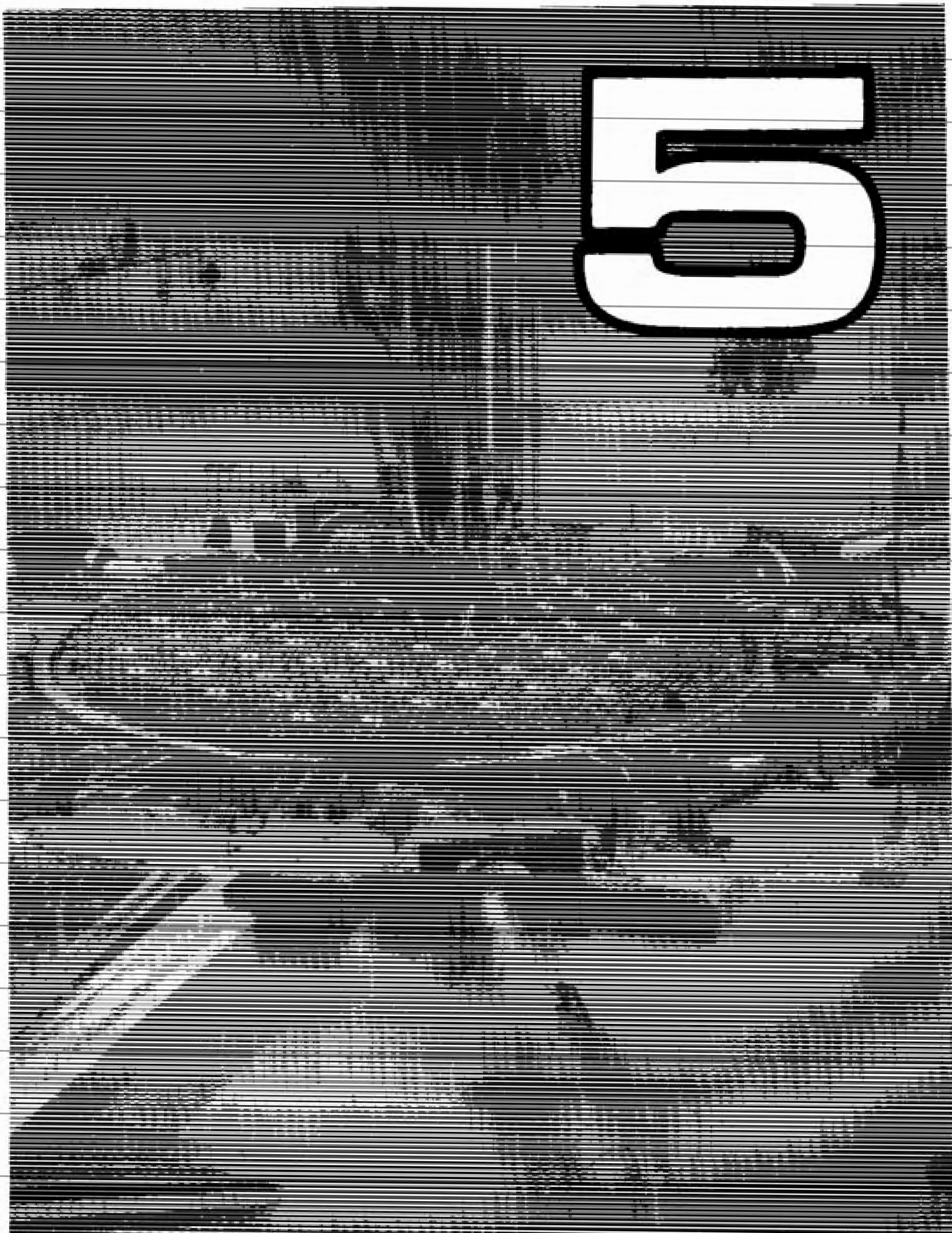
Congressional Committees and Subcommittees with Direct Nuclear Warhead Acquisition Responsibilities (1985)

House Committee on Appropriations
Subcommittee on Defense
Subcommittee On Energy and Water Development (DOE)
House Committee on Armed Services
Subcommittee on Investigation
Subcommittee on Procurement & Military Nuclear Systems (DOE)
Subcommittee on Research and Development
Subcommittee on Seapower & Strategic & Critical Materials
Senate Committee on Appropriations
Subcommittee on Defense
Subcommittee on Energy and Water Development
Senate Committee on Armed Services
Subcommittee on Defense Acquisition Policy
Subcommittee on Strategic & Theater Nuclear Forces (DOE)
Subcommittee on Sea Power and Force Projection

Military Characteristics and Stockpile-to-Target Sequence.

Military Characteristics The MC report states performance requirements and physical characteristics for those parts of a nuclear weapon that are the sole responsibility of the DOE to design, develop, certify, and produce The report begins as a statement of DOD performance objectives (e g , yield, weight, size, fuzing options), and key parameters (physical, functional, environmental, vulnerability, safety, and reliability) Preliminary MCs are prepared by the requesting military service and included in the Phase 1 report Upon formal acceptance by DOE, final MCs are included as part of the Phase 3 study After approval by the MLC, they are published and distributed by the Defense Nuclear Agency

Stockpile-to-Target Sequence STS reports supplement MC by describing the logistical and operational concepts for the warhead and the delivery systems These reports also describe the physical environments through which the nuclear warhead will pass STS also defines the logistics involved in moving nuclear warheads to and from the stockpile for quality assurance testing, modification and retrofit, and the recycling and replenishment of "limited life components" (e g , tritium reservoirs) The STS begins in Phase 1 and is continuously reviewed and revised throughout the life of the warhead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Chapter Five
Nuclear Materials Production Technologies and Processes

This chapter describes basic technologies and processes widely used or being perfected to produce nuclear materials, especially in the United States The descriptions are meant to inform without undue technical detail [1] The topics covered are uranium mining and milling, uranium enrichment, production reactor operations, nuclear fuel processing, and heavy water production

Uranium Mining and Milling[2]

In the last forty years, uranium has developed from a commodity of minor commercial use to one vital for nuclear weapons and for producing electrical energy

Most uranium ores mined in the United States lie in sandstone deposits of New Mexico, Wyoming, Colorado, Texas, Utah, and Arizona Recently the concentration of uranium oxide (U_3O_8) in processed ore has averaged about 0 12 percent The efficiency of recovery has risen to a historical high of about 96 percent, from a low of less than 90 percent in 1978 Historical trends of processed ore grades, and efficiencies of U_3O_8 recovery are shown in Figure 5 1

Open pit and underground mines coupled with conventional mills account for most annual uranium concentrate production in the United States (about 70 percent in 1983) Uranium is also recovered by solution mining (8 percent of capacity, mainly in Texas); nonconventional means as a byproduct of the production of phosphoric acid from phosphate rock (in mills along the Gulf Coast); and by heap leaching (see below) of dumps and tailings containing low uranium concentrations

Mining[3]

Conventionally, uranium ore is recovered by deep underground mining and by open pit mining of surface deposits Uranium ore deposits in sandstone generally occur in layers lying parallel to the host rock beds The ore bodies are generally irregular in shape and size, ranging from small deposits only a few meters in width and length to deposits tens of meters thick, hundreds of meters wide, and thousands of meters long The quantity of ore contained in a deposit ranges from a few hundred tons to several million tons

Uranium ore more than 150 meters below the surface is generally recovered from underground mines These mines are worked from vertical or inclined shafts, depending on depth and geologic conditions As deeper deposits are developed, vertical shafts that range in depth to a maximum of about 900 meters are used

The *main* (production) *shafts* in modern mines are circular and concrete-lined with inside diameters ranging from 3 to 5 meters Extending out from the main shaft, tunnels called *haulage drifts* extend horizontally below the ore bodies The drifts, usually 2 5 by 2 7 meters in cross-section with a 1 percent upward gradient, facilitate ore removal and mine drainage Finally, openings called *raises* are established between the haulage drift and the ore layers Raises provide access for miners, materials, fresh air, exhaust air, and broken ore Raises are generally about 1 2 meters in diameter and are steel-lined

To facilitate removal, ore bodies are divided into suitably sized blocks called *stopes* that can be conveniently mined First, a network of drifts (tunnels) is developed within the ore body, removing 30 to 35 percent of the ore and providing access to the remainder, which is then extracted The commonly used "stoping" method, called "modified room-and-pillar," entails a drift network of 2 meter by 2 meter tunnels called *development drifts* These drifts are driven in the ore body to produce a series of pillars, 12 meters by 12 meters in cross-section

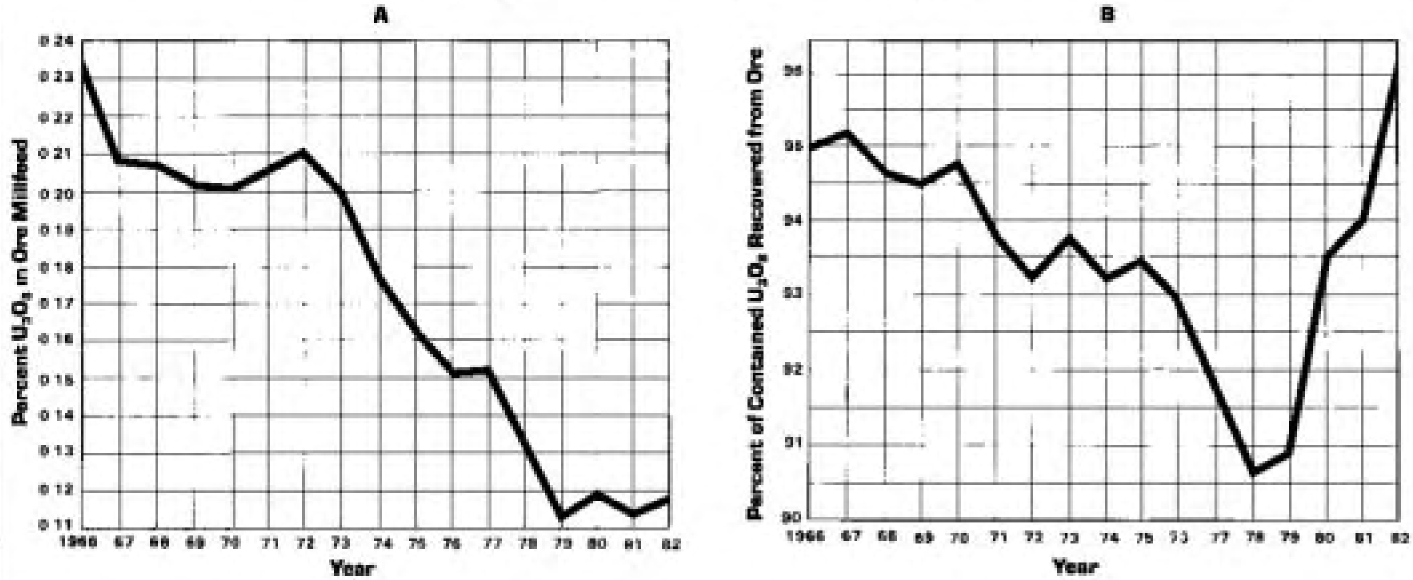
Ore extraction usually begins from the far end of the mine As the pillars are removed, the roof is sometimes allowed to cave in (if the area is not below the water table) After blasting, the loose ore is removed to the nearest stope exit There it is hauled along the development drifts to vertical raises and gravity fed to the haulage drifts From there it is transported to the main shaft for hoisting to the surface

Depending on the concentration of the uranium in the ore, the material is shipped by truck to a mill, usually nearby, or piled up at the mine site for recovery of the uranium by heap leaching

1 For a more rigorous treatment of most of these processes see Manson Benedict Thomas H Pigford and Hans Wolfgang Levi *Nuclear Chemical Engineering* (New York: McGraw Hill, 1981)

2 This material is based on Draft Environmental Impact Statement for Standards for the Control of Byproduct Materials from Uranium Ore Processing (EPA 520/1-83-022 U.S. EPA Washington DC March 1983); Statistical Data of the Uranium Industry (GJO-100(82) DOE Grand Junction Colorado 1 January 1982); Report of the Nonproliferation Alternative Systems Assessment Program (DOE/NE-0001/3 DOE Washington DC June 1980), Volume 3

3 EPA Proposed Standard for Radon 222 Emissions to Air from Underground Uranium Mines (Draft) EPA 520/1 85 010 14 February 1985 p 2-6 ff



Source: Statistical Data of the Uranium Industry GJO-100(83) U S DOE Grand Junction Area Office 1 January 1983 p 47

Figure 5 1 **(A)** Grade of uranium ore processed **(B)** The percentage of uranium recovered from processed ore

Percentage of U_3O_8 in ore processed annually at U S uranium mills (A), and the percentage of the contained U_3O_8 that is recovered (B)

Milling

In the conventional milling process, uranium is extracted from the crude ore and concentrated into an intermediate semi-refined product, uranium oxide (U_3O_8, or yellowcake) Milling typically increases the uranium oxide content from 0 1 percent in the ore to 85 to 95 percent in the concentrate The remainder of the material (essentially the total mass for low-grade ores) is dumped into piles of mill tailings Most of the radioactivity associated with the ore, consisting primarily of radium and its daughter products, goes into tailings

Two conventional processes remove uranium from ore: the *acid-leach process* and the *alkaline-leach process* About 80 percent of the current milling is done by sulfuric acid leaching When it is not economical to leach high-alkaline ores with acid, they are leached with an alkaline solution Acid leaching is preferred for ores with 12 percent or less limestone Several mills include circuits for both processes

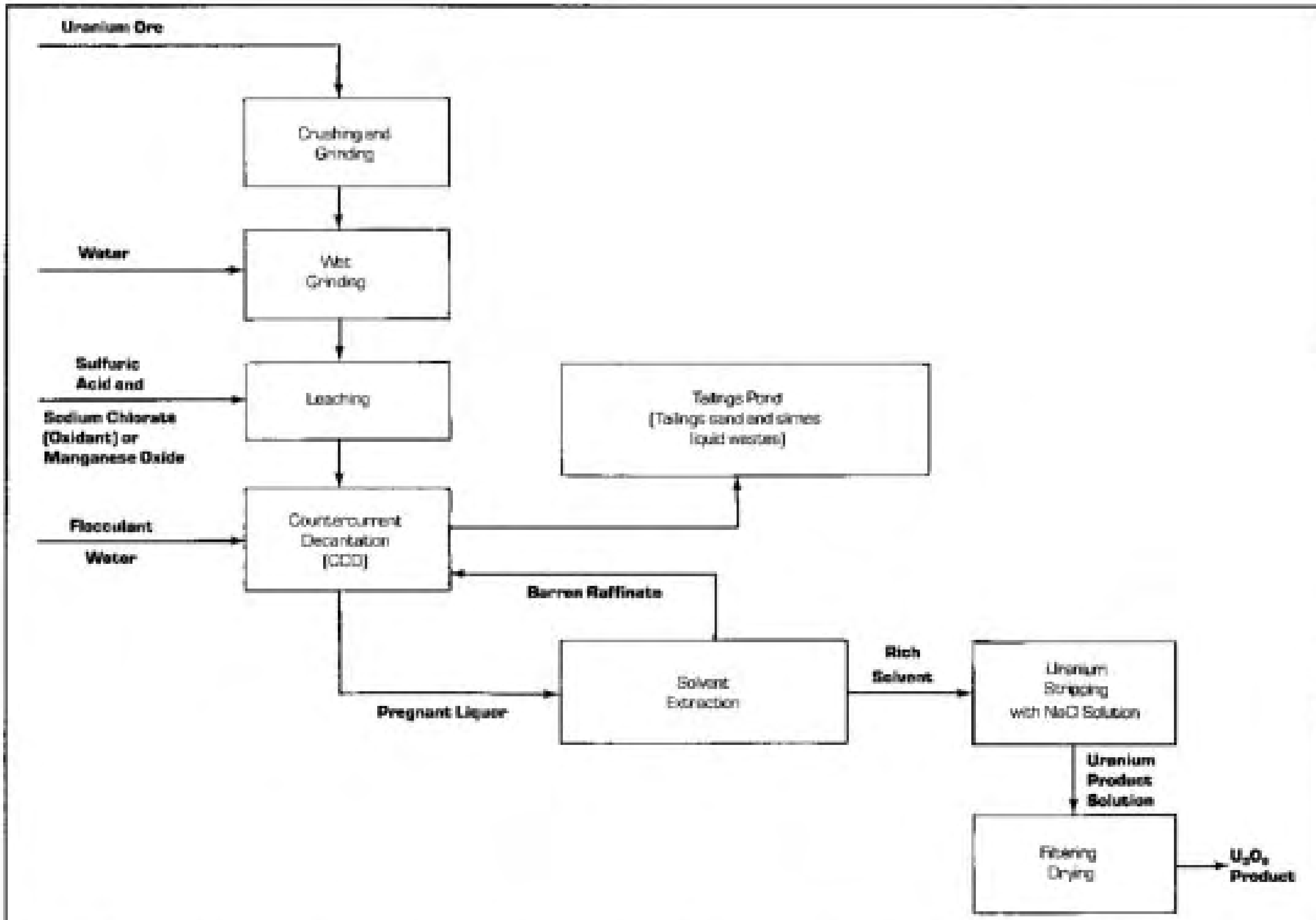
Figure 5 2 shows a flow diagram of the process at a conventional mill that produces U_3O_8 and solid and liquid waste tailings

The first step of conventional milling is crushing and grinding the ore to a grain size suitable for leaching Ore characteristics and the leaching process dictate the natural grain size (Alkaline leaching requires much finer grinding) Belt feeders convey the ore from the crushing circuit to the grinding circuit Samples are taken along the way for routine laboratory analysis "Rod and ball" mills grind the ore to approximately 28 mesh (0 60mm) for the acid-leach process or to 200 mesh (0 074mm) for the alkaline-leach process The ores are then wet ground (with water added) with the aid of classifiers, thickeners, or screens that size the ore and return coarser particles for further grinding Water consumption is reduced by recirculating mill solutions; for example, by recycling the clarified effluent from the grinding circuit thickener [4]

After grinding, the ore is leached to remove uranium Sulphuric-acid leaching is compatible with several chemical concentration and purification processes, including ion exchange, solvent extraction, or a combination of both The slurry from the grinding operation (50 to 65 percent solids) is discharged into the leaching circuit, which consists of several tanks in series Sulfuric acid is continuously added For U S mills, acid consumption ranges from 20 to 60 kilograms of sulfuric acid per metric ton of ore An oxidant (either $NaClO_3$ or MnO_2) is also continuously added, with the sulfuric acid, to dissolve uranium in the ore Iron must be present in the solution for the oxidant to be effective Ore leaching proceeds at atmospheric pressure and slightly above room temperature Most uranium in the ore is dissolved, as well as other materials such as uranium daughter products, iron, and aluminum The leaching time is about seven hours

After ore leaching is completed, the pregnant liquor containing the dissolved uranium is removed from the tailings solids in what is called the countercurrent decantation (CCD) circuit This operation first sends the slurry to hydrocyclones (liquid separators) that separate

4 Wet milling may be used in place of both the crushing and fine grinding steps This process uses a rotating steel cylinder The tumbling action of the lifters (large pieces of ore) and a small charge of 8 to 10 centimeter steel balls breaks down the ore



Source: Adapted from Draft Environmental Impact Statement for Standards for the Control of Byproduct Materials from Uranium Ore Processing (EPA 520/ 1-82-022 U S EPA Washington DC March 1983)

Figure 5 2 Flow diagram for the Acid-Leach Process in uranium milling The most widely used process for recovering U_3O_8 (yellowcake) from uranium ore is by leaching with sulfuric acid

the underflow of coarse sand The sand fraction is subsequently washed in a series of classifiers Overflows from the classifiers and the hydrocyclones are combined, and the fine suspended solids (slimes) are washed Substances called flocculants are added to promote settling of the suspended solids The solids are washed with fresh water and the recycled barren raffinate from the solvent extraction circuit After thorough washing, sand and slime is pumped as a slurry to the tailings ponds

Following solid-liquid separation in the CCD circuit, the uranium is recovered from the leach solution by organic solvent extraction The "rich" solvent solution is then stripped of its uranium, and the uranium product solution is further processed into U_3O_8 (yellowcake)

Heap-leaching

Most mills are not designed to process uranium ores of less than 0 04 percent U_3O_8 Consequently, uranium is often extracted from such ores by a heap-leach process[5] Heap-leaching also recovers uranium as a byproduct of copper mining and in uranium mining when the ore body is so small, or situated so far from milling facilities that shipping the ore to a mill is not economical

Ore to be heap-leached is placed upon a gently sloped, impermeable pad and saturated from above with a leaching solution The impermeable pad is generally a plastic sheet, although asphalt and concrete have been used A network of pipes and drain tiles collect the product (leachate) that percolates to the bottom of the ore piles The percolated leachate is recirculated until the

5 Uranium recovery by heap-leaching is used for low grade (0 01 to 0 03 percent U_3O_8) sandstone uranium ores

uranium concentration in the solution reaches 0 06 to 0 1 grams of U_3O_8 per liter The concentrated solution then passes through resin ion-exchange columns for uranium extraction

The most commonly used leaching chemicals are sulfuric acid and ammonium carbonate solutions When water from the uranium mine is used in the leaching process, uranium in the mine water is also recovered In an efficient operation about 80 percent of the uranium is extracted from the ore Heap-leach piles are commonly about 100 meters long, 6 to 8 meters high, with beams separating the piles in segments about 20 meters wide

Chemical Conversion

Conversion refers to processes that occur mainly at two stages in the fuel cycle: before uranium enrichment and prior to the fabrication of reactor fuel and targets Before enrichment in a gaseous diffusion or gas centrifuge plant, uranium ore concentrate (principally U_3O_8) is refined and converted into volatile uranium hexafluoride (UF_6) feed Before fuel fabrication, the uranium must be converted from a form that reflects its earlier processing history (variously, UF_6 or the oxides U_3O_8 or UO_3 or UO_2) to one suitable for fuel, usually uranium metal or uranium dioxide (UO_2) powder, depending upon circumstances [6]

Two commercial processes in the United States convert uranium ore concentrates to UF_6: the dry process (at Metropolis, Illinois) and the wet process (at Gore, Oklahoma) Dry processing involves the reduction of the U_3O_8 ore concentrate to uranium dioxide (UO_2), and fluorination to uranium hexafluoride (UF_6), followed by fractional distillation of the UF_6 as a final purification step The first step of wet processing is chemical solvent extraction to prepare a high-purity uranium trioxide (UO_3) feed prior to the reduction, hydrofluorination, and fluorination steps The DOE-owned feed plant at Fernald, Ohio, uses the wet process to convert ore concentrates to UO_3 and UF_4 These are both convertable to UF_6 at the DOE's gaseous diffusion plant in Paducah, Kentucky

Uranium Enrichment

Naturally occurring uranium contains only 0 711 percent (by weight) of the fissile isotope U-235 along with 99 3 percent of non-fissile U-238 and trace amounts of U-234 Enrichment processes concentrate the U-235 Enriched uranium is used for a wide range of applications Enriched to about 1 percent U-235, it fuels plutonium production reactors (e g , the N-Reactor); to about 3 to 4 percent, it fuels commercial light water power reactors; to about 20 percent or greater, it fuels research and test reactors; to about 93 5 percent, it is used in U S nuclear warheads; and to 97 3 percent, it fuels U S submarine reactors The depleted uranium (the enrichment plant *"tails"*) is fabricated into components (e g , tampers) of nuclear warheads and into targets for the plutonium production reactors Because of its high density it is used in a variety of other military and commercial applications including antitank bullets and ballast

From World War II to the present, a number of very different processes have been developed for enriching uranium (and other multi-isotope elements, as well) Early attempts at separating uranium isotopes employed the electromagnetic process (the Calutron), thermal diffusion, gaseous diffusion, and the gas centrifuge Today, gaseous diffusion and the gas centrifuge dominate uranium enrichment worldwide Both enrich a gaseous feed of uranium hexafluoride (UF_6) molecules of uranium atoms compounded with fluorine Coming into use, with varying degrees of acceptance, are several other isotope separation methods: laser isotope separation, plasma separation, chemical enrichment, and aerodynamic processes

Enrichment Concepts

Two of the most important concepts underlying operation of all enrichment plants are *material balance* and *separative work*

Material Balance

Uranium is neither created nor destroyed in the enrichment process Material balance implies that the amount of uranium that enters an enrichment plant (as the feed stream) equals the amount that leaves It leaves in two streams—one containing enriched product with a U-235 concentration greater than the feed, and the other containing depleted uranium *tails* with a lesser U-235 concentration Despite shifts in the concentration of the uranium isotopes (e g U-235), the amount of each isotope entering the plant in the feed equals the amount leaving in the product and tails streams

Suppose, for example, a customer orders 50,000 kg of 3 percent enriched uranium (containing 1500 kg U-235) and the plant operates with a tails assay of 0 2 percent To do its job the plant requires a feed of 274,000 kg of natural uranium (containing about 1950 kg U-235) and, along with the desired product, produces a tails stream containing 224,000 kg depleted uranium (containing 450 kg U-235) The amount of material in and out of the plant balances; that is, *feed is equal to product plus tails* both for the total amount of uranium (274,000 kg = 50,000 kg + 224,000 kg) and for the amount of U-235 (1950 kg = 1500 kg + 450 kg)

The second column of Table 5 1 gives the quantity of feed needed per kilogram of product for the product assays contained in the first column and for a tails assay of 0 2 percent Other situations may be calculated directly [7]

6 Savannah River is planning to fabricate highly enriched production reactor fuel from U_3O_8 by powder metallurgy

7 Material balance At equilibrium, the outflow of product P and tails T from the cascade must equal the inflow of feed Thus, for all uranium $F = P + T$, and for the U-235 alone $x_f F = x_p P + x_t T$ so that the ratio of feed to product for given U-235 fractions is:

$$F/P = (x_p - x_t)/(x_f - x_t)$$

where

x_p = assay of the product weight fraction of U 235

x_f = assay of the feed (normally 0 00711) weight fraction of U-235 and

x_t = assay of the cascade tails weight fraction of U-235

Separative Work

Separative work measures the effort expended in separating the feed into product and tails Enrichment demands effort: the larger the concentration of U-235 in the product and the smaller the concentration in the tails, the greater the effort required The amount of separative work is expressed quantitatively in kilogram separative work units (kg SWUs or simply SWUs) The separative work performed by an enrichment plant (or smaller enrichment unit such as a single gas centrifuge machine) is proportional to the quantity of feed (kilograms) and independent of "assay" (the concentration of U-235) In many plants the capital investment is proportional to the separative work capacity, and the annual operating costs are proportional to the amount of separative work done Enrichment services are sold in dollars per SWU; the DOE price to commercial customers in 1984 ranged from $138 to $149 per SWU

The separative work used by the enrichment plant may also be determined from Table 5 1 The third column shows that the enrichment of natural uranium to 3 percent at tails assay of 0 2 percent requires 4 306 kg SWU per kilogram of product Thus the production of 50,000 kg of 3 percent enriched uranium requires about 215,300 SWU

Similarly, one can determine how much 93 percent enriched uranium the customer could have acquired for the same number of SWUs According to Table 5 1, 235 55 SWU are expended per kilogram of 93 percent product at 0 2 percent tails assay, and 181 605 kg of natural uranium feed are required Consequently, the expenditure of 215,300 SWUs produces only 914 kg of 93 percent enriched uranium and requires about 166,000 kg of feed

SWU requirements in other situations may be calculated directly [8]

Enrichment Terminology

Below, a number of terms commonly used in describing the design, construction, and operation of an enrichment plant are discussed

Stage

The basic separating unit in an enrichment plant is a *stage* A stage, for example, could be a single porous gaseous diffusion barrier, a single gas centrifuge, or a number of either connected in parallel An entering stream of natural uranium with a U-235 assay x = 0 00711 (or, more generally, uranium with any fraction x of U-235 and 1 - x of U-238) divides into two streams leaving the stage: an enriched (or *heads*) stream with a U-235 fraction *y* and a depleted (or *tails*) stream with fraction z (*y* is greater than x and z is less than x) (See Figure 5 3)

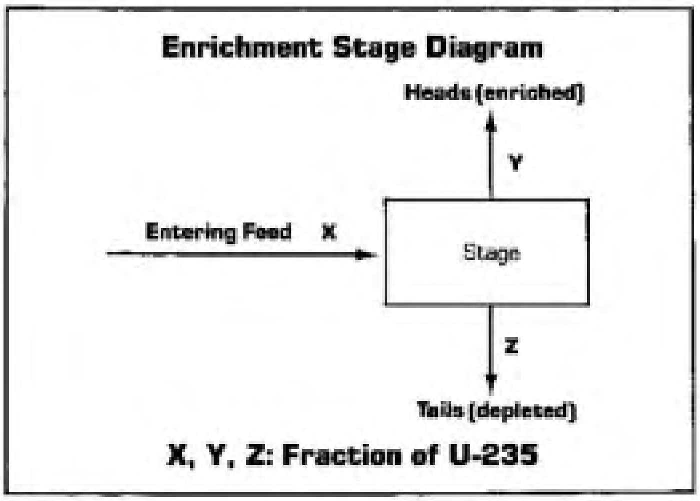


Figure 5 3 Enrichment stage diagram

Separation Factor

The elementary separation factor of a single stage measures the degree of separation achieved in the enriched stream relative to the depleted stream In the enriched stream the atom fraction of U-235 is equal to *y*, the atom fraction of U-238 is 1 - *y*, and the *abundance ratio* of U-235 to U-238 is defined as *y*/(1 - *y*) Similarly, in the depleted stream, the abundance ratio is given by z/(1 - z) The *separation factor* of the stage is defined as the abundance ratio of the enriched stream divided by the abundance ratio of the depleted stream A separation factor of one means that no separation has occurred For a separation factor just slightly greater than one (e g , 1 0043, typical of a gaseous diffusion stage), many stages are usually required to achieve the desired degree of separation

Cascade

Because the stage separation factor is usually small, stages are connected in series to form a *cascade* in order to achieve the desired separation of U-235 between the product (enriched) and tails (depleted) streams

The cascade illustrated in Figure 5 4 is "tapered," with the number of parallel-connected units in each stage (proportional to the stage capacity) decreasing as the product and waste ends are approached The separative work capacity of the cascade is the sum of the separative capacities (SWU/yr) of the individual stages

The gas centrifuge plant designed by Urenco provides a typical example of an enrichment cascade [9] It is composed of tens of thousands of identical centrifuge machines When these are configured for enriching natural uranium to 3 percent U-235 with 0 2 percent tails,

8 The separative work per unit of product may be computed from:

$$S/P = [V(x_p) - V(x_t)] - (F/P)[V(x_f) - V(x_t)]$$

where

$$V(x) = (2x-1)\ln[x/(1-x)],$$

and $V(x_p)$, $V(x_t)$ and $V(x_f)$ are the values of V(x) at the assays of product, cascade tails and feed respectively

For derivation of these formulas see AEC, Gaseous Diffusion Plant Operations (Oak Ridge Operations Office, Report No ORO-884, 1972)

9 IAEA International Nuclear Fuel Cycle Evaluation, Volume 2 (Vienna, 1980), p 84

Table 5 1
Enriching Services[a]

Product Assay (wt. % U-235)	0 2 Percent Tails Assay Standard Table of Enriching Services: Feed Component (Normal) (kg U Feed/kg U Product)	0 2 Percent Tails Assay Standard Table of Enriching Services: Separative Work Component (kg SWU/kg U Product)	Product Assay (wt. % U-235)	0 2 Percent Tails Assay Standard Table of Enriching Services: Feed Component (Normal) (kg U Feed/kg U Product)	0 2 Percent Tails Assay Standard Table of Enriching Services: Separative Work Component (kg SWU/kg U Product)
0 20	0 000	0 000	2 60	4 697	3 441
0 25	0 098	-0 100	2 80	5 088	3 871
0 30	0 196	-0 158	3 00	5 479	4 306
0 35	0 294	-0 189	3 20	5 871	4 746
0 38	0 352	-0 197	3 40	6 262	5 191
0 40	0 391	-0 198	3 60	6 654	5 638
0 42	0 431	-0 197	3 80	7 045	6 090
0 44	0 470	-0 194	4 00	7 436	6 544
0 46	0 509	-0 189	4 50	8 415	7 690
0 48	0 548	-0 182	5 00	9 393	8 851
0 50	0 587	-0 173	5 50	10 372	10 022
0 52	0 626	-0 163	6 00	11 350	11 203
0 54	0 665	-0 151	7 00	13 307	13 587
0 56	0 705	-0 137	8 00	15 264	15 995
0 58	0 744	-0 123	9 00	17 221	18 422
0 60	0 783	-0 107	10 00	19 178	20 863
0 65	0 881	-0 062	12 00	23 092	25 782
0 70	0 978	-0 012	14 00	27 006	30 737
0 711 (Normal)	1 000	0 000	16 00	30 920	35 719
0 75	1 076	0 044	18 00	34 834	40 724
0 80	1 174	0 104	20 00	38 728	45 747
0 85	1 272	0 168	25 00	48 532	58 389
0 90	1 370	0 236	30 00	58 317	71 084
0 95	1 468	0 307	35 00	68 102	83 816
1 00	1 566	0 380	40 00	77 887	96 616
1 10	1 761	0 535	50 00	97 456	122 344
1 20	1 957	0 698	60 00	117 025	148 235
1 30	2 156	0 868	70 00	136 595	174 302
1 40	2 348	1 045	80 00	156 164	200 605
1 50	2 544	1 227	85 00	165 949	213 892
1 60	2 740	1 413	90 00	175 734	227 341
1 70	2 935	1 603	92 00	179 648	232 796
1 80	3 131	1 797	93 00	181 605	235 550
1 90	3 327	1 994	94 00	183 562	238 328
2 00	3 523	2 194	96 00	187 476	244 842
2 20	3 914	2 602	98 00	191 389	269 882
2 40	4 305	3 018			

a The equation for S/P in the table is based on the separation of a binary mixture—for example U-235 and U-238 Natural uranium however contains a third isotope U-235 assaying about 0 0055 percent by weight The uranium enrichment plants enrich U-235 along with U-235 At U-235 assays greater than about 94 percent there is sufficient U-234 present in the isotopic mixture being processed to require a minor isotope correction Table 5 1 incorporates such a correction on the separative work component for product assays above 94 percent U-235 For example at a product assay of 98 percent U-235 the tabulated separative work per unit product is about 8 percent higher than the value obtained from the equation above for a pure U-235 U-238 mixture

Source U S AEC *Gaseous Diffusion Plant Operations* (Oak Ridge Operations Office Report No ORO-684 1972) p 37

they are arranged into twelve stages with an overall annual capacity of 1 0 million SWU If the cascade was reconfigured to produce highly enriched uranium (by increasing the number of stages with fewer centrifuges per stage), the SWU capacity of the cascade would still be 1 0 million SWU, but the product flow rate would be decreased and fewer kilograms of product would be produced per year

Enriching and Stripping Sections

In Figure 5 4, feed entering near the center of the cascade is enriched to the desired product composition in the *enriching section* The *stripping section* increases the

5

Gaseous Diffusion Process

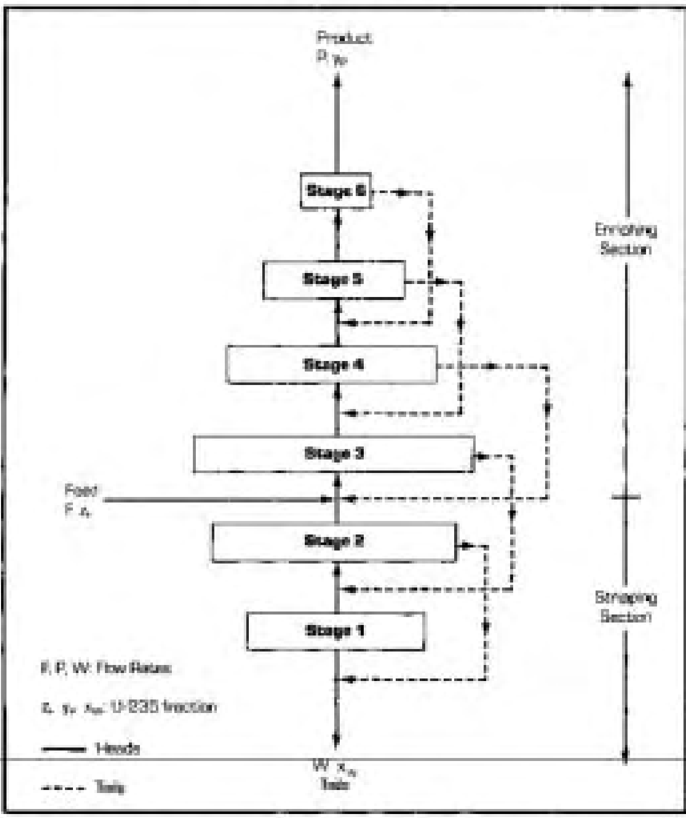


Figure 5 4 Cascade diagram Countercurrent Recycle Cascade

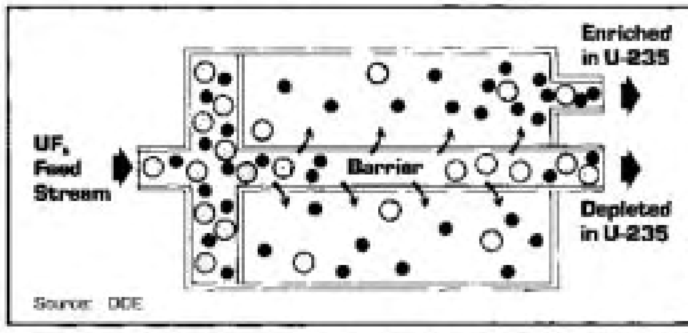


Figure 5 5 Schematic diagram of a diffuser in a gaseous diffusion plant

recovery of U-235 from the feed by decreasing the fraction of U-235 in the tails The sole purpose of the stripping section is to reduce the amount of feed required to make a given amount of product [10]

The number of stages in a cascade depends on the elementary separation factor for each stage This separation factor may be rewritten as the product of the *heads separation factor* (the abundance ratio of the enriched stream divided by the abundance ratio of the feed stream) and the *tails separation factor* (the abundance ratio of the feed stream divided by the abundance ratio of the depleted stream) For example, in a so-called "symmetrical gaseous diffusion stage," the heads and tails separation factors are equal, each with a value of 1 0021 As material moves up through the enriching section, the heads separation factor is compounded This determines the number of stages needed for the desired enrichment Likewise, compounding the tails separation factor in the stripping section reduces the U-235 concentration from the feed assay to the desired concentration in the tails, thus determining the number of stages in this section

Ideal Cascade

Figure 5 4 shows a *countercurrent recycle cascade* The tails from each stage feed into the input stream of the preceding stage making it a *symmetrical* cascade This cascade is *ideal* if the U-235 concentration is the same in all streams that merge together The flow between stages in an ideal cascade is miminum, making for lowest cost of operation At each stage, the streams moving away from the ends of the cascade—the tails stream in the enriching section and the heads stream in the stripping section—are known as *reflux* (because they flow back toward the center) In an ideal cascade, the ratio of the heads flow rate to feed flow rate at each stage (known as *cut theta*) is just slightly less than one half Other flow arrangements require different "cuts"

The ideal cascade is tapered, and the width of each stage (i e , the number of units) is proportional to the heads flow rate from the stage The cascade is widest at the feed point, and as the product end is approached, the U-235 concentration increases and the flow rate drops The separative work performed by an ideal cascade is proportional to the total "interstage flow," the sum of heads and tails flows emerging from all stages

At startup, an operating cascade must be run without withdrawal of enriched product for a period of time known as the *equilibrium time* This practice builds up the plant's *working inventory* of U-235 The period may amount to several months of normal production

Enrichment Processes

Gaseous Diffusion Process

Gaseous diffusion is the technology principally in use worldwide for enriching uranium (see Table 5 2) Each stage of a cascade consists of compressors, heat exchangers, and a diffuser that houses membranes In the enrichment process, a feed of UF_6 gas is compressed and flows past the diffuser's porous membrane barrier (see Figure 5 5) Some of the gas molecules contain U-235, others contain U-238 The molecules with U-235 pass preferentially through the membrane micropores to form an enriched product Stages have capacities of several thousand SWUs per year, and a plant may consist of several thousand stages The power consumption of a gaseous diffusion plant (GDP) is about 2400 kwh/SWU This is five to twenty times greater than consumption for a gas centrifuge plant While gaseous diffusion is an established enrichment technology, most countries construct-

10 Benedict op cit p 652

Table 5.2

Worldwide Uranium Enrichment Capacity: Existing and Planned

(in millions of SWU/yr)

	Existing Capacity		Planned Capacity		Production
Supplier	**Process**	**1985**	**1990**	**1995**	**FY 1983**
United States					
Oak Ridge, TN	diffusion	7.9	0.0[a]	(7.9)[b]	
Paducah, KY	diffusion	11.4	11.4	11.4	
Portsmouth, OH	diffusion	8.0	8.0	8.0	
AVLIS Plant	AVLIS	0.0	0.0	(13.2)[b]	0.0
Subtotal U.S.		27.3	19.4	19.4-29.4[b]	12.0
France					
Eurodiff	diffusion	10.8	10.8	10.8	5.5
Cogema	laser	0.0	0.0	1.0[c]	0.0
West Germany, Netherlands, United Kingdom					
Urenco	centrifuge	1.0	2.0	3	0.6-0.8
Soviet Union					
domestic	?	?	?	?	
export	diffusion	3.0	2-3	2-3	2-3
Japan	centrifuge	0.05	0.2	1-2	?
South Africa	helicon	0.03	0.3	0.3	?
Brazil	jet-nozzle	0.01	0.1	0.2	?
	centrifuge (labscale)[d]		?	?	0.0
Australia	centrifuge	0.0	0.0	1.0	0.0
Pakistan	centrifuge	0.0	0.005	0.0	—
TOTAL		42	45-46	59	

a Oak Ridge GDP placed on standby at end of FY 1985. DOE plans (1985) to bring Oak Ridge back into service in 1991.

b DOE plans to replace one GDP (probably Oak Ridge) with a plant based on AVLIS technology in the mid-1990s. This plant will probably be constructed in increments with a final capacity of 10 million SWU.

c *Nuclear Fuel* (17 June 1985): 3-4.

d Leonard S. Spector, *Nuclear Proliferation Today* (New York: Vintage Books, 1984), p. 272.

Source: Based on statement of Robert Civiak in HSTC Energy Conservation and Power, Serial No. 98-118, 21 October 1983 and 1 March 1984, p. 124.

ing or planning new facilities are choosing more energy efficient processes.

In a simple gaseous diffusion stage, the porous diffusion barrier has micropores 10 nanometers in diameter (1 nm is one billionth of a meter), smaller than the mean free path of the molecules. About half of the feed gas passes through the barrier to the low pressure side, where the gas is slightly richer in U-235 than the feed. The selective passage of U-235-containing molecules through the barrier is due to their slightly greater mean speed than heavier molecules containing U-238. The lighter molecules strike the barrier at greater frequency and pass through more often.

The separation factor for a gaseous diffusion stage equals the ratio of the mean speeds of the lighter and heavier molecules. It has the value 1.0043.[11] This small separation factor requires, in practice, many stages connected in series to form a cascade in order to achieve the

11 The separation factor is defined as the ratio of the fraction of U-235 to the fraction of U-238 in the enriched UF_6 divided by the corresponding ratio in the depleted gas. Since at fixed temperature the mean speed of a molecule is inversely proportional to the square root of its mass, the separation factor is found by taking the square root of the ratio of the mass of a UF_6 molecule of U-238 (352 mass units) to the mass of a UF_6 molecule of U-235 (349 mass units): separation factor = square root of 352/349 = 1.0043.

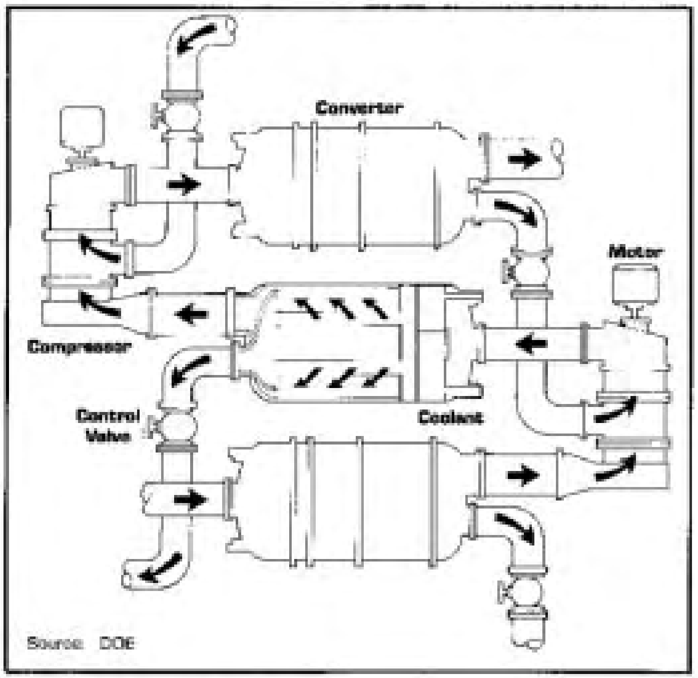


Figure 5 6 Gaseous diffusion stage arrangement in a cascade

desired degree of enrichment In each stage of a gaseous diffusion cascade (see Figure 5 6) compressors take partially depleted gas from the next higher stage and partially enriched gas from the next lower stage as the feed This entering stream is compressed and cooled before passage through the diffusion barrier

Gas Centrifuge Process

In the centrifuge process a feed of uranium hexafluoride (UF_6) gas is enriched in a rapidly rotating cylinder Separation of uranium isotopes is brought about by the combined effects of a centrifugal force field and countercurrent circulation Each stage of a gas centrifuge enrichment plant consists of one or more high speed machines connected in parallel, with pipes and valves

The first gram quantities of uranium enriched by gas centrifuge were obtained in 1941 at the University of Virginia by J W Beams During World War II development was carried out by Westinghouse and Standard Oil of New Jersey, but the project was discontinued in favor of other processes During and after the war, the German engineer G Zippe devised a simple method of inducing countercurrent flow by internal scoops and baffles He produced a small and mechanically simple machine Larger and more complex centrifuges were developed by others The centrifuge process is a mature technology in Europe at the Urenco plant and is coming into increased use in other countries (see Table 5 2) From 1977 until 1985, when construction of the Portsmouth GCEP was cancelled in favor of atomic vapor laser isotope separation, it was the leading technology for new U S enrichment capacity

A gas centrifuge machine consists of a long, thin vertical cylinder made from strong material (fiberglass, aluminum, steel, graphite fiber) rotating at high speed about its axis in an evacuated casing Urenco centrifuges are reported to have a peripheral speed of 400 m/s Rotors of the U S Set V advanced gas centrifuges (AGC) were designed with high strength materials able to sustain even higher speeds

UF_6 gas introduced into the cylinder (see Figure 5 7) is set into rotation Centrifugal acceleration increases the outer rim concentration of the heavier U-238 hexafluoride molecules relative to the lighter U-235 molecules [12] This radial separation of the uranium isotopes is greatly enhanced by a countercurrent flow induced in the UF_6 gas along the vertical axis of the rotating cylinder (see Figure 5 7) The effects of the radial separation and the axial flow combine to produce a large isotopic separation along the central axis Depleted uranium is removed from one end of the cylinder and enriched uranium from the other [13]

The "heavy" stream enriched in U-238 moves downward near the rim (see Figure 5 7) while the "light" stream enriched in U-235 moves upward along the central axis The U-235 gradient induced by this flow increases upward along the axis The section of the cylinder above the central feed point serves as an enriching *section*, and UF_6 enriched in U-235 is scooped out at the top from the light stream The section of the rotating cylinder below the feed point is the *stripping section*, and depleted UF_6 is scooped out at the bottom from the heavy stream

Separation factors of 1 2 to 1 5 or higher can be achieved for the centrifuge [14] While single stage separation factors are substantially larger than in a gaseous diffusion cascade, the throughput of material is much smaller Consequently a large-capacity centrifuge plant requires a large number of machines connected in parallel to obtain the necessary flow Furthermore, a single stage will not suffice; several must be connected to form a cascade

Separative work capacity ranges from 5 SWU/yr for European machines to 200 SWU/yr for U S Set III machines at Portsmouth U S Set V machines, in advanced stages of development when the Portsmouth GCEP plant was cancelled in 1985, were designed for separative work capacities of about 600 SWU/yr Urenco cascades comprise tens of thousands of centrifuges in some twelve stages with overall capacity of 1 0 to 2 2 million SWU/yr The first U S processing building at Portsmouth was to have 5760 Set III machines with a capacity

12 At the rim the ratio of the concentration of U-238 to the concentration of U 235 is greater than this same ratio evaluated at the axis by the factor exp ($\Delta M v_r^2/2RT$) where ΔM is the isotopic mass difference of U 238 and U-235 (3 atomic mass units) v_r is the velocity at the rim R is the gas constant and T is the absolute temperature For v_r = 500 meters/sec and T = 300°K the ratio of concentrations at the rim is 1 162 times the ratio at the axis In addition the gas pressure at the rim is 45 million times the gas pressure on the axis

13 The countercurrent flow may be induced in a number of ways: (1) by a series of scoops and baffles (as in Figure 5 7) that remain stationary while the cylinder rotates (2) by heating one end of the centrifuge and cooling the other, or (3) by pumps external to the machine

14 DOE United States Gas Centrifuge Program for Uranium Enrichment UCC-ND 1077 Rev 2 (4/81); Stanley Whitley *Reviews of Modern Physics* 56 1 (January 1984): 67-97 Most of the unclassified information on centrifuge operation dates from the 1960s

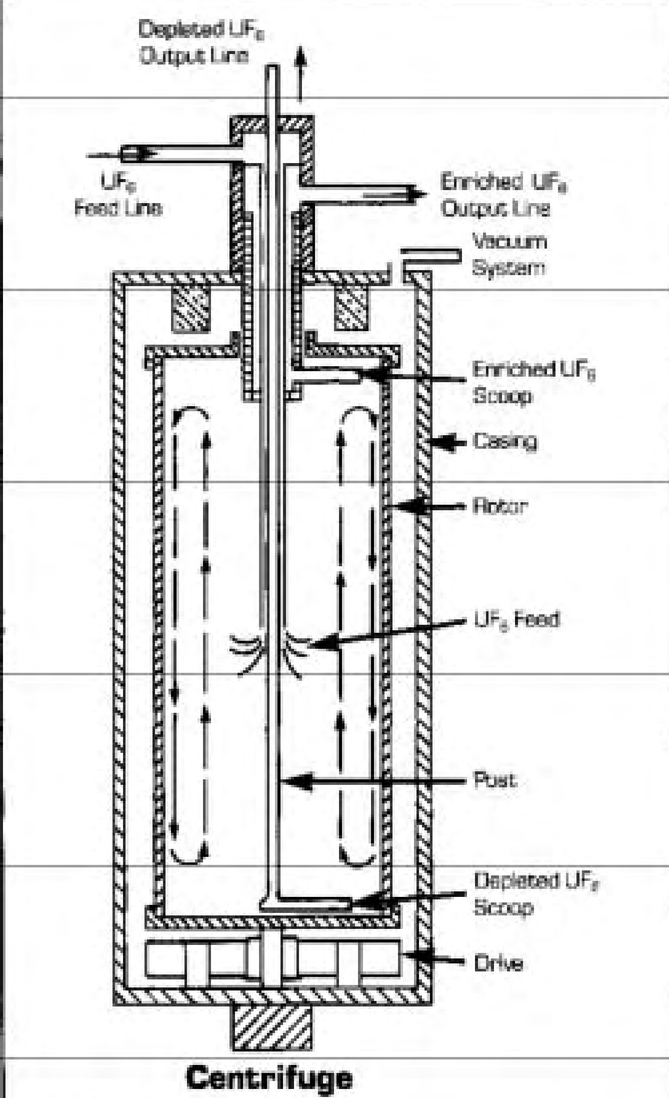


Figure 5 7 Illustration of a Centrifuge Enrichment Stage Natural UF_6 feed enters along the axis of the centrifuge and enriched product is withdrawn at the top near the rim

of 1 1 million SWU/yr [15] Power consumption in a gas centrifuge plant ranges from 100 to 400 kwh/SWU, substantially less than for a gaseous diffusion plant

The degree of enrichment in a single machine depends on several factors: the mass difference of the isotopes being separated, the peripheral speed of the rotor, and the length of the centrifuge Other things being equal, the separative capacity of a centrifuge is proportional to its length

Increasing the length and the peripheral speed increases both its separation factor and its separative capacity [16] Strength limitations restrict the peripheral speed to some 400 m/s for aluminum alloy, 500 m/s for glass fiber, and 700 m/s for carbon fiber-epoxy resin composite Titanium and steel alloys and the composite materials have brought major increases in strength [17] U S advanced gas centrifuge Set V machines (600 SWU/yr) are made of new high strength rotor materials, permitting greatly increased rotational speeds [18]

A centrifuge rotor may go into resonant vibrations as it spins through critical speeds ("criticals") where the rotational frequency equals the natural frequency of vibration of the rotor As the length (Z) increases, flexural (longitudinal) vibrations become a hazard because the larger the ratio Z/d of rotor length to diameter (d) the smaller the critical speed at which these modes occur Avoidance of flexural resonances can be achieved with Z/d of about 7 and a peripheral speed less than 400 m/s using an aluminum, steel, or titanium rotor [19] Subcritical operation with greater length to diameter ratios requires a material with a higher "modulus of flexure "[20] The U S Set V machines were probably designed with "criticals" at higher speeds than for Set III machines The estimated Z/d ratio is about 20 for both

Atomic Vapor Laser Isotope Separation (AVLIS)

In the AVLIS enrichment process, a stream of uranium metal vapor feed is irradiated by visible light from organic dye lasers to selectively excite and ionize U-235 atoms The ions are swept out of the vapor by electric fields into an enriched product stream that is deposited on solid or liquid collectors Technical uncertainties in the development of the AVLIS process are associated with laser reliability at high pulse rate and high energy density, optical propagation of laser pulses in multistage setups, and reliability of the atomic vapor collector system Power consumption is estimated at 65 kwh/SWU The AVLIS process is under development in the United States, United Kingdom, France, Italy, Japan, and Israel In the United States, the AVLIS process is currently being developed at Lawrence Livermore National Laboratory [21]

An AVLIS plant may consist of a single module or a multicell array It may be used to enrich natural uranium or strip depleted tails According to DOE, the AVLIS process can be configured to operate at any tails assay [22] The separative capacity of the AVLIS module used by DOE in its advanced enrichment selection process (1985) was

15 *Nuclear Fuel* (27 February 1984) p 3; (6 June 1983) p 9

16 For rotor length Z, diameter *d* and peripheral speed *v* the separative capacity is proportional to v^4Z and the separation factor is proportional to v^2Z/d Whitley Reviews of Modern *Physics* (January 1984): 69 70

17 Ibid p 69

18 DOE Uranium Enrichment 1983 Annual Report, ORO-842 (undated) p 10 *For the same* feed density and Z/d ratios the peripheral speed for Set V machines is greater than for Set III machines (200 SWU) by a factor of $(600/200)^{1/4}$ = 1 3

19 Whitley Reviews of *Modern Physics*: 78

20 Ibid

21 Nuclear Fuel (12 March 1984): 2 In the United States the *AVLIS* process was originally developed at LLNL and by Jersey Nuclear-Avco Isotopes (JNAI) The JNAI program was canceled See H A Bethe *Science* (30 July 1982): 398; *Physics Today* (November 1982): 70 In April 1982 the LLNL *AVLIS* process was selected by DOE over other advanced isotope separation (AIS) processes (MLIS and PSP) for continued development for uranium enrichment; *Nuclear Fuel* (28 February 1983): 4; DOE Press *Release* 5 June 1985; *Nuclear Fuel* (17 June 1985): 9 ff

22 HSTC Serial No 98-116 21 October 1983 1 March 1984 p 236 It has also been stated that the technology is designed for 0 047 percent tails; HAC FY 1985 DOE Part 6 p 587

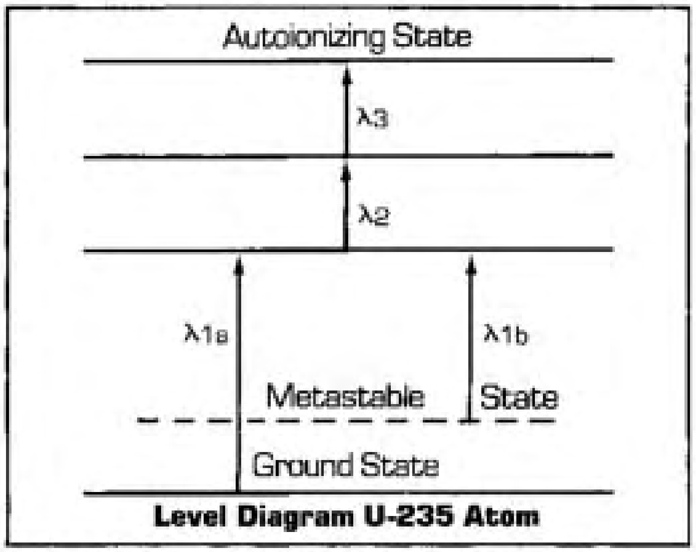


Figure 5 8 Energy level diagram of U-235 atom showing states consecutively excited by visible photons from tunable dye lasers in AVLIS process

870,000 SWU/yr [23]

In 1985, DOE selected the AVLIS process over the advanced gas centrifuge (AGC) to provide new enrichment capacity in the mid-1990s and beyond The LLNL AVLIS process was also selected eariler for the plutonium special isotope separation (SIS) program to enrich plutonium in the isotope Pu-239

In the LLNL AVLIS process[24] a supersonic beam of uranium vapor atoms is produced by bombarding liquid uranium metal feed with a beam from an electron gun and is then cooled by expansion The vapor beam enters a separation chamber system into which four distinct wavelengths of visible (red-orange) light from tunable dye lasers is directed The tunable dye lasers are pumped by high-repetition-rate copper-vapor lasers that emit green light The green light does not degrade the organic dye Many stages of copper-vapor laser amplification are required, and large modularized copper-vapor lasers have been tested at Livermore

Atoms of U-235 in the ground state are selectively excited by absorption of a sequence of visible photons from tunable dye lasers operating at three wavelengths λ_{1a}, λ_2, and λ_3 (see Figure 5 8) Atoms of U-235 cooled to the lowest metastable state are first excited by a fourth laser of wavelength λ_{1b} and then by light of wavelengths λ_2 and λ_3 In both cases the last photon absorbed puts the U-235 atom into an *autoionizing* excited state that quickly decays into an ionized (positively charged) uranium atom and an electron The total energy suppled to each atom is in excess of 6 13 electron volts (eV), the ionization energy of U-235

The multiple photon process optimizes excitation and ionization of the U-235 atoms while ionizing the U-238 atoms by only a negligible amount The atomic absorption spectrum of uranium atoms in metal vapor is extremely complex with over 300,000 lines at visible wavelengths For many of these lines there is sufficient displacement between the peaks in the U-235 and U-238 photon absorption cross-sections for the corresponding transition (the isotope shift in absorption frequencies is about one part in 50,000) so that the peaks do not overlap This allows selective photoexcitation of the U-235 atoms by lasers of sufficiently narrow bandwidth (one part in a million) Each step in the ionization process takes advantage of an isotopic shift, so the use of several steps ensures the selectivity of U-235 over U-238

In the separation chamber positively charged ions, primarily U-235, are diverted from the vapor stream by an electric field to negatively charged collector plates The un-ionized atoms move beyond the product collectors to tails collectors or to another enrichment cell (see Figure 5 9) In the LLNL design uranium is to be collected as liquid, but, should liquid collection prove unworkable, uranium will be recovered as solid Although few U-238 atoms are photoionized, a significant amount of U-238 is collected in the product U-238 ions are created by charge exchange collisions with ionized U-235 atoms and are diverted to the collector plates along with neutral vapor atoms that are scattered directly to the collectors The uranium vapor density must not be so high that these effects are appreciable (The upper limit is about 10 trillion atoms/cm^3)

Physical dimensions of the module depend on the photon absorption cross-section (photon efficiency) and laser pulse repetition rates These require collector dimensions along the vapor beam of some ten centimeters and effective optical path lengths along the laser beams of some hundred meters The effective optical path lengths are achieved by reflecting the laser beams through the vapor a number of times, at the possible expense of degrading the spatial quality of the beam because of diffraction and inhomogeneities in the index of refraction

Research on plutonium laser isotope separation based on the AVLIS process is being conducted at Livermore using the same laser systems that are used for enriching uranium However, for plutonium enrichment the "unwanted" isotopes—Pu-240 and Pu-242—are ionized and swept out of the vapor beam, while for uranium enrichment the desired isotope U-235 is ionized by the laser light [25] The separator-collector technologies used in the two applications of AVLIS differ, due to the high toxicity of plutonium and to differences in critical mass and other physical properties of plutonium and uranium DOE plans to operate a special isotope separation (SIS)

23 DOE Process Evaluation Board Uranium Enrichment Technology and Assessment 15 May 1985; reproduced in *Nuclear Fuel* (17 June 1985): 18

24 DOE Report of the Energy Research and Advisory Board (ERAB) Study Group on Advanced Isotope Separation November 1986 p 39 ff (hereafter Study Group); Laser Enrichment—No Easy Path to Proliferation *Nuclear Engineering International* (April 1980): 13; Physics Today (July 1970): 17

25 HAC FY 1986 EWDA Part 7 p 676

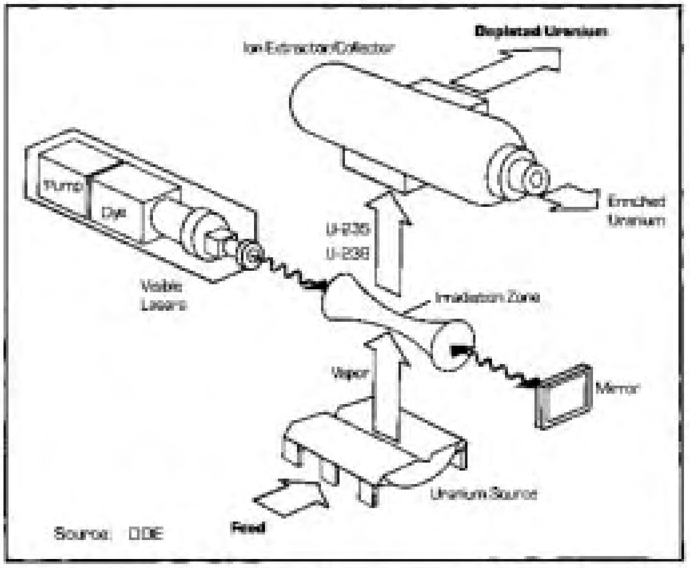


Figure 5 9 Illustration of the Atomic Vapor Laser Isotope Separation Process

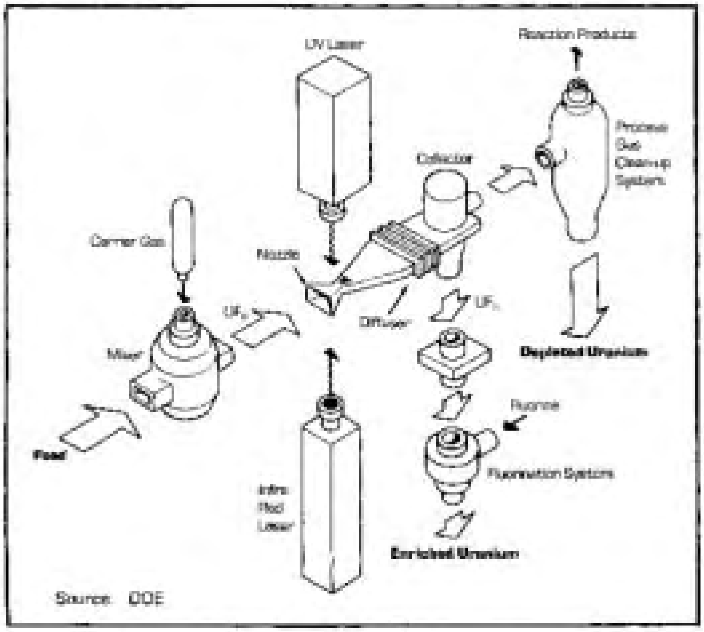


Figure 5 10 Illustration of the Molecular Laser Isotope Separation Process

plant for plutonium enrichment at Hanford in the 1990s using the AVLIS process

Molecular Vapor Laser Isotope Separation[26]

In the molecular vapor laser isotope separation process (MLIS) lasers are used to select molecules containing U-235 from a gas feed of UF_6 Specifically, fluorine atoms are selectively photodissociated from UF_6 molecules containing U-235 The resulting enriched stream of UF_5 condenses and is filtered out of the gas as a solid

The MLIS process was developed at Los Alamos National Laboratory for both uranium and plutonium enrichment (the latter using a feed of PuF_6) [27] Although DOE selected AVLIS technology over MLIS for a future plutonium enrichment plant, MLIS research continues on a small scale at LANL and the non-fissile isotopes Pu-240 and Pu-242 are being separated for weapons research

Although individual MLIS enrichment units have a large separation factor, an MLIS enrichment plant is conceived as a staged system to achieve flexibility Components in a unit include an expansion nozzle, a compressor, and infrared and ultraviolet lasers Technical uncertainties in MLIS development concern laser performance at high repetition rates and high intensity The estimated power consumption of an MLIS plant is about 77 kwh/SWU

In the MLIS process, the UF_6 feed together with a carrier gas of nitrogen or argon is first cooled by rapidly expanding it through a nozzle (see Figure 5 10) The supersonic gas which emerges from the nozzle is irradiated by a carbon dioxide (CO_2) infrared laser that selectively excites vibrational modes in molecules containing U-235 [28] An ultraviolet laser light (from a xenon chloride excimer laser) is then used to dissociate fluorine atoms from the excited gas molecules, producing an enriched product stream of UF_5 that precipitates out of the gas flow as a fine powder The gas stream is recompressed through a diffuser where the UF_5 powder is filtered out The resulting tails stream of depleted UF_6 is pumped to another stage for further processing, and the UF_5 may be refluorinated for further enrichment

Plasma Separation Process

In the plasma separation process (PSP) uranium metal vapor is ionized and injected into a high vacuum chamber containing a uniform axial magnetic field, produced by a superconducting coil (see Figure 5 11) Radiofrequency energy is introduced by an electric field superimposed perpendicular to the magnetic field and tuned to oscillate at a frequency of 127 kilohertz, the "cyclotron resonance frequency" of the U-235 ions In the vacuum chamber, U-235 ions selectively absorb the radio-frequency energy As a result, their orbits increase

26 DOE FRAS Study Group, pp 31 32.

27 At the end of April 1982 DOE selected the AVLIS uranium enrichment technology over MLIS for full-scale engineering development; *Inside Energy* (7 May 1982) In August 1982 AVLIS was also chosen over MLIS for a plutonium enrichment plant

28 UF_6 molecules have an octahedral structure with the uranium atom at the center and the six fluorine atoms at the corners The molecule can vibrate in six modes but only two involve motion of the uranium atom Each of these two exhibits an isotopic shift vibrating at slightly different frequencies, depending on whether the atom at the center is U-235 or U 238 Of these two, the mode in which the uranium atom and two opposite fluorine atoms move up and down perpendicular to the plane of the other four fluorine atoms (the "infrared-active stretching fundamental") is important for the MLIS process Vibration of this mode in UF_6 gas molecules is strongly excited by infrared light of about 16 000 nm (1 nm is one billionth of a meter) from a carbon dioxide (CO_2) laser (also an H_2 Raman laser CF_4 laser, or tunable semiconductor laser) Because of the isotopic shift molecules with U 235 atoms may be selectively set into vibration without disturbing molecules with U 238 atoms This excitation is followed by dissociation with an ultraviolet laser at 308 nm to form UF_5 The energy of the ultraviolet laser is insufficient to dissociate the unexcited UF_6 Benedict et al *Nuclear Chemical Engineering* p 916; Jack F Aldridge et al "Measurement and analysis of the infrared-active stretching fundamental (ν_3) of UF_6 *Journal of Chem Phys* (1 July 1985): 34 38 provides a rigorous treatment of MLIS related UF_6 spectroscopy

5

Other Processes

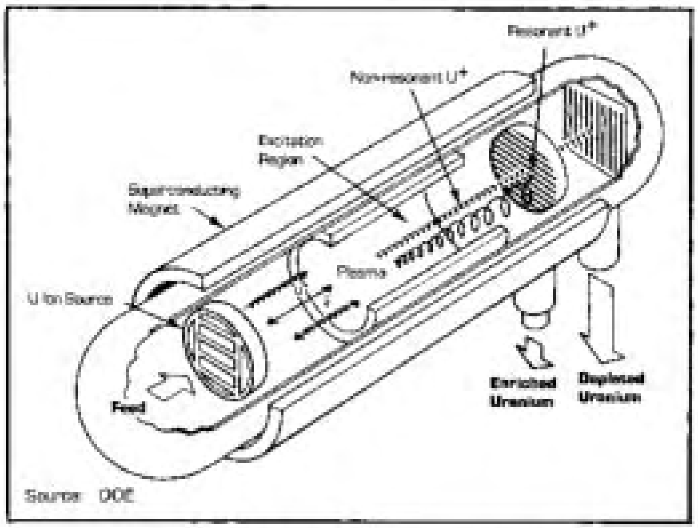


Figure 5 11 Illustration of the Plasma Isotope Separation Process

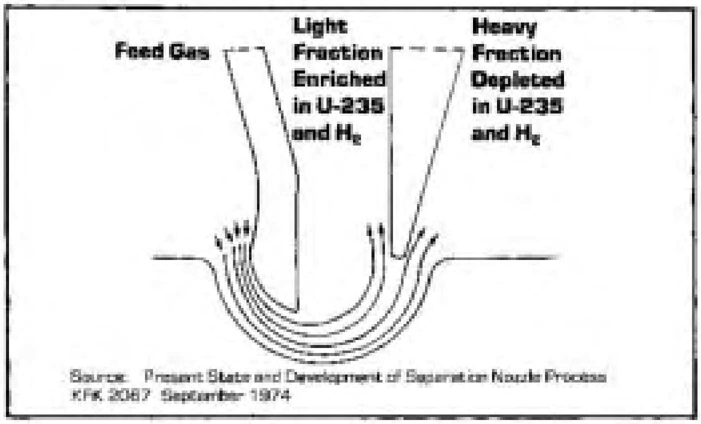


Figure 5 12 Cross-section of the Jet Nozzle System

in diameter until the U-235 ions intersect collector plates aligned parallel to the magnetic field The product on the collector plates is enriched in U-235, while the U-238 ions, with small diameter orbits, pass through to the tails plate [29]

The success of the PSP is based on a 1 percent difference between the cyclotron resonance frequencies at which U-235 and U-238 ions spiral about the field lines in a uniform magnetic field [30] Components of a PSP enrichment unit include an ion source, a superconducting magnet, a radio-frequency oscillator, and a collector system Power consumption is about 221 kwh/SWU [31]

PSP has been under development by TRW, Inc since 1976 It was a candidate (along with AVLIS and MLIS) in DOE's advanced isotope separation program until AVLIS was selected in 1982 for further development Currently, TRW's PSP process is being developed by DOE Defense Programs to remove "unwanted" uranium-236 (and U-234 and U-238) that builds up in irradiated fuel during operation of the Savannah River production reactors A PSP plant is scheduled to operate at Savannah River in the late 1980s

Chemical Enrichment

Chemical enrichment of uranium depends on an exchange reaction between two chemical species in two different phases At phase equilibrium there is a difference in uranium isotopic composition in the two phases One phase may be stationary, or the two phases may move in countercurrent flow The separation factor, depending on the phases used, ranges from 1 0013 to 1 0030

Components of an enrichment unit, depending on the chemical phases, may include exchange columns, packed towers, mixer settlers, pumps, and piping

Chemical enrichment is a maturing technology France leads in industrial development Demonstration on a laboratory scale is occurring in the United States and Japan The French ion exchange enrichment process, called Chemex, has moved into the pilot stage with a 1/10-scale (1000 SWU/yr) plant scheduled to start up at Pierrelatte in September 1984 [32] The Chemex process uses trivalent uranium for the aqueous phase, with tetravalent uranium in a lighter organic phase Chemex exchange is instantaneous and is reported to have a very high separation factor, four times that for other reactions

The French Pierrelatte pilot plant will have "a few" pulse columns 10 meters high and 380 millimeters in diameter As conceived, a commercial Chemex plant would have twenty exchange columns per cascade, arranged in modules of two vertical cascades, with columns 25 to 30 meters high and 1 2 to 1 6 cm in diameter Each cascade would be capable of producing 250,000 SWU/yr, and an industrial module would have a capacity of 500,000 SWU/yr

Aerodynamic Processes

Two aerodynamic processes have been developed to an industrial scale: the Becker jet nozzle process developed at Karlsruhe, West Germany, and the helikon process developed in Valindaba, South Africa

In both the jet nozzle process (see Figure 5 12) and the helikon process, a mixture of UF_6 gas and hydrogen gas flows at high speed in a sharply curved path The resulting centrifugal acceleration partially separates the lighter and heavier uranium isotopes [33] The helikon uses an advanced vortex system to separate isotopes

For the jet nozzle process an enrichment stage—a single nozzle or several nozzles connected in parallel—

29 DOE, ERAB Study Group p 32

30 Singly charged ions of mass M moving in a uniform magnetic field of strength B spiral about the direction of the field at a frequency given by the expression $f = 1.52 \times 10^3$ B/M where B is magnetic field strength in gauss and M is in atomic mass units (AMU) The difference in ion mass of 3 AMU between U-238 and U-235 results in the 1 percent difference in their cyclotron frequencies The radiofrequency field oscillating in phase with the motion of the ionized U 235 atoms increases their orbital radius without affecting the U-238 atoms

31 DOE ERAB *Study Group* p 18

32 Nucleonics Week (7 June 1984): 11

33 See Allan S Krass Peter Boskma Boelie Elzen and Wim A Smit *Uranium Enrichment and Nuclear Weapons Proliferation* London: Taylor and Francis 1983) p 110; Benedict et al *Nuclear Chemical Engineering* p 817

has a separation factor of about 1 015 For the helikon, a module is the basic unit and the separation factor is on the order of 1 025 Currently jet nozzles with openings ranging from 25 to 100 microns are being used on the laboratory scale or being designed for pilot plants [34] A commercial-size jet nozzle plant for LEU production would have about 450 stages Power consumption is estimated to be 3000 to 5000 kwh/SWU for both aerodynamic processes, larger than for gaseous diffusion

Both jet-nozzle and helikon processes are maturing technologies A jet-nozzle pilot plant with a capacity of 10,000 SWU/yr is scheduled to operate in Brazil in 1985-89 [35] The plant in Brazil is being constructed by West Germany Eventual expansion to 200,000 SWU/yr is planned A helikon plant with a capacity in excess of 30,000 SWU/yr is operating in South Africa (see Table 5 2)

Production Reactors

Nuclear production reactors manufacture plutonium-239 and tritium for warheads and other purposes, plutonium-238 as a heat source to power space reactors, and a variety of other isotopes with military, commercial, and medical uses

The history of production reactors began on 2 December 1942, in the midst of World War II, when the Chicago Pile No 1 (CP-1) went critical CP-1 first demonstrated a sustained chain reaction, a crucial step in the government's S-1 program to develop the atomic bomb Built by Enrico Fermi and his associates under the football stadium at the University of Chicago, the crude reactor (or "atomic pile") was fashioned from layers of graphite blocks embedded with spheres of natural uranium metal or uranium oxide (about 35 MT of uranium and 340 MT of graphite) CP-1 was soon dismantled (in order to recover the uranium) and rebuilt outside of Chicago at Argonne with a tenfold increase in power from its original 200 watts The reactor, called CP-2, was completed in March 1943 and demonstrated plutonium production on a small scale

The first large-scale reactor for plutonium production, X-10 (or the Clinton Pile), was built at Oak Ridge, Tennessee, in 1943 X-10 used cylindrical slugs of natural uranium that were pushed through horizontal channels in a graphite block and removed without dismantling the reactor The Oak Ridge reactor began operation on 4 November 1943 at 800 Kw_t and was up to 3800 Kw_t by June 1944 By the end of February 1944, it was producing plutonium at the rate of several grams per month The air-cooled X-10 was to be the pilot model for helium-cooled reactors to be built at the Hanford Reservation Construction began there before X-10 was completed and the design was changed to use water cooling from the Columbia River

Construction of the B-Reactor at Hanford began in June 1943 and was completed in September 1944 By early 1945, three reactors (B, D, F) were completed, and each had a design power of 250 Mw_t at startup These provided the plutonium for the first nuclear implosion devices

Following the end of World War II, additional production reactors were built in the U S at Hanford and Savannah River The first Soviet production reactor began operating at Kyshtym on 10 June 1948 The first two U K production reactors began operating at Windscale in 1951, each with a design power rating of 115 Mw_t They were followed between 1956 and 1959 by eight dual-purpose Magnox reactors (for the production of plutonium and electricity) at Calder Hall and Chapel Cross, each with a power rating of 200 Mw_t French production reactors were constructed at Marcoule The operation of the 40 Mw_t G1 reactor began there in 1956 followed by the G2 reactor (250 Mw_t) in 1959 and the G3 reactor (250 Mw_t) in 1960

Nuclear Processes

Two nuclear processes are fundamental to the production of plutonium and tritium (see Figure 5 13)

Plutonium-239 is produced in reactors through the absorption of neutrons in uranium-238 target material and two subsequent beta decays:

$$n + U\text{-}238 \rightarrow U\text{-}239 \xrightarrow[24m]{\beta} Np\text{-}239 \xrightarrow[2\ 4d]{\beta} Pu\text{-}239$$

Tritium (H-3 or T) is formed through the absorption of neutrons in targets of lithium-6, which has a large cross-section for slow neutrons:

$$n + Li\text{-}6 \rightarrow Li\text{-}7 \rightarrow He\text{-}4 + T$$

Producing these isotopes in quantity requires a copious supply of neutrons This is achieved in a reactor, where a sustained and controlled chain reaction of fissioning uranium-235 nuclei provides a steady flux of neutrons to bombard selected target materials

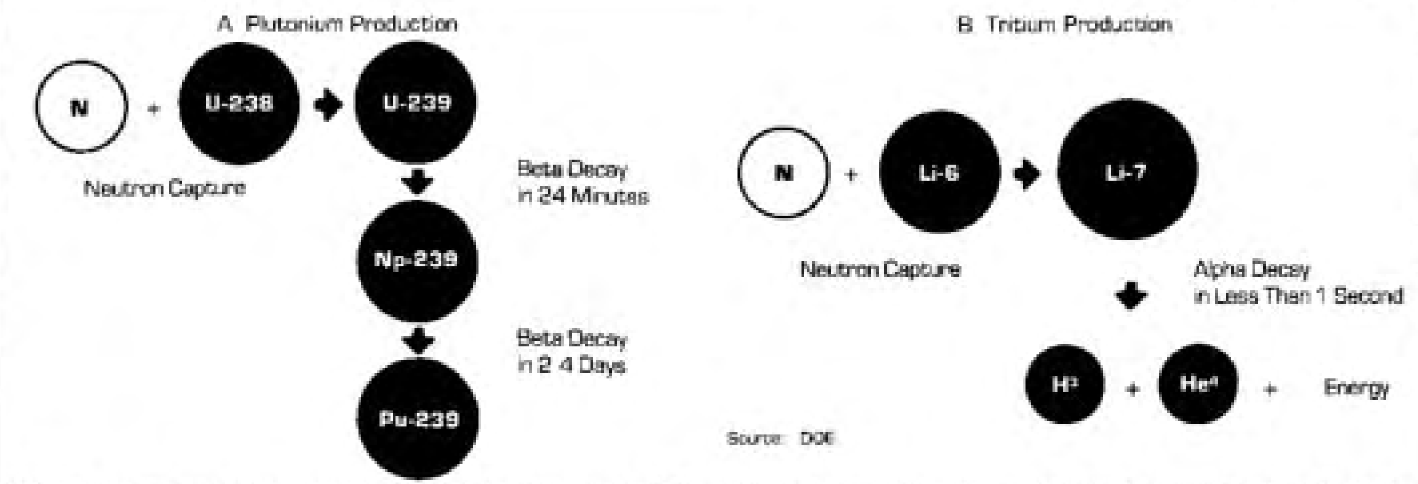
Categories of Plutonium

As a reactor operates and quantities of plutonium-239 are produced, heavier isotopes of plutonium (Pu-240, 241, 242) are also made by subsequent neutron captures The rate at which these other isotopes build up depends not only on the design and operating power of the reactor but also the length of time the fuel remains in it (see Figure 5 14) The fuel exposure or "burnup" is often measured in units of megawatt days per metric ton of fuel (Mwd/MT)

DOE identifies its plutonium stocks as supergrade (or high-purity), weapon-grade, fuel-grade, or reactor-grade The purity of the plutonium is defined in terms of

34 Nuclear Fuel (3 December 1984): 7

35 Ibid



(A) In plutonium production, a neutron is absorbed in a uranium-238 nucleus to form uranium-239 which transforms into plutonium-239 through two beta-decays

(B) In tritium production, a neutron is absorbed in a lithium-6 nucleus to form lithium-7 which decays into a tritium nucleus (H-3) and an alpha particle (He-4)

Figure 5 13 Nuclear processes for Plutonium-239 and Tritium

the major isotopic contaminent, Pu-240 The DOE categories are:[36]

Plutonium Category	Percent Pu-240
Supergrade (high purity)	2 to 3
Weapon-grade	less than 7
Fuel-grade	7 to less than 19
Reactor-grade	19 or greater

The plutonium in U S nuclear warheads contains about 93 percent Pu-239, about 6 5 percent Pu-240, and very small quantities of other plutonium isotopes [37]

Plutonium Equivalence

Savannah River reactors breed tritium in highly enriched lithium-6 target elements, blankets, and control rods While the thermal neutron capture cross section of Li-6 is seventeen times that of U-238, the breeding rates of plutonium and tritium atoms are about the same, limited by neutron availability of about one fission On this basis, one gram of tritium can be produced in place of 72 grams of weapon-grade plutonium [38] Thus for simplicity in accounting overall reactor performance, 1 kg of tritium is counted as 72 kg of *plutonium equivalent* Since a number of different isotopes are produced in a variety of target materials, it is convenient to describe reactor productivity in terms of plutonium equivalent

Reactor Operations

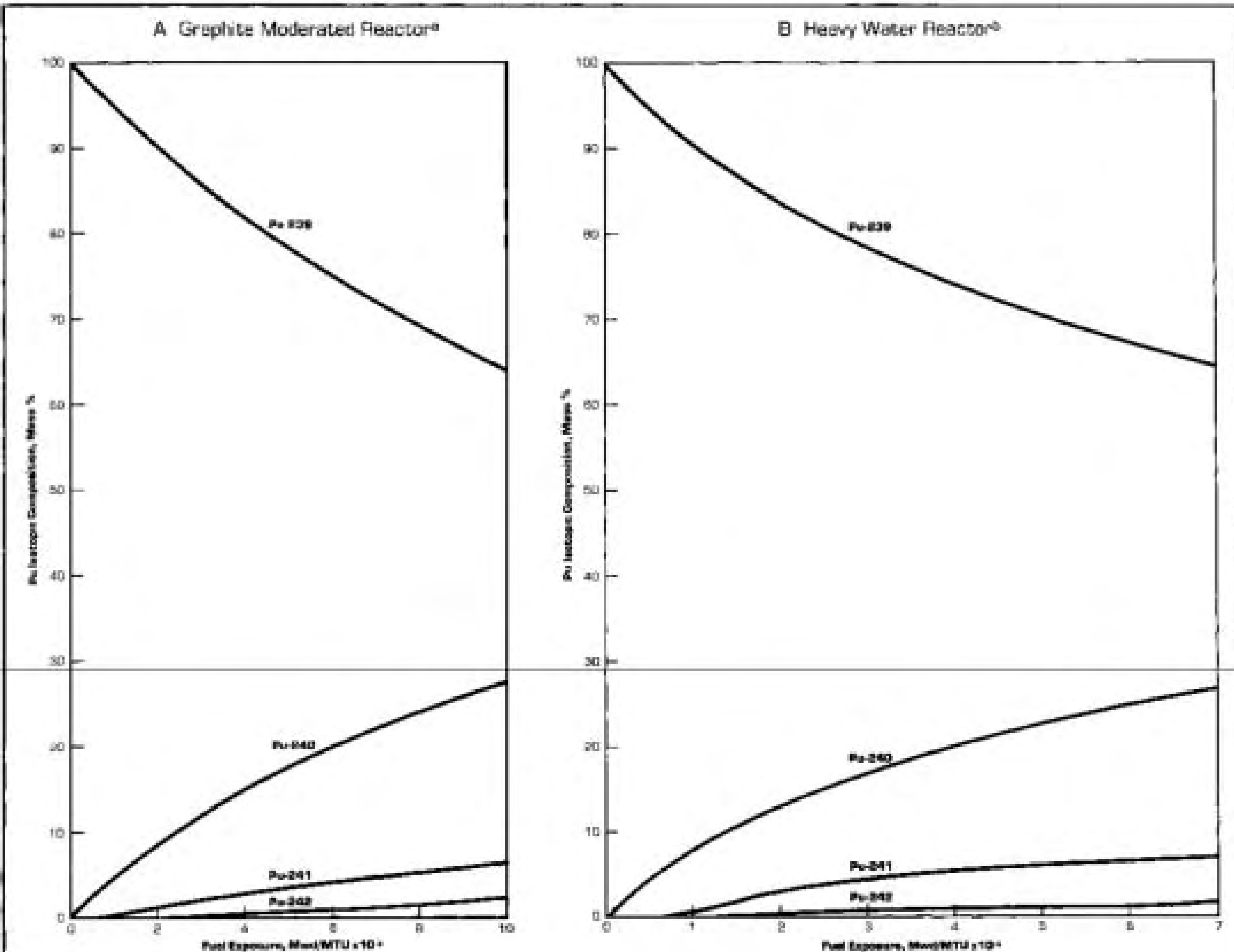
A production reactor core consists of a lattice of assemblies of fuel and target material These are imbedded in moderator material, either rigid graphite or heavy water The moderator slows the fast fission neutrons to enhance the probability of capture in U-235 or in targets The fuel and target materials may be arranged in the core in various ways They may, for example, be in separate intermingled assemblies as with HEU fuel drivers and depleted uranium Alternatively, each assembly may contain both fuel and target material—for example, highly enriched uranium and lithium-6, or slightly enriched uranium alone There are also positions in the core for control rods containing lithium, cadmium, or boron They can be moved in and out of the core to absorb excess neutrons and maintain reactor operation or bring about shutdown

The reactor core may be surrounded by a neutron reflector often of the same material as the moderator The heat produced in the core by fission is removed by a cooling system using heavy water, ordinary water, gas, or air The core and reflector are further surrounded by shielding to protect personnel from radiation A steel thermal shield absorbs gamma rays and must be cooled Outside the thermal shield a biological shield of concrete absorbs neutrons and gamma rays

Targets are discharged when the desired product is attained When separate HEU fuel assemblies are used they are usually burned until the chain reaction can no longer be sustained In the production of weapon-grade plutonium, the targets must be discharged frequently to limit the production of unwanted isotope Pu-240 formed by neutron irradiation of Pu-239

Deuterium (in heavy water) slows down neutrons in production reactors more efficiently than moderator graphite It requires fewer collisions and less volume to slow a fast neutron down to thermal energies Consequently, heavy water moderated reactors are generally

36 HASC, FY 1982 DOE p 170
37 DOD Interservice Nuclear Weapons School Glossary Kirtland AFB 1975 p 56 The W80 0 SLCM warhead was originally designed to use supergrade plutonium
38 HASC, FY 1982 DOE p 172 Thus a given number of neutrons from fission can produce essentially the same number of atoms of tritium or plutonium since 1 gram of tritium is equivalent to 239/3 = 80 grams of Pu 239



a Data given for a CO2-cooled Magnox reactor
b Data given for a natural uranium CANDU reactor

Source: NUS Corporation Heavy Element Concentrations in Power Reactors SND-120-2 May 1977

Figure 5 14 Plutonium isotopic composition as a function of fuel exposure

more compact than those moderated by graphite The *neutron flux* (the number of neutrons crossing a square centimeter per second) in the heavy water reactor is higher, by perhaps an order of magnitude (e g , 10^{14} n/cm^2-s vs 10^{13} n/cm^2-s) Heavy water is also much less likely to capture thermal neutrons than graphite

Reactor Fundamentals

In the fission of one uranium nucleus, about 2 4 fast neutrons (energy of about 1 MeV) are emitted following the absorption of a slow neutron The nucleus is split into two fragments of unequal mass, and about 200 MeV of energy is released Essentially the same thing occurs for nuclei of Pu-239 formed in a production reactor Like U-235, Pu-239 is fissionable by slow neutrons The energy released is carried away mainly as kinetic energy of the fission fragments, but also by neutrons, gamma rays, and other particles Most of these products are stopped in the reactor and their energy is converted into heat The fast neutrons collide with moderator atoms, losing energy and slowing down in a sequence of elastic collisions In this way fission neutrons become thermal[39] with good chances for capture by another U-235 nucleus The uranium isotope U-238, although usually present in

39 Thermal neutrons are neutrons in thermal equilibrium with the surrounding matter, thus equally likely to lose or to gain energy in collisions with the moderator atoms The kinetic energy of thermal neutrons is typically less than 0 1 eV

quantity, is not fissionable by slow neutrons

To sustain the chain reaction, at least one fission neutron must survive the slowing down process and be absorbed by another U-235 nucleus so as to cause another fission Besides slowing, other possible fates for fast neutrons are (1) leakage from the reactor; (2) fission of U-238 or U-235 atoms by fast neutrons, an extremely small contribution in thermal reactors; (3) parasitic capture of neutrons by the moderator, structural materials, control rods and fission products; (4) non-fission capture of thermal neutrons in U-235 to produce U-236; (5) absorption of thermal neutrons in U-238; and (6) absorption of neutrons at intermediate (between fast and thermal) energies in U-238 as they slow down

The last two processes—(5) and (6)—are of singular importance in a plutonium production reactor There, about one or more neutrons per fission breed plutonium (or tritium during tritium production with lithium targets) This means that about one gram or more of plutonium is created for each megawatt day of heat generated in the reactor (since the fission of 1 05 grams of U-235 generates one megawatt day of heat) The efficiency of conversion of fissile fuel to plutonium is described by the *conversion ratio*, the number of fissile atoms produced per fissile atom consumed The conversion ratio is usually about 0 8 or greater, since on the average about 1 2 thermal neutrons are absorbed in a U-235 nucleus per fission Some of the fissile atoms consumed in a production reactor are plutonium atoms themselves A slow neutron absorbed in Pu-239 either produces fission or is captured to form the isotope Pu-240 For every neutron captured, about two neutrons produce fissions In the production of weapon-grade plutonium, when about 6 percent of the net plutonium is Pu-240, some 12 percent of the plutonium produced has been fissioned

The capture of intermediate energy neutrons while they are slowing down through the "resonance region" of U-238 is termed resonance capture, an important process for production reactors [40] Enhancing resonance capture increases the conversion ratio In power reactor design the probability of resonance capture is reduced by making the fuel lattice spacing sufficiently large to suppress the reentry of fisson neutrons into the fuel before they have become thermalized

The probability of resonance capture also depends on the relative amounts of fertile material (U-238) and moderator in the reactor core In a production reactor, because of the competition for neutrons, the quantity of U-238 must be limited or the chain reaction will be endangered This is particularly true of graphite-moderated reactors, where neutrons are also absorbed in the graphite Heavy water-moderated production reactors, such as the Savannah River reactors, can have a much greater resonance capture probability, with a resulting conversion ratio that may be slightly greater than unity in some cases The lattice spacing between fuel elements in the Savannah River reactors is substantially less than for commercial heavy water-moderated reactors

A reactor cannot operate before a certain critical mass of fissile material has been assembled Leakage and absorption of neutrons must be balanced by neutrons emerging from fission The critical mass of assembled uranium decreases with increasing enrichment and may be reduced by surrounding the core with a reflector The ability of a reactor to sustain a chain reaction is measured by the neutron *multiplication factor*, k, the ratio of the number of neutrons produced by fission in any one generation to the number produced in the preceding generation Reactors are designed with k's slightly greater than unity to allow growth in the number of neutrons until the desired power and flux levels are achieved in the core Systematic adjustment of control rods then keeps the multiplication factor at a value of one The *excess reactivity* (the difference between 1 and k^{-1}) is enhanced by increasing the amount or enrichment of the fuel It is decreased by adding neutron-absorbing target materials At startup, the initial reactivity decreases with temperature rise and with the formation of the fission product, xenon, a strong neutron absorber [41]

The multiplication factor is proportional to the probability that neutrons, as they slow down, escape capture in U-238 resonances But the production of plutonium (i e , a large conversion ratio) is favored by a small "resonance escape probability " These seemingly conflicting objectives of high multiplication factor and small resonance escape probability are best met in a heavy water-moderated reactor There, excess reactivity is generally large The objectives are not met so easily in a graphite-moderated, natural uranium-fueled reactor, where k is only a few percent greater than unity at best

Fuel Processing

Irradiated fuel and targets from production or power reactors are chemically processed mainly for the separation and recovery of fissile uranium and plutonium In addition, particular isotopes are recovered for special applications These include plutonium-238, the fission products strontium-90, cesium-137, and krypton-85, and the by-product transuranic elements neptunium, americium, curium, and californium

Due to the presence of fission products, fuel discharged from a reactor is intensely radioactive Before processing it is first cooled in ponds for five months to a year This permits short-lived isotopes to decay

A number of methods have been developed for chemically processing irradiated fuel The most common method is the PUREX (Plutonium-URanium-EXtraction) process Two early U S methods for separating plutonium and other elements from irradiated fuel—the bis-

40 The resonance region of U-238 extends from neutron energies of 6 eV to 200 eV

41 The effect of xenon was discovered in 1943 when the first Hanford production reactor went subcritical shortly after startup

muth phosphate process and the Redox process—are important historically, but no longer in use

Early Methods

The bismuth phosphate process was developed during World War II at the Metallurgical Laboratory of the University of Chicago [42] It was used to separate the first microgram quantities of plutonium produced in 1942 in the Washington University (St Louis, Missouri) cyclotron The bismuth phosphate process was then developed on an engineering scale and demonstrated at the Oak Ridge X-10 plant in 1944 It was put into full operation at Hanford's B plant in late 1944 to separate plutonium from irradiated production reactor fuel At Hanford between December 1944 and February 1956, when the bismuth phosphate process was discontinued, 7000 MT of irradiated fuel (heavy metal) were processed in the B plant [43]

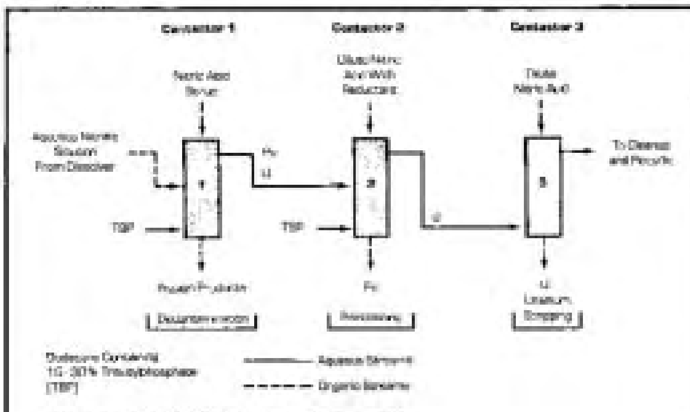
The bismuth phosphate process recovered plutonium, but was unable to separate and recover uranium from the fission products This was its most serious disadvantage The process was used for extracting radioactive substances at low concentration After the irradiated fuel elements containing uranium, plutonium, and fission products were dissolved in nitric acid, bismuth nitrate and sodium phosphate were added to the solution Plutonium phosphate was precipitated, along with bismuth phosphate

The Redox process was the first countercurrent extraction process used in the United States for large-scale extraction of plutonium and uranium from irradiated fuel Unlike the bismuth phosphate process it could operate continuously rather than in batches It was developed at Argonne National Laboratory and installed at Hanford in late 1951 Between January 1952 and June 1966, when the process was discontinued, 19,000 MT of irradiated fuel were processed by the Redox method at Hanford [44]

In the Redox process, plutonium, uranium, and fission products were recovered and discharged in separate streams Irradiated fuel was dissolved in nitric acid, producing an aqueous solution of uranyl nitrate, plutonyl nitrate, and fission product nitrates This was followed by the introduction of an organic solvent, hexone, in which the uranyl and plutonyl nitrates concentrated Fission product nitrates were left in the aqueous phase In three subsequent steps, the fission products were first removed in the aqueous phase, the plutonium was then chemically reduced and removed in the aqueous phase as plutonium nitrate, and finally the uranyl nitrate was transferred back to the aqueous phase

PUREX Process

PUREX is today the most widely used process for separating plutonium, uranium, and (sometimes) neptunium from fission products in irradiated fuel PUREX is a solvent extraction process Fuel is dissolved in an aqueous solution of nitric acid, and the desired chemical elements are extracted in a series of steps by countercurrent flow with an organic solvent



Source: DOE NASAP op cit Vol 9 p 347

Figure 5 15 Simplified diagram of the PUREX Process

The PUREX process was developed at the Knolls Atomic Power Laboratory of General Electric, demonstrated at the Oak Ridge National Laboratory, and adopted by DuPont for the Savannah River Plant, where operation began in November 1954 Success there led to the replacement of Redox by PUREX at Hanford in January 1956 At Hanford 67,000 MT of irradiated fuel were processed using the PUREX method prior to the termination of PUREX operations in December 1971 [45] The plant has since been restarted

The PUREX process was also used in the commercial reprocessing plant operated at West Valley, New York from 1966 to 1972 It was planned for use in General Electric's unsuccessful reprocessing plant at Morris, Illinois and in the uncompleted Allied General Nuclear Services reprocessing plant at Barnwell, South Carolina (see Table 5 3)

Figure 5 15 shows a simplified diagram of the PUREX process [46] Irradiated uranium fuel is first dissolved in nitric acid forming an aqueous solution of uranyl nitrate ($UO_2(NO_3)_2$), tetravalent plutonium nitrate ($Pu(NO_3)_2$), and fission product nitrates The aqueous solution is then fed to the center of a countercurrent solvent extraction contactor (Figure 5 15, contactor 1)

The contactor is fed from the bottom with organic solvent tributyl phosphate (TBP) in solution with hydrocarbon dodecane It is fed from the top with dilute nitric acid The uranyl and plutonium nitrates concentrate in the organic solvent along with some fission products The nitric acid scrub cleans the solvent of fission products, which leave the bottom in an aqueous stream while the plutonium and uranium leave from the top in the

42 Benedict Nuclear Chemical Engineering, pp 21 458-66

43 DOE Hanford 1983 a briefing book prepared for site visit by EPA Staff to the Hanford Reservation 18-19 October 1983

44 Ibid

45 Ibid

46 DOE Report of the Nonproliferation Alternative Systems Assessment Program (NASAP) Vol 9 June 1980 pp 342 ff

Table 5 3

U.S. Plants Using PUREX

Plant	Owner	Dates of Operation	Capacity MTU/year	Maximum % U-235	Minimum Cooling Days	Decladding
Military						
Hanford	DOE	1955-71 1983-present	2300[a]	18	180	Chemical
Savannah River						
(F area)	DOE	1954-present	2700	Natural	200	Chemical
(H area)	DOE	1954-present	15	100	150	Electrolytic
ICPP[b]	DOE	1953-present	1-2[c]	100	120	Chemical & Electrolytic
Commercial						
West Valley	Nuclear Fuel Services	1966-72	300[d]	93	150	Shear-leach
Barnwell	Allied General Nuclear Services	[e]	1500	5	160	Shear-leach
Morris[f]	General Electric	[g]	300	?	?	Shear-leach

a The PUREX plant capacity is limited by waste handling operations in the decladding process With modifications capacity could be increased to 3100 MT/yr (DOE DEIS, Operation of PUREX and Uranium Oxide Plant Facilities-0089D May 1982 p 3 15) A change to shear-leach decladding is planned by FY 1992

b Idaho Chemical Processing Plant PUREX modified for recovery of highly enriched uranium only

c Estimated ICPP processed 28 8 MT of HEU through FY 1984 over a period of thirty-two years

d About 250 MT of LWR fuels and 375 MT of metal fuels were processed (DOE NASAP Vol 9 p 342)

e Neither completed nor licensed

f Midwest Fuel Recovery Plant at Morris Illinois

g Completed but never operated due to flawed technical design Work was suspended in 1974

Source: Benedict *Nuclear Chemical Engineering* p 466

organic stream Sometimes neptunium is also extracted in the organic stream (e g , at both Savannah River and Hanford)

The uranium and plutonium are separated from each other in further extraction steps involving valence changes of plutonium The organic stream containing tetravalent plutonium nitrate and uranyl nitrate is fed to contactor 2 (Figure 5 15) This second contactor is also fed from the bottom with TBP, and from the top with a dilute nitric acid solution of ferrous sulfamate that reduces the plutonium to the trivalent state, leaving the uranium in its hexavalent state As a result, the plutonium is transferred to the aqueous phase and leaves the bottom of the contactor The uranium and neptunium remain in the organic stream

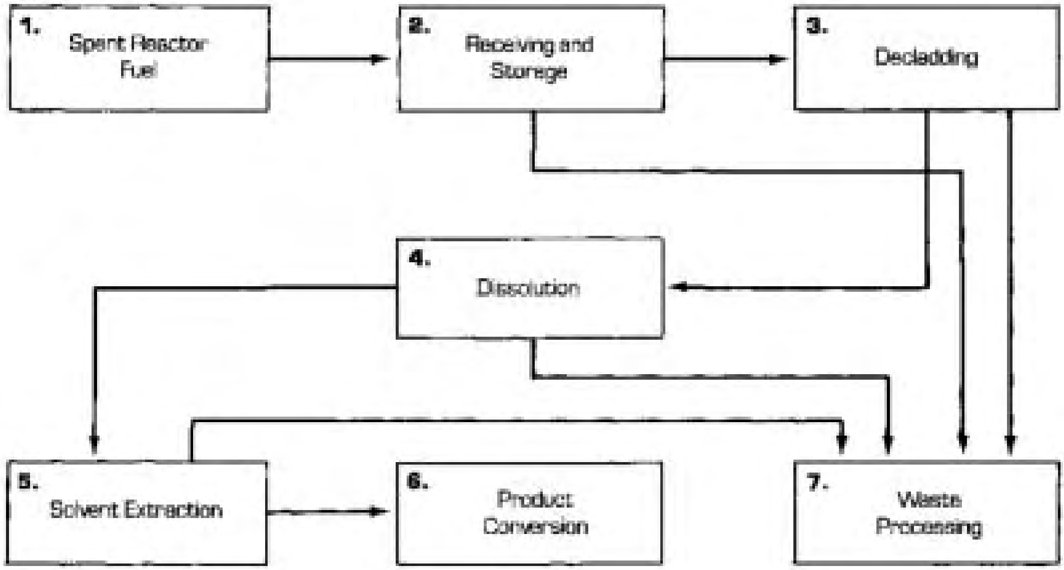
Finally, the organic stream containing uranyl nitrate is fed to the bottom of contactor 3 The solvent is stripped by dilute nitric acid (or water) entering from the top of the contactor The separated uranium (and, sometimes, neptunium) then leaves the contactor in the aqueous phase When neptunium is extracted, it is further separated from the uranium by solvent extraction in a second uranium cycle, not shown in Figure 5 15

The acid Thorex process, a modification of the PUREX process, was developed at Oak Ridge National Laboratory to separate thorium and uranium-233 from fission products in irradiated thorium fuels In all respects it is similar to the PUREX process A Thorex process also can be devised to accommodate separation of plutonium along with thorium and uranium

Heavy Water Production

The main heavy water (D_2O) production process in use throughout the world since the early 1950s has been the dual-temperature water-hydrogen sulfide exchange process, also known as the Girdler-Sulfide (GS) process [47] U S production of heavy water in World War II was almost solely by water distillation, but this process is now generally used in plants only as the final enrichment

47 The Girdler Corporation under DuPont direction designed the first large post-war heavy water plant in the United States at Dana Indiana which began production in April 1952 and closed in 1959



Fuel Processing Steps

The flow diagram summarizes the steps in the processing of irradiated fuel for PUREX and other solvent extraction processing methods

Steps 1 and 2: Spent Fuel Storage The irradiated fuel is cooled in ponds, from five months at a minimum to a year, after removal from the reactor to permit short-lived isotopes to decay

Step 3: Chemical or Mechanical Decladding Aluminum clad metal alloy fuels from production and research reactors may be chemically declad by dissolving the aluminum in an aqueous solution of sodium hydroxide (with sodium nitrate added to prevent hydrogen evolution) The metal fuel is later dissolved in nitric acid (see Step 4)

The "Zirflex" process is used to remove the zirconium cladding from N-Reactor fuel In this process, zirconium or zircalloy cladding is dissolved in a boiling solution of ammonium fluoride

A separate decladding step is not required when electrolytic dissolution in nitric acid is used This process dissolves metal fuel along with aluminum, steel, or zirconium cladding It is used at Savannah River and at the Idaho Chemical Processing Plant (see Step 5)

Zirconium and steel clad fuel bundles from commercial power reactors are cut into short lengths to expose the oxides of fissionable materials and fission products for dissolution in nitric acid This procedure may also be used for metal fuels, such as N-Reactor fuel

Gases evolved during chemical and mechanical decladding, including fission product krypton and xenon and some iodine, carbon-14, and tritium, are sent to the off-gas treatment system for retention or disposal

Step 4: Dissolution Metal fuels from which the aluminum cladding has been chemically removed are dissolved in nitric acid Metal clad metallic fuels are electrolytically dissolved in nitric acid In commercial power reactors using oxide fuels (UO2), the oxides are leached out of the sheared fuel rods and dissolved in nitric acid, and the cladding is discharged as waste The aqueous solution of fission products and fissionable materials is transferred to the solvent extraction area

Step 5: Solvent Extraction Uranium, plutonium, and sometimes neptunium, are concentrated in an organic solvent (e g , TBP) and separated from the fission products, which are left in the aqueous phase The process is carried out in a series of countercurrent extraction contactors which may be either pulse columns or a battery of mixer-settlers

Step 6: Product Conversion The product streams are converted to oxide powders, plutonium into PuO_2 and uranium into UO_3 or UO_2

Step 7: Waste Processing The waste stream containing the fission products is stored and processed further

Figure 5.16 Flow diagram for nuclear fuel processing

step, following initial concentration by the GS process or other processes [48] Through 1980 some 90 percent of D_2O production worldwide (including the United States and Canada) utilized the GS process for the initial enrichment step and water distillation for final concentration [49]

The GS process and water distillation are the principal "self-contained" processes, where heavy water is the sole product and natural water is the feed In addition, there are several "parasitic processes," where heavy water is a by-product, usually of a plant producing synthetic ammonia Such plants operate, for example, in India

Currently, about a dozen heavy water plants operate or are planned worldwide Since 1982, the world's heavy

48 The first pure samples were produced by electrolysis of water and this process was used in the first large industrial scale plant that began operation at Rjukan Norway in 1934

49 Benedict *Nuclear Chemical Engineering* p 710

water production capacity has decreased, due to a drop in demand and large existing inventories In early 1982, the Heavy Water Plant at Savannah River, the only U S plant operating, was shut down[50] By 1985, Canada, a major commercial producer, had cut its heavy water production capacity to 1600 MT/yr from a high of 4000 MT/yr of operating and planned capacity A further reduction of capacity to 800 MT/yr is expected by 1987[51]

Heavy water is used as moderator and coolant in the CANDU and other natural uranium-fueled commercial power reactors Heavy water is used in the U S nuclear warhead program as the moderator and coolant in Savannah River production reactors Deuterium derived from heavy water is an important ingredient of nuclear warheads, both as solid lithium-6 deuteride and as a gas (D_2) Deuterium, either mixed with tritium or as lithium deuteride, is an essential ingredient in the fuel proposed for fusion reactors

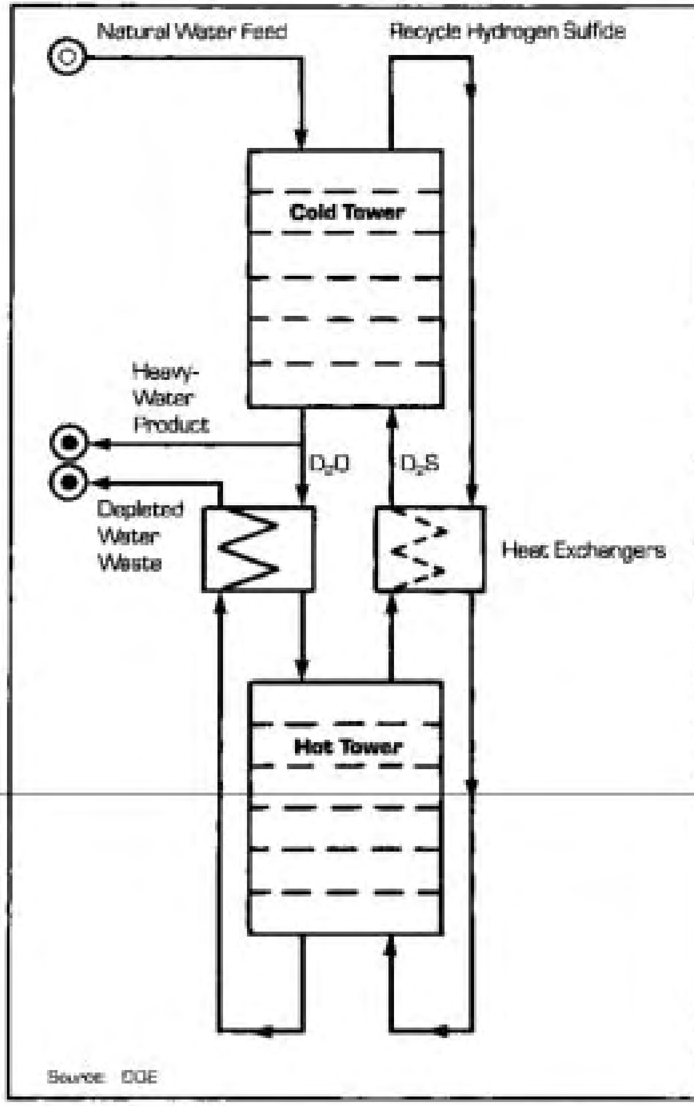
Dual-Temperature Water-Hydrogen Sulfide Exchange (GS Process)

The GS process concentrates heavy water (D_2O) from its natural abundance of about 0 015 percent to between 8 and 15 percent Deuterium is exchanged between deuterium-rich hydrogen sulfide gas (H_2S) and ordinary water to increase the concentration of deuterium in the water The chemical exchange reaction that occurs is

$$\underset{\text{(liquid)}}{H_2O} + \underset{\text{(gas)}}{HDS} \rightleftharpoons \underset{\text{(liquid)}}{HDO} + \underset{\text{(gas)}}{H_2S}$$

Enrichment takes place in a series of exchange columns In a one-stage, single-temperature water-hydrogen sulfide exchange process, natural water is fed in at the top of a sieve-plate exchange column The water becomes progressively enriched in deuterium as it flows down the column in "countercurrent" contact with upflowing deuterium-enriched hydrogen sulfide gas Heavy water product is drawn off the bottom of the column and hydrogen sulfide gas, depleted in deuterium, is drawn off the top

In the GS process there are both hot tower and cold tower stages (see Figure 5 17) The cold tower produces enriched heavy water product and depleted hydrogen sulfide (as in a one-stage process) In turn, the hot tower produces enriched hydrogen sulfide feed ("reflux") for the cold tower by countercurrent flow between some enriched heavy water drawn from the output of the cold tower and the depleted hydrogen sulfide received from the hot tower The hydrogen sulfide flows back and forth between the towers in a closed cycle Because of the higher temperature in the hot tower, the water there is overly enriched in deuterium and consequently transfers deuterium to the hydrogen sulfide[52]



Source: DOE

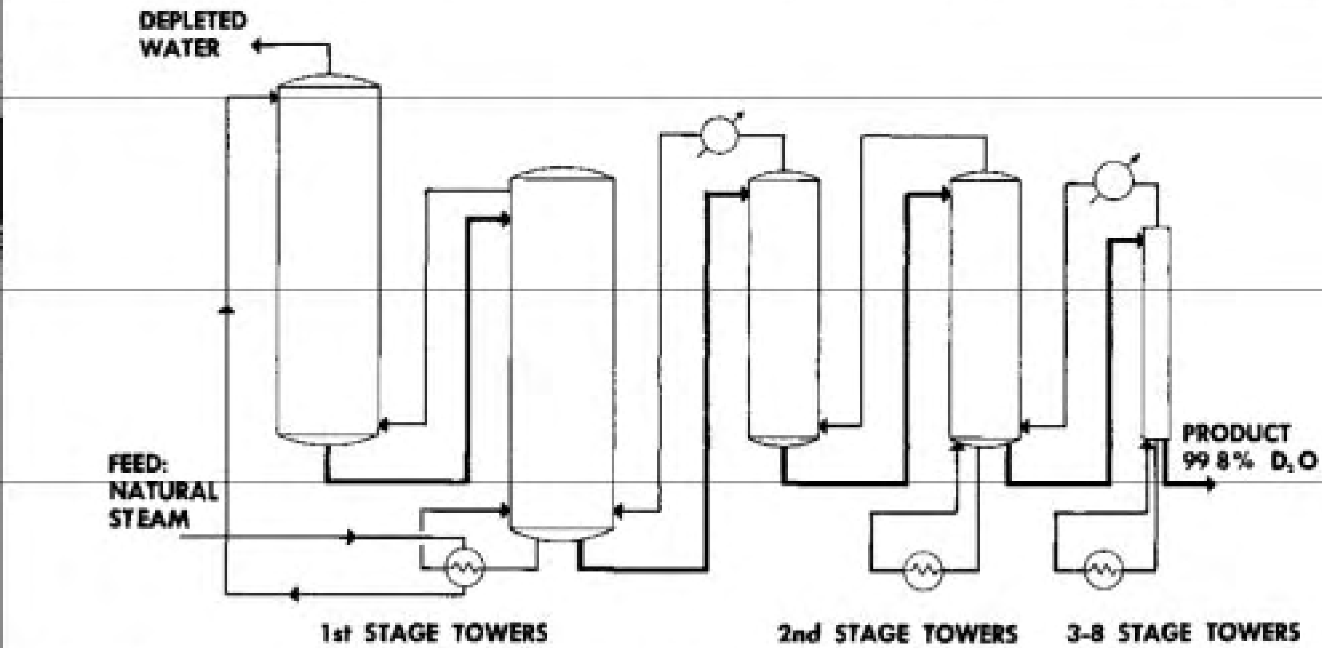
Figure 5 17 Dual-Temperature Water-Hydrogen Sulfide Exchange Process

In the GS process, the desired enrichment of D_2O is achieved by operating two or three sets of towers in series The Savannah River heavy water plant was constructed with 24 two-stage separating units that operated in parallel, with each unit consisting of a hot tower stage and a cold tower stage

50 For the U S D_2O inventory see Table 3 23

51 Ontario Hydro Bruce B (800 MT/yr) Ontario Hydro's Bruce A (800 MT/yr) was shut down in 1984, and Atomic Energy of Canada Ltd (AECL)'s Glace Bay and Port Hawkesbury plants (each 400 MT/yr) will be shut down by the end of 1986; *Nucleonics Week* (30 May 1985): 3 In May 1985 Ontario Hydro had 10 615 MT of heavy water of which 1875 MT was in storage (most of this to go into reactors under construction); Ontario Hydro Corporate Relations private communication to Thomas B Cochran 3 July 1985 By the end of 1983 AECL had stockpiled 1700 MT enough for the initial loadings of three 600 Mw CANDU units; *Nuclear Fuel* (6 July 1984): 6

52 The degree of enrichment is characterized by the separation factor which is the deuterium-to-hydrogen abundance ratio (the number of D atoms divided by the number of H atoms) in the liquid divided by the deuterium-to-hydrogen abundance ratio in the gas The value of the separation factor is about 2 32 at 32°C and 1 80 at 138°C decreasing with temperature Benedict *Nuclear Chemical Engineering* pp 787-88



Source: Eight stage at Morgantown West Virginia; John F Hogerton The Atomic Energy Deskbook (New York, Reinhold Publishing Corporation 1963) p 567

Figure 5 18 Production of heavy water by water distillation

Water Distillation Process

The water distillation process is normally used as an intermediate or final concentration step in heavy water production At Savannah River, it was originally used as the second step (following the GS process) for increasing the D_2O concentration from 13 5 percent to 90 percent, with final concentration to 99 75 percent by electrolysis Later the electrolysis step was dropped Now in most facilities worldwide employing the GS process, water distillation is the final concentration step, concentrating D_2O from 8 percent to greater than 99 75 percent

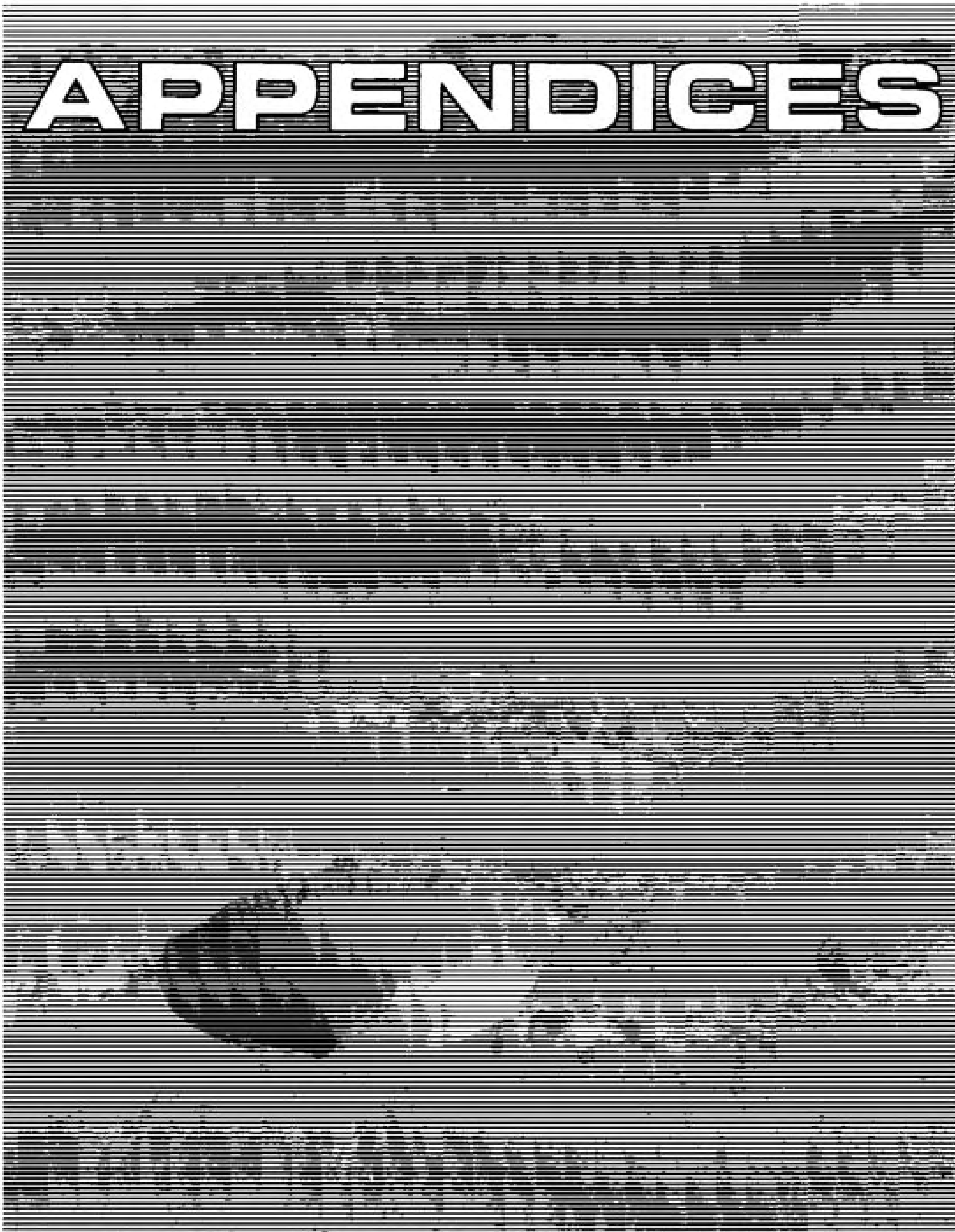
The water distillation process is based on the fact that the boiling point of ordinary water is 0 8°C lower than that of heavy water Thus, water vapor that develops above ordinary liquid is depleted in deuterium, leaving the remaining liquid slightly enriched [53]

In the eight-stage plant shown in Figure 5 18, the first two stages are each composed of two-tower units (actually, each stage is several such units connected in parallel) The last five stages are single towers In stage three, for example, water is vaporized in the reboiler and steam passes upward in the tower through the descending liquid water Depleted vapor from the top of the column is condensed and sent backward to the bottom of the last tower in stage 2 Meanwhile water enriched in deuterium is drawn from the bottom of tower 3 and pumped forward to the top of stage 4 By connecting several stages in series, a high degree of enrichment is attained in the product

At the Savannah River Heavy Water Plant, a rework unit of four distillation towers and associated equipment continues to remove water from recycled D_2O after its use in production reactors as reactor coolant and moderator [54]

53 At the boiling point of ordinary water, the separation factor (the deuterium to hydrogen abundance ratio in the liquid divided by the same ratio in the gas) is equal to about 1 03 The difference from 1 00 is small but significant

54 DOE Environmental Development Plan Special Nuclear Materials Production EDP 0056 July 1980 p II-5


APPENDICES

Appendix A
DOE Contractors Performing Nuclear Weapons Related Work

The research, development, and production of nuclear warheads is carried out in government owned, contractor operated (GOCO) facilities (see *Nuclear Weapons Databook*, Volume III) Nuclear warheads proceed from concept to realization in the GOCO laboratories and plants In contrast to DOD with its thousands of contractors and subcontractors producing components and integrated systems and providing services, the DOE's partnership with the private sector is through a few corporations (see *Nuclear Weapons Databook*, Volume I,for corporate contractors of individual systems)

The control of access to 'Restricted Data' (as defined by the Atomic Energy Act of 1954, as amended) is part of the rationale for producing weapons in GOCO plants The act classified as Restricted Data all information concerning the design or manufacture of nuclear warheads Another reason was the unique requirements associated with nuclear warhead production Novel capabilities were required involving new and costly materials where economies of scale in production are not possible Economic and environmental considerations dictate recovery of as many residues as possible from the manufacturing processes Production of new warheads depends upon nuclear materials recovered from old warheads Security requires accountability for these materials In many cases, the materials are chemically active or radioactive Their handling necessitates special fabrication techniques and safety, health, and environmental protection precautions involving unique state-of-the-art technology Manufacturing processes require a high degree of control, with high reliability requirements

The nature of the production complex has not changed significantly in over forty years of weapon production, first by the AEC, then ERDA, and presently by DOE The technological sophistication and range of both design requirements and production techniques continuously evolves, sometimes dramatically

The DOE contracts with corporations and industrial firms for operation of the GOCO facilities and performance of such work as DOE specifies The contracts are normally for five years to help assure continuity of operation Generally, contractors are expected to operate the plants in accordance with the contractor's own industrial practices and experience (with such differences as are dictated by the nature of the products and the use of public funds) and to treat the divisions operating the government plants as if they were divisions of the home corporation

Laboratory work, production schedules, and quantities to be produced are set by DOE without contract modifications Funding is provided annually and is based not only upon delivery of a prescribed amount of product or hardware but also upon the minimum level of effort that may be necessary to perform directed work Contracts are negotiated on a fixed fee basis or in a cost-plus-award fee basis

Contractor/ Contract Completion Date	Description
AiResearch Manufacturing Co , subsidiary of the Garrett Corp 07/31/84	R&D on gas centrifuge enrichment technology (commercial nuclear, potential nuclear weapons and naval reactor applications); operates gas centrifuge Pilot Assembly and Balance Facility at Naval Weapons Station, Seal Beach, CA
Allied Corp	(see Bendix Kansas City Division)
AT&T Technologies, Inc	(see Sandia Corp)
Associated Universities, Inc Brookhaven Upton, L I , NY 11719 12/31/87	Operates the Brookhaven National Laboratories; conducts research on inertial confinement fusion, safeguards and waste management (approximately 1 percent of the BNL effort)
Atlantic Richfield Hanford Co , Subsidiary of Atlantic Richfield Co	Responsible for fuel reprocessing, waste management and general support at Hanford Reservation
Atomics International	(see Rockwell International Corp)
Babcock & Wilcox Co Lynchburg, VA 24505 numerous contracts through 12/31/91	Reactor core development and preproduction work for naval reactor program; fabricates naval reactor cores
Babenco Corporation 12/84	Construction of the High Explosive Machining Facility at the Pantex Plant; final assembly and retirement of nuclear weapons

Contractor/ Contract Completion Date	Description
Batelle Memorial Institute Richland, WA 99352 09/30/88	Operates the Pacific Northwest Laboratory, which conducts research on defense waste management
Bechtel Corporation San Francisco, CA 94101/94119 numerous contracts through 12/31/87	Project architect/engineer for the Waste Isolation Pilot Plant (WIPP) in New Mexico for storage of transuranic wastes; managing contractor for the Formally Utilized Sites Remedial Action Plan (FUSRAP)
Bendix Kansas City Div., Allied Corp Kansas City, MO 64141 12/31/86	Operates Kansas City Plant; produces electrical, mechanical, and plastic components of nuclear weapons
Black & Veatch Overland Park, KS 66212 12/31/85	Utilities and equipment replacement, restoration and upgrade at Y-12
Blount Brothers Corp Montgomery, AL 36192 01/18/87	Radiation hardened integrated circuits facility
Boeing Engineering and Construction Co., subsidiary of Boeing Co., Inc Seattle, WA 98101 03/03/87	Designs and manufactures gas centrifuges for GCEP project (commercial nuclear, potential nuclear weapons, and naval reactor applications)
Calculon Corp Germantown, MD 20767 01/02/86	ADP and telecommunications support
Catalytic, Inc Philadelphia, PA 10/31/84	Construction manager for FAST Project, Idaho Chemical Processing Plant
University of California (Board of Regents) Berkeley, CA 94720 Los Alamos, NM 87544 09/30/87	Operates Los Alamos National Laboratory, Lawrence Livermore National Laboratory and Lawrence Berkeley National Laboratory
Centel Business Systems Las Vegas, NV 89109 09/30/88	Telephone upgrades at NTS, Tonopah Test Range, and Las Vegas facilities
University of Chicago Lemont, IL 60439 09/30/88	Operates Argonne National Laboratory (ANL) Approximately 1 to 2 percent of ANL research is funded by the DOE Defense Programs in ICF research, safeguards, and defense waste management

Contractor/ Contract Completion Date	Description
Computer Sciences Corp Las Vegas, NV 89109 09/30/89	Operates ADP and communications at DOE facilities in Nevada
Cornell University Ithaca, NY	Support contractor of hardware design for pulse power technology used by SNLA for inertial confinement fusion research and weapons effects simulation
E I duPont de Nemours & Co Aiken, SC 29801 09/30/89	Operates Savannah River Plant; production of plutonium and tritium heavy water and radioisotopes; loading of tritium reservoirs for weapons
EG&G Energy Measurements, Inc subsidiary of EG&G, Inc (formerly Edgerton, Germeshausen, and Grier, Inc) Las Vegas, NV 89125 12/31/87	Technical contractor at Nevada Test Site; responsible for instrumentation of nuclear testing (see also Reynolds Electrical and Engineering Co and EG&G Idaho, Inc)
EG&G Idaho, Inc., subsidiary of EG&G, Inc Idaho Falls, ID 83401 09/30/86	Operating contractor at Idaho National Engineering Laboratory
Electro Nuclear, Inc	Development of gas centrifuge enrichment technology (commercial nuclear applications; potential nuclear weapons and naval reactor applications)
Exxon Nuclear Idaho Co subsidiary of Exxon Nuclear of the Exxon Corporation; Idaho Falls, ID 83401 09/30/84	Operated Idaho Chemical Processing Plant at INEL until March 1984; manages Project X at INEL (DOD reimbursible) to develop a special manufacturing capability
F&H Construction Livermore, CA 94551 10/23/87	Weapons laboratory building construction at LLNL
Fenix and Sisson, Inc Las Vegas, NV 89114 12/31/88	Engineers and drills test holes at the Nevada Test Site
Fluor Engineers & Construction, Inc Irvine, CA 92730 09/30/86	A-E design of cancelled GCEP buildings
Gardner Zemke Corporation Albuquerque, NM 02/22/85	Upgrading the electrical service at the Pantex Plant; final assembly and retirement of nuclear weapons

Contractor/ Contract Completion Date	Description
Garrett Corporation Los Angeles, CA 90009 02/28/86	Manufactures gas centrifuges for GCEP project (commercial nuclear, potential nuclear weapons and naval reactor applications) Operated the Hanford Works from 1943 to 1946
General Electric Company Saint Petersburg, FL 33543 09/30/88	Operates the Pinellas Plant; producer of neutron generators for nuclear weapons Operated the Hanford Reservation from 1946-1964
General Electric Company Schenectady, NY 09/30/88	Operating contractor, Naval Reactors Office, Knolls Atomic Power Laboratory, Schnectady, New York
Goodyear Aerospace Corp , wholly owned subsidiary of the Goodyear Tire and Rubber Company Akron, OH 44309 02/28/86	Manufactures gas centrifuges for GCEP project (commercial nuclear, potential nuclear weapons and naval reactor applications)
Goodyear Atomic Corp , wholly owned subsidiary of the Goodyear Tire and Rubber Company Piketon, OH 4566 06/30/88	Operating contractor for the Portsmouth Gaseous Diffusion Plant
Henfel Phelps Construction 06/85	Construction of new assembly bays at the Pantex Plant; final assembly and retirement of nuclear weapons
Holmes and Narver Las Vegas, NV 09/30/85	Provide architect-engineering services at Nevada Test Site
Iowa State University Ames, IA 50011 12/31/88	Operates Ames Laboratory; conducts nondestructive material evaluations for Defense Programs in the fuel processing area (2 to 3 percent of Ames Lab effort)
John R Selby, Inc Los Alamos, NM 07/06/84	Construction of new detonator facility at Los Alamos, NM
J A Jones Construction Service Richland, WA 12/31/85	Construction, maintenance, and management at Hanford
K L House Construction Co , Inc Albuquerque, NM 87108 12/16/85	Construction of simulation technology laboratory at Sandia
KMS Fusion, Inc Ann Arbor, MI 48106 12/31/86	Fabricates inertial fusion targets, develops production methods, and conducts research on short-wavelength ICF physical processes with a small neodymium glass laser (CROMA) in support of DOE ICF program at LLNL
Leland Stanford Jr University Stanford, CA 08/30/87	Operation of the Stanford Synchrotron Radiation Laboratory at SLAC
Lindblad Construction Co Kansas City, MO 04/18/85	Construction at Kansas City Plant
Lovelace Biological & Environmental Research Institute Albuquerque, NM 87123 06/30/89	Research on biological effects of exposure to fission products
Martin Marietta Energy Systems, Inc , subsidiary of Martin Marietta Corporation 09/30/89	Operates (since 1 April 1984) Oak Ridge and Paducah Gaseous Diffusion Plants, the Oak Ridge Y-12 Plant, and the Oak Ridge National Laboratory (Prior contractor was Union Carbide Corporation - Nuclear Division)
Mason & Hanger-Silas Mason Company, Inc Amarillo, TX 79120 09/30/86	Designed, constructed, and operates the Pantex Plant; final assembly and retirement of nuclear weapons
M-K National Co Idaho Falls, ID 83707 12/31/88	Provides construction management services at Idaho National Engineering Laboratory
Monsanto Research Corp , subsidiary of Monsanto Chemical Co Miamisburg, OH 45342 09/30/88	Operates the Mound Facility, development, production, and surveillance of weapon components (chemical explosive detonators) Monsanto Chemical Co conducted plutonium research during the Manhattan Project and managed Clinton Laboratories (now ORNL) from 1 July 1945 to 1948
National Distillers and Chemical Corp	Fifty percent owner of RMI, Inc , which manufactures fuel for the production reactors at the Ashtabula Plant

Contractor/ Contract Completion Date	Description
Page and Wirtz Construction Co 05/15/83	Former construction contractor for the High Explosives Facility at Pantex Plant (not a major contractor in 1984)
Presearch, Inc Oak Ridge, TN 08/30/88	Systems support for enrichment activities at Oak Ridge
Reedy Creek Utilities Co Lake Buena Vista, FL 32830 07/31/87	Contractor for WIPP, transuranic waste demonstration plant
Reynolds Electrical and Engineering Company, Inc , subsidiary of EG&G, Inc Las Vegas, NV 89114 09/30/89	Principal support contractor operating the Nevada Test Site
RMI Co (formerly Reactive Metals, Inc), owned by National Distillers and Chemical Corp and the United States Steel Corp (50 percent each) Ashtabula, OH 44004 09/30/86	Owns the Astubula Plant, which manufactures fuel for the production reactors
University of Rochester Rochester, NY 14623 06/30/87	Major support laboratory for the inertial confinement fusion (ICF) program
Rockwell Hanford Operations, division of Rockwell International Corp Richland, WA 99352 09/30/88	Operating contractor for the PUREX processing plant and other fuel processing and waste management operations at Hanford
Rockwell International Corp , Atomic International Div Golden, CO 80401 12/30/85	Operates Rocky Flats Plant, Golden, CO; Santa Susana Field Laboratories (SSFL); Rockwell Hanford Operations operates PUREX plant
Rust Engineering 9/30/89	Miscellaneous construction activities at the Oak Ridge Reservation; road maintenance and water plant
Sandia Corp , AT&T Technologies, Inc Albuquerque, NM 87107 09/30/88	Operates Sandia Laboratories in NM, Livermore, CA, and Tonopah, NV
Stone & Webster Engineering Corp Piketon, OH 45661 12/31/88	Construction of the canceled GCEP
Swinerton & Walberg Co Golden, CO 80401 06/11/87	Construction at Rocky Flats Plant
TRW, Inc Redondo Beach, CA 09/30/84	Research on the Plasma Separation Process (PSP), advanced isotope separation process for uranium enrichment (commercial nuclear applications; potential nuclear weapons and naval reactor fuel applications) and plutonium purification (weapons applications)
UNC Nuclear Industries Richland, WA 99352 12/31/86	Operates the N-reactor and is responsible for N-reactor fuel fabrication at Hanford
Union Carbide Corp Nuclear Division Oak Ridge, TN 37830 09/30/86	Operates and manages Oak Ridge and Paducah facilities
United Nuclear Corp , Naval Products Div Uncasville, CT 06382 numerous contracts through 03/05/92	Fabricates naval reactor cores
Wackenhut Services, Inc Las Vegas, NV 89114 Aiken, SC 12/31/86	Security guard services at NTS and SRP
Westinghouse Electric Corp , Bettis Atomic Power Lab West Mifflin, PA 15122 09/30/88	Operates Bettis Atomic Power Laboratory; operates the Naval Reactor Facility at INEL; research, development, testing, and evaluation of naval reactor propulsion plants, technical support contractor for the Waste Isolation Pilot Plant (WIPP), a geologic disposal facility for defense nuclear waste
University of Virginia 09/30/84	Research and development of gas centrifuge enrichment technology (commercial nuclear, potential nuclear weapons and naval reactor applications)
Westinghouse Hanford Co Richland, WA 99352 12/31/87	Operates the Hanford Engineering Development Laboratory (HEDL); defense nuclear waste processing development
Westinghouse Idaho Nuclear Company, Inc (WINCO) Idaho Falls, ID 83401 09/30/89	Operates the Idaho Chemical Processing Plant (ICPP), the waste calcining facility, the Fluorinel Dissolution Process Facility (FAST), and the Rover Fuel Processing Facility, all at Idaho National Engineering Laboratory (INEL)

Contractor/ Contract Completion Date	Description
Westinghouse Materials Company of Ohio Cincinnati, OH 45239	Operates the Feed Materials Production Center, which manufactures fuel for the production reactors
Zia Company Los Alamos, NM 12/31/85	Maintaince, support, and construction contractor at Los Alamos National Laboratory

Appendix B
Known U.S. Nuclear Tests: July 1945-31 December 1985

This appendix summarizes known nuclear tests conducted by the United States from July 1945 through 31 December 1985 It includes tests announced by the United States and tests not announced by the United States but which have been detected by seismic means and made public by other scientific institutions Table B 1 lists the tests chronologically Tables B 2 to B 4 summarize the tests by type, location, and purpose Table B 5 summarizes the tests by year and estimated yield These tables exclude unannounced tests that have not been detected and reported by various scientific institutions Between four and eleven such tests are estimated to have occurred in the time period 1980-84 [1]

All U S nuclear tests conducted prior to the signing of the Limited Test Ban Treaty (banning the testing of nuclear weapons in the atmosphere, in outer space, and in the water) on 5 August 1963 have been publicly announced by the U S government An explicit policy to not announce all tests was adopted by the Reagan administration in 1982 [2]

1 See *Nuclear Weapons Databook* Working Paper 86 1, *Unannounced U S Nuclear Weapons Tests 1980 1984* Thomas B Cochran Robert S Norris William M Arkin and Milton M Hoenig January 1986

2 Ibid

Table B 1
Known U.S. Nuclear Tests July 1945-31 December 1985

Event Name (and Comments)[a]	Date[b] (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose[c]	Yield[d]
Trinity	07-16-45	Alamogordo, NM	LANL	Tower	100	WR	19 Kt
Little Boy	08-05-45	Hiroshima, Jap	LANL	B-29 Airdrop	1900±50	Warfare	15 Kt
Fat Man	08-09-45	Nagasaki, Japan	LANL	B-29 Airdrop	1650±33	Warfare	21 Kt
	OPERATION CROSSROADS Operation CROSSROADS was at that time the largest peacetime military operation ever conducted with 240 ships, 156 aircraft, and 42,000 personnel The two tests used FAT MAN type bombs similar to the one dropped on Nagasaki The purpose of the tests was to determine the effects of nuclear detonations on naval ships, planes and on animals The first test weapon, shot ABLE, was dropped by a B-29 ("Dave's Dream") on a fleet of more than ninety vessels in Bikini Lagoon and exploded 980 feet short and 1870 feet left of the target The test weapon in BAKER was encased in a watertight steel caisson suspended beneath a medium landing ship anchored in the midst of the target fleet An additional deep underwater detonation, CHARLIE, was planned but was not conducted						
Able	06-30-46	Bikini	LANL-DOD	B-29 Airdrop	520	WE	23 Kt
Baker	07-24-46	Bikini	LANL-DOD	Underwater	-90	WE	23 Kt
	OPERATION SANDSTONE The three tests of Operation SANDSTONE were the first proof tests since TRINITY Second generation warhead design principles were tested using composite cores and levitated cores Ten thousand two hundred personnel participated						
X-Ray Most weapons in the stockpile in early 1948 were Mark-IV of this type	04-14-48	Enewetak	LANL	Tower	200	WR	37 Kt
Yoke	04-30-48	Enewetak	LANL	Tower	200	WR	49 Kt
Zebra	05-14-48	Enewetak	LANL	Tower	200	WR	18 Kt

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield

OPERATION RANGER

Operation RANGER was the first series of atmospheric tests held at the Nevada Proving Ground (now NTS) and were the first devices tested in the United States since TRINITY. In November 1950 scientists at Los Alamos decided that a series of small nuclear tests were needed in preparation for the upcoming GREENHOUSE series to establish satisfactory design criteria related to the variation of yield with compression of the fissile material. RANGER was a series of experiments involving devices using a fraction of a critical mass ("fractional crit"). The concept of a "fractional crit" originated in 1944 during the Manhattan Project. The White House approved the tests on 11 January 1951 accelerating the establishment of the Nevada Proving Ground. During the eleven days a total of five devices were dropped from a B-50 bomber. All of the devices detonated approximately 1100 to 1400 feet over Frenchman Flat.

Able	01-27-51	NTS	LANL	B-50 Airdrop	1060	WR	1 Kt
Baker	01-28-51	NTS	LANL	B-50 Airdrop	1080	WR	8 Kt
Easy	02-01-51	NTS	LANL	B-50 Airdrop	1080	WR	1 Kt
Baker-2	02-02-51	NTS	LANL	B-50 Airdrop	1100	WR	8 Kt
Fox	02-06-51	NTS	LANL	B-50 Airdrop	1435	WR	22 Kt

OPERATION GREENHOUSE

Two of the GREENHOUSE tests were thermonuclear experiments. Shot GEORGE produced the first significant U.S. thermonuclear reaction. GEORGE was an experiment using a fission bomb to ignite a small quantity of deuterium and tritium that contributed only a small amount to the yield. Shot ITEM was a major contribution to the development of thermonuclear weapons. It was the first test of a boosted fission device using deuterium and tritium. Shot DOG was probably a test of the B6. Fifteen thousand mice, swine, and dogs were used during GREENHOUSE to test the lethality range of blast, heat and radioactivity.

Dog	04-07-51	Enewetak	LANL	Tower	300	WR	70 Kt
Easy Probably the B5	04-20-51	Enewetak	LANL	Tower	300	WR	47 Kt
George First thermonuclear experiment	05-08-51	Enewetak	LANL	Tower	200	WR	225 Kt
Item Tested principle of tritium boosting	05-24-51	Enewetak	LANL	Tower	200	WR	45.5 Kt

OPERATION BUSTER-JANGLE

The five LANL weapon development tests constituted the BUSTER phase held in October and November 1951, the second series held at NTS. The objective of these tests was to evaluate new devices for possible inclusion in the stockpile. The two weapons effects tests of the JANGLE phase were meant to help determine the military utility of surface and underground nuclear detonations. The first three of eight Desert Rock troop exercises were held during BUSTER-JANGLE. These exercises were designed to explore the conditions and tactics of the atomic battlefield. The Mk-5 was tested sometime during 1951, possibly during BUSTER. A prototype of the B8 was tested during BUSTER and possibly the B7.

Able The ABLE device partially misfired	10-22-51	NTS	LANL	Tower	100	WR	<0.1 Kt
Baker	10-28-51	NTS	LANL	B-50 Airdrop	1118	WR	3.5 Kt
Charlie	10-30-51	NTS	LANL	B-50 Airdrop	1132	WR	14 Kt
Dog	11-01-51	NTS	LANL	B-50 Airdrop	1417	WR	21 Kt
Easy	11-05-51	NTS	LANL	B-45 Airdrop	1314	WR	31 Kt
Sugar	11-19-51	NTS	DOD	Surface	3.5	WE	1.2 Kt
Uncle	11-29-51	NTS	LANL-DOD	Crater	-17	WE	1.2 Kt

OPERATION TUMBLER-SNAPPER

Operation TUMBLER-SNAPPER was a series of eight atmospheric tests at NTS. The purpose of the first phase, TUMBLER, was to collect information on the effect of the height of burst on overpressure. The peak blast overpressure of the devices used during GREENHOUSE/BUSTER-JANGLE were lower than predicted and TUMBLER was designed to investigate the reasons. The accuracy of the GREENHOUSE/BUSTER-JANGLE data was affirmed, and in general the TUMBLER shots gave a more comprehensive description of blast phenomena than had been previously known. A further objective was to learn more about the dust "sponge" effect and the relationship of dust to radiation. The purpose of the SNAPPER phase was to test potential warhead designs for inclusion in the stockpile and to study techniques to be

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
	used during Operation IVY Shot EASY was the first test using beryllium as a tamper material Ten thousand six hundred DOD personnel participated in Desert Rock IV						
Able	04-01-52	NTS	LANL-DOD	B-50 Airdrop	793	WE	1 Kt
Baker	04-15-52	NTS	LANL-DOD	B-50 Airdrop	1109	WE	1 Kt
Charlie	04-22-52	NTS	LANL-DOD	B-50 Airdrop	3447	WR	31 Kt
Dog	05-01-52	NTS	LANL-DOD	B-45 Airdrop	1040	WR	19 Kt
Easy	05-07-52	NTS	LANL	Tower	300	WR	12 Kt
Fox	05-25-52	NTS	LANL	Tower	300	WR	11 Kt
George	06-01-52	NTS	LANL	Tower	300	WR	15 Kt
How	06-05-52	NTS	LANL	Tower	300	WR	14 Kt
	OPERATION IVY						
	Event MIKE was the first test of an experimental thermonuclear device in which a substantial portion of the energy was generated by the fusion of hydrogen isotopes It used liquid deuterium Event KING was the largest fission weapon ever detonated, presumed to be a prototype of the B18 Super Oralloy bomb						
Mike Experimental thermonuclear device; produced a crater 6240 feet in diameter and 164 feet deep	10-31-52	Enewetak	LANL	Surface		WR	10 4 Mt
King	11-15-52	Enewetak	LANL	B-36 Airdrop	1480	WR	500 Kt
	OPERATION UPSHOT-KNOTHOLE						
	The major purposes of Operation UPSHOT-KNOTHOLE were to test devices for possible inclusion in the stockpile; to improve military tactics, equipment, and training for the atomic battlefield; and to enhance civil defense requirements by measuring and assessing blast effects upon dwellings, shelters, automobiles, etcetera Some objectives were to improve the nuclear weapons used for strategic bomber delivery and those used for tactical battlefield situations, and to establish military doctrine for the tactical use of nuclear weapons The yields ranged from 1 to 61 Kt and included three airdrops, seven tower shots, and an artillery firing using a 280mm cannon Approximately 21,000 DOD personnel from the four armed services paticipated in Desert Rock V The third and fifth tests of the series were LLNL's first tests since being established as the second design laboratory the year before These two tests were fizzles						
Annie	03-17-53	NTS	LANL	Tower	300	WR	16 Kt
Nancy	03-24-53	NTS	LANL	Tower	300	WR	24 Kt
Ruth LLNL fizzle of uranium hydride core	03-31-53	NTS	LLNL	Tower	300	WR	0 2 Kt
Dixie	04-06-53	NTS	LANL	B-50 Airdrop	6020	WR	11 Kt
Ray LLNL fizzle of uranium hydride core	04-11-53	NTS	LLNL	Tower	100	WR	0 2 Kt
Badger Was expected to yield 40 Kt	04-18-53	NTS	LANL	Tower	300	WR	23 Kt
Simon Predicted yield was 35 Kt	04-25-53	NTS	LANL	Tower	300	WR	43 Kt
Encore	05-08-53	NTS	DOD-LANL	B-50 Airdrop	2423	WE	27 Kt
Harry	05-19-53	NTS	LANL	Tower	300	WR	32 Kt
Grable A 280mm 85-ton cannon fired an atomic artillery projectile using the Mk-9 warhead that was detonated at a height of 524 feet above Frenchman Flat, NTS The top of the mushroom cloud reached an altitude of 35,000 feet	05-25-53	NTS	DOD-LANL	Airburst	524	WR	15 Kt
Climax Probably a test of the B7	06-04-53	NTS	LANL	B-36 Airdrop	1334	WR	61 Kt

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
	OPERATION CASTLE						
	Operation CASTLE was the culmination in the development of the super, or hydrogen, bomb that began in 1950. The objectives were threefold: first, to fire six or seven experimental thermonuclear devices, including proof tests of three emergency capability weapons (EC14, EC16 and EC17)—the test firing of one of these, presumably the EC16, was contingent upon the results of the other six tests; second, to obtain diagnostic information on these tests necessary to evaluate their performance; and third, to obtain effects information on devices in the megaton range. The first two shots fired, BRAVO and ROMEO, gave yields considerably above those expected just prior to actual detonation and led to the conclusion that a lithium deuteride "dry bomb" was practical for stockpiling purposes. Since this type of device was appreciably simpler to use than a liquid deuterium bomb, the Los Alamos test of the EC16 was cancelled and an alternative device inserted in its place (probably shot NECTAR). The seventh shot of the CASTLE series, ECHO, an LLNL design, was withdrawn following the failure of KOON. The total fission yield for all tests in the three year period 1952-54 was 37 Mt. Device nicknames in parentheses.						
Bravo ("Shrimp") Experimental thermonuclear device using lithium deuteride. Produced a crater with a diameter of 6000 feet and a depth of 240 feet. Expected yield 6 Mt (presumed range 4 to 8 Mt)	02-28-54	Bikini	LANL	Surface	7	WR	15 Mt
Romeo ("Runt I") Test of EC14. Expected yield 8 Mt (range 1.5 to 15 Mt)	03-26-54	Bikini	LANL	Barge		WR	11 Mt
Koon ("Morgenstern") LLNL fizzle. Expected yield 1.5 Mt (range 0.33 to 4 Mt)	04-06-54	Bikini	LLNL	Surface		WR	110 Kt
Union ("Alarm Clock") Expected yield 5 to 10 Mt (range 1 to 18 Mt)	04-25-54	Bikini	LANL	Barge		WR	6.9 Mt
Yankee ("Runt II") Test of EC17. Expected yield 9.5 Mt (range 7.5 to 15 Mt)	05-04-54	Bikini	LANL	Barge		WR	13.5 Mt
Nectar ("Zombie") Expected yield 2 to 3 Mt (range 1 to 5 Mt)	05-13-54	Enewetak	LANL	Barge		WR	1.69 Mt
	OPERATION TEAPOT						
	Operation TEAPOT, a series of fourteen tests held at NTS, was authorized by President Eisenhower on 30 August 1954. Some of the tests were for the purpose of expanding the variety of tactical weapons, including those primarily designed for defensive purposes. These tests would most likely be the EC25/W25 warhead for the GENIE, and the W31 for the NIKE HERCULES missile and ADM. Approximately 8000 DOD personnel took part in Desert Rock VI. According to a joint AEC-DOD press release, "the mission of Exercise Desert Rock VI ... (is) to teach its soldiers to view nuclear weapons in their proper perspective ... that powerful though these weapons are, they can be controlled and harnessed ... and that despite the weapons' destructiveness there are defenses against them on the atomic battlefield." The third shot of the series, TESLA, was LLNL's first successful test, two-and-one-half years after the establishment of the laboratory.						
Wasp	02-18-55	NTS	LANL	B-36 Airdrop	762	WE	1 Kt
Moth	02-22-55	NTS	LANL	Tower	300	WR	2 Kt
Tesla Predicted yield 2 Kt	03-01-55	NTS	LLNL	Tower	300	WR	7 Kt
Turk	03-07-55	NTS	LLNL	Tower	500	WR	43 Kt
Hornet	03-12-55	NTS	LANL	Tower	300	WR	4 Kt
Bee	03-22-55	NTS	LANL	Tower	500	WR	8 Kt
Ess	03-23-55	NTS	DOD	Crater	-67	WE	1 Kt

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Purpose was to prepare a subsurface emplacement site for an atomic demolition munition test, emplace the munition, backfill the shaft, and fire the munition It made a crater 290 feet in diameter and 56 feet deep It was probably the low-yield option of the W31							
Apple-1	03-29-55	NTS	LANL	Tower	500	WR	14 Kt
Wasp Prime	03-29-55	NTS	LANL	B-36 Airdrop	737	WR	3 Kt
Ha	04-06-55	NTS	DOD	B-36 Airdrop	36620	WE	3 Kt
Post	04-09-55	NTS	LLNL	Tower	300	WR	2 Kt
Met	04-15-55	NTS	LANL-DOD	Tower	400	WE	22 Kt
Apple-2	05-05-55	NTS	LANL	Tower	500	WR	29 Kt
Zucchini	05-15-55	NTS	LANL	Tower	500	WR	28 Kt

OPERATION WIGWAM

Operation WIGWAM was a single test conducted approximately 400 miles southwest of San Diego, California One of only five underwater tests ever held, the WIGWAM device was suspended by cable from a towed unmanned barge to a depth of 2000 feet in water that was approximately 16,000 feet deep The major purpose of WIGWAM was to determine the fatal range a deeply detonated nuclear weapon would have on a submarine and on surface ships The weapon used was the B7, "Betty" nuclear depth charge

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Wigwam North 29 Degrees West 126 Degrees	05-14-55	Pacific	DOD	Underwater	-2000	WE	30 Kt

PROJECT 56

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Project 56 No 1	11-01-55	NTS	LANL	Surface		SE	Zero
Project 56 No 2 (Pu dispersal)	11-03-55	NTS	LANL	Surface		SE	Zero
Project 56 No 3 (Pu dispersal)	11-05-55	NTS	LANL	Surface		SE	No Yield
Project 56 No 4 (Pu dispersal)	11-18-55	NTS	LANL	Surface		SE	Very Slight

OPERATION REDWING

The objectives of REDWING were to proof test certain weapons in stockpile or to be stockpiled in the near future, to continue developmental research on promising weapons, and to continue long range research on new techniques, ideas and designs The seventeen shots in the REDWING series of mid-1956 were primarily to test high-yield thermonuclear devices that could not be tested in Nevada All REDWING shots except CHEROKEE tested new weapon developments CHEROKEE was less a scientific experiment and more a demonstration to the world of U S ability to drop a hydrogen bomb from a bomber The AEC reported that Operation REDWING "gave important information relating to developing means of reducing fall-out from weapon firing, weapons for defensive purposes, and new design principles " Of the new weapon types, nine tests were sponsorerd by LANL and seven by LLNL The test shots fired at Enewetak had smaller yields than those fired at Bikini High-yield warheads likely tested at REDWING were LANL's B/W28 (bomb/HOUND DOG), B/W39 3 75 Mt (bomb/SNARK, REDSTONE), and W49 1 4 Mt (THOR, ATLAS D, JUPITER) and LLNL's B/W27 (bomb/REGULUS II) Lower yield warheads probably included the W40 (BOMARC, LACROSSE), W44 (ASROC), and W45 (MADM, TERRIER, LITTLE JOHN) The total fission yield for all REDWING tests was 9 Mt; the total fission yield for tests over 1 Mt was 8 Mt

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Lacrosse	05-04-56	Enewetak	LANL	Surface	17	WR	40 Kt
Cherokee First air drop by United States of a thermonuclear weapon—probably B36 bomb	05-20-56	Bikini	LANL	B-52 Airdrop	4350 ± 150	WR	Several Mt
Zuni	05-27-56	Bikini	LLNL	Surface	9	WR	3 5 Mt
Yuma	05-27-56	Enewetak	LLNL	Tower	205	WR	

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Erie	05-30-56	Enewetak	LANL	Tower	300	WR	
Seminole	06-06-56	Enewetak	LANL	Surface		WR	13.7 Kt
Flathead	06-11-56	Bikini	LANL	Barge	15	WR	
Blackfoot	06-11-56	Enewetak	LANL	Tower	200	WR	
Kickapoo	06-13-56	Enewetak	LLNL	Tower	300	WR	
Osage	06-16-56	Enewetak	LANL	B-36 Airdrop	670±35	WR	
Inca	06-21-56	Enewetak	LLNL	Tower	200	WR	
Dakota	06-25-56	Bikini	LANL	Barge		WR	
Mohawk	07-02-56	Enewetak	LLNL	Tower	300	WR	
Apache	07-08-56	Enewetak	LLNL	Barge		WR	
Navajo	07-10-56	Bikini	LANL	Barge		WR	
Tewa Produced a crater of 4000 feet diameter and 129 feet depth	07-20-56	Bikini	LLNL	Barge		WR	5 Mt
Huron	07-21-56	Enewetak	LANL	Barge	WR		
	PROJECT 57						
Project 57 No. 1 (Pu dispersal)	04-24-57	Bombing Range, NV	AEC	Surface		SE	Zero
	OPERATION PLUMBOB Operation PLUMBOB, the sixth series held at NTS, included twenty-four detonations and six safety experiments. The series was approved by President Eisenhower on 28 December 1956. The purposes of PLUMBOB were to proof test certain air defense and anti-submarine warheads scheduled for early production; to conduct development tests of components and mockups that provided design information for thermonuclear devices to be fired in Operation HARDTACK I, including devices having higher yield-to-weight ratios; to conduct exploratory and development tests directed toward achieving more efficient use of nuclear material and warheads of smaller size and weight; and to conduct a deep underground test to explore that mode of testing. Sixteen thousand DOD personnel participated in Desert Rock VII and VIII. The prototype for the W30 warhead for the TALOS missile was tested and the W34 warhead for the LULU, ASTOR, and HOTPOINT anti-submarine weapons may have been tested during PLUMBOB.						
Boltzmann	05-28-57	NTS	LANL	Tower	500	WR	12 Kt
Franklin	06-02-57	NTS	LANL	Tower	300	WR	140 Tons
Lassen	06-05-57	NTS	LLNL	Balloon	500	WR	0.5 Tons
Wilson	06-18-57	NTS	LLNL	Balloon	500	WR	10 Kt
Priscilla Purpose was to study the effects of a nuclear weapon with a known yield. The weapon was drawn from the stockpile.	06-24-57	NTS	LANL-DOD	Balloon	700	WR	37 Kt
Coulomb-A	07-01-57	NTS	LANL	Surface		SE	Zero
Hood	07-05-57	NTS	LLNL	Balloon	1500	WR	74 Kt
Diablo	07-15-57	NTS	LLNL	Tower	500	WR	17 Kt
John An F-89J fired a GENIE (AIR-2A) air-to-air rocket with a W25 warhead. The rocket traveled 4240 meters in 4.5 seconds after release, before detonating.	07-19-57	NTS	DOD	Rocket	18500	WE	2 Kt
Kepler	07-24-57	NTS	LANL	Tower	500	WR	10 Kt
Owens	07-25-57	NTS	LLNL	Balloon	500	WR	9.7 Kt
Pascal-A First underground test. The hole was 485 feet deep and 3 feet in diameter.	07-26-57	NTS	LANL	Shaft	-500	SE	Slight
Stokes	08-07-57	NTS	LANL	Balloon	1500	WR	19 Kt

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Saturn	08-10-57	NTS	LLNL	Tunnel	-100	SE	Zero
Shasta	08-18-57	NTS	LLNL	Tower	500	WR	17 Kt
Doppler	08-23-57	NTS	LANL	Balloon	1500	WR	11 Kt
Pascal-B	08-27-57	NTS	LANL	Shaft	-500	SE	0.3 Kt
Franklin Prime	08-30-57	NTS	LANL	Balloon	750	WR	4.7 Kt
Smoky	08-31-57	NTS	LLNL	Tower	700	WR	44 Kt
Galileo	09-02-57	NTS	LANL	Tower	500	WR	11 Kt
Wheeler	09-06-57	NTS	LLNL	Balloon	500	WR	197 Tons
Coulomb-B	09-06-57	NTS	LANL	Surface		SE	0.3 Kt
Laplace	09-08-57	NTS	LANL	Balloon	750	WR	1 Kt
Fizeau	09-14-57	NTS	LANL	Tower	500	WR	11 Kt
Newton	09-16-57	NTS	LANL	Balloon	1500	WR	12 Kt
Ranier	09-19-57	NTS	LLNL	Tunnel	-899	WR	1.7 Kt
First detonation contained underground. Seismic waves detected 2300 miles away in Alaska							
Whitney	09-23-57	NTS	LLNL	Tower	500	WR	19 Kt
Charleston	09-28-57	NTS	LLNL	Balloon	1500	WR	12 Kt
Morgan	10-07-57	NTS	LLNL	Balloon	500	WR	8 Kt
	PROJECT 58						
Pacal-C	12-06-57	NTS	LANL	Shaft		SE	Slight
Coulomb-C	12-09-57	NTS	LANL	Surface		SE	0.5 Kt
Pascal-C and Coulomb-C were safety tests of two designs being fired in their final version at HARD-TACK							
	PROJECT 58 A						
Venus	02-22-58	NTS	LLNL	Tunnel		SE	<1 Ton
Uranus	03-14-58	NTS	LLNL	Tunnel		SE	<1 Ton

OPERATION HARDTACK I

Operation HARDTACK I included thirty-five tests, all but three of which were at Enewetak and Bikini. Planned at a time when pressures were building for a test moratorium, scientists tried to include tests for as many weapon types as possible. Originally each lab had requested twenty shots and DOD ten shots. HARDTACK was divided into three parts. The first was development tests of warhead types of which LANL sponsored fifteen and LLNL sponsored fifteen. These tests probably included the W38 (ATLAS E/F, TITAN I), B41, B43, the W47 (POLARIS), the B/W53 (bomb/TITAN II), and B/W46 (bomb/TITAN II-cancelled), and prototypes for the W56 and W59 warheads for the MINUTEMAN ballistic missiles. The second part was two shots sponsored by DOD to improve the understanding of the effects of underwater explosions on Navy ships. The third part, also sponsored by DOD, included three high-altitude shots to study ballistic missile defense possibilities. The tests also provided information on the electromagnetic pulse effect from low yield-bursts on electronic components.

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Yucca	04-28-58	Pacific	DOD	Untethered Helium Balloon	86000	WE	
North 12 degrees 37 minutes East 163 degrees 01 minutes							
Cactus	05-05-58	Enewetak	LANL	Surface		WR	18 Kt
Fir	05-11-58	Bikini	LLNL	Barge		WR	
Butternut	05-11-58	Enewetak	LANL	Barge		WR	
Koa	05-12-58	Enewetak	LANL	Surface		WR	1.37 Mt
Produced a crater 4000 feet in diameter and 171 feet deep							
Wahoo	05-16-58	Enewetak	DOD-LANL	Underwater	-500	WE	
Holly	05-20-58	Enewetak	LANL	Barge		WR	
Nutmeg	05-21-58	Bikini	LLNL	Barge		WR	
Yellowwood	05-26-58	Enewetak	LANL	Barge		WR	

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Magnolia	05-26-58	Enewetak	LANL	Barge		WR	
Tobacco	05-30-58	Enewetak	LANL	Barge		WR	
Sycamore	05-31-58	Bikini	LLNL	Barge		WR	
Rose	06-02-58	Enewetak	LANL	Barge		WR	
Umbrella (in lagoon	06-08-58	Enewetak	DOD	Underwater	-150	WE	
Maple	06-10-58	Bikini	LLNL	Barge		WR	
Aspen	06-14-58	Bikini	LLNL	Barge		WR	
Walnut	06-14-58	Enewetak	LANL	Barge		WR	
Linden	06-18-58	Enewetak	LANL	Barge		WR	
Redwood	06-27-58	Bikini	LLNL	Barge		WR	
Elder	06-27-58	Enewetak	LANL	Barge		WR	
Oak Possibly the B/W53; produced a crater 4400 feet in diameter and 183 feet deep	06-28-58	Enewetak	LANL	Barge		WR	8.9 Mt
Hickory	06-29-58	Bikini	LLNL	Barge		WR	
Sequoia	07-01-58	Enewetak	LANL	Barge		WR	
Cedar	07-02-58	Bikini	LLNL	Barge		WR	
Dogwood	07-05-58	Enewetak	LLNL	Barge		WR	
Poplar	07-12-58	Bikini	LLNL	Barge		WR	
Scaevola	07-14-58	Enewetak	LANL	Barge		SE	Low
Pisonia	07-17-58	Enewetak	LANL	Barge		WR	
Juniper Last of twenty-three tests held at Bikini Atoll	07-22-58	Bikini	LLNL	Barge		WR	
Olive	07-22-58	Enewetak	LLNL	Barge		WR	
Pine	07-26-58	Enewetak	LLNL	Barge		WR	
Teak The flash of light was visible from Hawaii, 700 miles away	08-01-58	Johnston Island Area	DOD	Redstone Rocket	252,000	WE	Mt Range
Quince	08-06-58	Enewetak	LLNL-DOD	Surface		WR	
Orange	08-12-58	Johnston Island Area	DOD	Redstone Rocket	141,000	WE	Mt Range
Fig Last of forty-three tests held at Enewetak	08-18-58	Enewetak	LLNL-DOD	Surface		WR	

OPERATION ARGUS

Operation ARGUS was a series of three very-high-altitude tests carried out shortly after the conclusion of HARDTACK I in the South Atlantic about 1100 miles southwest of Capetown, South Africa. It was the only clandestine test series conducted in the seventeen-year period of atmospheric testing. Specially modified X-17a three-stage ballistic missiles were fired from the USS *Norton Sound* (AVM 1) carrying low-yield warheads. The ARGUS operation was not intended as a test of nuclear weapons or their destructive effects. It was an experiment designed to provide information on the trapping of electrically charged particles in the earth's magnetic field with the objective of assessing how very-high-altitude nuclear detonations might interfere with communications equipment and ballistic missile performance.

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Argus I About 300 miles altitude South 38.5 degrees, West 11.5 degrees	08-27-58	South Atlantic	DOD	Rocket		WE	1-2 Kt
Argus II About 300 miles altitude South 49.5 degrees, West 8.2 degrees	08-30-58	South Atlantic	DOD	Rocket		WE	1-2 Kt
Argus III About 300 miles altitude South 48.5 degrees, West 9.7 degrees	09-06-58	South Atlantic	DOD	Rocket		WE	1-2 Kt

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
	OPERATION HARDTACK II						
	Operation HARDTACK II was a series of thirty-seven tests, the last the United States conducted before adopting a test moratorium. Nineteen of the tests were conducted to evaluate the yield and efficiency of newly developed nuclear devices. The other eighteen were safety experiments designed to determine the stability of nuclear devices during transportation and storage. After a flurry of thirteen tests in seven days at the end of October, the United States did not test again for more than thirty-four months.						
Otero	09-12-58	NTS	LANL	Shaft		SE	38 Tons
Bernalillo	09-17-58	NTS	LANL	Shaft		SE	15 Tons
Eddy (possibly the W47)	09-19-58	NTS	LANL	Balloon	500	WR	83 Tons
Luna	09-21-58	NTS	LANL	Shaft		SE	1.5 Tons
Mercury	09-23-58	NTS	LLNL	Tunnel		SE	Slight
Valencia	09-26-58	NTS	LANL	Shaft		SE	2 Tons
Mars	09-28-58	NTS	LLNL	Tunnel		SE	13 Tons
Mora	09-29-58	NTS	LANL	Balloon	1500	WR	2 Kt
Colfax	10-05-58	NTS	LANL	Shaft		SE	5.5 Tons
Hidalgo	10-05-58	NTS	LANL	Balloon	377	SE	77 Tons
Tamalpais	10-08-58	NTS	LLNL	Tunnel	−330	WR	72 Tons
Quay	10-10-58	NTS	LANL	Tower	100	WR	79 Tons
Lea	10-13-58	NTS	LANL	Balloon	1500	WR	1.4 Kt
Neptune	10-14-58	NTS	LLNL	Tunnel		SE	115 Tons
Hamilton	10-15-58	NTS	DOD-LLNL	Tower	50	WR	1.2 Tons
Logan	10-16-58	NTS	LLNL	Tunnel	−830	WR	5 Kt
Dona Ana	10-16-58	NTS	LANL	Balloon	450	WR	37 Tons
Vesta	10-17-58	NTS	LLNL	Surface		SE	24 Tons
Rio Arriba	10-18-58	NTS	LANL	Tower	72.5	WR	90 Tons
San Juan	10-20-58	NTS	LANL	Shaft		SE	Zero
Socorro	10-22-58	NTS	LANL	Balloon	1450	WR	6 Kt
Wrangell	10-22-58	NTS	LLNL	Balloon	1500	WR	115 Tons
Rushmore	10-22-58	NTS	LLNL	Balloon	500	WR	188 Tons
Oberon	10-22-58	NTS	LLNL	Tower	25	SE	Zero
Catron	10-24-58	NTS	LANL	Tower	72.5	SE	21 Tons
Juno	10-24-58	NTS	LLNL	Surface		SE	1.7 Tons
Ceres	10-26-58	NTS	LLNL	Tower	25	SE	0.7 Tons
Sanford	10-26-58	NTS	LLNL	Balloon	1500	WR	4.9 Kt
De Baca	10-26-58	NTS	LANL	Balloon	1500	WR	2.2 Kt
Chavez	10-27-58	NTS	LANL	Tower	52.5	SE	0.6 Tons
Evans	10-29-58	NTS	LLNL	Tunnel	−848	WR	55 Tons
Humboldt	10-29-58	NTS	DOD-LLNL	Tower	25	WR	7.8 Tons
Mazama	10-29-58	NTS	LLNL	Tower	50	WR	Zero
Santa Fe	10-30-58	NTS	LANL	Balloon	1500	WR	1.3 Kt
Blanca	10-30-58	NTS	LLNL	Tunnel	−835	WR	22 Kt
Ganymede	10-30-58	NTS	LLNL	Surface		SE	Zero
Titania	10-30-58	NTS	LLNL	Tower	25	SE	0.2 Tons
	OPERATION NOUGAT						
	Hereafter, with the exceptions of DOMINIC I and DOMINIC II, operations are by Fiscal Year. FY 1962-FY 1976 (1 July 1961-30 September 1976) and FY 1977-FY 1985 (1 October 1976-30 September 1985) (Number per fiscal year.)						
Antler	09-15-61	NTS		Tunnel	−1318	WR	2.6 Kt
Shrew	09-16-61	NTS		Shaft	− 322	WR	Low
Boomer	10-01-61	NTS		Shaft	?	WR	Low
Chena	10-10-61	NTS		Tunnel	− 838	WR	Low
Mink	10-29-61	NTS		Shaft	− 630	WR	Low
Fisher	12-03-61	NTS		Shaft	−1191	WR	13.4 Kt
Gnome	12-10-61	Carlsbad, NM		Shaft	−1184	1st PS	3 Kt
Mad	12-13-61	NTS		Shaft	− 594	WR	0.50 Kt
Ringtail	12-17-61	NTS		Shaft	−1192	WR	Low
Feather	12-22-61	NTS		Tunnel	− 812	WR	Low
Stoat	01-09-62	NTS		Shaft	− 982	WR	5.1 Kt
Agouti	01-18-62	NTS		Shaft	− 856	WR	6.4 Kt
Dormouse	01-30-62	NTS		Shaft	−1191	WR	Low

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Stillwater	02-08-62	NTS		Shaft	− 595	WR	3 07 Kt
Armadillo	02-09-62	NTS		Shaft	− 786	WR	7 1 Kt
Hard Hat Purpose was to test the capability of underground structures to withstand strong motions generated by an underground nuclear detonation in hard rock	02-15-62	NTS	DOD	Shaft	− 943	WE	5 7 Kt
Chinchilla	02-19-62	NTS		Shaft	− 492	WR	1 9 Kt
Codsaw	02-19-62	NTS		Shaft	− 696	WR	Low
Cimarron	02-23-62	NTS		Shaft	−1000	WR	11 90 Kt
Platypus	02-24-62	NTS		Shaft	− 190	WR	Low
Pampas	03-01-62	NTS		Shaft	−1191	1st UK	Low
Danny Boy Crater diameter 265 feet, depth 84 feet, in basalt	03-05-62	NTS	DOD-LLNL	Crater	− 110	WE	0 43 Kt
Ermine	03-06-62	NTS		Shaft	− 240	WR	Low
Brazos	03-08-62	NTS		Shaft	− 841	WR	8 4 Kt
Hognose	03-15-62	NTS		Shaft	− 784	WR	Low
Hoosic	03-28-62	NTS		Shaft	− 814	WR	3 40 Kt
Chinchilla II	03-31-62	NTS		Shaft	− 446	WR	Low
Dormouse II	04-05-62	NTS		Shaft	− 856	WR	10 6 Kt
Passaic	04-06-62	NTS		Shaft	− 766	WR	Low
Hudson	04-12-62	NTS		Shaft	− 495	WR	Low
Platte	04-14-62	NTS		Tunnel	− 628	WR	1 85 Kt
Dead	04-21-62	NTS		Shaft	− 634	WR	Low

OPERATION DOMINIC I

The 1962 tests in the Christmas and Johnston Island areas and elsewhere in the Pacific constituted Operation DOMINIC I. These tests were also part of either Operation NOUGAT or Operation STORAX depending on whether they occurred in FY 1962 or FY 1963, respectively.

Operation DOMINIC I was a series of thirty-six atmospheric nuclear detonations held at several Pacific Ocean locations from April to November 1962. With the four continental tests of DOMINIC II these were the last atmospheric tests conducted by the United States. No longer able to use the atolls of Enewetak and Bikini, the United States entered into an agreement with the United Kingdom in early 1962 to use Christmas Island for twenty-five of the tests. In return the British were allowed to participate in the nuclear test program at NTS. Another ten tests took place in the Johnston Island area.

Four types of tests were carried out: (1) About twenty devices were detonated for weapons development purposes. In these tests, progress was made in nuclear technology that resulted in significant increases in the yield-to-weight ratios, more efficient use of nuclear materials, reduction of the fission component of total yield, and increased safety and reliability of stockpiled weapons. Among the DOMINIC devlopment tests were some failures occurring in cases where designs involved a substantial extension of known technology; (2) Several stockpiled bombs and warheads were proof tested. These weapons had been designed after HARDTACK and manufactured during the moratorium. The designs had extrapolated to the maximum extent practicable the nuclear weapons technology developed during HARDTACK and previous tests. Each of the nuclear weapons proof tested functioned satisfactorily; (3) A third group were five high altitude effects tests from the kiloton to megaton range. The FISHBOWL portion of the DOMINIC tests investigated the ability of the intercontinental missiles systems, the early warning systems, and the command and control systems to operate in a nuclear environment. Some failures occurred. Three THOR rockets malfunctioned in flight (Bluegill, 2 June; Starfish, 19 June; Bluegill Double Prime, 15 October) and had to be destroyed, with their warheads. On 25 July (Bluefish Prime) a THOR missile blew up on the launch pad on Johnston Island, causing extensive damage. The nuclear warhead was destroyed by radio command causing extensive alpha contamination of the launch pad; (4) Proof tests of two complete nuclear weapons systems were carried out. The entire POLARIS and ASROC system including the delivery vehicles, missiles, and nuclear warheads were tested under realistic conditions.

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Adobe	04-25-62	Christmas Island Area	LANL	B-52 Airdrop		WR	Intermediate
Aztec	04-27-62	Christmas Island Area	LANL	B-52 Airdrop		WR	Intermediate
Black	04-27-62	NTS		Shaft	−714	WR	Low

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Arkansas	05-02-62	Christmas Island Area	LLNL	B-52 Airdrop		WR	Low Mt
Questa	05-04-62	Christmas Island Area	LANL	B-52 Airdrop Freefall		WR	Intermediate
Frigate Bird The submarine *USS Ethan Allen* (SSBN-608), launched a POLARIS missile while submerged about 155 nm east northeast of Christmas Island in the Pacific Ocean, North 4 degrees 50 minutes, West 149 degrees 25 minutes. The warhead traveled about 1020 nm toward the island, detonating as an airburst. The yield of the W47 warhead on the POLARIS A2 SLBM was not announced but is estimated to be 600 Kt. Shot FRIGATE BIRD was the first and only operational test of a U.S. SSBN/SLBM weapon system.	05-06-62	Pacific	LLNL	POLARIS A2 Rocket		WR	600 Kt
Paca	05-07-62	NTS		Shaft	−848	WR	Low
Yukon	05-08-62	Christmas Island Area	LLNL	B-52 Airdrop Parachute		WR	Intermediate
Mesilla	05-09-62	Christmas Island Area	LANL	B-52 Airdrop Freefall		WR	Intermediate
Arikaree	05-10-62	NTS		Shaft		WR	Low
Muskegon	05-11-62	Christmas Island Area	LLNL	B-52 Airdrop Parachute		WR	Intermediate
Swordfish The *USS Agerholm* (DD-826) steaming in an area about 370 nm west-southwest of San Diego, California, North 31 degrees 14 minutes, West 124 degrees 13 minutes, fired an anti-submarine rocket (ASROC) at a target raft about 4000 yards away. The W44 warhead detonated underwater, producing a low yield. Among other things the test was meant to determine the effect of the nuclear explosion on the sonar gear of destroyers and submarines. Shot SWORDFISH is the last of only five underwater tests.	05-11-62	Pacific	DOD	Underwater		WE	Low
Encino	05-12-62	Christmas Island Area	LANL	B-52 Airdrop Freefall		WR	Intermediate

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Aardvark	05-12-62	NTS		Shaft	−1424	WR	40 Kt
Swanee	05-14-62	Christmas Island Area	LLNL	B-52 Airdrop Parachute		WR	Intermediate
Eel	05-19-62	NTS		Shaft	− 714	WR	Low
Chetco	05-19-62	Christmas Island Area	LLNL	B-52 Airdrop Parachute		WR	Intermediate
White	05-25-62	NTS		Shaft	− 632	WR	Low
Tanana	05-25-62	Christmas Island Area	LLNL	B-52 Airdrop Parachute		WR	Low
Nambe	05-27-62	Christmas Island Area	LANL	B-52 Airdrop Freefall		WR	Intermediate
Raccoon	06-01-62	NTS		Shaft	− 539	WR	Low
Packrat	06-06-62	NTS		Shaft	− 860	WR	Low
Alma	06-08-62	Christmas Island Area	LANL	B-52 Airdrop Freefall		WR	Intermediate
Truckee	06-09-62	Christmas Island Area	LLNL	B-52 Airdrop Parachute		WR	Intermediate
Yeso	06-10-62	Christmas Island Area	LANL	B-52 Airdrop Freefall		WR	Low Mt
Harlem	06-12-62	Christmas Island Area	LLNL	B-52 Airdrop Parachute		WR	Intermediate
Des Moines	06-13-62	NTS		Tunnel	− 660	WR	Low
Rinconada	06-15-62	Christmas Island Area	LANL	B-52 Airdrop Freefall		WR	Intermediate
Dulce	06-17-62	Christmas Island Area	LANL	B-52 Airdrop Freefall		WR	Intermediate
Petit	06-19-62	Christmas Island Area	LLNL	B-52 Airdrop Parachute		WR	Low
Daman I	06-21-62	NTS		Shaft	− 854	WR	Low
Otowi	06-22-62	Christmas Island Area	LANL	B-52 Airdrop Freefall		WR	Intermediate
Bighorn	06-27-62	Christmas Island Area		B-52 Airdrop Parachute		WR	Mt Range
Haymaker	06-27-62	NTS		Shaft	−1340	WR	67 Kt
Marshmallow Purpose was to study effects on equipment and materials at a simulated high altitude	06-28-62	NTS	DOD-LLNL	Tunnel	−1030	WE	Low
Bluestone	06-30-62	Christmas Island Area	LLNL	B-52 Airdrop Parachute		WR	Low Mt
Sacramento	06-30-62	NTS		Shaft	− 489	WR	Low
	OPERATION STORAX (68)						
Sedan Excavation experiment—crater 1280 feet diameter, 320 feet deep—thermonuclear device	07-06-62	NTS		Crater	− 635	2nd PS	104 Kt
	OPERATION DOMINIC II The four weapons effects tests at NTS in July of 1962 constituted Operation DOMINIC II and were also part of Operation STORAX						
Little Feller II Used a W54 stockpile warhead	07-07-62	NTS	DOD	Surface	3	WE	Low
Starfish Prime High altitude: 450 km	07-09-62	Johnston Island Area	DOD	THOR Rocket		WE	1.4 Mt
Sunset	07-10-62	Christmas Island Area	LANL	B-52 Airdrop Freefall		WR	Intermediate
Pamlico	07-11-62	Christmas	LLNL	B-52 Airdrop		WR	Low Mt

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
		Island Area		Parachute			
Johnie Boy (possibly an ADM)	07-11-62	NTS	DOD	Crater	−2	WE	0.5 Kt
Merrimac	07-13-62	NTS		Shaft	−1356	WR	Intermediate
Small Boy	07-14-62	NTS	DOD	Tower	10	WE	Low
Little Feller I Warhead was a stockpiled W54 (DAVY CROCKETT)	07-17-62	NTS	DOD	Surface	3	WE	Low
Wichita	07-27-62	NTS		Shaft	−493	WR	Low
York	08-24-62	NTS		Shaft	−744	WR	Low
Bobac	08-24-62	NTS		Shaft	−676	WR	Low
Raritan	09-06-62	NTS		Shaft		WR	Low
Hyrax	09-14-62	NTS		Shaft	−711	WR	Low
Pebe	09-20-62	NTS		Shaft	−792	WR	Low
Allegheny	09-29-62	NTS		Shaft	−692	WR	Low
Androscoggin	10-02-62	Johnston Island Area	LLNL	B-52 Airdrop Parachute		WR	Intermediate
Mississippi	10-05-62	NTS		Shaft	−1622	WR	115 Kt
Bumping	10-06-62	Johnston Island Area	LLNL	B-52 Airdrop Parachute		WR	Low
Roanoke	10-12-62	NTS		Shaft	−510	WR	Low
Wolverine	10-12-62	NTS		Shaft		WR	Low
Chama	10-18-62	Johnston Island Area	LLNL	B-52 Airdrop Freefall		WR	Low Mt
Tioga	10-18-62	NTS		Shaft		WR	Low
Bandicoot	10-19-62	NTS		Shaft	−792	WR	Low
Checkmate (high altitude—tens of kms)	10-20-62	Johnston Island Area	DOD	STRYPI Rocket (XM-33)		WE	Low
Bluegill Triple Prime High altitude: tens of kms	10-26-62	Johnston Island Area	DOD	THOR Rocket		WE	Submegaton
Santee	10-27-62	NTS		Shaft	−1048	WR	Low
Calamity	10-27-62	Johnston Island Area	LLNL	B-52 Airdrop Parachute		WR	Intermediate
Housatonic	10-30-62	Johnston Island Area	LLNL	B-52 Airdrop Parachute		WR	Mt Range
Kingfish High altitude: tens of kms	11-01-62	Johnston Island Area	DOD	THOR Rocket		WE	Submegaton
Tightrope (high altitude—tens of kms) Last U.S. atmospheric test	11-04-62	Johnston Island Area	DOD	NIKE HERCULES Rocket		WE	Low
St. Lawrence	11-09-62	NTS		Shaft		WR	Low
Gundi	11-15-62	NTS		Shaft		WR	Low
Anacostia	11-27-62	NTS		Shaft	−747	3rd PS	Low
Taunton	12-04-62	NTS		Shaft		WR	Low
Tendrac	12-07-62	NTS		Shaft	−993	2nd UK	Low
Madison	12-12-62	NTS		Tunnel	−1320	WR	Low
Numbat	12-12-62	NTS		Shaft	−761	WR	Low
Manatee	12-14-62	NTS		Shaft		WR	Low
Casselman	02-08-63	NTS		Shaft	−944	WR	Low
Acushi	02-08-63	NTS		Shaft	−856	WR	Low
Ferret	02-08-63	NTS		Shaft		WR	Low
Hatchie	02-08-63	NTS		Shaft		WR	Low
Chipmunk	02-15-63	NTS		Shaft		WR	Low
Kaweah	02-21-63	NTS		Shaft	−745	4th PS	Low
Carmel	02-21-63	NTS		Shaft	−536	WR	Low
Jerboa	03-01-63	NTS		Shaft		WR	Low
Toyah	03-15-63	NTS		Shaft		WR	Low
Gerbil	03-29-63	NTS		Shaft	−917	WR	Low

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Ferret Prime	04-05-63	NTS		Shaft	– 793	WR	Low
Coypu	04-10-63	NTS		Shaft		WR	Low
Cumberland	04-11-63	NTS		Shaft		WR	Low
Kootanai	04-24-63	NTS		Shaft		WR	Low
Paisano	04-24-63	NTS		Shaft		WR	Low
Gundi Prime	05-09-63	NTS		Shaft		WR	Low
Double Tracks (Pu dispersal)	05-15-63	Bombing Range, NV		Surface		ST	Zero
Harkee	05-17-63	NTS		Shaft		WR	Low
Tejon	05-17-63	NTS		Shaft		WR	Low
Stones	05-22-63	NTS		Shaft	–1289	WR	Intermediate
Clean Slate I (Pu dispersal)	05-25-63	Bombing Range, NV		Surface		ST	Zero
Pleasant	05-29-63	NTS		Shaft		WR	Low
Clean Slate II (Pu dispersal)	05-31-63	Bombing Range, NV		Surface		ST	Zero
Yuba	06-05-63	NTS		Tunnel	– 786	WR	Low
Hutia	06-06-63	NTS		Shaft	– 442	WR	Low
Apshapa	06-06-63	NTS		Shaft		WR	Low
Clean Slate III (Pu dispersal)	06-09-63	Bombing Range, NV		Surface		ST	Zero
Mataco	06-14-63	NTS		Shaft	– 642	WR	Low
Kennebec	06-25-63	NTS		Shaft	– 740	WR	Low
Limited Test Ban Treaty signed 5 August 1963							
	OPERATION NIBLICK (27)						
Pekan	08-12-63	NTS		Shaft	– 992	WR	Low
Satsop	08-15-63	NTS		Shaft	– 738	WR	Low
Kohocton	08-23-63	NTS		Shaft	– 835	WR	Low
Ahtanum	09-13-63	NTS		Shaft	– 740	WR	Low
Bilby	09-13-63	NTS		Shaft	–2344	WR	249 Kt
First underground test reported felt in Las Vegas							
Grunion	10-11-63	NTS		Shaft	– 857	WR	Low
Tornillo	10-11-63	NTS		Shaft	– 489	5th PS	Low
Clearwater	10-16-63	NTS		Shaft	–1785	WR	Intermediate
Shoal	10-26-63	Fallon, NV		Shaft	–1205	VU	12 Kt
Anchovy	11-14-63	NTS		Shaft	– 854	WR	Low
Mustang	11-15-63	NTS		Shaft	– 544	WR	Low
Greys	11-22-63	NTS		Shaft	– 987	WR	Intermediate
Sardine	12-04-63	NTS		Shaft	– 860	WR	Low
Eagle	12-12-63	NTS		Shaft	– 540	WR	Low
Fore	01-16-64	NTS		Shaft	–1610	WR	20-200 Kt(19)
Oconto	01-23-64	NTS		Shaft	– 868	WR	<20 Kt
Klickitat	02-20-64	NTS		Shaft	–1616	6th PS	20-200 Kt(24)
Pike	03-13-64	NTS		Shaft	– 376	WR	<20 Kt
Hook	04-14-64	NTS		Shaft	– 668	WR	<20 Kt
Sturgeon	04-15-64	NTS		Shaft	– 491	WR	<20 Kt
Turf	04-24-64	NTS		Shaft	–1663	WR	20-200 Kt(100)
Pipefish	04-29-64	NTS		Shaft	– 859	WR	<20 Kt(15)
Backswing	05-14-64	NTS		Shaft	– 536	WR	<20 Kt
Minnow	05-15-64	NTS		Shaft	– 792	WR	<20 Kt
Ace	06-11-64	NTS		Shaft	– 862	7th PS	<20 Kt
Fade	06-25-64	NTS		Shaft	– 673	WR	<20 Kt
Dub	06-30-64	NTS		Shaft	– 847	8th PS	<20 Kt(9)
	OPERATION WHETSTONE (36)						
Bye	07-16-64	NTS		Shaft	–1277	WR	20-200 Kt
Cormorant	07-17-64	NTS		Shaft	– 691	3rd UK	<20 Kt
Alva	08-19-64	NTS		Shaft	– 545	WR	<20 Kt

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Canvasback	08-22-64	NTS		Shaft	−1469	WR	<20 Kt(18)
Haddock	08-28-64	NTS		Shaft	−1193	WR	<20 Kt
Guanay	09-04-64	NTS		Shaft	− 856	WR	<20 Kt(12)
Auk	10-02-64	NTS		Shaft	−1484	WR	<20 Kt(12)
Par	10-09-64	NTS		Shaft	−1325	9th PS	38 Kt
Barbel	10-16-64	NTS		Shaft	− 849	WR	<20 Kt
Salmon Decoupling experiment	10-22-64	Hattiesburg, MS		Shaft	−2717	VU	5.3 Kt
Forest	10-31-64	NTS		Shaft	−1249	WR	<20 Kt
Handcar	11-05-64	NTS		Shaft	−1319	10th PS	12 Kt
Crepe	12-05-64	NTS		Shaft	−1323	WR	20-200 Kt(10)
Drill	12-05-64	NTS		Shaft		WR	3.4 Kt
Parrot	12-16-64	NTS		Shaft	− 592	WR	1.3 Kt
Mudpack Purpose was to obtain information concerning ground shock	12-16-64	NTS	DOD	Shaft	− 496	WE	2.7 Kt
Sulky	12-18-64	NTS		Shaft	− 90	11th PS	0.092 Kt
Wool	01-14-65	NTS		Shaft	− 706	WR	<20 Kt
Cashmere	02-04-65	NTS		Shaft	− 762	WR	<20 Kt
Alpaca	02-12-65	NTS		Shaft	− 737	WR	<20 Kt
Merlin	02-16-65	NTS		Shaft	− 972	WR	10.1 Kt
Wishbone Purpose was to study effects on equipment and materials	02-18-65	NTS	DOD-LLNL	Shaft	− 588	WE	<20 Kt
Wagtail	03-03-65	NTS		Shaft	−2459	WR	20-200 Kt(65)
Cup	03-26-65	NTS		Shaft	−1761	WR	20-200 Kt(35)
Kestrel	04-05-65	NTS		Shaft	−1466	WR	<20 Kt
Palanquin	04-14-65	NTS		Crater	− 280	12th PS	4.3 Kt
Gum Drop Purpose was to study effects on equipment and materials	04-21-65	NTS	DOD	Tunnel	−1000	WE	<20 Kt(8)
# (21:44:02.8)	04-23-65	NTS (36.96 115.94)		?	?	?	?
Tee	05-07-65	NTS		Shaft	− 624	WE	<20 Kt
Buteo	05-12-65	NTS		Shaft	−2282	WR	<20 Kt
Scaup	05-14-65	NTS		Shaft	−1401	WR	<20 Kt
Cambric	05-14-65	NTS		Shaft		WR	0.75 Kt
Tweed	05-21-65	NTS		Shaft	− 822	WR	<20 Kt
Petrel	06-11-65	NTS		Shaft	− 593	WR	1.3 Kt
Diluted Waters Purpose was to study effects on equipment and materials	06-16-65	NTS	DOD-LLNL	Shaft	− 640	WE	<20 Kt
Tiny Tot Purpose was to obtain information on ground shock. First known nuclear detonation conducted on a rock surface within an underground cavity	06-17-65	NTS	DOD	Tunnel	− 360	WE	<20 Kt
	OPERATION FLINTLOCK (40)						
Bronze	07-23-65	NTS		Shaft	−1741	WR	20-200 Kt(60)
Mauve	08-06-65	NTS		Shaft	−1053	WR	<20 Kt(18)
Centaur	08-27-65	NTS		Shaft	− 564	WR	<20 Kt
Screamer	09-01-65	NTS		Shaft	− 890	WR	<20 Kt(12)
Charcoal	09-10-65	NTS		Shaft	−1494	4th UK	20-200 Kt
Elkhart	09-17-65	NTS		Shaft	− 720	WR	<20 Kt

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Long Shot	10-29-65	Amchitka, AK	DOD	Shaft	−2300	VU	80 Kt
Sepia	11-12-65	NTS		Shaft	− 791	WR	<20 Kt
Corduroy	12-03-65	NTS		Shaft	−2236	WR	20-200 Kt(100)
Emerson	12-16-65	NTS		Shaft	− 853	WR	<20 Kt
Buff	12-16-65	NTS		Shaft	−1642	WR	20-200 Kt(36)
Maxwell	01-13-66	NTS		Shaft	− 601	WR	<20 Kt
Lampblack	01-18-66	NTS		Shaft	−1842	WR	20-200 Kt(32)
Dovekie	01-21-66	NTS		Shaft	−1093	WR	<20 Kt
Plaid II	02-03-66	NTS		Shaft	− 886	WR	<20 Kt
Rex	02-24-66	NTS		Shaft	−2204	WR	19 Kt
Red Hot Purpose was to study ground shock	03-05-66	NTS	DOD	Shaft	−1330	WR	<20 Kt
Finfoot	03-07-66	NTS		Shaft	− 642	WR	<20 Kt
Clymer	03-12-66	NTS		Shaft	−1303	WR	<20 Kt
Purple	03-18-66	NTS		Shaft	−1092	WR	<20 Kt
Templar	03-24-66	NTS		Shaft	− 495	13th PS	<20 Kt
Lime	04-01-66	NTS		Shaft	−1842	WR	<20 Kt
Stutz	04-06-66	NTS		Shaft	− 739	WR	<20 Kt(5)
Tomato	04-07-66	NTS		Shaft	− 742	WR	<20 Kt
Duryea	04-14-66	NTS		Shaft	−1786	WR	70 Kt
Pin Stripe Purpose was to study effects on equipment and material	04-25-66	NTS	DOD	Shaft	− 970	WE	<20 Kt(4)
Traveller	05-04-66	NTS		Shaft	− 646	WR	<20 Kt
Cyclamen	05-05-66	NTS		Shaft	−1001	WR	12 Kt
Chartreuse	05-06-66	NTS		Shaft	−2183	WR	73 Kt
Tapestry	05-12-66	NTS		Shaft	− 810	WR	<20 Kt(10)
Piranha	05-13-66	NTS		Shaft	−1800	WR	20-200 Kt(100)
Dumont	05-19-66	NTS		Shaft	−2200	WR	20-200 Kt(190)
Discus Thrower Purpose was to study ground shock transmissions	05-27-66	NTS	DOD-LANL	Shaft	−1106	WE	22 Kt
Pile Driver Purpose was to study nuclear detonation effects on underground structures	06-02-66	NTS	DOD-LANL	Tunnel	−1518	WE	62 Kt
Tan	06-03-66	NTS		Shaft	−1839	WR	20-200 Kt(140)
Puce	06-10-66	NTS		Shaft	−1592	WR	<20 Kt
Double Play Purpose was to study effects on equipment and materials	06-15-66	NTS	DOD-LLNL	Tunnel	−1075	WE	<20 Kt
Kankakee	06-15-66	NTS		Shaft	−1494	WR	20-200 Kt
Vulcan	06-25-66	NTS		Shaft	−1057	14th PS	25 Kt
Halfbeak	06-30-66	NTS		Shaft	−2688	WR	365 Kt
	OPERATION LATCHKEY (27)						
Saxon	07-28-66	NTS		Shaft	− 500	15th PS	<20 Kt
Rovena	08-10-66	NTS		Shaft	− 635	WR	<20 Kt
Derringer	09-12-66	NTS		Shaft	− 835	WE	<20 Kt(12)
Daiquiri	09-23-66	NTS		Shaft	−1841	WR	<20 Kt
Newark	09-26-66	NTS		Shaft	− 750	WR	<20 Kt(4)
Simms	11-05-66	NTS		Shaft	− 650	16th PS	<20 Kt
Ajax	11-11-66	NTS		Shaft	− 782	WR	<20 Kt
Cerise	11-18-66	NTS		Shaft	− 693	WR	<20 Kt
Sterling Decoupling experiment	12-03-66	Hattiesburg, MS		Shaft	−2717	VU	380 Tons

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
New Point Purpose was to study effects on equipment and materials	12-13-66	NTS	DOD-LLNL	Shaft	– 800	WE	<20 Kt(10)
Greeley	12-20-66	NTS		Shaft	–3965	WR	870 Kt
Nash	01-19-67	NTS		Shaft	–1194	WR	20-200 Kt(49)
Bourbon	01-20-67	NTS		Shaft	–1836	WR	20-200 Kt(29)
Ward	02-08-67	NTS		Shaft	– 844	WR	<20 Kt(10)
Persimmon	02-23-67	NTS		Shaft	– 981	WR	<20 Kt(3)
Agile	02-23-67	NTS		Shaft	–2400	WR	20-200 Kt(130)
Rivet III	03-02-67	NTS		Shaft	– 890	WR	<20 Kt
Fawn	04-07-67	NTS		Shaft	– 889	WR	<20 Kt
Chocolate	04-21-67	NTS		Shaft	– 769	WR	<20 Kt(7)
Effendi	04-27-67	NTS		Shaft	– 719	WR	<20 Kt
Mickey	05-10-67	NTS		Shaft	–1639	WR	20-200 Kt(10)
Commodore	05-20-67	NTS		Shaft	–2449	WR	250 Kt
Scotch	05-23-67	NTS		Shaft	–3207	WR	155 Kt
Knickerbrocker	05-26-67	NTS		Shaft	–2069	WR	76 Kt
Switch	06-22-67	NTS		Shaft	– 990	17th PS	<20 Kt
Midi Mist Purpose was to study effects on equipment and materials	06-26-67	NTS	DOD-LLNL	Tunnel	–1230	WE	<20 Kt(9)
Umber	06-29-67	NTS		Shaft	–1018	WE	<20 Kt(8)
	OPERATION CROSSTIE (33)						
Stanley	07-27-67	NTS		Shaft	–1587	WR	20-200 Kt
# (14:00 01 0)	08-04-67	NTS (37 01 116 15)		?	?	?	?
Washer	08-10-67	NTS		Shaft	–1525	WR	<20 Kt
Bordeaux	08-18-67	NTS		Shaft	–1069	WR	<20 Kt
Door Mist	08-31-67	NTS	DOD	Tunnel	–1463	WE	<20 Kt(9)
Yard	09-07-67	NTS		Shaft	–1700	WR	20-200 Kt
Marvel	09-21-67	NTS		Shaft	– 572	18th PS	2 2 Kt
Zaza	09-27-67	NTS		Shaft	–2188	WR	20-200 Kt(170)
Lanpher	10-18-67	NTS		Shaft	–2343	WR	20-200 Kt(140)
Sazerac	10-25-67	NTS		Shaft	– 992	WR	<20 Kt
Cobbler	11-08-67	NTS		Shaft	–2200	WR	<20 Kt(7)
Gasbuggy	12-10-67	Farmington, NM		Shaft	–4240	19th PS	29 Kt
Stilt	12-15-67	NTS		Shaft	–1092	WR	<20 Kt(2)
Hupmobile Established many of the criteria for underground diagnostics still used today	01-18-68	NTS		Shaft	– 810	WE	7 4 Kt
Staccato	01-19-68	NTS		Shaft	–1455	WR	20-200 Kt
Faultless	01-19-68	Central Nevada		Shaft	–3200	WR	200-1000 Kt(1200)
Cabriolet	01-26-68	NTS		Crater	– 170	20th PS	2 3 Kt
# (15:30:01 0)	01-31-68	NTS (36 89 116 12)		?	?	?	?
Knox	02-21-68	NTS		Shaft	–2116	WR	20-200 Kt(200)
Dorsal Fin	02-29-68	NTS	DOD	Tunnel	–1345	WE	<20 Kt(20)
Buggy 5 simultaneous detonations Counts as one test Produced ditch 254 feet across, 855 feet long and 65 feet deep	03-12-68	NTS (Area 30)		Crater	– 135	21st PS	5 4 Kt
Pommard	03-14-68	NTS		Shaft	– 686	WR	1 5 Kt
Stinger	03-22-68	NTS		Shaft	–2191	WR	20-200 Kt(160)
Milk Shake	03-25-68	NTS	DOD	Shaft	– 868	WE	<20 Kt(10)
Noor	04-10-68	NTS		Shaft	–1250	WR	20-200 Kt(20)

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Shuffle	04-18-68	NTS		Shaft	−1615	WR	20-200 Kt(25)
Scroll	04-23-68	NTS		Shaft	− 735	VU	<20 Kt(6)
Boxcar	04-26-68	NTS		Shaft	−3800	WR	1.3 Mt
# (16:00:01.0)	05-03-68	NTS (37.00 115.99)		?	?	?	?
Clarksmobile	05-17-68	NTS		Shaft	−1550	WR	20-200 Kt(15)
Tub	06-06-68	NTS		Shaft	− 620	WR	<20 Kt
Rickey	06-15-68	NTS		Shaft	−2242	WR	20-200 Kt(300)
Chateaugay	06-28-68	NTS		Shaft	−1992	WR	20-200 Kt(58)
	OPERATION BOWLINE (30)						
Tanya	07-30-68	NTS		Shaft	−1250	WR	20-200 Kt(10)
Diana Moon	08-27-68	NTS	DOD	Shaft	− 794	WE	<20 Kt
Sled	08-29-68	NTS		Shaft	−2393	WR	20-200 Kt(260)
Noggin	09-06-68	NTS		Shaft	−1909	WR	20-200 Kt(110)
Knife A	09-12-68	NTS		Shaft	−1089	WR	<20 Kt
Stoddard	09-17-68	NTS		Shaft	−1535	22nd PS	20-200 Kt(13)
Hudson Seal	09-24-68	NTS	DOD	Tunnel	−1092	WE	<20 Kt(10)
Knife C	10-03-68	NTS		Shaft	− 989	WR	<20 Kt(3)
# (14:30:04.0)	10-10-68	NTS (36.99 116.26)		?	?	?	?
# (18:30:04.0)	10-31-68	NTS (36.87 116.27)		?	?	?	?
Crew	11-04-68	NTS		Shaft	−1980	WR	20-200 Kt(22)
Knife B	11-15-68	NTS		Shaft	−1191	WR	<20 Kt(8)
# (15:30:05.0)	11-15-68	NTS (37.00 116.31)		?	?	?	?
Ming Vase	11-20-68	NTS	DOD	Tunnel	−1010	WE	<20 Kt(12)
Tinderbox	11-22-68	NTS		Shaft	−1442	WR	<20 Kt(3)
Schooner	12-08-68	NTS		Crater	− 350	23rd PS	30 Kt
Tyg	12-12-68	NTS		Shaft	− 670	WR	<20 Kt(20)
# (15:20:01.0)	12-12-68	NTS (37.01 116.11)		?	?	?	?
Benham	12-19-68	NTS		Shaft	−4600	WR	1.15 Mt
Packard	01-15-69	NTS		Shaft	− 810	WE	10.0 Kt
Wineskin	01-15-69	NTS		Shaft	−1700	WR	20-200 Kt(40)
Vise	01-30-69	NTS		Shaft	−1490	WR	20-200 Kt(40)
Cypress	02-12-69	NTS		Tunnel	−1350	WE	<20 Kt(15)
Barsac	03-20-69	NTS		Shaft	− 998	WR	<20 Kt(10)
Coffer	03-21-69	NTS		Shaft	−1525	WR	<100 Kt(35)
Thistle	04-30-69	NTS		Shaft	−1838	WR	20-200 Kt
Blenton	04-30-69	NTS		Shaft	−1829	WR	20-200 Kt
Purse	05-07-69	NTS		Shaft	−1964	WR	20-200 Kt(180)
Torrido	05-27-69	NTS		Shaft	−1669	WR	20-200 Kt(22)
Tapper	06-12-69	NTS		Shaft	− 994	WR	<20 Kt(12)
	OPERATION MANDREL (43)						
Ildrim	07-16-69	NTS		Shaft	−1346	WR	20-200 Kt(6)
Hutch	07-16-69	NTS		Shaft	−1800	WR	20-200 Kt(300)
Spider	08-14-69	NTS		Shaft	− 784	WR	<20 Kt
Pliers	08-27-69	NTS		Shaft	− 784	WR	<20 Kt
Rulison	09-10-69	Grand Valley, CO		Shaft	−8443	24th PS	47 Kt
Minute Steak	09-12-69	NTS	DOD	Shaft	− 867	WE	<20 Kt(10)
Jorum	09-16-69	NTS		Shaft	−3800	WR	<1 Mt(700 Kt)
Milrow (seismic calibration)	10-02-69	Amchitka, AK		Shaft	−4000	WR	1 Mt
Pipkin	10-08-69	NTS		Shaft	−2025	WR	200-1000 Kt(82)
Cruet	10-29-69	NTS		Shaft	− 855	WR	11 Kt
Pod	10-29-69	NTS		Shaft	−1025	WR	20-200 Kt
Calabash	10-29-69	NTS		Shaft	−2050	WR	110 Kt
Scuttle	11-13-69	NTS		Shaft		WR	<20 Kt
Piccalilli	11-21-69	NTS		Shaft	−1292	WR	20-200 Kt(17)
Diesel Train	12-05-69	NTS	DOD	Tunnel	−1375	WE	<20 Kt(16)
Grape A	12-17-69	NTS		Shaft	−1807	WR	20-200 Kt(61)
Lovage	12-17-69	NTS		Shaft	−1240	WR	<20 Kt

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Terrine	12-18-69	NTS		Shaft	-1500	WR	20-200 Kt(28)
Fob	01-23-70	NTS		Shaft	- 675	WR	<20 Kt
Ajo	01-30-70	NTS		Shaft	- 998	WR	<20 Kt(20)
Grape B	02-04-70	NTS		Shaft	-1819	WR	20-200 Kt(120)
Labis	02-05-70	NTS		Shaft	-1450	WR	25 Kt
Diana Mist	02-11-70	NTS	DOD	Tunnel	-1310	WE	<20 Kt(9)
Cumarin	02-25-70	NTS		Shaft	-1340	WR	20-200 Kt(25)
Yannigan	02-26-70	NTS		Shaft	-1287	WR	20-200 Kt(100)
Cyathus	03-06-70	NTS		Shaft	- 950	WR	8.7 Kt
Arabis	03-06-70	NTS		Shaft	- 820	WR	<20 Kt
Jal	03-19-70	NTS		Shaft	- 988	WR	<20 Kt(6)
Shaper	03-23-70	NTS		Shaft	-1839	WR	20-200 Kt(93)
Handley	03-26-70	NTS		Shaft	-3957	WR	>1 Mt(1900 Kt)
Snubber	04-21-70	NTS		Shaft	-1125	WE	<20 Kt(6)
Can	04-21-70	NTS		Shaft	-1310	WR	20-200 Kt(8)
Beebalm	05-01-70	NTS		Shaft	-1280	WR	<20 Kt(1)
Hod	05-01-70	NTS		Shaft	- 870	WR	<20 Kt(6)
Mint Leaf	05-05-70	NTS	DOD	Tunnel	-1330	WE	<20 Kt(28)
Diamond Dust	05-12-70	NTS	DOD	Tunnel	- 830	VU	<20 Kt
Cornice	05-15-70	NTS		Shaft	-1455	WR	20-200 Kt(39)
Manzanas	05-21-70	NTS		Shaft	- 789	WR	<20 Kt(1)
Morrones	05-21-70	NTS		Shaft	-1580	WR	20-200 Kt(20)
Hudson Moon	05-26-70	NTS	DOD	Tunnel	-1386	WE	<20 Kt(9)
Flask	05-26-70	NTS		Shaft	-1743	25th PS	105 Kt
# (12:00:01 0)	05-28-70	NTS (37 18 116 06)		?	?	?	?
Arnica	06-26-70	NTS		Shaft	-1015	WR	20-200 Kt
OPERATION EMERY (12)							
Tijeras	10-14-70	NTS		Shaft	-1839	WR	20-200 Kt(94)
# (14:30:01 0)	10-28-70	NTS (37 27 115 98)		?	?	?	?
Abeytas	11-05-70	NTS (36 99 116 05)		Shaft	-1291	WR	20-200 Kt(11)
# (15:00:01 0)	11-19-70	NTS		?	?	?	?
Artesia	12-16-70	NTS		Shaft	-1592	WR	20-200 Kt
Cream	12-16-70	NTS		Shaft	- 965	WR	<20 Kt
Carpetbag	12-17-70	NTS		Shaft	-2171	WR	220 Kt
Baneberry	12-18-70	NTS		Shaft	- 910	WR	10 Kt
Embudo	06-16-71	NTS	LANL	Shaft	- 994	WR	<20 Kt(18)
Laguna	06-23-71	NTS	LANL	Shaft	-1493	WR	20-200 Kt(10)
Harebell	06-24-71	NTS	LLNL	Shaft	-1702	WR	20-200 Kt(40)
Camphor	06-29-71	NTS	DOD	Tunnel	?	WE	<20 Kt
OPERATION GROMMET (20)							
Diamond Mine	07-01-71	NTS	DOD	Tunnel	- 873	VU	<20 Kt
Miniata	07-08-71	NTS	LLNL	Shaft	-1735	26th PS	83 Kt
Algodones	08-18-71	NTS	LANL	Shaft	-1731	WR	20-200 Kt(66)
# (14:00:00 0)	09-22-71	NTS (37 07 115 97)		?	?	?	?
Pedernal	09-29-71	NTS	LANL	Shaft	-1242	WR	<20 Kt
Cathay	10-08-71	NTS	LLNL	Shaft	-1240	WR	<20 Kt(7)
# (14:30:02 0)	10-14-71	NTS (37 32 116 14)		?	?	?	?
Cannikin Proof test of W71 warhead for SPARTAN ABM missile	11-06-71	Amchitka, AK	LLNL	Shaft	-5875	WR	<5 Mt
Diagonal Line	11-24-71	NTS	DOD	Shaft	- 867	WE	<20 Kt
# (15:45:03 4)	11-30-71	NTS (37 16 116 15)		?	?	?	?
Chaenactis	12-14-71	NTS	LLNL	Shaft	-1085	WR	20-200 Kt(24)
# (21:44:59 0)	02-03-72	NTS (36 98 115 81)		?	?	?	?
# (21:00:01 0)	03-30-72	NTS (36 97 116 05)		?	?	?	?
Longchamps	04-19-72	NTS		Shaft	-1071	WR	<20 Kt
Misty North	05-02-72	NTS	DOD	Tunnel	-1238	WE	<20 Kt(19)

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
# (14:00:02 0)	05-11-72	NTS (37 25 116 11)		?	?	?	?
Zinnia	05-17-72	NTS	LLNL	Shaft	−1059	WR	<20 Kt(8)
Monero	05-19-72	NTS	LANL	Shaft	−1763	WR	<20 Kt(7)
# (16:30:01 0)	06-28-72	NTS (37 12 116 04)		?	?	?	?
# (18:30:03 0)	06-29-72	NTS (37 10 116 21)		?	?	?	?
	OPERATION TOGGLE (15)						
Diamond Sculls Used full scale SPARTAN missile	07-20-72	NTS	DOD	Tunnel	−1391	WE	<20 Kt(21)
# (13:30:01 0)	07-25-72	NTS (37 02 116 03)		?	?	?	?
Oscuro	09-21-72	NTS	LANL	Shaft	−1839	WR	20-200 Kt(130)
Delphinium	09-26-72	NTS	LLNL	Shaft	− 970	WR	15 Kt
# (15:15:04 0)	11-09-72	NTS (37 25 116 32)		?	?	?	?
Flax	12-21-72	NTS	LLNL	Shaft	−2258	WR	20-200 Kt(27)
Miera	03-08-73	NTS	LANL	Shaft	−1866	WR	20-200 Kt(67)
Angus	04-25-73	NTS	LANL	Shaft	−1486	WR	20-200 Kt(21)
Starwort	04-26-73	NTS		Shaft	−1850	WR	90 Kt
Rio Blanco Three devices fired in a single emplacement hole at 5840, 6230 and 6690 ft., respectively	05-17-73	Rifle, CO	LLNL	Shaft		27th PS	Three 33 Kt Devices
# (13:30:01 1)	05-24-73	NTS (37 18 116 09)		?	?	?	?
Dido Queen	06-05-73	NTS	DOD	Tunnel	−1284	WE	<20 Kt(26)
Almendro	06-06-73	NTS	LANL	Shaft	−3490	WR	200-1000 Kt(570)
# (14:44:59 6)	06-21-73	NTS (37 06 115 99)		?	?	?	?
Portulaca	06-28-73	NTS	LLNL	Shaft	−1530	WR	20-200 Kt(60)
	OPERATION ARBOR (8)						
Husky Ace	10-12-73	NTS	DOD	Tunnel	−1356	WE	<20 Kt(9)
Bernal	11-28-73	NTS	LANL	Shaft		WR	<20 Kt
# (19:00:07 0)	12-12-73	NTS (37 06 116 57)		?	?	?	?
Latir	02-27-74	NTS	LANL	Shaft		WR	20-200 Kt(150)
# (14:14:59 9)	05-22-74	NTS (37 06 116 11)		?	?	?	?
Fallon	05-23-74	NTS	LLNL	Shaft		5th UK	20-200 Kt
# (14:40:00 5)	06-06-74	NTS (36 96 116 02)		?	?	?	?
Ming Blade	06-19-74	NTS	LANL/DOD	Tunnel		WE	<20 Kt(20)
	OPERATION BEDROCK (18)						
Threshold Test Ban Treaty signed 3 July 1974; submitted to U.S. Senate for ratification on 29 July 1976							
Escabosa	07-10-74	NTS	LANL	Shaft		WR	20-200 Kt(170)
# (14:00:01 3)	07-18-74	NTS (37 10 116 10)		?	?	?	?
Puye	08-14-74	NTS	LANL	Shaft		WR	<20 Kt(40)
Portmanteau	08-30-74	NTS	LLNL	Shaft		WR	20-200 Kt(200)
# (14:00:00 3)	09-26-74	NTS (36 97 116 00)		?	?	?	?
Stanyan	09-26-74	NTS	LLNL	Shaft		WR	20-200 Kt(100)
Hybla Fair	10-28-74	NTS	DOD	Tunnel		WE	<20 Kt
# (13:30:04 2)	12-16-74	NTS (37 11 116 32)		?	?	?	?(4)
Topgallant	02-28-75	NTS		Shaft		WR	20-200 Kt(185)
Cabrillo	03-07-75	NTS		Shaft		WR	20-200 Kt(120)
Dining Car	04-05-75	NTS	DOD	Tunnel		WE	<20 Kt(20)
Edam	04-24-75	NTS		Shaft		WR	20-200 Kt(9)
Obar	04-30-75	NTS		Shaft		WR	20-200 Kt(41)
Tybo	05-14-75	NTS	LLNL	Shaft		WR	200-1000 Kt(380)
Stilton	06-03-75	NTS	LLNL	Shaft	−2398	WR	20-200 Kt(275)
Mizzen	06-03-75	NTS		Shaft	−1516	WR	20-200 Kt(160)

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
Mast	06-19-75	NTS	LANL	Shaft	−2992	WR	200-1000 Kt(520)
Camembert	06-26-75	NTS	LLNL	Shaft	−4300	WR	200-1000 Kt(750)
	OPERATION ANVIL (19 with TQ)						
Marsh	09-06-75	NTS	LANL	Shaft	−1400	WR	<20 Kt(15)
Husky Pup	10-24-75	NTS	LANL/DOD	Tunnel		WE	<20 Kt(15)
Kasseri	10-28-75	NTS	LLNL	Shaft		WR	200-1000 Kt(1200)
# (15:30:00 3)	11-18-75	NTS (36 59 116 03)	?			?	?
Inlet	11-20-75	NTS	LANL	Shaft	−2680	WR	200-1000 Kt(500)
Leyden	11-26-75	NTS	LLNL	Shaft	−1050	WR	<20 Kt(5)
Chiberta	12-20-75	NTS	LLNL	Shaft	−2348	WR	20-200 Kt(160)
Muenster	01-03-76	NTS	LLNL	Shaft	−4759	WR	200-1000 Kt(600)
Keelson	02-04-76	NTS	LANL	Shaft	−2099	WR	20-200 Kt(200)
Esrom	02-04-76	NTS	LLNL	Shaft	−2148	WR	20-200 Kt(150)
Fontina	02-12-76	NTS	LLNL	Shaft	−3998	WR	200-1000 Kt(900)
Cheshire	02-14-76	NTS	LLNL	Shaft	−3828	WR	200-500 Kt(350)
Estuary	03-09-76	NTS	LANL	Shaft	−2850	WR	200-500 Kt(350)
Colby	03-14-76	NTS	LLNL	Shaft	−4175	WR	500-1000 Kt(900)
Pool	03-17-76	NTS	LANL	Shaft	−2883	WR	200-500 Kt(500)
Strait	03-17-76	NTS		Shaft	−2558	WR	200-500 Kt(200)
Mighty Epic	05-12-76	NTS	DOD	Tunnel		WE	<20 Kt
Billet	07-27-76	NTS		Shaft		WR	20-150 Kt
Banon	08-26-76	NTS		Shaft		6th UK	20-150 Kt
	OPERATION FULCRUM (11)						
Chevre	11-23-76	NTS	LLNL	Shaft		WR	<20 Kt
Redmud	12-08-76	NTS	LANL	Shaft	−1401	WR	<20 Kt
Asiago	12-21-76	NTS		Shaft	−1086	WR	<20 Kt
Rudder	12-28-76	NTS	LANL	Shaft	−4205	WR	20-150 Kt
Marsilly	04-05-77	NTS	LLNL	Shaft	−2263	WR	20-150 Kt
Bulkhead	04-27-77	NTS	LANL	Shaft	−1948	WR	20-150 Kt
Crewline	05-25-77	NTS	LANL	Shaft	−1850	WR	20-150 Kt
Strake	08-04-77	NTS	LANL	Shaft	−1699	WR	20-150 Kt
Scantling	08-19-77	NTS	LANL	Shaft	−2299	WR	20-150 Kt
Ebbtide	09-15-77	NTS	LANL	Shaft	−1250	WR	<20 Kt
Coulommiers	09-27-77	NTS	LLNL	Shaft	−1738	WR	20-150 Kt
	OPERATION CRESSET (19)						
Bobstay	10-26-77	NTS	LANL	Shaft	−1250	WR	<20 Kt
Hybla Gold	11-01-77	NTS	DOD	Tunnel	−1283	WE	<20 Kt
Sandreef	11-09-77	NTS	LANL	Shaft	−2298	WR	20-150 Kt
Seamount	11-17-77	NTS	LANL	Shaft	−1220	WR	<20 Kt
Farallones	12-14-77	NTS	LLNL	Shaft	−2191	WR	20-150 Kt
Campos	02-13-78	NTS	LLNL	Shaft	?	WR	<20 Kt
Reblochon	02-23-78	NTS	LLNL	Shaft	−2158	WR	20-150 Kt
# (15:00:00 1)	03-16-78	NTS (37 01 116 10)	?		?	?	?
Iceberg	03-23-78	NTS	LANL	Shaft	−2099	WR	20-150 Kt
Backbeach	04-11-78	NTS	LANL	Shaft	−2004	WR	20-150 Kt
Fondutta	04-11-78	NTS	LLNL	Shaft	−2076	7th UK	20-150 Kt
Transom No nuclear yield; device was destroyed by Hearts detonation on 09-06-79	05-10-78	NTS	LANL	Shaft	?	WR	Zero
# (17:00:00 -0)	06-01-78	NTS (37 03 116 04)	?		?	?	?
# (13 59:59 3)	07-07-78	NTS (37 10 116 01)	?		?	?	?
Lowball	07-12-78	NTS	LANL	Shaft	−1850	WR	20-150 Kt
Panir	08-31-78	NTS	LLNL	Shaft	−2234	WR	20-150 Kt
Diablo Hawk	09-13-78	NTS	DOD	Tunnel	−1373	WE	<20 Kt
Draughts	09-27-78	NTS	LANL	Shaft	−1450	WR	20-150 Kt
Rummy	09-27-78	NTS	LANL	Shaft	−2099	WR	20-150 Kt

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
	OPERATION QUICKSILVER (18)						
Emmenthal	11-02-78	NTS	LLNL	Shaft	−1889	WR	<20 Kt
Quargel	11-18-78	NTS	LLNL	Shaft	−1778	8th UK	20-150 Kt
# (17:07:29 8)	12-01-78	NTS (37 03 116 04)		?	?	?	?
Farm	12-16-78	NTS	LLNL	Shaft	−2260	WR	20-150 Kt
Baccarat	01-24-79	NTS	LANL	Shaft	−1069	WR	<20 Kt
Quinella	02-08-79	NTS		Shaft	−1899	WR	20-150 Kt
Kloster	02-15-79	NTS	LLNL	Shaft	−1758	WR	20-150 Kt
Memory	03-14-79	NTS		Shaft	−1200	WR	<20 Kt
# (15:59:59 7)	05-11-79	NTS (36 98 116 01)		?	?	?	?
Pepato	06-11-79	NTS	LLNL	Shaft	−2234	WR	20-150 Kt
Chess	06-20-79	NTS	LANL	Shaft	−1099	WR	<20 Kt
Fajy	06-28-79	NTS	LLNL	Shaft	−1761	WR	20-150 Kt
Burzet	08-03-79	NTS	LLNL	Shaft	−1476	WR	20-150 Kt
Offshore	08-08-79	NTS	LANL	Shaft	−1299	WR	20-150 Kt
Nessel	08-29-79	NTS	LLNL	Shaft	−1522	9th UK	20-150 Kt
Hearts	09-06-79	NTS	LANL	Shaft	−2099	WR	20-150 Kt
Detonation destroyed Transom device that did not detonate on 05-10-78							
Pera	09-08-79	NTS	LLNL	Shaft	− 656	WR	<20 Kt
Sheepshead	09-26-79	NTS	LLNL	Shaft	−2099	WR	20-150 Kt
	OPERATION TINDERBOX (15)						
Backgammon	11-29-79	NTS	LANL	Shaft	− 751	WR	<20 Kt
Azul	12-14-79	NTS	LLNL	Shaft	− 672	WR	<20 Kt
Detonation destroyed Peninsula device that was damaged during emplacement on 10-23-75. The Peninsula device was not tested							
Tarko	02-28-80	NTS	LLNL	Shaft	−1210	WR	<20 Kt
Norbo	03-08-80	NTS	LLNL	Shaft	− 889	WR	<20 Kt
Liptauer	04-03-80	NTS	LLNL	Shaft	−1368	WR	20-150 Kt
Pyramid	04-16-80	NTS	LANL	Shaft	−1899	WR	20-150 Kt
Colwick	04-26-80	NTS	LLNL	Shaft	−2078	10th UK	20-150 Kt
Canfield	05-02-80	NTS	LANL	Shaft	−1151	WR	<20 Kt
Flora	05-22-80	NTS	LANL	Shaft	−1099	WR	<20 Kt
Kash	06-12-80	NTS	LLNL	Shaft	−2116	WR	20-150 Kt
Huron King	06-24-80	NTS	DOD	Shaft	−1050	WE	<20 Kt
Part of an Air Force and National Security Agency program to improve the database on nuclear hardening design techniques for satellites. A vertical line of sight test using a small DSCS III prototype							
Tafi	07-25-80	NTS	LLNL	Shaft	−2230	WR	20-150 Kt
Verdello	07-31-80	NTS	LANL	Shaft	−1200	WR	<20 Kt
Bonarda	09-25-80	NTS	LANL	Shaft	−1250	WR	20-150 Kt
Riola	09-25-80	NTS	LLNL	Shaft	−1391	WR	<20 Kt
	OPERATION GUARDIAN (16)						
Dutchess	10-24-80	NTS	LANL	Shaft	−1401	11th UK	<20 Kt
Miners Iron	10-31-80	NTS	DOD	Tunnel	−1279	WE	<20 Kt
A test to evaluate the nuclear hardness of candidate materials for MX							

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
components such as motor cases, ablative nozzle, propellant and external booster parts. The test used 2000 channels of data							
Dauphin	11-14-80	NTS	LLNL	Shaft	−1050	WR	<20 Kt
Test associated with development of a nuclear pumped x-ray laser							
Serpa	12-17-80	NTS	LLNL	Shaft	−1879	12th UK	20-150 Kt
Baseball	01-15-81	NTS	LANL	Shaft	−1850	WR	20-150 Kt
Clairette	02-05-81	NTS	LANL	Shaft	−1161	WR	<20 Kt
Seco	02-25-81	NTS	LLNL	Shaft	− 750	WR	<20 Kt
Vide	04-30-81	NTS	LLNL	Shaft	−1059	WR	<20 Kt
Aligote	05-29-81	NTS	LANL	Shaft	−1050	WR	<20 Kt
Harzer	06-06-81	NTS	LLNL	Shaft	−2089	WR	20-150 Kt
Niza	07-10-81	NTS	LLNL	Shaft	−1118	WR	<20 Kt
Pineau	07-16-81	NTS	LANL	Shaft	− 669	WR	<20 Kt
Havarti	08-05-81	NTS	LLNL	Shaft	− 656	WR	<20 Kt
Islay	08-27-81	NTS	LLNL	Shaft	− 964	WR	<20 Kt
Trebbiano	09-04-81	NTS	LANL	Shaft	−1000	WR	<20 Kt
Cernada	09-24-81	NTS	LANL	Shaft	− 699	WR	<20 Kt
	OPERATION PRAETORIAN (22)						
Paliza	10-01-81	NTS	LANL	Shaft	−1548	WR	20-150 Kt
Tilci	11-11-81	NTS	LLNL	Shaft	−1460	WR	20-150 Kt
Rousanne	11-12-81	NTS	LANL	Shaft	−1699	13th UK	20-150 Kt
Akavi	12-03-81	NTS	LLNL	Shaft	−1620	WR	20-150 Kt
Caboc	12-16-81	NTS		Shaft	−1099	WR	<20 Kt
Jornada	01-28-82	NTS	LANL	Shaft	−2099	WR	20-150 Kt
Molbo	02-12-82	NTS	LLNL	Shaft	−2135	WR	20-150 Kt
Hosta	02-12-82	NTS		Shaft	−2099	WR	20-150 Kt
Tenaja	04-17-82	NTS	LANL	Shaft	−1171	WR	<20 Kt
Gibne	04-25-82	NTS	LLNL	Shaft	−1870	14th UK	20-150 Kt
Kryddost	05-06-82	NTS	LLNL	Shaft	−1099	WR	<20 Kt
Bouschet	05-07-82	NTS	LANL	Shaft	−1850	WR	20-150 Kt
Kesti	06-16-82	NTS	LLNL	Shaft	− 948	WR	<20 Kt
Nebbiolo	06-24-82	NTS	LANL	Shaft	−2099	WR	20-150 Kt
Monterey	07-29-82	NTS	LLNL	Shaft	−1312	WR	20-150 Kt
Atrisco	08-05-82	NTS	LANL	Shaft	−2099	WR	20-150 Kt
Queso	08-11-82	NTS	LLNL	Shaft	− 708	WR	<20 Kt
Cerro	09-02-82	NTS	LANL	Shaft	− 751	WR	<20 Kt
Huron Landing	09-23-82	NTS	DOD	Tunnel		WE	<20 Kt
Simultaneous with Diamond Ace. A horizontal line of sight test on MX components. It was one of the largest, most complex tests DNA ever did, using 3000 channels of data to assess 400 separate experiments							
Diamond Ace	09-23-82	NTS	DOD	Tunnel		WE	<20 Kt
Simultaneous with Huron Landing. The first event in the DISTANT ARBOR series. A joint DNA/DOE test to provide detailed di-							

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
agnostic data of the radiation output ofa low-yield nuclear device							
Frisco	09-23-82	NTS	LLNL	Shaft	−1479	WR	20-150 Kt
Borrego	09-29-82	NTS	LANL	Shaft	−1850	WR	<150 Kt
	OPERATION PHALANX (18)						
Seyval	11-12-82	NTS	LANL	Shaft	−1200	WR	<20 Kt
Manteca	12-10-82	NTS	LLNL	Shaft	−1355	WR	20-150 Kt
Coalora	02-11-83	NTS	LANL	Shaft	− 997	WR	<20 Kt
Cheedam	02-17-83	NTS	LLNL	Shaft	−1125	WR	<20 Kt
Cabra	03-26-83	NTS	LLNL	Shaft	−1778	WR	20-150 Kt
Test associated with development of a nuclear pumped x-ray laser							
Turquoise	04-14-83	NTS	LANL	Shaft	−1748	WR	<150 Kt
Armada	04-22-83	NTS	LLNL	Shaft	− 869	15th UK	<20 Kt
Crowdie	05-05-83	NTS	LLNL	Shaft	−1279	WR	<20 Kt
Mini Jade	05-26-83	NTS	LANL/DOD	Tunnel		WE	<20 Kt
A test to obtain data to predict ground motion and cratering prediction. The test was conducted in a hemispherical cavity having an eleven meter radius							
Fahada	05-26-83	NTS	LANL	Shaft	−1260	WR	<20 Kt
Danablu	06-09-83	NTS	LLNL	Shaft	−1050	WR	<20 Kt
Laban	08-03-83	NTS	LLNL	Shaft	−1069	WR	<20 Kt
Sabado	08-11-83	NTS	LANL	Shaft	−1050	WR	<20 Kt
# (13:59:59 9)	08-27-83	NTS (37 19 115 99)		?	?	?	?
Chancellor	09-01-83	NTS	LANL	Shaft	−2050	WR	20-150 Kt
Tomme/Midnight Zephyr	09-21-83	NTS	LLNL/DOD	Tunnel	−1328	WE	<20 Kt
The second event in the DISTANT ARBOR series. A joint DNA/DOE test to provide data for a low yield test bed							
# (18 24:59 7)	09-21-83	NTS (37 11 116 04)		?	?	?	?
Techado	09-22-83	NTS	LANL	Shaft	−1748	WR	<150 Kt
	OPERATION FUSILEER (16)						
# (15 59:59 2)	12-09-83	NTS (37 02 115 97)		?	?	?	?
Romano	12-16-83	NTS	LANL	Shaft	−1889	WR	20-150 Kt
Test associated with development of a nuclear pumped x-ray laser							
Gorbea	01-31-84	NTS	LLNL	Shaft	?	WR	20-150 Kt
Midas Myth/Milagro	02-15-84	NTS	LANL/DOD	Tunnel	?	WE	<20 Kt
The first test in a series of three to validate hardness specifications for major elements of the triad. This 800 foot line of sight test provided data on the nuclear hardness of strategic reentry systems, specifically the MX's Mark 21. First use of glass strand fiber optics cables,							

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
which provide clearer reception of data and are secure from "tapping," thus improving the level of security							
Tortugas	03-01-84	NTS	LANL	Shaft	–2096	WR	20-150 Kt
Agrini	03-31-84	NTS	LLNL	Shaft	–1050	WR	<20 Kt
Mundo	05-01-84	NTS	LANL	Shaft	–1860	16th UK	20-150 Kt
# (13:49:59 6)	05-02-84	NTS (37 19 116 02)	?		?	?	?
# (15:59:59 3)	05-16-84	NTS (37 09 115 99)	?		?	?	?
Caprock	05-31-84	NTS	LANL	Shaft	–1968	WR	20-150 Kt
Duoro	06-20-84	NTS	LANL	Shaft	–1250	WR	20-150 Kt
# (13:59:59 9)	07-12-84	NTS (37 19 116 01)	?		?	?	?
Kappeli	07-25-84	NTS	LLNL	Shaft	–2099	WR	20-150 Kt
Correo (test of W84 warhead)	08-02-84	NTS	LLNL	Shaft	–1099	SC	<20 Kt
Dolcetto	08-30-84	NTS	LANL	Shaft	–1200	WR	<20 Kt
Breton	09-13-84	NTS	LLNL	Shaft	–1584	WR	20-150 Kt
	OPERATION GRENADIER (16)						
# (18:13:59 3)	10-02-84	NTS (37 08 115 99)	?		?	?	?
Villita	11-20-84	NTS	LANL	Shaft	?	WR	<20 Kt
Egmont	12-09-84	NTS	LLNL	Shaft	–1807	17th UK	20-150 Kt
Tierra (test of B83 bomb)	12-15-84	NTS	LLNL	Shaft	–2099	SC	20-150 Kt
# (16:19:59 7)	12-20-84	NTS (36 97 116 00)	?		?	?	?
Vaughn	03-15-85	NTS	LANL	Shaft	–1401	WR	20-150 Kt
Cottage	03-23-85	NTS	LLNL	Shaft	–1689	WR	20-150 Kt
Test associated with development of a nuclear pumped x-ray laser							
Hermosa	04-02-85	NTS	LANL	Shaft	–2089	WR	20-150 Kt
Misty Rain	04-06-85	NTS	LLNL/DOD	Tunnel	?	WE	<20 Kt
The second in a series to validate hardness specifications. A 900 foot line of sight test in support of the MX system, specifically the Mk21 reentry vehicle. Also included was a satellite vulnerability experiment to test its electronics in a radiation environment. Some X-ray laser lethality testing was also conducted							
Towanda	05-02-85	NTS	LANL	Shaft	–2168	WR	20-150 Kt
Salut	06-12-85	NTS	LLNL	Shaft	?	WR	20-150 Kt
Ville	06-12-85	NTS	LLNL	Shaft	– 961	WR	<20 Kt
Maribo	06-26-85	NTS	LLNL	Shaft	–1250	WR	<20 Kt
Serena	07-25-85	NTS	LLNL	Shaft	–1958	WR	20-150 Kt
Chamita	08-17-85	NTS	LANL	Shaft	–1089	WR	<20 Kt
Ponil	09-27-85	NTS	LANL	Shaft	–1200	WR	<20 Kt
	OPERATION CHARIOTEER (15)						
Mill Yard	10-09-85	NTS	LANL/DOD	Tunnel		WE	<20 Kt
A second cavity experiment, similar to MINI Jade, to obtain data on cratering phenomenology and airburst phenomena. Also addressed issues on							

Event Name (and Comments)	Date (GCT)	Location	Sponsor	Type	Height of Burst (ft)	Purpose	Yield
superhardening silos and the basing of the small ICBM The shot used a very low yield device detonated at ground level in a 22 meter diameter hemispherical cavity							
Diamond Beech	10-09-85	NTS	LLNL/DOD	Tunnel		WE	<20 Kt
Third and final proof test for low yield test bed							
Rocquefort	10-16-85	NTS	LLNL	Shaft		WR	20-150 Kt
Kinibito	12-05-85	NTS	LANL	Shaft		18th UK	20-150 Kt
Goldstone	12-28-85	NTS	LLNL	Shaft		WR	20-150 Kt
Test associated with development of a nuclear pumped X-ray laser							

Footnotes for Table B 1

Source: DOE *Announced United States Nuclear Tests, July 1945 through December 1984* NVO-209 (Rev. 5) Nevada Operations Office, January 1985. Nuclear Explosions 1945-Aug 17 1985, printout, Swedish National Defense Research Institute; U.S. Department of Interior/Geological Survey Preliminary Determination of Epicenters monthly; Ola Dahlman and Hans Israelson *Monitoring Underground Nuclear Explosions* (Amsterdam: Elsevier Scientific Publishing Company, 1977) pp. 383-99; Stockholm International Peace Research Institute Yearbooks 1968-83 through 1985; Defense Nuclear Agency volumes supporting Nuclear Test Personnel Review program: Project Trinity 1945-1946 (DNA 6029F), Operation Crossroads 1946 (DNA 6032F), Operation Sandstone 1948 (DNA 6033F), Operation Ranger 1951 (DNA 6022F), Operation Greenhouse 1951 (DNA 6034F), Operation Buster-Jangle 1951 (DNA 6023F); Shots Able to Easy (DNA 6024F); Shots Sugar and Uncle (DNA 6025F); Operation Tumbler-Snapper 1952 (DNA 6019F); Shots Able Baker Charlie, and Dog (DNA 6020); Shots Easy, Fox, George and How (DNA 6021F); Operation Ivy 1952 (DNA 6036F); Operation Upshot-Knothole 1953 (DNA 6041F); Shots Annie to Ray (DNA 6017F); Shot Badger (DNA 6015F); Shot Simon (DNA 6016F); Shots Encore to Climax (DNA 6018F); Operation Castle 1954 (DNA 6035F); Operation Teapot 1955 (DNA 6009F); Shots Wasp to Hornet (DNA 6010F); Shot Bee (DNA 6011F); Shots Ess through Met and Shot Zucchini (DNA 6013F); Shot Apple 2 (DNA 6012F); Operation Wigwam (DNA 6000F); Operation Redwing 1956 (DNA 6037F); Plumbob Series 1957 (DNA 6005F); Shots Boltzmann to Wilson (DNA 6008F); Shot Priscilla (DNA 6003F); Shot Hood (DNA 6002F); Shots Diablo to Franklin Prime (DNA 6006F); Shot Smoky (DNA 6004F); Shot Galileo (DNA 6001F); Shots Wheeler to Morgan (DNA 6007F); Operation Hardtack I 1958 (DNA 6038F); Operation Hardtack II 1958 (DNA 6026F); Operation Dominic I 1962 (DNA 6040F); Operation Dominic II (DNA 6027F); Safety Experiments November 1955 - March 1958 (DNA 6030F); Projects Gnome and Sedan (DNA 6029F); Operations Nougat and Whetstone (DNA 6320F); Operations Flintlock and Latchkey (DNA 6321F); Operation Castle Report of the Manager Santa Fe Operations Pacific Proving Ground Spring of 1954 Contract No DNA 001-79-C-0455; DNA, *Compilation of Local Fallout Data from Test Detonations 1945-1962 Extracted from DASA 1251*, Volume II - Oceanic U.S. Tests Contract No DNA 001-79-C-0081 1 May 1979; DOD-DOE, *The Effects of Nuclear Weapons* compiled and edited by Samuel Glasstone and Philip J. Dolan Third Edition 1977; Lee Bowen *History of the Air Force Atomic Energy Program Volume IV The Development of Weapons* (Washington D.C.: U.S. Air Force Historical Division History 1956) pp. 235-315; Robert A. Divine, *Blowing on the Wind: The Nuclear Test Ban Debate 1954-1960* (New York: Oxford University Press 1978); Bruce A. Bolt *Nuclear Explosions and Earthquakes: The Parted Veil* (San Francisco: W. H. Freeman and Company 1976)

a The symbol # in lieu of a test name denotes a test not announced by DOE. The parenthesis following # is the time of the shot (GCT). After the NTS site notation in the Location column the latitude (N) and longitude (W) are given in parentheses

b Greenwich Civil Time

c Purposes abbreviated key follows: WR = Weapons Related; WE = Weapons Effects; SE = Safety Experiment; ST = Storage-Transport; VU = Vela Uniform; SC = Stockpile Confidence; nth UK = Joint U.S./UK Test; nth PS = Plowshare

d The nomenclature for test yields varied according to information policy governing specific years. In some cases no yield information has been released; in a few cases the terms "very slight" and "slight" were used without amplification. Except for tests where specific yields or relative specific yields such as "about 2 Kt", "several Mt", "less than 0.1 Kt", et cetera were announced, test yields are given in these terms:
1945 through 1963:
- Low (less than 20 Kt)
- Intermediate (20 to 200 Kt)—all tests except Operation DOMINIC I
- Intermediate (20 to 1000 Kt)—Operation DOMINIC I
- Submegaton (less than one Mt but more than 200 Kt)
- Megaton Range
- Low Megaton (from one to several Mt)

1964 through February 1976:
- Less than 20 Kt
- 20 to 200 Kt
- 200 to 1000 Kt

March 1976:
During a series of high-yield tests conducted during this month two ranges were added and the 200 to 1000 Kt range was dropped
- 200 to 500 Kt
- 500 to 1000 Kt

Since March 1976:
On 31 March 1976 the Soviet Union and the United States agreed to limit the maximum yield of undergroBund tests to 150 Kt. The yield ranges now reported are:
- Less than 20 Kt
- Less than 150 Kt
- 20 to 150 Kt

Figures in parentheses are from Dahlman and Israelson *Monitoring Underground Nuclear Explosions* and may carry a high degree of uncertainty. In cases where precise yields are given by DOE Dahlman and Israelson estimates are excluded

Table B 2

Known U.S. Nuclear Tests by Type

TESTS		
Underground	Shaft[a]	491[b]
	Tunnel[c]	57
	Crater[d]	9
	Unknown	43
	Subtotal	600
Atmospheric	Tower[e]	56
	Airdrop[f]	52
	Barge[g]	36
	Surface[h]	28
	Balloon[i]	25
	Rocket[j]	12
	Artillery[k]	1
	Subtotal	210
Underwater		5
WARFARE		
Airdrop		2
	TOTAL	817

a A nuclear device exploded at the bottom of a drilled or mined vertical hole
b Includes eighteen joint U.S./UK tests
c A nuclear device exploded at the end of a long horizontal drift mined into a mountain or mesa
d A nuclear device placed shallow enough underground to produce a throw-out of earth when exploded
e A nuclear device mounted at the top of a steel or wooden tower and exploded in the atmosphere
f A nuclear device dropped from an aircraft
g A nuclear device exploded from a barge moored in the lagoon at Enewetak or Bikini. This technique, first used in 1954, was to compensate for the lack of land at the Pacific Proving Ground
h A nuclear device placed on or close to the Earth's surface
i A nuclear device suspended from a balloon and exploded in the atmosphere
j A nuclear device launched by rocket and exploded in the atmosphere
k This category is identified by DOE as "airburst," referring to an explosion of a nuclear weapon at such a height that the expanding fireball does not touch the Earth's surface prior to the time the fireball reaches its maximum luminosity. The only airburst event reported by DOE, however, is Event Grable (25 May 1953), an atomic artillery shell fired from a 280mm cannon

Table B 3

Known U.S. Nuclear Tests by Location

Pacific	4	
Johnston Island Area[a]	12	
Enewetak[b]	43	
Bikini[c]	23	
Christmas Island Area[d]	24	
	106	Total Pacific
Nevada Test Site (underground)	589	
Nevada Test Site (atmospheric)	100	
	689	Total Nevada Test Site
Alamogordo, New Mexico	1	
Hiroshima, Japan	1	
Nagasaki, Japan	1	
Carlsbad, New Mexico	1	
Hattiesburg, Mississippi	2	
Grand Valley, Colorado	1	
Rifle, Colorado	1	
Farmington, New Mexico	1	
Central Nevada	1	
Fallon, Nevada	1	
Bombing Range, Nevada	5	
Amchitka, Alaska	3	
	19	Total
South Atlantic	3	
	817	GRAND TOTAL

a Johnston Island, a possession of the United States since the acquisition of Hawaii in the nineteenth century, is about 700 nm west-southwest of Hawaii
b Enewetak, part of the Marshall Islands, is approximately 2380 nm southwest of Honolulu. It encloses a lagoon 23 miles in diameter and has a total land area of 2.75 square miles
c Bikini is 189 nm east of Enewetak. Its islands consist of about 2.7 square miles of surface area and encircles a lagoon that is 25 miles long and 15 miles wide, with a maximum depth of about 200 feet
d Christmas Island is an atoll lying 2 degrees north of the equator, approximately 1200 nm south and slightly east of Hawaii. A British possession, it was used to test UK nuclear devices in 1957-58

Table B 4

Known U.S. Nuclear Tests by Purpose

Warfare	2	
Weapons Related[a]	613	
Weapons Effects	88	
Safety Experiment[b]	33	
Plowshare[c]	27	
Vela Uniform[d]	7	
Storage-Transportation[e]	4	
Unknown	43	
	817	TOTAL

a Includes eighteen joint U.S./UK tests
b An experiment designed to confirm a nuclear explosion will not occur in case of an accidental detonation of the explosive associated with the device
c Application of nuclear explosives to develop peaceful uses for atomic energy between 1961-1973
d Vela tests are nuclear explosions designed to provide information so as to improve the capability of detecting, identifying, and locating underground nuclear explosions
e Detonation of combinations of high explosives and nuclear materials designed to study distribution of nuclear materials during accidents in several transportation and storage configurations

Table B 5
Known U.S. Nuclear Tests by Year with Estimated Yields

Year	Number[a]	Cumulative Total Yield (Kt)[b]		Cumulative Yield (Kt)
1945	3	3	55	55
1946	2	5	46	101
1947	0	5	0	101
1948	3	8	104	205
1949	0	8	0	205
1950	0	8	0	205
1951	16	24	500	705
1952	10	34	11004	11709
1953	11	45	252	11961
1954	6	51	48200	60161
1955	18	69	197	60358
1956	18	87	17000	77358
1957	32	119	346	77704
1958	77	196	35500	113204
1959	0	196	0	113204
1960	0	196	0	113204
1961	10	206	56	113260
1962	98(2)	304	24102	137362
1963	43[c]	347	615	137977
1964	30(1)	377	999	138976
1965	30(1)	407	576	139552
1966	40	447	2189	141741
1967	29	476	1245	142986
1968	39	515	4736	147722
1969	29	544	2836	150558
1970	33	577	3020	153578
1971	15	592	4800	158378
1972	15	607	274	158652
1973	12	619	960	159612
1974	13(1)	632	744	160356
1975	17	649	4012	164368
1976	16(1)	665	4484	168852
1977	12	677	424	169276
1978	18(2)	695	542	169818
1979	16(1)	711	492	170310
1980	17(3)	728	410	170720
1981	17(1)	745	366	171086
1982	19(1)	764	568	171654
1983	18(1)	782	280	171934
1984	19(2)	801	528	172462
1985	16(1)	817	492	172954

a Includes eighteen joint U.S./UK tests and Hiroshima and Nagasaki. The number of joint U.S./UK tests in each year are given in parentheses.

b The nomenclature for test yields varied according to information policy governing specific years. In forty-six cases DOE provided no yield information. In other cases the exact yield or a yield range was given. In the latter case three formats have been used below. The yields following the "=" signs are the authors estimates of the average yield in each range, which were used to compute the total annual and cumulative yields.

1945 through 1963:
- Low (less than 20 Kt) = 8 Kt
- Intermediate (20 to 200 Kt)—all tests except Operation Dominic I = 50 Kt
- Intermediate (20 to 1000 Kt)—Operation Dominic I = 200 Kt
- Submegaton (less than one Mt, but more than 200 Kt) = 300 Kt
- Megaton Range = 5.0 Mt
- Low Megaton (from one to several Mt) = 1.4 Mt

1964 through February 1976:
- Less than 20 Kt = 6 Kt
- 20 to 200 Kt = 50 Kt
- 200 to 1000 Kt = 300 Kt

During a series of high-yield tests conducted during March 1976, two ranges were added, and the 200 to 1000 Kt range was dropped:
- 200 to 500 Kt = 300 Kt
- 500 to 1000 Kt = 750 Kt

Since March 1976:

On 31 March 1976, the Soviet Union and the United States agreed to limit the maximum yield of underground tests to 150 Kt. The yield ranges now reported are:
- Less than 20 Kt = 6 Kt
- 20 to 150 Kt = 50 Kt
- Less than 150 Kt = 20 Kt

The forty-three tests announced by the National Defense Research Institute but not by DOE are assumed to be less than 20 Kt (averaging 6 Kt).

Announced tests with no yield data in 1955 and 1958 were calculated from yield data in tables provided by the AEC in a Note to Editors and Correspondents which were provided to the JCAE on 5 May 1959.

c Number pre-treaty 333, post-treaty 484.