

# **OVERVIEW OF ROCKY FLATS OPERATIONS**

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**PREFACE**

This report provides an overview of the operations at Rocky Flats, how it fits into the Department of Energy's nuclear weapons complex, and some of the issues surrounding the Rocky Flats litigation, Cook, et al., v. Rockwell International Corp., et al. (No. 90-K-181 (D. Colo.) The introduction gives a very brief overview. This is followed by various sections where some of these issues are developed in more detail. Some of the issues are enumerated in greater detail in reports of other experts and in documents cited herein. This report represents my own observations and convictions and is not a summary of the work of other experts in the case.

## Introduction

Rocky Flats Plant is one of several large industrial plants that was used in the manufacture of nuclear weapons. The plant is located on a 6,551 acre site (11 square miles) between Boulder and Golden, Colorado, about 16 miles northwest of Denver, [Rockwell, RFP Site Environmental Report for 1988, p. 1].<sup>1</sup> Major plant structures, including more than 100 buildings, are located within a 384 acre security-fenced area, which is surrounded by a “buffer zone” [Ibid.]. Several creeks, including North and South Walnut Creek and Woman Creek, flow generally west to east through the site on their way to communities downstream [CERE, p. 5-22].

Rocky Flats made components for nuclear weapons out of several toxic materials. Typically, the components were made out of either plutonium, which is very toxic, uranium, which is less toxic, or a composite of these two radioactive materials. The plant contained, shipped and received tons of these materials annually. Americium-241 and thorium-232 were also handled in at least kilogram quantities, and curium-244, hydrogen-3 (tritium), neptunium-237, and thorium-228 were handled in less than kilogram quantities [ChemRisk, Task Report 1, 1991, p. 15]. Many of the components also contained beryllium, which while not radioactive, is also very toxic. In addition, there were many other hazardous materials handled at the plant, including large quantities of volatile organic cleaning solvents, some of which are known carcinogens [ChemRisk, Task 1 Report, March 1991; ChemRisk, Task 2 Report, June 1991]. ChemRisk conducted a screening process of some 8,000 chemical and product names used at Rocky Flats and identified 20 chemicals plus pesticides/herbicides that could have exposed off-site populations to health hazards during the operating history of the plant [ChemRisk, Task 2 Report, June 1991, p. 73 and Table 3-17].

All nuclear weapons contain some type of fissile material, an essential ingredient of the warhead, because it can sustain the nuclear chain reaction, which releases explosive energy. The primary types of fissile material used in U.S. nuclear weapons are plutonium and highly-enriched uranium. Rocky Flats manufactured weapon components made of these materials. Because plutonium and highly-enriched uranium are fissile, if too much of these materials are brought together in one location, they can undergo a spontaneous nuclear chain reaction—what is called a criticality event. Although the energy released is nothing akin to that released in a military nuclear weapon, it nevertheless is likely to be sufficient to kill people nearby, and in some circumstances it can release radioactivity to the environment. Therefore, these materials must be handled with special care to prevent the inadvertent assembly of a critical mass of fissile material. In some chemical and physical forms plutonium is pyrophoric, meaning it can catch fire spontaneously, adding to its danger.

Because plutonium and highly-enriched uranium are the essential ingredients of nuclear weapons and because they are very difficult and costly to produce, it is essential that they be well

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<sup>1</sup> In 1972 the plant consisted of about 2,520 acres of fenced property [Boss, 1972].

protected to prevent their theft and unauthorized use. It also is essential that all of these materials be carefully accounted for, in order to determine whether the physical protection systems that are used to prevent the diversion of these materials are adequate.

In making weapon components, Rocky Flats generated large quantities of plutonium residues and plutonium contaminated waste. The terms “residue,” “scrap,” and “waste” are sometimes used interchangeably, but to be more precise the term “residue” is often reserved to describe low-grade scrap materials where valuable constituents, such as plutonium, are judged to be feasibly and economically recoverable, as opposed to “waste” materials where recovery is not considered to be cost effective. In other words, plutonium residues are meant to be recycled, and plutonium wastes are meant to be discarded. This distinction is clouded by the fact that most of what used to be considered a plutonium residue is now considered to be a waste.

Rocky Flats was a government-owned contractor-operated (GOCO) plant. Government oversight was provided by the U.S. Department of Energy (DOE), from 1976 to the present, and its predecessor agencies, the Atomic Energy Commission (AEC) from 1947 to 1974, and the Energy Research and Development Administration (ERDA) from 1974 to 1976. A series of major defense contractors actually operated Rocky Flats for the government. The Dow Chemical Company ran the Rocky Flats Plant from the beginning of operations in 1952 until the end of FY 1975 (June 30, 1975). Rockwell International took over on July 1, 1975 and ran the plant until December 31, 1989, a short time after plutonium production operations had been shut down. Since January 1, 1990 the clean-up of the Rocky Flats Plant has been the responsibility of EG&G from 1990 to 1995, and then Kaiser-Hill from 1995 to the present. [For further discussion see Cochran, et al., *Nuclear Weapons Databook*, Volume 2-3, 1987].

### **Nuclear Weapon Design Basics**

It is helpful, though not essential, to understand a few basics about how nuclear weapons are designed in order to appreciate the Rocky Flats Plant’s role in the warhead manufacturing process. The following material is from the public record, is well known and to my knowledge is not in dispute.

All of the stockpiled nuclear weapons in the U.S. arsenal were of three basic types: a) pure fission weapons, b) boosted fission weapons, or c) thermonuclear weapons. The early pure fission weapons were all bombs, and they were called “atomic bombs.” Later nuclear weapons were designed for other means of delivery as well. For example, they were placed on missiles, incorporated into artillery shells, and used as land mines. The terms “warhead”, or “nuclear warhead” are more precise generic terms that distinguish the “warhead” from the “delivery vehicle.” A nuclear warhead contains a “physics package,” which is the nuclear portion, and a variety of other components. With respect to the latter, the warhead might contain, for example, one or more of the following components: an arming mechanism, altimeter, battery, parachute, and warhead (or bomb) casing. Rocky Flats primary mission was the manufacture of certain components within the “physics package.” The other components were manufactured elsewhere.

[For further discussion of weapon design basics see Cochran, et al., *Nuclear Weapons Databook*, Volume 1, Chapter 2, 1984; Cochran and Paine, “The Amount of Plutonium and Highly-Enriched Uranium Needed for Pure Fission Nuclear Weapons,” 1995; and Cochran and Paine, “The Role of Hydronuclear Tests,” 1995].

### ***Pure Fission Weapons***

Two basic fission weapon design approaches that are used to achieve a supercritical mass of fissile material are the implosion technique and the gun assembly technique. The less efficient gun assembly technique—used in the bomb, called *Little Boy*, dropped on Hiroshima— involves the assembly without compression of two subcritical masses into a single supercritical mass capable of sustaining a rapid nuclear chain reaction. This technique almost of necessity requires the use of uranium, highly enriched in the isotope uranium-235, for the fissile material. During the Manhattan Project, highly-enriched uranium (HEU) was given the code-name, “oralloy.” HEU and “oralloy” were terms subsequently used interchangeably. There were a few atomic bombs of the gun-assembly type built prior to the operation of Rocky Flats, and a few atomic artillery shells of this design built subsequently. Most, if not all of these gun-assembly components were manufactured elsewhere. Some may have been manufactured at Rocky Flats in the early years, but since these are made of uranium, and since our primary interest is in the plutonium activities, we can move directly to a discussion of the implosion type weapons.

In the more efficient implosion technique, a peripheral charge of chemical high explosive (HE) is detonated in a manner designed to compress (i.e., implode) a subcritical mass into a supercritical configuration, i.e., a configuration that can sustain a rapidly multiplying nuclear chain reaction. In an implosion type weapon the fissile material is typically either plutonium, highly-enriched uranium, or a composite of the two materials. In the most straightforward design the core of fissile material is a solid sphere or cylinder, surrounded by a reflector/tamper, which in turn is surrounded by the HE. The neutron reflector serves to reflect escaping neutrons back into the fissile material during the nuclear chain reaction. The tamper is meant to hold the fissile material together in a supercritical configuration for a longer period of time than it would be held together if there were no tamper. Early atomic bombs used thick uranium tampers, that also served as a reflector. Later designs replaced the thick uranium tamper with a thin beryllium reflector.

A sphere has the smallest surface-to-volume ratio, and therefore the smallest neutron loss and smallest critical mass. Other geometries are used where the diameter of the device must be kept small—to fit, for example in an artillery shell. To obtain a given yield considerably less fissile material is needed for an implosion weapon than for a gun-assembly weapon.

For spherical geometries, the fissile and reflector/tamper components are typically fabricated as hemispherical shapes that are then nested and bonded together. The fissile material and reflector/tamper components may be plated, or sealed within a thin metal (e.g., stainless steel) shell to prevent corrosion. The entire package of materials within the HE—the fissile

material, tamper/reflector and stainless steel shell--is called the "pit" of the warhead, analogous to the pit of a peach.

The first implosion type fission weapons used a plutonium core surrounded by a thick uranium tamper. The first device, tested at *Trinity*, and the bomb, called *Fat Man*, dropped on Nagasaki were implosion designs, each with a spherical core of 6.2 kilograms (kg) (13.7 pounds) of plutonium.<sup>2</sup>

Implosion type weapons were also made with highly-enriched uranium (HEU) cores. Because HEU has a larger critical mass, more HEU was required than plutonium in the early "solid" core designs. Nevertheless, HEU was cheaper to make and more plentiful, so the U.S. stockpiled HEU as well as plutonium cores. In 1955, the Dow Chemical Company was studying the criticality hazard associated with the storage of HEU or alloy spheres in arrays [Schuske, 1955]. Measurements and/or calculations were taken using 25, 30 and 31.5 kg or alloy spheres, therefore, it is reasonable to assume that the masses of some or alloy cores manufactured at Rocky Flats were in this range, and 20 to 30 kg or alloy cores were stockpiled. In 1948 the first nuclear weapon test was conducted of a device with a "composite core," wherein a small inner plutonium component (probably on the order of two kg), was surrounded by a thicker or alloy shell. These composite cores made more efficient use of the available plutonium and HEU, and began to replace the all plutonium and all HEU cores made previously. All of these plutonium, HEU and composite cores were often called "capsules" and they could be stored separately from the rest of the nuclear weapon. In the 1950s, the earlier "solid," or "solid-pack" fissile core with its thick (typically 0.5 to 2.5 inch) natural uranium tamper gave way to a more efficient hollow core design—a thin shell of fissile material (usually plutonium) surrounded by a thin beryllium reflector, all sealed within a stainless steel outer shell. Full scale production of the hollow pits began at Rocky Flats in about 1958 [See Young, 1977, p. 33]. The amount of plutonium used in the hollow core pit, was larger than the amount typically used in the composite core, although still much less than that used in the Trinity device.

### ***Boosted fission weapons***

By incorporating thermonuclear fuel (also called fusion fuel)--typically a mixture of deuterium and tritium gas (or lithium hydrides)--directly into (or proximate to) the core of fissile material the efficiency of the fission bomb can be greatly increased; that is, one can obtain a much higher yield from a given quantity of fissile materials, or alternatively, the same yield from a much smaller quantity. In U.S. weapons using boosted fission cores the fusion material, a mixture of a few grams of deuterium and tritium gas, is normally stored in a gas reservoir external to the pit. Shortly before the warhead is timed to explode, the gas mixture is supplied to the hollow pit through a connecting tube by explosively breaking the connecting seal. Rocky

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<sup>2</sup> For those who have not quite mastered the metric system and are use to thinking in terms of pounds, one kilogram equals 2.2046226 pounds. For our purposes, to approximate the number of pounds, just double the number of kilograms.



Flats manufactured the hollow boosted fission pits. The gas reservoirs were also fabricated at Rocky Flats, but were filled and installed at other DOE sites.

### ***Thermonuclear weapons***

Thermonuclear, or fusion, warheads, are nuclear warheads that incorporate fusion materials into the design. Strictly speaking, a boosted fission warhead is a thermonuclear warhead. However, when speaking of thermonuclear weapons, we are usually referring to a staged device, where the radiation from a fission explosive is contained and used to transfer energy to compress and ignite a separate component containing the fusion fuel. The fission explosive device is called the primary, and in a two stage device the fusion component is called the secondary. The primary, which may be a pure fission device or a boosted fission device, is also sometimes called a “trigger,” in the sense that it “triggers” the thermonuclear explosion. This is why it is often said that Rocky Flats manufactures the nuclear “triggers,” referring to the core of the primary. The cores of the primaries of modern two-stage thermonuclear warheads are all boosted. The average plutonium content of a modern stockpiled warhead averages about 3 kg. The secondary usually contains both thermonuclear materials and fissile material, primarily uranium. The secondary does not have to contain both; it could be a pure fission component or a pure fusion component. In addition to the pits, Rocky Flats manufactured some of the uranium components in the secondaries until this activity was transferred to the Y-12 Plant at Oak Ridge.

This brief introduction provides sufficient information to better understand the mission and activities at Rocky Flats.

### **History of Rocky Flats Operations**

The two nuclear weapons dropped on Japan were designed, developed and fabricated at Los Alamos during the Manhattan Project. Stockpiled nuclear weapons continued to be manufactured at Los Alamos, and until 1949 this was the principal manufacturing site. In subsequent years Los Alamos National Laboratory (LANL) maintained a capability to manufacture nuclear warhead devices, and designed and assembled warheads for testing in at the Nevada Test Site. Beginning in 1949, plutonium cores were manufactured at the Plutonium Process and Storage Facility (Z Plant) on the Hanford Reservation in the state of Washington. Construction of Rocky Flats began in 1951, and production of nuclear weapons components there commenced in 1952. The Z Plant stopped manufacturing plutonium weapon components in December 1965, but continued to process plutonium into metal and recover plutonium from scrap and residues [Teal, 199, p. 1-120]. The Rocky Flats Plant operated in a production mode until 1989. Since the halt of production operations, Rocky Flats production activities have been shifted to LANL, albeit, on a much reduced scale.

The principal activity at Rocky Flats from 1952 to 1989 was the manufacture of nuclear weapon pits. In the early days these were “solid-pack” plutonium and HEU cores, followed by

composite cores, followed by hollow cores for boosted fission weapons and two-stage thermonuclear weapons. As noted earlier Rocky Flats also manufactured uranium components for thermonuclear secondaries and tritium reservoirs.

Rocky Flats received its plutonium raw materials from three primary sources, the Hanford Reservation (beginning in April 1953), Savannah River Site (beginning in 1955), and the return of cores and pits recovered from obsolete warheads disassembled elsewhere, primarily at Pantex in Amarillo, Texas [Dow, "A Report on Radiation Problems," 1968, pp. 23 and 25]. Rocky Flats processed by chemical and other means, the virgin plutonium from Hanford and Savannah as necessary to convert it to a relatively pure metal alloy. The plutonium recovered from obsolete pits was also processed to remove americium-241, a radioactive decay product of plutonium-241. The plutonium alloy was molded into the required shapes, and then machined to its final dimensions. The plutonium, uranium and beryllium components were then assembled and in the case of the newer pits, sealed within an airtight shell of stainless steel to which was attached a tritium delivery tube. The final assembled pit was then sent to another plant for final assembly of the weapon. In recent years final assembly took place at the Pantex Plant.

In sum, Rocky Flats was primarily in the business of manufacturing nuclear weapon "pits" for implosion type fission weapons and thermonuclear primaries. The fissile components of gun assembly type fission weapons and the secondaries of thermonuclear weapons were mostly fabricated elsewhere. The pits manufactured at Rocky Flats, and the other components manufactured at other Department of Energy facilities, were sent elsewhere, e.g., Pantex in Amarillo, Texas, for final assembly.

### *Plutonium Operations*

A complete plutonium weapons fabrication and processing facility was maintained at Rocky Flats since the first plutonium was received. Plutonium feed came from three main sources: the Hanford Reservation, the Savannah River Site, and recovery of plutonium components from retired weapons. Plutonium parts fabricated elsewhere were first received at Rocky Flats in March 1952, and assembled into weapon components. The first plutonium feed, as plutonium nitrate solution, arrived at Rocky Flats from Hanford in April 1953, and attempts at processing in Building 771 were started in May 1953 [Dow, "A Report on Radiation Problems," 1968, p. 23]. Early in 1955 the Savannah River Plant started shipping plutonium metal as buttons to Rocky Flats. During the period 1953 to 1955, the plutonium feed received as plutonium nitrate solution arrived in containers of about 1 liter in size [Young, 1977, p. 34; Zodtner and Rogers, 1964, p. 5].

In the early period all plutonium production operations through finished plutonium components were performed in one building, Building 71 (now called Building 771) [Dow, "A Report on Radiation Problems," 1968, p. 8; ChemRisk, Task 3&4 Final Draft Report, 1992, p. 60]. Plutonium in nitrate form was chemically processed into metal buttons which were introduced directly into the casting process. The plutonium in the form of cast shapes were then machined into weapon component parts. The assembly of plutonium components and non-

plutonium parts was done in Building 991 [ChemRisk, Task 3&4 Final Draft Report, 1992, p. 60].

It was also necessary to recycle plutonium contaminated scrap and residues to recover and reuse the plutonium. Sources of casting feed, therefore, included not only plutonium buttons produced in Chemical Operations (Building 771), but also rejected parts, feed ingots, rolling mill scrap and briquettes from machine turnings [Young, 1977, pp. 34-35]. In addition, obsolete weapons from storage sites were disassembled and the plutonium component parts were recycled.

Chemical Operations, the plutonium recovery operations in Building 771, often described in terms of two functional divisions—"fast" and "slow" recovery operations, also called "Fast Recycle" and "Slow Recycle." The fast recovery operation processed relatively pure metal, oxide and "skull" materials through a series of processes, including dissolution, evaporation, participation, calcination, hydrofluorination and reduction to pure recycle metal buttons. It processed plutonium nitrate solution, turning the liquid to a solid (powder) and then to a pure metal. The metal buttons were sent to the foundry for casting or to storage [ChemRisk, Task 3&4 Final Draft Report, 1992, p. 60].

The slow recovery operation, also in Building 771, received materials with greater concentrations of impurities and therefore required more pre-processing before entering the fast side process for conversion to metal [ChemRisk, Task 3&4 Final Draft Report, 1992, p. 60]. The primary goal of slow recovery operations was to reduce the amount of plutonium in numerous categories of residues deemed suitable for plutonium recovery, including scrap metal, filter sludge, graphite molds, graphite scarfings, sand, slag, crucibles, insulation, analytical laboratory residues, air filters, incinerator ash, dry box gloves and other combustibles and washables. In the early period the americium was removed by the slow recovery process. The slow recycle facility included incineration, leaching, dissolution, concentration, purification, ion exchange processes, and chloride salt processing [Young, 1977, pp. 35-36].

With age plutonium—particularly plutonium in the older retired weapons—builds up a small concentration of americium-241 (Am-241) as a result of the radioactive decay of plutonium-241 (Pu-241). Americium-241 reduces the effectiveness of the plutonium in weapons and is a nasty contaminant that contributed significantly to the radiation exposure of the Rocky flats workers.<sup>3</sup> When the concentration of Am-241 becomes too high it is desirable to remove it before refabricating the plutonium into new weapon parts. In 1957 an americium line was installed in Building 771. The processes used for extraction, purification, and recovery of americium evolved over the years. The recovered americium-241 was shipped to Oak Ridge [CERE, 1995].

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<sup>3</sup> "Our major radiation exposure control problems at Rocky Flats in 1958 and 1959 was caused by a sudden influx of 'site return items' and subsequent recovery of americium. The effect of this program was with us before we in Health Physics were aware of what was going on. Once the problem was defined it took about 1½ years to shield the area adequately;" "Summary of Radiation problems at Rocky Flats," Rocky Flats, ca. November 1967.

In 1968 a molten salt extraction process was introduced so that essentially pure plutonium metal, such as metal from site returns, could be processed. The output from this process, in the form of molten salt buttons, served as recycle feed into the casting operation at the foundry in Building 777 [ChemRisk, Task 3&4 Final Draft Report, 1992, pp. 69-71].

In the earlier period of Rocky Flats operations cast shapes for “capsule” type weapons were made in the foundry and then transferred to the machine shop for machining. In 1956 fabrication techniques for thin-shell hollow pits were being developed in the Building 771 Fabrication and Inspection area [Dow, “A Report on Radiation Problems,” 1968, p. 25]. During the first half of 1957 efforts to develop fabrication and assembly techniques for the thin-shell pits continued in Building 771 [Ibid.]. It was recognized that the amount of plutonium scrap resulting from the fabrication processes, which would require chemical processing, would be significantly greater than the scrap from capsule type weapons that had been in production since 1953 [Ibid., pp. 25-26]. This scrap consisted of more metal lathe turnings, coolant oils, graphite from casting operations, more combustibles, more drybox gloves, and other miscellaneous residues. [Ibid., p. 26]. This change in weapon design, and the phase out of plutonium fabrication operation at the Hanford Z Plant, resulted in three problems: the necessity to increase the capacity of the chemistry facility, higher radiation exposure to the hands of workers, and a growing backlog of plutonium contaminated residues [Ibid.]. Large quantities of plutonium-contaminated oils and solvents accumulated because the contractor did not provide the needed processes or disposal options when the plant shifted to the production of new thin-shell hollow pits [See Meyer, et al., RAC, February 1996, p. 1]. The residues were stored for future processing due to the lack of processing capacity, beginning in about 1958, much of it outside in 30 and 55 gallon drums at the 903 Pad [Ibid., p. 3]. These drums were the origin of most of the plutonium that was released to the environment from Rocky Flats.

Since the installation of a rolling mill in October 1958 for the production of hollow pits, ingots were cast for rolling and forming. Pressed shapes were transferred to the machine shop where they were machined to specified dimensions for assembly and shipment off-site [Young, 1977, p. 35]. Some weapon components, including pit components, must be shaped to an accuracy of a few millionths of an inch [DOE, “Closing the Circle on the Splitting of the Atom,” 1995, p. 19.]. This can result in increased scrap and residue production.

Plutonium foundry, fabrication and assembly operations began in newly constructed Buildings 776 and 777 during the summer of 1957. A rolling and forming operation was started in Building 776 during FY 1958 for the production of hollow pits. A new modular plutonium fabrication facility, Building 707, was placed in operation in 1971. The new facility included foundry, rolling, forming, machining, assembly, inspection and “autoclave” operations for the production of bonded weapons [Young, 1977, p. 33].

In 1968, it was decided to replace Building 771 recovery operations. Groundbreaking took place in 1973 for what was to become Building 371. The new facility was plagued with problems from the onset of construction, and delays prevented “cold start-up” before 1981.

Design flaws finally resulted in Building 371 chemical processing being shut down in 1985 before ever achieving full-scale operation. [ChemRisk, Task 3&4 Final Draft Report, 1992, p. 60].

A more extensive treatment of plutonium operations at Rocky Flats can be found in ChemRisk, "Operations History," Task 3&4 Final Draft Report, 1992, pp. 59-96].

### *Enriched Uranium and Beryllium Operations*

Here, I will not go into detail regarding enriched-uranium and beryllium operations, since my focus is on plutonium. The uranium and beryllium operations are described more extensively in ChemRisk, "Operations History," Task 3&4 Final Draft Report, 1992, pp. 74-77. Here, suffice it to say, enriched uranium was first received at Rocky Flats in March 1952 [Young, 1976, p. 73]. Fabrication of enriched-uranium parts began a year later and was discontinued in 1965 [Ibid.; and Rockwell, "Classification of Rocky Flats ID Data," 1979, p. 9]. During 1962, enriched uranium operations (the oralloy line) was moved to the Oak Ridge Y-12 Plant [ChemRisk, Task 5 Draft Report, 1992, p. 147]. Enriched uranium (oralloy) component operations left the plant in 1964, along with the uranium recovery operations [ChemRisk, "Operations History," Task 3&4 Final Draft Report, 1992, p. 77]. Beryllium operations became part of the primary production line in 1958 [Ibid., p. 75].

### **Radioactivity**

Before discussing the toxicity of plutonium quantitatively, it may be useful to review a few basics about radioactivity and the assessment of health effects.

### *Terminology*

"**Radiation**," refers to energetic x-rays, gamma-rays, alpha particles, beta particles and neutrons. These different forms of radiation are emitted when radionuclides undergo radioactive decay. They are referred to as "**ionizing radiation**" because as they pass through, or are absorbed within matter, including human tissue, they excite or ionize atoms and molecules. This in turn can cause chemical and physical changes in the matter. When this radiation is absorbed in the human body these changes can result in deleterious health effects, including cancer and genetic effects.

Chemical compounds are made up of **elements**, of which there are just over 100, e.g., hydrogen, helium, oxygen, lead, zinc, uranium, plutonium. A hydrogen atom consists of a nucleus containing a single proton and an electron orbiting around it. The nucleus of a helium atom has two protons in the nucleus and two orbiting electrons. Heavier elements have an even greater number of protons. Elements are distinguished by the number of protons in the nucleus of the atom. Uranium has 92 protons in the nucleus and plutonium has 94. With one exception the nuclei of atoms also contain neutrons, which are similar to protons but without an electrical

charge. Atoms of the same element must have the same number of protons, but can have a different number of neutrons. We distinguish them by calling them “**isotopes**” of the element. Thus, an element can have several isotopes. We call the collection of isotopes of the various elements “**nuclides**.” We distinguish and identify the nuclides by the name of the element and a number that identifies the total number of protons and neutrons in the nucleus. For example, uranium-235 (abbreviated “U-235”) has 92 protons and 143 neutrons ( $92+143=235$ ) in the nucleus, and plutonium-239 (abbreviated Pu-239”) has 94 protons and 145 neutrons ( $94+145=239$ ). For our purpose we can use the terms “nuclides” and “isotopes” interchangeably.

Many isotopes (or nuclides) are stable, meaning they stick around essentially forever. The element lead, for example, has four stable isotopes: lead-204, lead-206, lead-207 and lead-208. Most isotopes (or nuclides) are not stable, but undergo spontaneous emissions of radiation by a process that we call “**radioactive decay**.” We call these “**radioisotopes**” (shorthand for “radioactive isotope”), or “**radionuclides**” (shorthand for “radioactive nuclide”). As before, for our purposes the terms “radionuclide” and “radioisotopes” are interchangeable.

The process of radioactive decay, or the property of the radionuclides (or radioisotopes) to emit radiation, is called “**radioactivity**.” Natural radioactivity has been known since 1896 when Becquerel discovered that uranium compounds emitted a penetrating radiation similar to x-rays, which we now call gamma-rays. Some radionuclides emit particles when they undergo radioactive decay. These include alpha particles, beta particles and neutrons. **Alpha particles** are two protons and two neutrons bound together, which makes them the same as the nucleus of a helium atom. **Beta particles** are electrons emitted from the nucleus.

When a radionuclide emits an x-ray or a gamma-ray, the number of protons and neutrons in the nucleus remains unchanged, and therefore it is left as the same nuclide but in a different “energy state.” But if a radionuclide emits an alpha particle, beta particle, or neutron, it changes into a new isotope that may be stable or itself radioactive. The original nuclide literally “disintegrates” or “decays.” As noted above we call the process “radioactive decay,” and we refer to the new nuclide as a “radioactive decay product,” or “daughter product.” Thus, “radioisotopes” emit “radiation” in a process we call “radioactivity” or “radioactive decay.”

We also refer to the amount of “radioactivity,” meaning the number of spontaneous disintegrations per unit time. There are two commonly used units of measure for this. The older unit is called the “**curie**” (abbreviated “Ci”), defined as 37,000,000,000 disintegrations per second. This unit was chosen in 1930 because it is the number of disintegrations per second taking place in one gram of naturally occurring radium. A newer unit, called the “**becquerel**” (abbreviated “Bq”), is defined as one disintegration per second. Thus,  $1 \text{ Ci} = 3.7 \times 10^{10} \text{ Bq}$ , where  $3.7 \times 10^{10}$  is a short hand way of writing 37,000,000,000.

### *Specific Activity*

The “**specific activity**” of a substance is the amount of activity per unit mass. The specific activities (measured in curies per gram), and the principal type of radiation emitted in the radioactive decay process, of some of the isotopes of interest to us, are:

<u>Nuclide</u>	<u>Specific activity (Ci/g)</u>	<u>Primary Decay Mode</u>
uranium-235	$1.922 \times 10^{-6}$	alpha
uranium-238	$3.03 \times 10^{-7}$	alpha
plutonium-238	17.119	alpha
plutonium-239	0.06204	alpha
plutonium-240	0.22696	alpha
plutonium-241	103.0	beta
plutonium-242	0.003926	alpha
americium-241	3.428	alpha

### *Radioactive Decay*

Each radionuclide decays (or disintegrates) at its own characteristic rate. It is convenient to measure the rate of radioactive disintegration of a particular radionuclide in terms of its “**half-life**,” defined as the time it takes for the concentration to be reduced to one-half of the amount that was there at time zero, that is, at the time when one starts counting. For example, the radioactive half-life of plutonium-239 is 24,110 years. This means that regardless of when you start your clock, it will take 24,110 years before there is only one-half of the plutonium-239 that was there when you started is left. Stated another way, the amount of plutonium-239 is reduced

by another factor of 2 every 24,110 years. The half-lives of some of the other radionuclides of interest to us are:

<u>Nuclide</u>	<u>Half-life</u>
uranium-235	703,700,000 years
uranium-238	4,468,000,000 years
plutonium-238	87.74 years
plutonium-239	24,110 years
plutonium-240	6,563 years
plutonium-241	14.4 years
plutonium-242	376,300 years
americium-241	432.7 years

Because the number of disintegrations of a particular isotope occurring per unit time is dependent on the amount present, it turns out that so long as the nuclide is not being replenished, then

at the end of 2 half-lives the concentration is reduced by a factor of  $2 \times 2 = 4$

at the end of 3 half-lives the concentration is reduced by a factor of  $2 \times 2 \times 2 = 8$

at the end of 4 half-lives the concentration is reduced by a factor of  $2 \times 2 \times 2 \times 2 = 16$

...

...

...

at the end of 10 half-lives the concentration is reduced by a factor of  $2^{10} = 1024$ .

and so forth. Therefore, if plutonium-239 is deposited in the environment, it will take about  $(24,000 \times 10 =)$  240,000 years—essentially forever in terms of human life—before the total activity is reduced by a factor of 1000 via radioactive decay.

Students of calculus have a shorthand way of expressing the same thing:

$$I = I_0 e^{-\lambda t},$$

where  $I$  is the concentration at time  $t$ ,  $I_0$  is the concentration at time  $t = 0$ ,  $e \approx 2.71828$  (called the Napierian constant), and  $\lambda = \ln(2)/T_{1/2}$ , where  $T_{1/2}$  is the half-life, and  $\ln(2) \approx 0.69315$ . Since the times of interest are rarely exact multiples of one half-life, the calculations are performed using this more complicated formula. Otherwise, the results are the same.

### *Assessing Health Effects*

In assessing the health effects due to exposure to radioactive materials, it is sometimes convenient to divide the calculations into several logical components. The first of these, called the “**source term**,” identifies the types and quantities of radionuclides released as a function of time and the locations of the release points. Once the source terms have been identified, one



calculates the transport of the radionuclides from the points of release to where the radionuclides can be either directly inhaled or ingested, or to where people can be exposed to external radiation from radionuclides concentrated in the surrounding air, water or as surface deposits. This is called the “**transport**” or “**pathway**” analysis.

Some radionuclides, such as plutonium dioxide, are in the form of particulate, or attach themselves to particulate, such as dust or rain drops. Radionuclides that are in the form of, or that attach themselves to, particulates can fall out of the atmosphere along the transport pathway and concentrate on the ground, in water, or on vegetation. Ground deposits can be re-suspended and blown to other locations, or can be leached into the soil locally. Once leached into the soil or groundwater some fraction of the radioactivity is taken up by plants. However, as noted earlier, for plutonium isotopes, the primary pathway of concern is via inhalation.

Unlike a chemical poison, the damage caused by radioactive materials is not caused by the radionuclides, but by the radiation they emit. The radiation can come from radionuclides undergoing radioactive decay while inside or outside of the body, so long as the radiation is absorbed within. Thus, the next step is to calculate the **radiation dose** to different parts of the body as inhaled or ingested radionuclides pass through, or concentrate in, various organs, other tissue, or the skeleton; or as the various body parts are irradiated by external gamma-rays and other types of radiation from the nearby concentrations in the air, in the water, or on surfaces.

For many years the basic unit of **absorbed dose** was the **rad**, defined as the absorption of 100 ergs of radiation in one gram of matter. Subsequently all radiation units have been converted to the metric system. [NCRP Report No. 82] The metric unit of absorbed dose is the **gray**, defined as the absorption of one joule of energy in one kilogram of matter and abbreviated (Gy). Since the biological damage caused by a given absorbed dose may differ depending upon the type of radiation -- x-radiation, beta-radiation, gamma-radiation, alpha radiation, or neutrons -- there is another quantity called the **dose equivalent** such that a unit of dose equivalent causes the same biological damage regardless of the type of radiation. To account for the fact that radiation exposure is often non-uniform--for example, when ingested radioactivity concentrates in one or more organs--there is a unit of dose called the **effective dose equivalent**. The effective dose equivalent is a weighted sum of the individual dose equivalents to specified organs and other tissue. The weighting factors were chosen based on the principle that the risk should be equal whether the whole body is irradiated uniformly or whether there is non-uniform radiation. Since some ingested radionuclides, such as plutonium, can expose tissue for years into the future we use **committed dose equivalent**, and **committed effective dose equivalent**, to represent the total dose projected to be received over a defined period of time, often taken as 50 years.

The old unit of dose equivalent, effective dose equivalent, and committed dose equivalent is the **rem**, and the new metric system unit is the **seivert**, abbreviated (**Sv**). To convert from the old system to the new metric system of units:

$$1 \text{ Gy} = 100 \text{ rad}$$

$$1 \text{ Sv} = 100 \text{ rem}$$

To convert from rad to rem (or Gy to Sv), the rad (or Gy) is multiplied by a quality factor and other modifying factors where appropriate. For x-radiation, beta-radiation and gamma-radiation the quality factor and the other modifying factors are all usually assumed to equal to one. In this case, 1 rad = 1 rem, and 1 Gy = 1 Sv. For alpha emitters, such as plutonium 239 and plutonium-240, the quality factor is often taken to be 20. For radiation emitted from such isotopes:

$$1 \text{ rad} = 20 \text{ rem} = 0.01 \text{ Gy} = 0.2 \text{ Sv.}$$

or

$$1 \text{ Gy} = 20 \text{ Sv} = 100 \text{ rad} = 2000 \text{ rem.}$$

Also, in such situations it is convenient to use the abbreviated term “dose” to refer to absorbed dose or dose equivalent.

Finally, one must estimate the **health effects** caused by the radiation absorbed in the various body parts and make judgments regarding their significance. The later is made difficult by the lack of consensus among experts regarding the health effects of low level radiation exposure, and the lack of uniform federal and state standards and recommendations of national and international radiation protection organizations [GAO, “Nuclear Health and Safety, Consensus on Acceptable Radiation Risk to the Public is Lacking” 1994].

All of these calculations are complicated by the fact that the releases, transport and exposures are all time dependent, and more often than not much of the desired data is missing and must be approximated if it is not to be ignored. Measurements are often sparse, uncertain, and sometimes erroneous. Scientists deal with these problems using a variety of formal and informal approaches, including by making “best estimates,” giving ranges to estimates, and by attaching “uncertainty limits” to estimates.

### ***As Low As Reasonably Achievable (ALARA)***

With regard to exposure of workers and the public to radiation, a basic tenant of the health physics profession is that radiation exposures must be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account. This requirement is not new; rather it used to be called As Low As Practicable (ALAP), but the two mean the same.

As noted by the Nuclear Regulatory Commission [NRC, 1977]:

The principle of maintaining occupational radiation exposures (as well as public exposures) “as low as reasonably achievable” (ALARA) is an extension of an original recommendation of the National Committee on Radiation Protection (now the National Council on Radiation Protection and Measurements (NCRP)) in its 1949 report (published in 1954 as Report No. 17 (Ref. 3)). In this early report, the NCRP introduced the philosophy of adopting the conservative assumption that any radiation exposure may carry some risk and recommended that radiation exposure be kept at a level “as low as practicable” (currently referred to as “ALARA”) below the recommended maximum permissible dose (MPD) equivalent.

Similar recommendations to keep exposures ALARA have been included in NCRP reports up to the present time (Ref. 4), as well as in the recommendations of the National Academy of Sciences-National Research Council (Ref. 5), the Federal Radiation Council (Ref. 6), and other independent scientific and professional organizations.

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3. National Bureau of Standards, “Permissible Dose from External Sources of Ionizing Radiation,” Handbook 59, Recommendations of the National Council on Radiation Protection (NCRP Report No. 17), Washington, D.C., September 24, 1954.
  4. National Council on Radiation Protection and Measurements, “Review of the Current State of Radiation Protection Philosophy,” Report No. 43, Washington, D.C., January 15, 1975.
  5. National Academy of Sciences-National Research Council, “The Effects on Population of Exposure to low levels of Ionizing Radiation,” Washington, D.C., 1972.
  6. Federal Radiation Council, “Background Material for the Development of Radiation Protection Standards,” Report no. 1, Washington, D.C., 1960.

Reflecting the long standing guidance of both the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements (NCRP), the NCRP in National Bureau of Standards, “Permissible Dose from External Sources of Ionizing Radiation,” Handbook 59 [see also, DOE “Closing the Circle on the Splitting of the Atom, 1995, p. 38] stated:

Controls of radiation exposure should be adequate to provide reasonable assurance that recommended levels of maximum permissible dose shall not be exceeded. **In addition, the NCRP reemphasizes its long-standing philosophy that radiation exposures from whatever sources should be as low as practical.** (emphasis supplied)

As evidenced by the following AEC staff analysis, Dow violated ALARA (in some cases

with AEC staff consent) with respect to occupational exposure of Dow's workers to radiation [AEC Staff Analysis, 1968]:

#### B. Dow Operating Philosophy

Dow has been shown to be conscientious about working within the radiation exposure limits imposed by the Commission, namely, 3 rems/quarter and 5 (N-18) rem whole body in a year. However, it appears that the contractor has not always adequately weighed the radiation exposure factor in determining if operations "were being conducted ...in such a manner as to assure that radiation exposure ... (is) limited to the lowest practical level." (AEC MC 0524). For example,

1. Dow production activities permitted exposure up to the AEC limits, leaving little margin for error and no resiliency for special tasks or process changes;
2. until very recently, Dow has not used administrative exposure guides to minimize the possibility of individual exposures in excess of AEC limits;
3. production activities have frequently been conducted on the basis of 1 rem/month exposure, the maximum average radiation exposure allowed under MC 0524 for those employees whose past radiation exposure experience is well below a 5 rem/year average.

With AEC's concurrence, Dow has been permitted to operate with exposures very near the AEC radiation limits. If exposures are to be minimized to the extent practicable, either the AEC limits or the Dow operating philosophy must be changed.

As will be evident from the discussion below, Dow also did not comply with ALARA with respect to public exposure to radiation due to environmental releases of plutonium.

***Conversion of Units***

Various quantities, such as Gy, Sv, rad, rem, Ci and Bq, can be expressed in a variety of ways, for example, with a prefix that is used to indicate a decimal multiple or submultiple of the basic unit:

1 TeraBq	= 1 TBq	= $10^{12}$ Bq	= 1,000,000,000,000 Bq	= 27 Ci
1 GigaBq	= 1 GBq	= $10^9$ Bq	= 1,000,000,000 Bq	= 27 mCi
1 MegaBq	= 1 MBq	= $10^6$ Bq	= 1,000,000 Bq	= 27 $\mu$ Ci
1 kiloBq	= 1 kBq	= $10^3$ Bq	= 1,000 Bq	= 27 nCi
1 Bq				= 27 pCi
1 Ci				= 37 GBq
1 milliCi	= 1 mCi	= $10^{-3}$ Ci	= 0.001 Ci	= 37 MBq
1 microCi	= 1 $\mu$ Ci	= $10^{-6}$ Ci	= 0.000001 Ci	= 37 kBq
1 nanoCi	= 1 nCi	= $10^{-9}$ Ci	= 0.000000001 Ci	= 37 Bq
1 picoCi	= 1 pCi	= $10^{-12}$ Ci	= 0.000000000001 Ci	= 37 mBq
1 femtoCi	= 1 fCi	= $10^{-15}$ Ci	= 0.000000000000001 Ci	= 37 $\mu$ Bq
1 attoCi	= 1 aCi	= $10^{-18}$ Ci	= 0.00000000000000001 Ci	= 37 nBq
1 millirem	= 1 mrem	= $10^{-3}$ rem	= 0.001 rem	
etc.				

## Plutonium

*We are concerned about plutonium for two reasons. The first is the health and safety of our workers and the environment. Plutonium is very toxic and radioactive, and it tends to destroy the containers we keep it in. If too much plutonium is brought too close together, a chain reaction could cause a burst of deadly radiation. A second reason is national security. In order to prevent the spread of nuclear weapons and the material to build them, the United States is trying to reduce the stockpiling of plutonium and induce other nations to follow suit. And of course, only a few kilograms of plutonium of any kind are needed to build a nuclear weapon.*

Thomas P. Grumbly,  
Under Secretary,  
U.S. Department of Energy  
1996

*In addition to being one of the most toxic elements known to man, plutonium and some plutonium compounds are highly pyrophoric and may spontaneously ignite; some isotopes are fissionable, creating a potential nuclear safety problem; and all isotopes are radioactive creating a potential radiation problem.*

John W. Lindsey  
Rocky Flats Division  
Dow Chemical Company  
November 4, 1970, p. 2.

### *Characteristics of Plutonium*

Plutonium metal is highly reactive and must be stored in inert atmosphere or at low temperatures in dry air in order to avoid corrosion. Plutonium forms compounds with various elements, including plutonium dioxide ( $\text{PuO}_2$ ).  $\text{PuO}_2$  is the plutonium equivalent of iron oxide ( $\text{FeO}_2$ ), which we know as rust.

Plutonium and its compounds, including  $\text{PuO}_2$ , if inhaled in particulate form, are extremely toxic. It is similarly very toxic if it enters the body via a wound. When inhaled, the toxicity of plutonium is greatest if the particles are very small, e.g., less than about ten microns (i.e., 0.00001 meter (m) = 0.01 millimeter (mm)) in diameter. These very small particles can penetrate deep into the lung. Most larger particles tend to be coughed up and swallowed, rather than be lodged in the lung. Once deposited in the lung, insoluble forms of plutonium, including  $\text{PuO}_2$ , tend to concentrate there, with a fraction of it slowly moving to other parts of the body, particularly the bone surface and liver. Inhaled plutonium is excreted from the body very slowly. When ingested (i.e., swallowed) plutonium is less toxic than when inhaled. This is because plutonium is not readily absorbed through the gut, but mostly passes through the body and is excreted. The toxicity of plutonium, therefore, is dependent in part on its chemical form,

which determines its mobility after being inhaled or ingested and the rate at which it is absorbed through the gut.

Relatively pure plutonium-239, as an uncorroded solid metal, or alloy, is sometimes handled with bare hands because the alpha radiation which it emits does not penetrate the skin. However, because plutonium in particulate form can be extremely dangerous if inhaled, even in minute quantities, plutonium metallurgy required that workers use gloveboxes equipped with safety and ventilation systems [DOE, "Closing the Circle on the Splitting of the Atom," 1995, p. 19].

### ***Plutonium Isotopic Concentrations***

At Rocky Flats, the plutonium processed, in scrap, and that which was released to the environment was a mix of isotopes. DOE categorizes plutonium as supergrade (high purity), weapon-grade, fuel-grade, or reactor grade. The purity of the plutonium is defined in terms of the major isotopic contaminant, plutonium-240. The DOE categories are:

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

There is yet another plutonium category that is not graded in the same way, namely high purity plutonium-238, where the concentration of Pu-238 is greater than 80 percent. This plutonium is used to make radioisotope thermoelectric generators (RTGs), a type of nuclear battery where the electricity is produced by conversion of the heat produced through radioactive decay of the isotope, in this case plutonium-238. Pu-238 RTGs are used as batteries in nuclear weapons and as power sources in satellites and other remote applications.

Since the plant startup in 1953 until 1968, there was a general increase in Pu-240 and Pu-241 concentrations up to the average level in 1968 of about 6 percent Pu-240 and 0.58 percent Pu-241. Between 1961 and 1968 the average Pu-241 concentration in Rocky Flats plutonium, except for a few low-Pu-241 streams, was within  $\pm 0.1$  percent of the 1968 average of 0.58 percent [Dow, 1968, p. 35]. The following percent isotopic concentrations, given in plutonium scrap declarations, are typical of the weapon-grade plutonium received by Rocky Flats from the Savannah River Site [Dow, 1974]:

<u>Batch</u>	<u>Pu-238</u>	<u>Pu-239</u>	<u>Pu-240</u>	<u>Pu-241</u>	<u>Pu-242</u>
SRP-45-50	0.011	93.8	5.8	0.3	0.02
SRP-51-52	0.0084	93.6	5.8	0.6	0.03

For these concentrations the specific alpha activity would be 0.073 Ci/g, about 20 percent greater than the value for pure plutonium-239.<sup>4</sup>

Krey and Krajewski quote the following percent concentrations as typical of Rocky Flats plutonium [Keay and Krajewski, 1972, Table 1]:

	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
	0.04 ± 0.01	93.4 ± 0.5	6 ± 0.5	0.58	0.04
	0.01				

While most of the plutonium processed at Rocky Flats was weapon-grade plutonium, some fuel-grade plutonium was processed beginning in the second half of calendar 1967 to make fuel elements for the Zero Plutonium Power Reactor (ZPPR), and some high-purity plutonium-238 was processed [Dow, "A Report on Radiation Problems," 1968, pp. 58, 61-63; see also, Putzier, 1995, pp. 186-187]. The plutonium feed for the ZPPR fuel elements was typically constituted as follows [Ibid., p. 17]:

	Pu-238	Pu-239	Pu-240	Pu-241	Am-241
ZPPR	?	87	11.5	1.45	0.1

As learned from recently declassified documents, for example, in 1960, Rocky Flats had a plutonium-238 program in support of Lawrence Livermore National Laboratory requirements [MacKay, 1960]. High purity (80%) plutonium-238 was being processed at Rocky Flats in the 1967-68 period [Dow, "A Report on Radiation Problems," 1968, p. 58], "plutonium-238 (E. Vejvoda Scrap)" is indicated in a 1971 Rocky Flats scrap declaration [Rockwell, 1982], and plutonium-238 concentrations of 0.238 percent and 1.397 percent are indicated in Dow "Analytical Requisitions" [Dow, November 8, 1976 and April 7, 1977].

The fact that we now know that fuel-grade plutonium and relatively pure plutonium-238 were processed at Rocky Flats, could explain some of the high plutonium-238 concentrations found in air, soil and animal tissue measurements taken near Rocky Flats. See, for example, Whicker, "Radioecology of Some Natural Organisms and Systems in Colorado," 1973, p. 24; Ibrahim, Webb and Kattel, 1995, Tables 2 and 3; and RAC, Phase II, Task 4, DRAFT, 1966, pp. III-6, 63-65. This new discovery information revealing high purity plutonium-238 operations at Rocky Flats calls into question all earlier studies of off-site plutonium contamination where data were disregarded because high plutonium-238 concentrations were thought to be inconsistent with that of weapon-grade plutonium.<sup>5</sup> For example, Ibrahim, Webb and Kattel, 1995, claimed on the basis of the plutonium-238 concentration, that Rocky Flats could not have been the source of plutonium measured in clinker kiln dust (waste material) at a cement factory 30 km from Rocky Flats. This conclusion is inappropriate based on what we now know. Further analysis is

<sup>4</sup> The plutonium-241 activity is not included, since its primary radioactive decay mode is beta decay.

<sup>5</sup> For weapon-grade plutonium typically handled at Rocky Flats, the plutonium-238 contribution is 2-3 percent of the total activity and the (Pu-239,240)/Pu238 ratio is about 40 to 50.



requires to resolve the likelihood that these kiln measurements represent plutonium from Rocky Flats. If further analysis shows that these data are likely to have been measurements of plutonium from Rocky Flats, it will be highly significant. It means there were other pathways by which plutonium was released from Rocky Flats to the environment that have not been analyzed.

RAC also appears to be poised to use plutonium isotopic ratios to determine the source of off-site plutonium [RAC, Phase II, Technical Memorandum: Evaluation of Background Concentrations of Plutonium in the Environment Around Rocky Flats Plant, DRAFT, 1995, pp. 8-12]. We now know that it is inappropriate to dismiss plutonium environmental samples as not being representative of Rocky Flats operations, solely on the basis that the isotopic ratios are inconsistent with those of weapon-grade plutonium.

The fact that fuel-grade plutonium and relatively pure plutonium-238 was processed at Rocky Flats, also means that one must be cautious in attempting to quantify the relative contribution of plant releases and global fallout in soil samples within a few tens of miles of the plant based on an analysis of isotopic ratios of soil samples taken after mid-1967. Krey and Krajewski, 1972, and Webb, 1992 and 1996, for example, failed to take into account the fuel-grade plutonium and Pu-238 campaigns at Rocky Flats in their analysis of plutonium deposition from the plant, which leads one to question those conclusions which were derived from isotopic ratio analysis [Krey and Krajewski, 1972; Webb, 1992 and Webb, 1996].

### ***Toxicity of Plutonium***

One way to measure the toxicity of plutonium is to examine the concentration of plutonium in the air and drinking water that would result in an adult member of the public being exposed at the limiting dose established under Federal regulations for exposure in unrestricted areas, i.e., off-site. The Environmental Protection Agency (EPA) regulations, under 40 CFR 61, subpart H, establish a 10 mrem/y public exposure limit for inhalation of radionuclides that applies to the DOE sites, and under 40CFR141, establishes a maximum drinking water contamination limit of 4 mrem/y for  $\beta$  and  $\gamma$  radiation, 5 pCi/l for radium, and 15 pCi/l for all other alpha emitters.

The radiation dose due to inhalation (and ingestion) of a radionuclide depends on the solubility of the radioactive material in tissue (inhalation) and the rate of absorption through the gut (ingestion). For plutonium-239 and -240, the annual limiting intake resulting in 10 mrem/y committed dose equivalent from inhalation and ingestion are [EPA, Federal Guidance Report 11, 1988, p. 113]:

<u>Isotope/Solubility</u>	<u>Inhalation</u>	<u>Ingestion</u>
Soluble Pu-239,-240	12 pCi/y	1.6 nCi/y
Insoluble Pu-239,-240	40 pCi/y	16 nCi/y

Assuming that an average adult breathes 22 cubic meters (m<sup>3</sup>) of contaminated air and drinks 2 liters (l) of contaminated water daily, the air and water concentrations to achieve these intakes would be:

<u>Isotope/Solubility</u>	<u>Inhalation</u>	<u>Ingestion</u>
Soluble Pu-239,-240 (10 mrem/y)	1.5 fCi/m <sup>3</sup>	2 pCi/l
Insoluble Pu-239.-240 (10 mrem/y)	5.0 fCi/m <sup>3</sup>	20 pCi/l
alpha emitter (40CFR141)		15 pCi/l

For insoluble weapon-grade plutonium (0.073 Ci/g), the 5.5 fCi/m<sup>3</sup> and 15 pCi/l limits equal:

$$\begin{aligned}
 0.07 \text{ pg/m}^3 \text{ of air} &= 0.00000000000007 \text{ g/m}^3 \text{ of air} \\
 200 \text{ pg/l of water} &= 0.0000000002 \text{ g/l of water}
 \end{aligned}$$

The State of Colorado has a regulation pertaining to construction and development activities, in terms of the permissible levels of plutonium contamination in uncontrolled (i.e., off-site) areas, namely “Contamination of the soil in excess of 2.0 disintegrations per minute [dpm] of plutonium per gram of dry soil or square centimeter of surface area (0.01 microcurie per square meter)” [Colorado Department of Public Health and Environment’s Rules and Regulations Pertaining to Radiation Control, Part IV, RH 4.60.1]. This translates into a limit of 0.9 pCi/g , or 0.9 pCi/cm<sup>2</sup>. The original proposed standard was ten times more restrictive.

These are extremely small quantities, which reflects the fact that plutonium is a very toxic material.

### **Toxicity of Beryllium**

Beryllium has been used by contractors, including Dow and Rockwell, of the DOE and its predecessor agencies since the early 1940s in many nuclear applications. Inhalation of small amounts of beryllium dust can lead to lung disease, called berylliosis [Walker, 1986; and DOE, “Beryllium, 1983]. While not radioactive, beryllium metal and several beryllium compounds have been shown to cause cancer in animal studies, is a suspected carcinogen in humans, and is considered carcinogenic by the U.S. Occupational Safety and Health Administration (OSHA) [DOE, “Beryllium, 1983, pp. 34-35 (old page numbers)]. “Inhalation is the primary route of uptake of insoluble beryllium. The latent period for beryllium varies greatly from periods of several months to several years. The disease is of long duration and is of progressive severity. In addition, it is not easy to diagnose, since abnormalities that occur are not specific for this disease.” [Sheppard, 1986]

## Rocky Flats Fires

There were two major fires at Rocky Flats that are known to have resulted in important releases of plutonium to the environment, one in 1957, and the second in 1969.

### *1957 Fire*

The 1957 fire began in Building 771 at about 10 pm on September 11, 1957 when metallic plutonium casting residues spontaneously ignited in a glovebox in Room 180 [ChemRisk, Task 5 Draft Report, 1992, p. 202]. The gloveboxes were constructed with combustible “plexiglas.” The plexiglas caught fire as did the attached rubber gloves [Voillequé, 1995, p. 1]. Combustible gases spread through the duct work and into the final filter plenum. Approximately 30 percent of the flammable chemical warfare system (CWS) filters, which removed plutonium from glovebox exhaust, were consumed [Young, 1977, p. 53].

After the September 1957 fire, there were reviews of fire safety at Rocky Flats that led to numerous recommendations of actions that needed to be taken [See, for example, Dow, 1957, pp. 25-27]. Many of the actions were not taken for reasons of cost and perceived production requirements. Following the 1957 fire Dow Chemical Company permitted the installation of flammable Benelex shielding in gloveboxes, failed to install and maintain adequate fire detection equipment, failed to provide adequate fire protection training, failed to install and maintain adequate fire breaks between working areas and permitted the piecemeal removal of the wall (a fire break) between buildings 776 and 777. As was noted by the AEC after the 1969 fire, the “776-777 complex was not designed or constructed to meet AEC fire safety standards – nor does it appear that any concerted effort over the years have been made to achieve these standards.” [AEC, 1969] As a consequence of Dow Chemical Company negligence, fires continued to plague Rocky Flats. I have not seen data for earlier years, but during the three year period, June 1966 through May 1969, a total of 164 fires of all kinds were reported to the fire department at Rocky Flats [Donnelly, 1969]. For the most part these were unanticipated fires as opposed to fires involving the routine processing of plutonium in Buildings 771 and 776 that were extinguished by the operator as part of his normal operation [Ibid.]. Of the 164 total, 31 fires directly involved plutonium, one of these the May 11, 1969 fire [Ibid.].

### *1969 Fire*

The May 11, 1969 started in a glovebox in one of the processing areas of Building 776/777. It is theorized that the fire started when plutonium briquettes spontaneously ignited in a metal storage container [See, for example, AEC, 1969]. Despite the fire hazard represented by the pyrophoric nature of plutonium and the hundreds of tons of flammable material in the building, there was only one operator on duty in the building when the fire broke out [Sauderland, *Denver Post*, June 29, 1969, p. 23]. Thus, the fire was allowed to spread before it was discovered. The fire burned for approximately four hours with some relatively minor flare-ups discovered as much as six hours after the first fire alarms [Dunn, 1977, p. 212]. Damage to the buildings was extensive, and while the fire is not believed to have breached the building roof,

exterior contamination was measured on the roof of Building 776, apparently due to failure of a filter. Plutonium was tracked out of Building 776 by firefighters and was detectable on the ground around the buildings. [Young, 1977, p. 56.]

The May 11, 1969 fire could have been much worse. Several hours into the fire, firemen noticed that the roof was getting soft and began watering it down. Had the roof collapsed, containment would have been lost and plutonium contaminated smoke released to the environment. This would have been a disaster of major proportions. According to the AEC, only the heroic efforts of the firefighters limited the burning [AEC, 1969]; hundreds of square miles could have been contaminated and the cleanup costs could have been astronomical [Giller, 1970]. This fire, and many of the early “unanticipated” fires, could, and should, have been prevented, had Dow Chemical Company given appropriate attention to the lessons learned from the earlier fires.

### **The 903 Pad**

The story of the 903 Pad is one of the more egregious examples of the disregard for public health and safety by Rocky Flats management. A chronology of 903 Area events has been developed by the Radiological Assessment Corporation [Meyer, et al., RAC, 1996, pp. 2-5; see also, Seed, et al., 1971, p. 6]. Due to poor waste management practices, Dow Chemical Company permitted the on-site buildup of radioactive waste and residues. In July 1958 a storage area for drum storage of radioactive waste/residues was established in the 903 area. Many of the 30 and 55 gallon drums contained plutonium contaminated lathe cutting oil from the plutonium machining of weapon components. The drums were stored outside, initially directly on the dirt. Dow Chemical Company discovered the drums were leaking in July 1959. At that time it would have, or should have, recognized that the plutonium was exposed to the environment and was capable of being carried off-site by the winds. Dow added a rust inhibitor to the barrels, but they continued to leak. In January 1964 large scale leakage of the drums was reported. Another two year lapsed before Dow started transferring oil out of the leaking drums. A year later, in January 1967, Dow began removing drums for processing in Building 774. By this time there were 5,237 drums, of which 3,572 were said to have contained plutonium. After the last of the drums were removed in June 1968, Dow burned the vegetation in October 1968, and began grading the site in November 1968, in preparation for paving it with asphalt, applied fill material on the site beginning in July 1969, and asphalt in November 1969. Dow permitted the grading to take place during high wind conditions, leading, or contributing, to additional excessive off-site contamination as the contaminated soil was blown off-site.

Also because of Dow’s poor waste management practices, it is not well known even to this day how much plutonium was in the drums or how much leaked out. The barrels were not properly labeled, so it was difficult to tell how old the drums were or how much plutonium each contained. Radiological Assessment Corporation (RAC) recently estimated a total of 9 to 18 kg of plutonium were in the drums and from 40 to 1,800 grams of plutonium leaked out into the soil.

## **Off-Site Plutonium Contamination**

There were four major *known* sources of off-site plutonium releases from the Rocky Flats Plant, from: a) routine filtered stack emissions, b) the 1957 fire, c) the 1969 fire, and d) the 903 Pad. Of course there were surely other releases that were smaller, simply missed, or went unreported. Over the years a number of investigators have made estimated the releases from one or more of these four known sources. We have not heard the end of efforts to quantify these releases, as new data will derive from expert testimony in the ongoing Rocky Flats litigation, Cook, et al., v. Rockwell International Corp., et al. (No. 90-K-181 (D. Colo.)). This brief review below does not address these new data, but is limited to selected previous estimates.

### ***Routine Filtered Stack Emissions***

Based on stack gas monitoring data, Ripple, et al., present ChemRisk's best estimate of the routine plutonium emissions between 1953 and 1989 as 0.22 MBq (6  $\mu$ Ci), with a 95 percent confidence range of 0.090-0.56 MBq (2.4-15  $\mu$ Ci). Using 0.073 Ci/g, this estimate is equivalent to 80  $\mu$ g Pu (range 30 - 300  $\mu$ g Pu).

### ***1957 Fire***

An estimated 9 to 25 kg of plutonium metal may have been involved in the 1957 fire [Voillequé, 1995]. Early estimates of total known and unknown quantities of plutonium released to the atmosphere as a consequence of the 1957 fire were reported as one gram (0.07 curies) [Young, 1977, p.54]. Rockwell International later claimed that 0.37 gram (0.025 curie) of plutonium were released through a filter system damaged in the 1957 fire. [Dunn, 1977, p. 10]. "Barrick (1981) provides the largest published estimate of the total release of radioactivity to the environment from the September 11, 1957 fire at Rocky Flats. Barrick estimates that the release was between 0.7 and 1.3 curies, with a most probable value of 1.0 curie. At 0.0734 Ci per gram of plutonium, a release of 1 curie corresponds to 14 grams of plutonium." [ChemRisk, Task 5 Draft Report, 1992, p. 202] Barrick's estimate is 26 to 57 times that of Rockwell. Mongan, et al., reporting on the ChemRisk study results, estimated 1.9 GBq (0.05 Ci) as an upper bound to the plutonium releases from the 1957 fire [Mongan, et al., 1996, pp. 510-521]. This corresponds to about 0.7 g of plutonium. Voillequé estimated releases from the main filter bank in the range 4 to 25 g of plutonium [Voillequé, 1995, p. 22].

### ***1969 Fire***

As indicated above, Rockwell claimed that while plutonium was tracked out of Building 776 by firefighters and was detectable on the ground around the buildings. [Young, 1977, p. 56.] ChemRisk [Task 8 Report], estimated that the 1969 fire released 2.8 mCi (40 mg) of plutonium. Voillequé estimates that approximately 7 mCi (range 2-20 mCi) was deposited on the roof and approximately 1 mCi (range 0.3-3 mCi) was deposited on the ground nearby [Voillequé, 1996].

**903 Pad**

Mongan, et al., present ChemRisk's estimate of the plutonium releases associated with the 903 Pad. The ChemRisk mean estimates are [Mongan, et al., 1996, p. 526; and ChemRisk, Task 6 Draft Report, 1993, p. 80]:

410 GBq (11 Ci) were re-deposited on the pad  
 520 GBq (14 Ci) escaped from the pad. [190 g of plutonium]  
 300 GBq ( 8 Ci) traveled beyond the security fence  
 250 GBq ( 7 Ci) escaped to beyond the site boundary of the uninhabited buffer zone  
 around the plant. [96 g of plutonium].

The uncertainty in these results, due to the application of the Fugitive Dust Model, according to Mongan, et al., and ChemRisk is about a factor of 10 [Ibid.].

The environmental releases from the 1969 fire and the 903 Pad were certainly avoidable, and represent a clear violation of the ALARA principle, a basic tenant of the health physics profession.

One of the problems for those who reside, or own property, near the Rocky Flats Plant, is that plutonium is extremely toxic; its contamination is invisible; it is difficult to measure, and it is exceedingly difficult to assess, or determine an upper limit on, an individual's risk of getting cancer as a result of exposure to plutonium—even by the experts. Moreover, there are the added risks associated with ongoing cleanup activities. Even the radioactive waste buried on site can be brought by gophers and other small animals to the surface where the contamination can be resuspended by the wind and blown off-site [Smallwood, 1996].

**The MUF Problem**

Dow Chemical Company was grossly negligent in its failure to adequately account for plutonium (and highly-enriched uranium) inventories during the initial period of operation of Rocky Flats—during the period from April 1953, when the first shipments of plutonium nitrate arrived on site from Hanford, through FY 1963 (June 1963). For over a decade, Dow did not systematically measure the plutonium in residues and scrap, set no limits on the plutonium content in scrap, failed to conduct frequent clean-out inventories of equipment and processes lines, and as a consequence allowed the cumulative plutonium inventory difference to climb to 665 kg—equivalent to the amount of plutonium in the pits of some 220 modern nuclear weapons.

For at least five years the annual plutonium inventory difference was running at several percent of throughput (as high as 8 percent in 1956), compared to less than one percent in later years after some of the inventory problems were brought under greater control. For a decade, Dow did not try to systematically address the reasons the inventory differences were so large.

As noted in a 1964 internal Rocky Flats MUF study, “The plutonium losses experienced during the entire history of the Rocky Flats plant have been significant. These losses have never been explained or properly justified and this study was conducted to determine their source and causes.” [Zodtner and Rogers, 1964]

In 1964, more than a decade after the plant started operations, Dow finally started addressing the inventory difference problem. But during a three year transitional period, the cumulative plutonium inventory difference climbed another 435 kg, or the equivalent of what is in 150 modern nuclear weapons.

Even during the five year period, FY 1980-FY 1984, when Rockwell International was operating the plant, the site-wide plutonium inventory differences were running 30 to 40 kg per year.

For relevance of Rocky Flats Plant MUF to off-site releases, see my companion report, “Plutonium Inventory Differences at the Rocky Flats Plant and Their Relation to Environmental Releases,” November 21, 1996.

### **The Criticality Problem**

*Until safety is given appropriate priority relative to production and until DOE instills a healthy, questioning attitude about nuclear safety in all of the people who work there, Rocky Flats Plant will not operate as safely as it can and should.*

Criticality Safety Assessment Team  
SCIENTECH  
September 1989. p. ES-5.

An inadvertent criticality event occurs when too much fissile material is brought together unintentionally to form a critical mass, thereby creating a runaway nuclear chain reaction. Since the assembly of the material into a critical mass is unintentional, the release of energy is extremely small compared to that released by a nuclear weapon or a nuclear power reactor; nevertheless, it can be lethal to those in the immediate vicinity. As indicated in a 1989 DOE funded review of criticality safety at Rocky Flats, “A criticality accident at the Rocky Flats Plant could produce a potentially lethal dose of neutrons and gamma radiation to workers at close range, could generate heat and fission products, and in extreme but low probability circumstances, could result in the release of radioactive material to the environment.” [SCIENTECH, p. ES-1]

The critical mass of fissile material depends upon a number of factors, including the type of fissile material, e.g., plutonium, high-enriched uranium, the chemical and isotopic

composition, density, shape, and the types and locations of surrounding materials. To get a flavor of the range of critical masses of materials used at Rocky Flats under selected conditions see Table 2. A sphere of dense ( $\alpha$ -phase) plutonium (3.12% Pu-240) inside a thick (5-30 cm) beryllium reflector has a critical mass between 2.5 and 5.5 kg, depending on the thickness of the beryllium. In solution, where the plutonium concentration is 20 to 40 grams per liter, the critical mass of plutonium can be as low as 500 grams.

Criticality accidents have been recognized as an important safety concern since the first such accident occurred on February 11, 1945 during the Manhattan Project. There were some 21 criticality accidents outside of reactors at AEC facilities United States between 1945 and 1964 resulting in the deaths of a half dozen workers [Thompson and Beckerley, 1964, pp. 608-612]. Many features were incorporated into the Rocky Flats Plant design to reduce the probability of an inadvertent criticality event, and the need to follow strict criticality safety operating procedures was well known to the AEC/ERDA/DOE and the Rocky Flats contractors.

During the entire history of the Rocky Flats Plant, from 1952 to the present, there was never a unplanned criticality event at Rocky Flats, or at least none reported. In this regard, however, Rockwell International, can be considered lucky, because as evidenced by the 1989 criticality safety review, Rockwell did not maintain adequate criticality conditions and practices at Rocky Flats [SCIENTECH, 1989]. The review team identified a case of excessive amount of plutonium which had accumulated in the duct work, unknown to the plant managers, and indications that similar situations may have occurred elsewhere. The review team also found situations where plutonium was stored in a manner that could result in a criticality accident if a store room were flooded or if the drums fell together, for example, during an earthquake. The team also indicated that there had been more than 600 procedural infractions recorded by the criticality safety program at Rocky Flats since 1962 [Ibid.]. These examples of Rockwell's failures are summarized in the Executive Summary of the 1989 review, which is included as Attachment A to my report.

### **Pondcrete**

Failure to adequately manage the huge quantities of radioactive and other hazardous residues and wastes at Rocky Flats was not limited to the issues surrounded the 903 Pad discussed above. Another notable example is Rockwell's efforts to dispose of radioactive solar pond sludge by sequestering it in concrete, what became known as "pondcrete." For a more extensive treatment of the pondcrete and other waste management issues at Rocky Flats, see U.S. v. Rockwell, 1992; and North, Budnitz and Chan, 1996.

On July 31, 1986 the U.S. Environmental Protection Agency (EPA), DOE and the Colorado Department of Public Health reached an agreement under which Rockwell, among other requirements, was to close and clean out solar evaporation ponds that had been used to evaporate waste water that had been contaminated with radioactivity and other hazardous materials, and process and ship off-site the contaminated waste removed from the pond [EPA,



DOE, Colo. Dept. of Health Compliance Agreement, July 31, 1986]. The ponds had been leaking into the groundwater.

Rockwell developed a process for solidifying the sludge at the bottom of the ponds by mixing it with concrete and making concrete blocks which were about 40 inches by 40 inches by 26 inches. These blocks weighed between 0.6 and 0.9 tons each. But Rockwell never perfected the process. Instead of hardening like concrete, many of the blocks were soft like putty. After sending some 2000 pondcrete blocks to Nevada for disposal, officials there refused to accept further shipments. Rockwell's response was to continue to make semi-soft pondcrete blocks in plastic lined cardboard boxes, and to store the boxes at the 750 Pad, protected only a tarp that frequently blew off in high winds. By the end of September 1987, there were over 10,000 such boxes of pondcrete stored at the 750 Pad. Running out of room, Rockwell began storing blocks at the 904 Pad as well.

Not surprisingly given these conditions, the blocks began to deteriorate. In May 1988, a box at the 904 pad fell and broke open. By this time some 16,500 blocks were stored outside at Rocky Flats. The DOE determined that 9,000 of these had deteriorated. There is no obvious way to repair the damage caused by Rockwell's failed pondcrete process and storage regime. The cleanup cost is likely to run into the hundreds of millions of dollars.

### **Conclusions**

The toxicity and hazardous nature of plutonium, uranium and beryllium were known to the plant's contractors well before the Rocky Flats Plant was built, and in fact to a large extent the plant was designed with these hazards in mind. The toxic nature of plutonium and beryllium, and the fact that there would be large volumes of hazardous residues and wastes produced, was recognized from the start. The concern over fires and criticality conditions, and that one must keep careful track of the whereabouts of plutonium and highly-enriched uranium was well known. But something went awfully wrong.

For 37 years the plant's first two contractors operated Rocky Flats with callous disregard for these hazards. The contractors placed highest priority on meeting warhead component production quotas, and failed to exercise the due diligence and meticulous attention to detail required to insure the public's health and safety. As a consequence there were fires that could have been prevented and should not have occurred. In violation of the ALARA principle, there were releases of plutonium to the environment that could have been prevented and should not have occurred, unnecessarily exposing the public to an increased risk of cancer. Private property was contaminated effectively forever. One contractor, Rockwell International, in 1992 pleaded guilty to committing ten environmental crimes, five of which were felonies [U.S. v. Rockwell, 1992]. There was a huge unnecessary buildup of radioactive waste. When the plant was shut down in 1989 for safety violations, it was left in a condition that has made cleanup of the site an expensive nightmare for the government. There were about 12.7 metric tons (t) of plutonium left at the plant [DOE, 1996, p. 20]. Some of the plutonium was stored in temporary plastic packaging, which has since begun to deteriorate, producing hydrogen gas that can contribute to

pyrophoric conditions [National Research Council, 1996, p. 13]. Even today there are thousands of drums of hazardous wastes stored in available spaces throughout the various building at Rocky Flats—another fire hazard waiting to happen. The site may never be cleaned up adequately, largely because of the egregious manner in which the plant was operated for more than three decades resulting in extensive contamination of the site and the accumulation of large volumes of toxic wastes.

The deplorable conditions at Rocky Flats did not have to exist. The United States was, and is, the richest industrialized country in the world. Dow and Rockwell International, the two contractors that operated Rocky Flats from 1952 to 1989, rank respectively, among the largest chemical and defense contractors in the country. They could have done the job right had they wanted and chosen to do so. Instead, the contractors placed profit ahead of public health and safety.

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Signed:

Date:

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**Table 1. Buildings at Rocky Flats Associated With Plutonium Use**

Building 371	Building 371 was designed to serve as a plutonium recovery facility and replace buildings 771 and 776. The new facility was plagued with problems from the onset of construction in 1980, and design flaws resulted in the chemical processing being shut down in 1985 before achieving full-scale operations. It is now used for storage of special nuclear materials, including solid mixed residues.
Building 374	Building 374, Process Waste Treatment Facility, was designed to replace Building 774 as the liquid process waste treatment facility. The building has 43,000 square feet of floor space, containing 33 tanks for receiving and storing liquid wastes for treatment, and containing equipment for acid neutralization.
Building 559	Building 559 started operating as an analytical laboratory. Historically the building performed chemical analyses to support the weapons manufacturing program. The building consists of 33,000 square feet of floor space. And houses glovebox lines and chemical hoods for -processing plutonium samples and solutions, and other hazardous materials.
Building 707	Building 707, Plutonium Manufacturing Building, started operating in 1969 as a plutonium fabrication and assembly building. Historically, the building cast, machined, and assembled plutonium components. The building consists of 200,000 square feet of floor space on two levels. The first level consists of individual modules separated by corridors. The modules (10) house glovebox lines for processing plutonium metal. Each module is dedicated to specific manufacturing processes, e.g., foundry operations (casting, rolling, forming), machining, welding, autoclave operations for the production of bonded weapons inspection, etc. The upper level housed mainly ventilation systems and other vital safety equipment. A modular plutonium fabrication facility was placed into operation in 1971. Building 707 also houses the X-4 Retriever Room ,which contains many forms of plutonium in storage cans arranged on two floors.
Building 771	Building 771 became operational in May 1953 and served as the original production facility at Rocky Flats. It is a two story building with 150,000 square feet of floor space. Plutonium operations were limited exclusively to Building 771 until the fire on August 15, 1957. In 1958 most of the Building 771 production functions were transferred to Building 776. From that point on, operations in Building 771 focused on plutonium recovery. Impure sources of plutonium (from oxides, rejected parts, lathe turnings, etc.) were transferred to Building 771, where they would undergo a series of

chemical operations, all designed to strip impurities from the plutonium. Pure plutonium metal was the final product for reuse in weapon production.

Building 774 Waste Treatment Facility. Processed the waste from the 903 pad beginning in January 1967.

Building 776/777 Building 776 and 777 were initially separated by a wall that was subsequently opened to form a single large unit, so that the two are often referred to as Building 776/777. Building 776/777 started operating in 1957 (FY1978) with Building 776 housing foundry and fabrication operations, and with Building 777 housing assembly operations. The building consists of 223,000 square feet of floor space and houses glovebox lines and hoods for processing plutonium metal and solutions. In 1969, following a significant industrial fire, all production operations were shut down, and solid waste operations were initiated to dispose of fire damaged equipment and wastes generated during cleanup operations. The manufacturing operations in Building 776 were transferred to Building 707 in 1972. A rolling and forming operation was started in Building 776 during FY 1978 for the production of hollow pits. Building 776 served as a waste storage and waste reduction building after that time. The baler was used to reduce the volume of low-level combustible waste. Building 776 houses the reduction and consolidation portions of the molten salt clean up line.

Building 777 was an assembly building. In a process called "briquetting, machine turnings were placed in metal baskets and dipped into a series of four open surface carbon tetrachloride baths prior to placing in a hydraulic press for puck production. Building 777 houses the vacuum distillation stage of the molten salt clean up line.

Since production operations ceased at Rocky Flats, Building 776/777 has been used to process solid wastes (primarily by size reduction) and store special nuclear materials and special nuclear material residues.

Building 779 Building 779 houses the vacuum melting stage of the molten salt clean up line.

Building 991 In building 991 the assembly of plutonium components and non-plutonium components took place.

**Table 2. Critical Mass Data**

Material	Shape	Condition	Density (g/cm <sup>3</sup> )	Critical Mass (kg)	Reference
U (93.86% U-235)	sphere	Unreflected	18.81	48.75	1, p. 4
Pu (4.5% Pu-240)	sphere	Unreflected	15.45 ( $\delta$ phase)	16.85	1, p. 40
Pu (5.2% Pu-240)	cylinder	Thick water reflector	19.74 ( $\alpha$ phase)	5.79	1, p. 40
Pu (NO <sub>3</sub> ) <sub>4</sub> (3.12% Pu-240)	solution	16 liters	60 g Pu/liter 310 g nitrite/liter	0.975	2, p. 54

Dow conducted a criticality analysis of plutonium-oxide (PuO<sub>2</sub>) in water in a pit (a storage area) with dimensions: 2 feet x 2 feet x 28 inches. If the pit collects water with PuO<sub>2</sub>, and assuming the plutonium is uniformly distributed in the water and over the bottom of the pit, the following values were calculated [Ref. 3]:

<u>Concentration of Pu in Water</u>	<u>Weight of Pu in Slab</u>	<u>Critical Height</u>
1 g/cm <sup>3</sup>	18.598 kg	1.97 inches (in)
0.5 g/cm <sup>3</sup>	10.431 kg	2.21 in
0.2 g/cm <sup>3</sup>	5.041 kg	2.67 in
0.05 g/cm <sup>3</sup>	0.730 kg	3.87 in

References:

- 1) H.C. Paxton, "Los Alamos Critical-Mass Data," Los Alamos Scientific laboratory, LA-3067-MS, Rev., December 1975.
- 2) H.C. Paxton, et al., "Critical Dimensions of Systems Containing U235, Pu239, and U233," Los Alamos Scientific Laboratory, TID-7028, June 1964.
- 3) L.E. DeMeuse, Memorandum to C.L. Schuske, Dow Chemical Company, May 25, 1969.