# Crude Nuclear Weapons

## Proliferation and the Terrorist Threat

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IPPNW Global Health Watch

Report Number 1

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Library of Congress Catalog Number:

On the Cover: Radiation Day at the Ecology School, Chelyabinsk, Russia — Photo by Robert Del Tredici; Spent Fuel Storage-Case Testing Pad, Idaho, USA — Photo by Robert Del Tredici; A Tomahawk Land-Attack Missile During the Gulf War — Photo courtesy US Department of Defense; Victim of Helicopter Attack in El Salvador — Photo by John Mottern; Soldier Extracting an Anti-Tank Landmine — Photo from IPPNW-Australia Landmines Education Kit; The Earth — Photo by Photodex, Inc.
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# The Authors

## International Physicians for the Prevention of Nuclear War (IPPNW)

Founded in 1980, in the midst of the Cold War, the International Physicians for the Prevention of Nuclear War came together with the vision that physicians, sharing a common duty to protect human health, could unite globally in opposition to nuclear weapons and nuclear war. Through research, education, and advocacy, IPPNW has helped to dispel myths about the capacity for survival after a nuclear war. As medicine can offer no answers to global annihilation, prevention of such catastrophe is the only remedy. A worldwide federation of national physicians' groups in over 80 countries, IPPNW was recognized for its contributions in 1984, when it was honored with the UNESCO Peace Education Prize, and in 1985, when IPPNW was awarded the Nobel Peace Prize.

In 1995, IPPNW launched its Abolition 2000 campaign. The goal of Abolition 2000 is to secure the commitment of the world's governments to a convention, by the year 2000, that sets a firm timetable for the elimination of all nuclear weapons.

## Gururaj Mutalik, M.D.

Gururaj Mutalik, M.D., is Executive Director of IPPNW. Prior to joining IPPNW, Dr. Mutalik worked for the World Health Organization in the areas of comprehensive health care, human resource development, and coordination of NGO and intergovernmental partnership programs and as head of the New York Office of WHO. He also served as Secretary of the WHO Commission on Health and Environmental Effects of Nuclear Weapons and Nuclear War. Dr. Mutalik was a dean and professor at a medical school in his native India. He is the author of over 75 articles in the areas of medicine, public health, disarmament, and development.

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Frank Barnaby worked at the Atomic Weapons Research Establishment, Aldermaston (1951-57) and was on the senior scientific staff of the Medical Research Council when he was a university lecturer at University College, London (1957-67). He was Executive Secretary of the Pugwash Conferences on Science and World Affairs (1967-70) and Director of SIPRI, the Stockholm International Peace Research Institute (1971-81). He was Guest Professor at the Free University, Amsterdam (1981-85) and Visiting Professor, Stassen Chair at the University of Minnesota (1985). He is currently a defense analyst and writer on military technology. His books include: *The Invisible Bomb* (Tauris, 1989) and *The Automated Battlefield* (Sidgwick and Jackson, 1987). He is author of Oxford Research Group's (ORG) *Current Decisions Report No. 12*, *The Plutonium Legacy: Nuclear Proliferation out of Control?* (April 1993), co-editor of the *Current Decisions Reports Nos. 13 and 14*, *Strengthening the Non-proliferation Regime* (December 1993) and *Political Aspects of Nuclear Non-proliferation* (August 1994), and is a regular contributor to other ORG publications.

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# Preface

Beirut. Oklahoma City. London. New York. Paris. Tel Aviv. Tokyo.

Although many of the world's cities have recently experienced the horrors of terrorism, the damage they have suffered is minuscule compared to what may lie ahead. What if a terrorist organization obtained nuclear weapons? The destructive force of even a crudely designed weapon could easily be 1,000-fold greater — and perhaps 20,000-fold greater — than the fertilizer bomb that devastated the US Federal Building in Oklahoma City.

As described in Part I of this report, the technical barriers to construction of a crude nuclear weapons are frighteningly easy to overcome. The loss of adequate nuclear safeguards in the former Soviet Union, combined with the ever-growing stockpiles of weapons-usable fissile material in the civilian sector, has all but removed the primary obstacle for would-be nuclear terrorists. Unless radical steps are taken urgently, it will not be a question of *whether* terrorists can acquire or build a nuclear device, but *when*. The simplest crude bomb design would use increasingly available plutonium oxide. Successful construction and use of such a device could kill or wound tens of thousands of people. Even if it fails to detonate properly in a nuclear explosion, the possible threat of widespread radioactive dispersion of the plutonium makes this weapon a particularly attractive weapon of terror.

Part II of the report presents estimates, based on a computer simulation, of the health and environmental effects of a "plutonium dispersal weapon" that produces no nuclear explosion. As the authors explain, some of these estimates are clearly questionable, because of important limitations in the computer model, but are aimed at beginning debate and action on the subject. Nonetheless, the principal conclusions appear quite solid: significant numbers of short-term physical health problems from radiation exposure are very unlikely, but thousands of additional cases of cancer would be expected over the ensuing 50 years. The most important immediate problem would be the severe social disruption that would likely result from widespread fear of radioactive contamination of the city and surrounding area.

As Part III makes clear, if our cities are to survive the 21st century, citizens throughout the world must unite in an urgent global campaign for the permanent elimination of all nuclear weapons, including establishment of the tightest possible international control of all weapons-usable fissile materials. The ingredients for an effective international strategy to prevent nuclear terrorist attacks are not radically different from the requirements for a comprehensive nuclear abolition regimen. Indeed, the increasing threat of nuclear terrorism should provide powerful impetus to the work of nuclear abolitionists.

Since IPPNW announced its commitment to an Abolition 2000 campaign in December 1994, hundreds of non-governmental organizations have joined together to work for the conclusion of an international agreement, by the year 2000, committing the world's governments to a firm timetable for the elimination of nuclear weapons. Many have already begun plans for "Abolition 2000: The Cities Campaign," which aims to mobilize the mayors and citizens of all the world's cities in support of nuclear abolition. Included in the Appendix is a simple guide by which any person can estimate the casualties resulting from a nuclear explosion on his or her own city.

It is our hope that this report will be a useful tool for all our Abolition 2000 partners, both present and future, as they work to safeguard our cities and our civilization for our children, grandchildren, and generations beyond.

Lachlan Forrow, M.D.
Chair, Board of Directors, IPPNW

Gururaj Mutalik, M.D.
Executive Director, IPPNW

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# Foreword

The disease of nuclearism, inflamed by the Cold War, has not abated with the end of the malignant East-West rivalry that had set it in motion. With the dissolution of the Soviet Union, it was widely believed that the nuclear stockpiles would at last be dismantled. This hope remains frustrated. While nuclear arsenals have been reduced, and further reductions are in the offing, the nuclear powers are not committed to abolition except as a remote possibility in a distant future. In fact, the recent unconditional and indefinite extension of the Non-Proliferation Treaty indicated that a majority of nations have acquiesced to the status quo. The nuclear powers justify their possession as a deterrent against nuclear blackmail by rogue states. Yet, paradoxically the very fact that some nations are permitted to stockpile nuclear weapons is a stimulus for proliferation and hastens the day when terrorism will go nuclear.

World power now closely parallels nuclear might. The fact that all members of the United Nations (UN) Security Council are nuclear club members punctuates this political reality. In an age of jealously competing sovereign states, the possession of nuclear weapons by the powerful invites emulation. As the *New York Times* editorialized, “The nuclear powers cannot continue to emphasize how essential nuclear arms are and at the same time expect other states to forgo them forever.” (4/17/95)

Nuclear apartheid cannot endure. The stimulus to proliferation derives largely from an inequitable world order and the growing economic divide between rich and poor countries. One fifth of the world lives on the edge of subsistence. At a time of potential abundance, more people are hungry than ever before. We end the century with far more desperately poor, illiterate, homeless, starving, and sick than we began. Nowhere are the inequities more in evidence than in the health sector. Eight hundred million people are without any health care at all. One-third of the world’s population lives in countries whose health care expenditures are far less than $12 per person per year (the bare minimum recommended by the World Bank) while the industrialized North spends more than $1,000 for health per person annually.

Recent UN figures indicate that from 1960 to 1990, per capita income rose eight-fold in the North while increasing only half as much in the deprived lands of the South. This divide is likely to widen further while accelerating over-consumption in the North and burgeoning population pressures in the developing countries. As vital raw materials, scarce minerals, fossil fuels, and especially water become depleted, Northern affluence will be sustained by imposed belt tightening of impoverished multitudes struggling for mere subsistence. This is an agenda for endless conflict and colossal violence.

The global pressure cooker will further superheat by the ongoing worldwide information revolution that exposes everyone to the promissory note of unlimited consumption, thereby instilling impatience and igniting more embers of social upheaval. If desperation grows, the deprived will be tempted to challenge the affluent in the only conceivable way that can make an impact, namely by going nuclear. Their possession enables the weak to inflict unacceptable damage on the strong.

Desperation and hopelessness breed religious fundamentalism and provide endless recruits ready to wreak vengeance, if necessary by self immolation in the process of inflicting unspeakable violence on others. A nuclear bomb affords “the cheapest and biggest bang for the buck.” No blackmail is as compelling as holding an entire city hostage. No other destructive device can cause greater societal disruption or exact a larger human toll. Terrorists will soon raise their sights to vaporizing a metropolitan area rather than merely pulverizing a building.

Such nuclear-inflicted mayhem could not be carried out without state sponsorship. The Middle East and South Asia provide numerous examples of governments promoting acts of terror by their ownsecret services or through proxy fanatical groups. Mastering nuclear bomb technology is increasing achievable by any sovereign state with the political will to do so. Existing nuclear armories constitute a source of the essential bomb ingredients. The more nations go nuclear, the greater the chance of these weapons being used by terrorists.

Nuclear know-how is widely disseminated. Thousands of nuclear engineers and scientists from the former Soviet Union are jobless and eager to practice their skills. Enriched fissile material is in abundant supply, with 65 tons of plutonium produced annually in civilian nuclear-power reactors. The stockpile will reach 1,600 tons by the year 2000. Frank Barnaby makes clear in Part 1 of this report that if only low technology were available, 6 kilograms of weapons-grade plutonium suffices for designing a 20-kiloton bomb of the size that devastated Nagasaki. The stockpiled plutonium is therefore equivalent to about a quarter-of-a-million nuclear devices each capable of laying waste to a large urban area.

One can puzzle with dismay that industrialized nations are not leading the pack in the quest for nuclear abolition. Yet, few societies are more susceptible to the malevolent consequences of a nuclear detonation than rich, urbanized, highly developed, industrialized countries. Their long-range security is categorically undermined by the spread of nuclearism. Nuclear weapons afford them scant advantage as they already command awesome military establishments capable of projecting their might speedily to the most remote corners of the earth.

At the dawn of the Atomic Age, physicians argued that for a disease without a cure, prevention is the exclusive remedy. A half century into the Nuclear Age, the case needs unequivocal restatement. Only total elimination of these genocidal weapons can guarantee that they will be never used again. The logic of this position is now being embraced by a number of former nuclear hawks, such as Robert MacNamara, former US Defense Secretary; General Andrew Goodpater, former NATO commander; and Air Force General Charles Horner, former head of the US Space Command.

From its inception, IPPNW maintained that political leaders respond not to historical imperatives but to the clamor of their constituencies. A well-informed public is not indispensable for this clamor to be sustained and effective. *Global Health Watch: IPPNW's Information Series* is part of an ongoing attempt to recruit the widest public in its campaign Abolition 2000, committed to the elimination of nuclear weapons from the arsenals of nations.

The onrushing new millennium can galvanize moral arousal to assure that the violent detritus spawned in our murderous century does not pass the threshold into the new age. Perhaps no obligation to future generations is more morally compelling than removing the nuclear sword of Damocles hovering over humankind.

Bernard Lown, MD
Co-Founder, IPPNW

As horrible as the tragedies in Oklahoma City and the World Trade Center were, imagine the destruction that could have resulted had there been a small nuclear device exploded there.

President Clinton
May 1995

This glass ball, about 8 cm in diameter, is the size of the plutonium core in the bomb exploded over Nagasaki. *Photo by Robert Del Tredici.*

# Issues Surrounding Crude Nuclear Explosives

## Part 1

**Frank Barnaby**

## Overview

The end of the Cold War has greatly reduced the risk of an imminent nuclear world war, but other nuclear risks have increased. These risks are related to the diversion of fissile materials — highly-enriched uranium or plutonium — by governments or sub-national groups for the fabrication of nuclear weapons or other nuclear explosive devices.

Any proliferation of nuclear weapons to countries that do not now have them will increase the risk that nuclear weapons will be used in a future war in an unstable region. Partly for this reason, the nuclear-weapon powers are anxious to prevent other countries from acquiring nuclear weapons.

However, a world where five states — China, France, Russia, the United Kingdom and the United States (the five permanent members of the UN Security Council) — are allowed to openly possess nuclear weapons while all other countries are required to renounce them is not sustainable. If this situation continues, nuclear weapons will inevitably spread. The nuclear-weapon powers therefore have a simple choice. They must either negotiate an international convention abolishing nuclear weapons or face an extremely unstable world of many nuclear-weapon powers in the near future. While the international community is trying to prevent the further spread of nuclear weapons, the political leaders and some of the military leaders of the nuclear-weapon powers try to justify the continued possession of nuclear weapons by claiming that they have significant utility. The nuclear-weapon powers cannot have it both ways. Unless they show by their behavior that they no longer believe that nuclear weapons have any utility, they must expect other countries to acquire them, and — sooner or later — our cities will begin to explode.

For the political leaders of the nuclear-weapon powers, the utility of their nuclear weapons may be confined to their mere possession. The actual use of the weapons may not enter their calculations. For example, so far as British and French politicians are concerned, the political utility of their nuclear weapons may be primarily to retain their permanent seats on the UN Security Council.

The fact is that very powerful conventional weapons can now be delivered with such precision that the use of nuclear weapons cannot be militarily or otherwise justified. The moral, legal, military and political reasons against the use of nuclear weapons are so strong that even military leaders advocate the use of conventional weapons as the preferred option under all imaginable circumstances.

Nevertheless, some continue to argue for the development and deployment of new types of nuclear weapons, including low explosive yields or so-called mini-nukes. The US nuclear-weapon laboratories, for example, are particularly keen on this new generation of nuclear weapons, largely to help justify the laboratories' continued existence. With explosive yields up to that of a thousand tons of TNT and accurately delivered to their targets by missiles, mini-nukes are, incredible though it may seem in the 1990s, seen by proponents to be usable on battlefields in future Third World conflicts. It is also argued that they would be useful in countering nuclear proliferation.

**Declared Nuclear-Weapon States**

China
France
Russia
United Kingdom
United States

**De Facto Nuclear-Weapon States**

India
Israel
Pakistan

**States with Suspected Nuclear-Weapon Ambitions**

Iran
Iraq
Libya
North Korea

So far, the mini-nuke argument has evaded public debate and scrutiny. Those from nuclear-weapon countries anxious to maintain and modernize the nuclear arsenals are using the fear of nuclear-weapon proliferation and nuclear terrorism as a smoke screen behind which to plan the research and development of their nuclear arsenals.

Bearing in mind that the nuclear-weapon powers are continuing to modernize their nuclear arsenals (*vertical proliferation*), it is important not to underestimate the risks arising from the spread of nuclear weapons to countries that do not now have them (*horizontal proliferation*) and the increasing risk of nuclear terrorism. The aim of this publication is to put these risks into perspective.

A useful debate on these issues requires some knowledge of the types of nuclear weapons likely to be of interest to horizontal proliferators, particularly smaller countries and sub-national groups. The first section will, therefore, describe the main components required to assemble a basic nuclear-fission weapon, which obtains all its explosive energy from nuclear fission. Both the implosion type of nuclear weapon, using plutonium or highly-enriched uranium, and gun-type, using highly-enriched uranium, will be described. Designers of these basic types of nuclear weapon would be so confident that their weapons would work that they would not need to test them using nuclear explosions. The weapons could, therefore, be fabricated and deployed clandestinely. South Africa is a prime example of a country that succeeded in carrying out such a clandestine nuclear program.

For decades, virtually all of the technical information necessary to build a crude nuclear weapon has been in the open scientific literature. The information presented in Part 1 is neither new nor technically complete. The difficulty of obtaining the necessary fissile materials to build a bomb has prevented this from happening. This may not be the case for much longer. This book is intended to raise public awareness in order to prevent nuclear terrorism.

# Nuclear-Explosive Devices by Sub-National Groups

Now that the Cold War is over, the fear of an imminent nuclear world war is greatly reduded. The main nuclear threat to global security is now reckoned to arise from the future spread of nuclear weapons to countries that do not now have them. There are concerns that Iran, Iraq, and North Korea have ambitions to become nuclear-weapon powers, although in practice it is unlikely that a new nuclear-weapon power will emerge in the next ten or fifteen years.

During this period, civil nuclear technologies will spread far and wide, as will the technologies for the production of ballistic missiles. This combination will be a very dangerous one and could lead to the spread of nuclear weapons at a fast rate.

Although it is unlikely that additional states will acquire nuclear weapons in the short term, the risk that state-sponsored or sub-national groups, such as terrorist groups, will acquire them is increasing. Nuclear proliferation with its potential for nuclear terrorism has replaced a nuclear world war as the most serious nuclear threat in the post Cold-War world, at least in the short term.

Sub-national groups had, until recently, believed that their aims would not be furthered by indiscriminately killing large numbers of people, including women and children, and/or contaminating large areas. But these groups continually feel the need to move to higher levels of violence. We have seen the level escalate from the sabotage of the Air India and PanAm jumbo jets to the Tokyo nerve gas attacks. With the explosion of a massive fertilizer and fuel-oil bomb in Oklahoma City, repeated explosions in Paris, and suicide bombings in Israel, terrorists drew no limits for whom they attacked or the methods they used. The moral restraints on mass killing are weakening, and the way is opening for the use of weapons of mass destruction — nuclear, biological, and chemical weapons. News reports indicated that Aum Shinrikyo scientists, responsible for the Tokyo attacks, had met with ex-Soviet nuclear specialists and had shown a strong interest in acquiring nuclear weapons.

It is perhaps not surprising that the trend of increasing violence that we see in society, as well as in wars, also extends to terrorism. Terrorists are now beginning to believe that only extremely violent actions will earn TV coverage, alongside the great violence of inter-state and civil wars. And TV coverage is an essential ingredient of a successful terrorist action, where “coercive terror” is used for political ends. The next rung on the terrorist ladder of escalation may well be the acquisition and use of a nuclear weapon. Until recently, most commentators argued that the most likely way in which a sub-national group would acquire a nuclear explosive would be by stealing a nuclear weapon either from a military stockpile or while it was being transported.

This fear has, with good reason, been enhanced by the break up of the former Soviet Union and the economic and social upheaval now evident in Russia. Will the 30,000 or so nuclear weapons in the ex-Soviet arsenal stay in safe hands? The majority of weapons may be relatively secure while they are in the hands of the military and the security service. But the risk that a few of them may get into the wrong hands is significant. Also troublesome is that if they do, we may not know it. It is very doubtful that a complete inventory of the ex-Soviet nuclear weapons exists. The Soviet bureaucracies were so confident that their nuclear weapons were safe that they may not have recorded them all.

But it is not only the fate of ex-Soviet nuclear weapons that we should worry about. As plutonium and highly-enriched uranium become more available worldwide, it is becoming increasingly possible for a sub-national group to steal, or otherwise illegally acquire, civil or military weapon-usable fissile material and fabricate its own explosive device with which to detonate it.[1] Concern about the theft of fissile materials has been considerably enhanced by recent incidents of the smuggling of such materials from Russia. For example, in December 1994, 3 kilograms (kg) of highly-enriched uranium was seized by the Czech authorities. And there are reports that nearly 400 kg of weapons-grade uranium had been confiscated by security police in December 1993 in Odessa in Ukraine. And during 1994, more than 400 grams of weapons-grade plutonium was seized in Germany. These and other smuggling incidents, which are almost certainly the tip of an iceberg, leave no doubt that a black market in fissile materials exists.[2]

The threat that a terrorist group will fabricate a nuclear explosive is not the only nuclear threat. Another is that a terrorist group could acquire plutonium and disperse it using a conventional explosion and an accompanying fire, contaminating a large urban area with radioactive isotopes. The second threat may be more likely than the first because it is simpler to achieve.

## Nuclear Terrorism

Terrorist groups have shown themselves to be sophisticated and skilled. The construction of the explosive device that destroyed the PanAm jumbo jet over Lockerbie, for example, required considerable expertise, as did the construction of the nerve gas weapon used in the Tokyo subway. The groups now have access to professional scientific and technical skills and to large sums of money.

Now with the increasing availability of weapons-usable fissile materials, the availability in the open literature of the technical information needed to design and fabricate a nuclear explosive, and the small number of competent people necessary to fabricate a primitive or crude nuclear explosive, we have cause for considerable concern.

Konrad Kellen lists a number of nuclear terrorist threats:

> making or stealing of a nuclear weapon and its detonation; the making or stealing of a nuclear weapon for blackmail; the damaging of a nuclear plant for radioactive release; the attack on a nuclear-weapons site to spread alarm; the attack on a nuclear plant to spread alarm; the holding of a nuclear plant for blackmail; the holding off-site of nuclear plant personnel; the theft of fissionable material for blackmail or radioactive release; the theft or sabotage of things nuclear for demonstration purposes; and an attack on a transporter of nuclear weapons or materials.[3]

This chapter will, however, concentrate only on possible designs of the crude or primitive nuclear explosives that may be considered useful by sub-national groups and the level of skills required for their construction. Three designs of crude nuclear explosives, adequate for most purposes of a group intent on nuclear terrorism, will be considered. The first is a gun-type nuclear explosive device using highly-enriched uranium as the fissile material. This is the simplest crude device to design and construct and the most likely one to produce a powerful nuclear explosion, possibly with an explosive yield of up to several kilotons. However, at present it would be harder for a terrorist group to acquire highly-enriched uranium than plutonium since almost all highly-enriched uranium is currently under military control. As described below, this situation will change as this bomb material moves to the civilian sector with the dismantlement of nuclear weapons. The second is an implosion-type device using a solid sphere of plutonium metal as the fissile material. This is essentially a crude version of the atomic bomb which destroyed Nagasaki. It is the most difficult of the three to design and construct, but is, as described below, within the capabilities of a large, well-financed terrorist group. It would, however, be difficult, although not impossible, to obtain with this design a nuclear explosion with an explosive yield greater than 10 or 15 kilotons (KT) using reactor-grade plutonium. The third is an implosion type device using plutonium oxide as the fissile material. This is perhaps the most likely nuclear device to be constructed by terrorists because of the increasing and widespread availability of plutonium oxide. It is likely that such a device would produce an explosive yield of tens, or hundreds, of tons, although it may also be attractive to terrorists because of the threat of the widespread dispersion of large amounts of plutonium even if the device produces no nuclear explosion.

To put the potential destructive force of crude nuclear weapons in perspective, the largest conventional bombs used in warfare so far had an explosive power equivalent to about 10 tons of TNT; it was christened "The Earthquake Bomb." This analogy (as well as the table to the left) ignores the effects of the ionizing radiation that is the essential characteristic of nuclear explosions.

### Arithmetic of Destruction

**Perspectives on Explosive Power**

| Explosive | TNT Equivalent |
|---|---|
| Nagasaki Bomb | 22 kilotons* |
| Hiroshima Bomb | 12.5 kilotons |
| Largest Conventional | 10 tons |
| Largest Terrorist Attack, Beirut | 5 tons |
| Khobar Towers, Saudi Arabi | 2.5 tons |
| Federal Building, Oklahoma City | 1.5 tons |
| World Trade Center, New York | 1 ton |

* All figures are approximate for general comparison.

## Nuclear Options for Terrorists

**Design:** Gun-Type Using Highly-Enriched Uranium
**Required Mass of Fissile Material** = 40 kilograms
**Potential Destructive Force** = 10 kilotons

Simplest fo design and construct, but more difficult for terrorists to obtain highly-enriched uranium than plutonium. Most likely to produce large explosion. Could be transported by, and detonated in, a vehicle. Design would be crude version of Hiroshima bomb.

**Design:** Implosion-Type Using Solid Plutonium Metal Sphere
**Required Mass of Fissile Material** = 8 kilograms
**Potential Destructive Force** = 10 kilotons

Most difficult device for terrorists to design and construct, but within the capabilities of a small, well-financed group. Requires specialized skills, facilities, materials, and tools. Difficult, but not impossible to produce large explosion using converted reactor-grade plutonium. Design would be crude version of Nagasaki bomb.

**Design:** Implosion-Typle Using Plutonium Oxide
**Required Mass of Fissile Material** = 35 kilograms
**Potential Destructive Force** = 10s to 100s of tons

The most likely choice for terrorists because plutonium oxide is more available and is simpler and safer to handle. Difficult to predict the explosive force, but is attractive to terrorists due to the threat of widespread radioactive dispersal. Mixed with incendiary materials, it could carry plutonium over a wide area.

## Terrorist Use of Highly-Enriched Uranium

There is a good deal of misunderstanding about the ease with which a subnational group could fabricate a nuclear explosive. Frequently, the precise type of nuclear weapon being discussed is not defined and this leads to inaccurate and misleading statements. Obviously, relatively unsophisticated devices, of a type which would satisfy the requirements of a terrorist group, are much easier to design and fabricate than the very sophisticated nuclear weapons required by the military.

An example of lack of clarity about the sort of nuclear device under consideration is a US Pentagon report, entitled *World Commerce in Nuclear Material*, which states that "the prevailing view among experts appears to be that fabrication of a bomb, even with high-grade weapons-usable material, would be extremely difficult but not impossible for a well-organized, well-financed terrorist group." What is meant by "bomb" is not explained, although the report suggests that it means "low-yield nuclear explosive device," not necessarily the simplest nuclear device.

While it is harder to obtain highly-enriched uranium, a terrorist group would find it easier to fabricate a nuclear device using highly-enriched uranium than one using plutonium, even weapons-grade plutonium. This is because:

> the neutron source from spontaneous fission in such material is smaller than in even the best grades of plutonium by a factor of more than a thousand. In the relatively slow-moving gun-type device one might wish to assemble a couple of critical masses or so, which would imply bringing together something like 50 kg of 94% U-235, since the critical mass with a reflector can be about half the bare critical mass of 52 kg.[4]

Luis Alvarez, a nuclear-weapon physicist, has emphasized the ease of constructing a nuclear explosive with highly-enriched uranium:

> With modern weapons-grade uranium, the background neutron rate is so low that terrorists, if they have such material, would have a good chance of setting off a high-yield explosion simply by dropping one half of the material onto the other half. Most people seem unaware that if separated HEU is at hand it's a trivial job to set off a nuclear explosion....even a high school kid could make a bomb in short order.[5]

Although by today's standards gun-type nuclear weapons are primitive, the design was chosen by South Africa in the 1970s for its military nuclear weapons. On March 24, 1993, then-President F. W. de Klerk surprised the world by announcing simultaneously to the South African parliament that South Africa had clandestinely built nuclear weapons and that it had dismantled them. According to de Klerk, South Africa fabricated six gun-type nuclear weapons, and the fissile components for a seventh, uncompleted device.

The nuclear weapons used highly-enriched uranium in a gun-type assembly. A mass of highly-enriched uranium, less than the critical mass, would be fired down a cylinder, into another less-than-critical mass of highly-enriched uranium placed at the end of the cylinder, forming a super-critical mass and creating a nuclear explosion. The smaller mass of uranium would be fired down the barrel, using a high-explosive charge placed behind it, into the larger mass, so that the critical mass would be formed quickly, and the fissile material would not be blown apart prematurely. The gun-type assembly requires a relatively large amount of highly-enriched uranium. On average, each South African nuclear weapon contained about 55 kg of highly-enriched uranium, enriched to about 90% in the isotope U-235 (the gun-type weapon dropped on Hiroshima contained about 60 kg at 80%). A mass of about 15 kg was to be fired down a barrel into a hollowed-out mass of about 40 kg[6] But, according to South Africa's Atomic Energy Corporation, there was no form of neutron initiator in its weapons, unlike most modern weapons. The designers relied on stray neutrons in the atmosphere, from, for example, cosmic rays, to initiate the fission chain reaction and, therefore, the nuclear explosion.

Each weapon was provided with a tungsten reflector, to reflect neutrons which escaped from the highly-enriched uranium while the fission chain reaction was underway, thereby increasing the efficiency of the weapon. The South African weapons each had an explosive yield of between 10 and 18 kt, were between 1.5 and 1.8 meters (m) long, with diameters of about 70 centimeters (cm), and weighed about 900 kg.

The design of South Africa's nuclear weapons was simple but effective. By today's standards, they were primitive weapons, museum pieces. However, a terrorist group could copy the design without much difficulty. It could even copy the fail-safe system used to prevent a nuclear explosion if the propellant went off accidentally: the cylinder used as the "gun barrel" was in two sections, normally kept out of alignment; to prepare the weapon for use, a small motor would rotate one section so that it locked in line with the other. It is, however, unlikely that a terrorist group would bother with this precaution.

A primitive gun-type weapon could use a thick-walled cylindrical "barrel", with an inner diameter of about 8 cm and a length of about 50 cm. A 15 kg cylindrical mass, 8 cm in diameter and 16 cm in height, would be suitable. A larger mass of uranium, weighing about 40 kg, about 15.3 cm in diameter, and about 16 cm in height, and with a hollowed out cylinder about 8 cm in diameter and 16 cm in height so that the smaller mass would fit snugly in it, would be placed at the bottom of the barrel.

A high-explosive charge would be placed at the top of the barrel, behind the smaller mass of uranium. This charge could be fired from a distance by a remote-control device operated by an electronic signal. The total length of the nuclear explosive device should be no more than about 1 m and its diameter about 25 cm. It should weigh no more than approximately 300 kg. It could thus easily be transported by, and detonated in, an ordinary van. A crude nuclear weapon using highly-enriched uranium should explode with an explosive power equivalent to that of several hundred to a few thousand, tons of TNT.

A significantly large terrorist group should have little difficulty in building a crude or primitive nuclear explosive device using highly-enriched uranium. The main problem the group would face is acquiring a large enough quantity of highly-enriched uranium (about 55 kg of uranium enriched to about 90% in U-235). Its illegal acquisition is likely to become easier as time goes on. As more American and ex-Soviet nuclear weapons are dismantled under disarmament treaties, the highly-enriched uranium removed from them will move from military control to civilian control, where its security is likely to be much more lax.

## Terrorist Use of Plutonium

Now and in the near future, a terrorist group may find it easier to acquire civil plutonium than highly-enriched uranium. The amount of separated plutonium available from civil reprocessing plants will rapidly increase, particularly as more reprocessing capacity becomes operational. This will be stored in a number of countries and will become easier to obtain illegally. Some officials believe that plutonium produced in nuclear-power reactors cannot be used in nuclear weapons or nuclear explosive devices. For example, Ambassador Ryukichi, former Japanese Ambassador for Non-Proliferation, stated: “Reactor-grade plutonium is of a nature quite different from what goes into the making of weapons...Whatever the details of this plutonium, it is quite unfit to make a bomb.”[7]

This statement is totally incorrect. The truth is that “All plutonium can be used directly in nuclear explosives. The concept of ...plutonium which is not suitable for explosives is fallacious. A high content of the plutonium 240 isotope (reactor-grade plutonium) is a complication, but not a preventative.”[8] And in the words of Hans Blix, Director General of the International Atomic Energy Agency, “The Agency considers high burn-up reactor-grade plutonium and in general plutonium of any isotopic composition...to be capable of use in a nuclear explosive device. There is no debate on the matter in the Agency’s Department of Safeguards.”[9] That reactor-grade plutonium can be used to fabricate nuclear weapons was proven by the US when it exploded at least one such device in the 1960s.

After plutonium has been removed from spent reactor fuel elements in a reprocessing plant, it is normally stored as the oxide (PuO2), rather than plutonium metal. If plutonium is stolen from a reprocessing plant it is, therefore, likely to be in the oxide form. A primitive nuclear explosive using plutonium would yield an explosion equivalent to that of more than 10 kt of TNT (like the design using highly-enriched uranium) if the plutonium was in metal form, using a design similar to that of the Nagasaki bomb. To convert the oxide into plutonium metal is a straight-forward chemical process.

A small group of people with appropriate skills could design and fabricate such a crude weapon, without access to classified literature. Amory B. Lovins, for example, a competent nuclear physicist, published all the physics data needed to design a crude nuclear device in the scientific journal *Nature*. The group would need access to machine-shop facilities, which could be hired. The machining of plutonium metal, to shape it into a sphere, for example, should be done in a fume cupboard, preferably in an atmosphere of an inert gas like argon.

A sub-national group would probably use an amount of plutonium close to the critical mass — about 8 kg of plutonium metal — so that it would not be necessary to use shaped conventional high explosives to compress the plutonium to produce a super-critical mass. It would be sufficient to simply stack the explosives around the plutonium. A large number of detonators — 50 or 60 — positioned in the conventional high explosive would produce a shock wave symmetrical enough to compress the plutonium satisfactorily. These detonators should be fired as simultaneously as possible. This can be done using an electronic circuit that generates a high-voltage square wave. The detonators could be fired by remote control.

## Terrorist Use of Plutonium Oxide

The construction of a nuclear explosive device using plutonium oxide is much simpler than that of one using plutonium metal. The oxide is safer to handle — plutonium metal may, for example, burst into flames in air (as sodium does) — and using this avoids the stage of conversion from the oxide to the metal. The disadvantage with plutonium oxide is that the critical mass is much higher than that of the metal. The critical mass of reactor-grade plutonium in the form of plutonium-oxide crystals is about 35 kg. If in spherical shape, this would be a radius about 9 cm compared to plutonium metal 13-20 kg.

In a crude nuclear explosive device, the plutonium oxide could be contained in a spherical vessel placed in the center of a large mass of a conventional high explosive. A number of detonators would be used to set off the explosive, probably by remote control. The shock wave from the explosion could compress the plutonium enough to produce some energy from nuclear fission. To maximize the probability of getting a significant amount of fission energy through a relatively small amount of compression, the amount of plutonium oxide used should be close to the critical mass. To achieve this, a neutron counter could be set up close to the containing vessel as it is being poured in. As soon as the counter indicates the presence of neutrons, the pouring should be stopped because the mass of oxide would then be close to critical.

The size of the nuclear explosion from such a crude device is impossible to predict. Such a device should have an explosive power of at least a hundred tons. An explosive force equivalent to 1,000 tons or more is not impossible, though unlikely. But even if it were only equivalent to the explosion of a few tens of tons of TNT, it could devastate the center of a large city. The explosive power of the device will depend mainly on how close to critical the mass of the plutonium oxide is. This, in turn, will depend on the risk the people making the device are prepared to take. If they get to close to criticality, they may be exposed to a strong burst of neutrons. Irradiation by neutrons is a major health hazard. The explosive power also depends on how effectively the explosion compresses the plutonium oxide sphere. Some of the energy released by the explosion will not go into the plutonium oxide; and some will heat it up instead of compressing it. Also, a more symmetrical compression will give a larger explosion. This is achieved by using a large number of detonators to set off the high explosive. The detonators could, again, be fired simultaneously by a circuit generating a high-voltage square wave with a fast rise time.

A crude nuclear device constructed by a terrorist group could be contained in a vehicle such as a van. The van could be positioned so that even if the device, when detonated, did not produce a significant nuclear explosion, the explosion of the chemical high explosives would widely disperse the plutonium. If incendiary materials were mixed with the high explosives, the explosion would be accompanied by a fierce fire. The plutonium would burn in the fire, producing small particles, which would be taken up into the atmosphere in the fire-ball and scattered far and wide downwind. Many of the particles would be small enough to be inhaled into the lung, where they would become embedded and would irradiate the surrounding tissue with alpha-particles, given off when the plutonium nuclei underwent radioactive decay. Irradiation by alpha-particles is very likely to cause lung cancer.

The threat of dispersion makes a crude nuclear explosive device using plutonium a particularly attractive weapon for nuclear terrorists. The widespread dispersal of large amounts of plutonium over an area of a city could make the area uninhabitable until it was decontaminated —a procedure which could take many months. The great fear of radioactivity among the general population considerably enhances the threat. Mere possession of plutonium by a terrorist group could be used to blackmail a government. The government would not need to be convinced that the group had the expertise to design and construct an effective nuclear explosive device. It would know that even an ineffective nuclear device would scatter plutonium over a large area, and this would be threat enough for the terrorists' purposes given the ensuing combination of health risks and social disruption. (See Part II for a detailed analysis of the immediate- and long-term implications of a plutonium dispersal weapon.)

## Could a Terrorist Group Make a Nuclear Explosive?

This question has been addressed by the scientists at the Office of Technology Assessment (OTA) of the US Congress. The OTA's conclusion is that:

> A small group of people, none of whom have ever had access to the classified literature, could possibly design and build a crude nuclear explosive device. They would not necessarily require a great deal of technological equipment or have to undertake any experiments. Only modest machine-shop facilities that could be contracted for without arousing suspicion would be required. The financial resources for the acquisition of necessary equipment on open markets need not exceed a fraction of a million dollars. The group would have to include at a minimum, a person capable of researching and understanding the literature in several fields and a jack-of-all trades technician. There is a clear possibility that a clever and competent group could design and construct a device which would produce a significant nuclear yield (i.e., a yield **much** greater than the yield of an equal mass of high explosive).[10]

There are some potential hazards in constructing a crude nuclear explosive device. They include:

> Those arising in the handling of a high explosive; the possibility of inadvertently inducing a critical configuration of the fissile material at some stage in the procedure; and the chemical toxicity or radiological hazards inherent in the materials used.[11]

However, Lovins argues that the hazards should not be exaggerated. He shows that the radiation dose rates from plutonium — including reactor-grade plutonium oxide — are such that they would not deter a person from handling it, and also that, by taking sensible precautions against achieving criticality accidentally (such as using a neutron counter to detect any neutrons emitted during the assembly of the plutonium), a terrorist group constructing a nuclear explosive would not face serious radiological hazards. In any case, in an era when suicide car bombings are undertaken without hesitation, such a group would probably be prepared to take some risks to achieve their purposes.

The explosive yield of a crude nuclear device using reactor-grade plutonium as the fissile material would be unpredictable. But this is not likely to bother a terrorist group. The group is likely to be satisfied with any yield above the equivalent of ten tons of TNT or so and such a device would disperse plutonium, even if there was no nuclear explosion.

# The Design of Nuclear-Fission Weapons

## The Fission Process

Isotopes able to sustain a fission chain reaction when they capture neutrons are called *fissile isotopes*. The most important fissile isotope of plutonium is plutonium-239 (Pu-239); the most important fissile isotope of uranium is uranium-235 (U-235). The nuclei of isotopes U-235 and Pu-239 undergo fission when they absorb (capture) any neutron, even one moving very slowly. In contrast, the nuclei of other isotopes of uranium and plutonium, such as U-238 and Pu-241, undergo fission only when they capture a neutron which has a velocity above a certain value. A chain reaction is, therefore, more possible using fissile isotopes like U-235 or Pu-239.

For example, when a nucleus of U-235 captures a neutron, a nucleus of the isotope U-236 is formed. The U-236 nucleus is very unstable and rapidly splits (undergoes fission) into two fragments (the fission fragments), which are nuclei of elements of lower atomic number. Similarly, if a Pu-239 nucleus captures a neutron, Pu-240 will be formed — this is also very unstable and rapidly undergoes fission. In both of these fission processes, neutrons (on average between two and three) and a burst of energy are emitted, as well as the fission products. The fission process can be represented by:

U-235 + neutron —> U-236 —> X + Y + 2.5 neutrons + energy
or
Pu-239 + neutron —> Pu-240 —> X + Y + 2.5 neutrons + energy.

Energy is released because the total sum of the masses of the fission products and neutrons is less than the mass of the "parent nucleus." The energy accompanying fission is equal to this mass difference multiplied by the square of the velocity of light (E=mc2). Although the mass difference is very small, the square of the velocity of light is a huge number and, therefore, the amount of energy given off is very large. In fact, the complete fissioning of one gram of U-235 would release about 23,000 kilowatt-hours of heat.

## Critical Masses

A basic nuclear weapon, of the type considered in this report, relies entirely on a nuclear fission chain reaction to produce a large amount of energy in a very short time — less than a millionth of a second — and, therefore, a very powerful explosion. A nuclear weapon can be fabricated from either Pu-239 or U-235; some nuclear weapons use both. Uranium-233 is also a fissile isotope, but it has not so far been used to a significant extent in nuclear weapons.

The minimum condition for maintaining a fission chain reaction is that, for each nucleus undergoing fission, at least one product neutron causes the fission of another nucleus. In a nuclear weapon, a fission chain reaction is produced and maintained for a long enough time to produce an explosion with the required explosive yield. The minimum mass of a fissile material that can sustain a nuclear fission chain reaction is called the *critical mass*.[12]

If this mass of material is exceeded, more neutrons are produced, and hence considerably more fissions occur, in each successive generation of fission. A nuclear explosion takes place when the number of neutrons within the fissile material increases rapidly and uncontrollably. A basic nuclear-fission weapon contains fissile material weighing less than the critical mass, so that the weapon does not explode prematurely. During detonation, its density is increased such that the critical mass is exceeded (a process called *assembly*), thus producing a nuclear explosion.

## Plutonium

Virtually all plutonium is man-made. Minute quantities, however, have been produced naturally in uranium deposits when uranium-238 nuclei have captured neutrons. There are various grades of plutonium, having different isotopic compositions, according to the way in which the plutonium is produced. Plutonium produced in commercial nuclear-power reactors, which are operated for the production of electricity, is called *reactor-grade plutonium*. Plutonium produced in military plutonium-production reactors, specifically for use in nuclear weapons, is called *weapons-grade plutonium*.[13] Plutonium may also be chemically extracted from MOX, or mixed oxide, reactor fuel, which contains a mixture of plutonium and uranium oxides.[14]

For the purposes of constructing a usable nuclear weapon, the distinction between "reactor-grade" and "weapons-grade" plutonium is somewhat artifical. In fact, reactor-grade plutonium *can* be used to fabricate nuclear weapons, and the United States exploded such a weapon in 1962. Nuclear-weapon designers, however, prefer weapons-grade plutonium. Reactor-grade plutonium contains a greater proportion of Pu-240,[15] which makes it less suitable for weapons applications. In fact, the less Pu-240 there is, the easier it is to use the material for a weapon.

The critical mass of reactor-grade plutonium is a little greater than that of weapons-grade plutonium. But the difference is not large — thirteen kilograms for a bare metal sphere of reactor-grade plutonium compared with 11 kg for weapons-grade plutonium.[16]

Whereas Pu-239 undergoes fission when it captures a neutron, Pu-240 undergoes fission spontaneously; it does not need an extra neutron. This means that in plutonium containing Pu-240 there is a flux of neutrons from spontaneous fission. For weapons-grade plutonium, the number of neutrons from spontaneous fission is 66 neutrons per second per gram; for reactor-grade plutonium, it is 360 neutrons per second per gram. The higher the number of spontaneous-fission neutrons, the greater the probability that the weapon will pre-detonate and explode with an unpredictable explosive yield. However, this can be compensated for by using faster implosion to compress a sub-critical mass into a super-critical one. The faster the implosion, the more predictable the yield of the nuclear explosion.

Another difference is the amount of heat generated by absorption of the alpha-particles produced by the radioactive decay of Pu-240. Weapons-grade plutonium generates about 2.5 watts per kg. A sphere of weapons-grade plutonium weighing about 4 or 5 kg, a typical weight used in a basic nuclear-fission

### Factors Influencing Critical Mass

- Nuclear properties of the fissile material.
- Shape of the material — a sphere is the optimum shape.
- Density of the fissile material — higher density is best.
- Purity of the fissile material.
- Physical surrounding of the material used for fission.*

* See footnote 12 for more information.

weapon, will have a temperature slightly higher than normal room temperature. It will feel slightly warm to the touch. Reactor-grade plutonium generates about 11 watts per kg. Measures must be taken to dissipate this excess heat if the material is used to fabricate a nuclear weapon. One possibility would be to use shells of plutonium (which would have a lower thermal capacity) rather than a solid sphere. Detonation of the high explosives would then force the shells together to form a super-critical mass.

Plutonium metal occurs in six different crystalline forms (called *phases*), depending on how it is produced. Each form has a different density, ranging from 15.92 to 19.80 grams per cubic centimeter (g $cm^{-3}$). As normally produced, plutonium metal is brittle and hard to machine into precise shapes. For use in nuclear weapons, plutonium is usually alloyed with gallium or indium. This makes it more machinable and prevents it from changing from one phase to another. It is important to prevent a phase change because the new phase will have a different density and hence a different volume, which may cause the shape to distort. One form of plutonium metal (called the *delta-phase*) is more stable (less likely to change phase) and more easily compressed than the other phases, so is more commonly used in nuclear weapons.

## Highly-Enriched Uranium

Naturally occurring uranium contains 0.7% U-235. Nuclear weapons use highly-enriched uranium, in which this proportion has been increased. A bare sphere of pure U-235 has a critical mass of 52 kg (compared with 10 kg for a bare sphere of pure Pu-239).[17] With uranium containing 93% U-235, the critical mass increases to 56 kg; with 40% U-235, it is 75 kg; and with 20% U-235, it is 250 kg. In practice, therefore, high concentrations of U-235 are needed for the manufacture of nuclear weapons. Weapons-grade highly-enriched uranium is normally regarded as uranium enriched to more than 90% in U-235. But uranium enriched to significantly lower percentages is still weapons-usable.

## Assembly Techniques

The *gun technique* can be employed in a nuclear weapon using enriched uranium. In this design, a mass of uranium less than the critical mass is fired into another less-than-critical mass of uranium. The sum of the two masses is greater than critical. In the Hiroshima bomb, for example, one mass of highly-enriched uranium was fired down the barrel of a naval gun into the second mass placed at the muzzle. The gun design is much simpler than the implosion design described below.

The gun technique is only used with highly-enriched uranium. This is because spontaneous fissions occur far more frequently in weapons-grade plutonium and may cause premature detonation while assembly is occurring.

The *implosion technique*, on the other hand, has an assembly time less than a tenth of that of the gun technique, so it can be used to assemble a super-critical mass of either highly-enriched uranium or plutonium. In a nuclear weapon using the implosion design, a sphere of fissile material (called the *core of the weapon*) is surrounded by conventional high explosives, such as TATB (triaminotrinitro-benzene) or HMX (cyclotetramethylenetetranitramine).

When detonated, the high explosive uniformly compresses the sphere of fissile material and increases its density. Critical mass is inversely proportional to the square of the density. Thus the originally less-than-critical mass of fissile material will, after compression, become super-critical, a fission chain reaction will take place, and a nuclear explosion will follow.

At the instant of maximum super-criticality, neutrons are fired into the fissile material from a "neutron gun"[18] to encourage the fission chain reaction. At this instant, the fissile material becomes liquefied, and its density may be increased to about ten times its original value.

The fissile material in the core of the weapon is surrounded by a spherical shell of a material such as beryllium that reflects back into the fissile material some of the neutrons which escaped through its surface without causing fission. The use of a neutron reflector significantly reduces the amount of fissile material needed for a critical mass. The beryllium shell is surrounded, in turn, with a shell of a heavy material, such as natural or depleted uranium, which acts as a tamper. The tamper is surrounded by the conventional high explosives. When the high explosives around the tamper are detonated, the shock wave produced causes the tamper to collapse inwards. The tamper converts the divergent detonation wave into a convergent shock wave. Its inertia helps to hold the fissile material together during the explosion, to prevent its premature disintegration, and thereby to obtain a larger explosion.[19] The same material, such as beryllium or uranium, can be used for both the tamper and the reflector. For example, a bare sphere of weapons-grade plutonium in the alpha-phase has a critical mass of 11 kg; the radius of a sphere of this weight is about 5 centimeters (cm) — about the size of a small grapefruit. If the plutonium sphere is surrounded by a natural uranium reflector, about 10 cm thick, the critical mass is reduced to about 4.4 kg, giving a sphere of radius about 3.6 cm — about the size of an orange.

The timing of the detonation of the chemical explosives is crucial for the efficient operation of the weapon; precision to the nearest thousandth of a millionth of a second is required. The shapes of the explosive segments (called explosive *lenses*) are complex and must be carefully calculated. The high explosive must be extremely pure and of constant consistency throughout its volume. Each explosive lens contains both fast and slow explosives. Normally, the more explosive lenses there are, the more symmetrical the shock wave and the more uniform the compression of the core. Typically, between 30 or 40 lenses are used in a nuclear-fission weapon. When detonated, the set of explosive lenses produce a shaped explosive front.

## Design and Manufacture

Nuclear weapons vary considerably in their complexity. The design of modern versions of the nuclear weapons that destroyed Hiroshima and Nagasaki would cause today's nuclear scientists and engineers little difficulty; all essential information required is in the open literature. The designers of these basic types of nuclear weapon could have sufficient confidence not to need to test their weapons, thus enabling clandestine manufacture and deployment.

Thermonuclear weapons, on the other hand, are much more complex. There are fewer details about their design in the open literature; designers would need access to sophisticated computers; and may need a program of nuclear testing (probably between five and ten tests) before deployment.[20] They could not, therefore, easily be deployed secretly.

### Components of Nuclear-Fission Weapons

If a country makes the political decision to manufacture nuclear weapons, it must acquire or produce a wide range of components. The main components required to assemble a nuclear weapon that obtains all its nuclear explosive yield from fission include:

- very high-quality conventional high explosives, having great purity throughout their volume;
- reliable detonators for these explosives;
- electronic circuits to fire the detonators in a very precise time sequence — typically, the circuit used to fire the detonators uses krytrons to generate short, high-current pulses which rise to amplitudes of about 4,000 volts in a few thousandths of a millionth of a second);[21]
- a tamper and a neutron reflector;
- a core of fissile material, preferably either weapon-grade plutonium or highly-enriched uranium (although reactor-grade plutonium or less enriched uranium could be used instead); and
- a neutron source to initiate the fission chain reaction.

The outermost component is the neutron gun. Then come the detonators, which operate from an electronic firing device — a *circuit* including other features like safety switches and arming circuits. These are embedded in a spherical shell of homogeneous high explosive. Then comes the tamper and the neutron reflector. The spherical core of the weapon is thus surrounded by a number of shells: the reflector, the tamper, and the high explosives.

A typical modern nuclear-fission weapon, with an explosive yield equivalent to that of about 20 kilotons (kt) of TNT and using implosion, would typically use 4 or 5 kg of weapons-grade plutonium or between 10 and 15 kg of weapons-grade uranium, surrounded by an efficient neutron reflector and tamper and about 100 kg of high explosive. The entire volume of the device would be about that of a football and its total weight roughly 200 kg.

The actual amount of weapons-grade plutonium or uranium used in an implosion-type nuclear-fission weapon varies considerably, according to the explosive yield required and the technology used. A designer with access to high technology (particularly to enable very fast implosion) could design a nuclear-fission weapon with an explosive yield of 1 kt TNT equivalent with as little as 1 kg of weapons-grade plutonium or 2.5 kg of weapons-grade uranium. With 2 kg of weapons-grade plutonium, he could design a nuclear-fission weapon with a 10-kt yield; and with 3 kg, he could design a 20-kt weapon. If only low technology is available, a designer would require about 6 kg of weapons-grade plutonium or 16 kg of weapons-grade uranium to design a 20-kt weapon. With 3 kg of weapon-grade plutonium or 8 kg of weapons-grade uranium, he could design a 1-kt weapon.[22]

In a nuclear explosion very high temperatures, of hundreds of millions of degrees centigrade, and very high pressures, of millions of atmospheres, build up in a very short time (about a half a millionth of a second). In this time, about 55 generations of fission take place. In less than a millionth of a second, the size and density of the fissile material have changed so that it becomes less than critical and the chain reaction stops.

The complete fission of 1 kg of Pu-239 would produce an explosive yield of 18 kt. Modern fission weapons have efficiencies approaching 45%, giving explosive yields of about 7 kt per kg of plutonium present.

## Current Stocks of Civil and Military Weapons-Usable Fissile Materials

Because plutonium produced in civil nuclear-power reactors can be used to manufacture effective nuclear weapons (that is, weapons-usable), the amount of civil plutonium available globally is of crucial importance in any discussion about the ease of fabricating nuclear weapons, either by a government or a sub-national group. Also important is the amount of weapons-grade plutonium and weapons-grade uranium being removed by the United States and Russia from dismantled nuclear weapons. The more weapons-usable and weapons-grade materials become available, the greater the risk that some will be illegally acquired and used to fabricate nuclear explosives.

Very little official information has been released by the nuclear-weapon powers about the amounts of military fissile materials — plutonium and highly-enriched uranium — they have produced. The US is the only country to release an estimate. The Department of Energy has stated that the amount of military plutonium produced so far in the United States is 110 tons (of this, about 95 tons is weapons-grade and 15 tons is reactor-grade), to within 2 tons. No other nuclear-weapon power has given any figures at all.

There is also a lack of information about stocks of civil fissile material, particularly plutonium. One problem is that the operators of civil nuclear-power plants are unable to measure directly the amount of plutonium produced in their nuclear-power reactors. All they can do is to try to calculate the amount of plutonium in their spent reactor fuel elements from estimates of the burn-up of the reactor fuel. These calculations are bound to contain inaccuracies and standards of material accountancy in nuclear facilities vary considerably.

For these reasons, the figures given below for stocks of civil and military fissile materials are estimates rather than precise amounts.

### *Civil and Military Plutonium*

As of mid-1995, the world's total stock of plutonium, civil and military, was about 1,500 tons (excluding the plutonium in the cores of the world's nuclear-power reactors).[23a] Of this, about 1,200 tons was civil plutonium. The world's nuclear-power reactors are currently producing about 65 tons of plutonium a year; by the year 2000, the total amount of plutonium in the world will be about 1,800 tons.

About 200 tons of the civil plutonium have been separated from spent nuclear-power reactor fuel elements in reprocessing plants. A further 30 tons are being reprocessed per year so that by the end of 1996 there will be as much separated civil plutonium as military plutonium. By the year 2000, there will be some 300 tons of separated civil plutonium. If current reprocessing plans go ahead, by the year 2010 there will be about 550 tons of separated civil plutonium. This means that the amount of civil plutonium as a percentage of total separated plutonium will have increased from about 30% in 1990 to about 70% in 2010.

By the year 2000, the amount of civil plutonium in store will have increased to about 250 tons. Of this, about 80 tons will be in France, about 50 tons in the United Kingdom, about 50 tons in Japan, and about 40 tons in each of Germany and Russia. Smaller amounts (less than 8 tons) will be in each of Belgium, India, Italy, the Netherlands, Spain, Switzerland, and the United States.

There are about 230 tons of military plutonium in the world's stockpile. A small amount of military plutonium is still being produced in Russia in two reactors which are also used for domestic heating purposes. No military plutonium is being produced in the United States. The United Kingdom and France have more plutonium than they need for planned military purposes. The amount of military plutonium that China plans to produce in the future is not publicly known. India and Israel are probably still producing plutonium but in relatively small amounts. The world's stock of military plutonium is, therefore, unlikely to increase by very much.

The United States has about 110 tons of military plutonium, about 70 tons of which are in nuclear weapons, and is dismantling about 1,800 nuclear weapons (probably containing about 7 tons of plutonium) per year. The United States has in store the cores (or *pits*, as they are called — grape-fruit sized shells of weapons-grade plutonium) of about 8,000 dismantled nuclear weapons, containing a total of about 32 tons of plutonium.

The amount of military plutonium in the former Soviet Union is probably about 125 tons, of which probably about 75 tons are in nuclear weapons. Russia is apparently also dismantling about 1,800 nuclear weapons (probably containing about 7 tons of plutonium) per year.

The United Kingdom has probably produced about 10 tons of military plutonium of which about 3 tons are in weapons. France is estimated to have produced roughly 6 tons of military plutonium. China probably has about 2 tons in its weapons. Israel has probably produced about 950 kg of military plutonium and India between 200 and 300 kg.

It is reasonable to assume that about 90 tons of the world's 230 tons of military plutonium are currently in nuclear weapons. About 14 tons of this plutonium are removed each year from dismantled nuclear weapons. By the year 2000, the total amount of military plutonium outside nuclear weapons is expected to have increased to about 160 tons, or about 70% of the world's total military plutonium.

**Civil Plutonium (Estimated) By the Year 2000**

| Country | Amount |
|---|---|
| France | 80 tons |
| UK | 50 tons |
| Japan | 50 tons |
| Germany | 40 tons |
| Russia | 40 tons |

**Less than 8 Tons**

Belgium
India
Italy
The Netherlands
Spain
Switzerland
United States

**Military Plutonium (Estimated)**

| Country | Amount |
|---|---|
| Former SU* | 125 tons |
| US | 110 tons |
| UK | 10 tons |
| France | 6 tons |
| China | 2 tons |
| Israel | 950 kg |
| India | 200-300 kg |

## *Highly-Enriched Uranium*

The situation with highly-enriched uranium is different. The bulk of the world's stock is military; only about 1% is civil. Moreover, the highly-enriched uranium removed from dismantled weapons can be disposed of more easily than plutonium, by mixing it with natural or depleted uranium to produce low-enriched uranium for nuclear-power reactor fuel. Low-enriched uranium is not usable in nuclear weapons. The situation is complicated, however, by the fact that highly-enriched uranium is used to fuel nuclear-powered warships. But, because of the surplus of highly-enriched uranium, it is likely that spent naval-reactor fuel will be permanently disposed of in geological repositories.

**ighly-Enriched Uranium Estimated)**

| ountry | Amount |
|---|---|
| ormer SU* | 1,000 tons |
| S | 700 |
| rance | 15 tons |
| K | 15 tons |
| hina | 15 tons |
| akistan | 150 kg |
| outh Africa | 360 kg |

SU = Soviet Union

There are about 1,900 tons of highly-enriched uranium in the world — about 700 tons in the United States, about 1,000 tons in the ex-Soviet Union, and about 15 tons in each of the United Kingdom, France, and China. Pakistan has probably produced about 150 kg and South Africa about 360 kg. Of this, about 410 tons are in active nuclear weapons (160 in the United States, 230 in Russia, 8 in France, 3 in the United Kingdom, and 7 in China). The implementation of existing US and Russian arms reduction agreements will contribute about 30 tons of highly-enriched uranium to the global stockpile. The reactors in American nuclear-powered warships have so far consumed about 100 tons of highly-enriched uranium as fuel and about the same amount will be needed for future fuel. Only about 20 tons of highly-enriched uranium is used in civil facilities, almost all of it as fuel in civil research reactors.

## Can Plutonium Be Safeguarded Effectively?

The purpose of a nuclear safeguards system is to provide assurance that nuclear materials are not being diverted from peaceful purposes to nuclear-weapon programs. International nuclear safeguards are implemented by the International Atomic Energy Agency (IAEA). Because of the danger that plutonium may be stolen or otherwise illegally acquired and used to produce nuclear weapons illegally by governments or sub-national groups, it is of crucial importance to know whether safeguards can be effectively applied to facilities that handle large amounts of plutonium — specifically, plants for reprocessing plutonium (separating plutonium from unused uranium and fission products in spent nuclear-power reactor fuel elements) and for the fabrication of fuel elements from mixed (plutonium and uranium) oxides (MOX).

In a bulk-handling facility, because of measurement uncertainties and the large amount of plutonium (typically about 7,000 kg a year in a commercial reprocessing plant) processed, conventional safeguards techniques are not sufficiently precise to ensure that the diversion of an amount of plutonium sufficient for the fabrication of a nuclear weapon would be detected. This has nothing to do with inefficiency or incompetence. Even using the best available and foreseeable safeguards technologies and accountancy techniques, the safeguards on plutonium bulk-handling facilities are ineffective. The plants most difficult to safeguard effectively are the large reprocessing plants.

Six large (commercial-scale) reprocessing plants are currently operating: B205 and THORP at Sellafield, England; the UP1, UP2, and UP3 plants at La Hague, France; RT1 at Chelyabinsk, Russia; and one at Tokai-Mura, Japan. The UP2-800 plant will begin operating during the 1990s at La Hague in France; and a Japanese plant, at Rokkasho-Mura, is scheduled to start operating soon after the year 2000. It should be noted that the design and operation of commercial reprocessing plants are very closely guarded secrets. There is, therefore, very little information in the literature about the effectiveness of safeguards at the plants or about possible diversion pathways. What information there is relates to very limited operational periods at the small reprocessing plant at Tokai (still in operation), Dounreay (still in operation) and Karlsruhe (closed down in 1991).

Six MOX-fabrication plants are operating or will operate at Sellafield, England; Dessel, Belgium;Marcoule and Cadarache, France; Tokai and Rokkasho-mura, Japan; and possibly at Hanau, Germany and Chelyabinsk, Russia.

## Material Accountancy

The most important safeguards measure used for the timely detection of the diversion of nuclear materials from peaceful to military uses is *material accountancy*. As applied to a nuclear facility, material accountancy is similar to any audit. The operator of the facility prepares a material balance covering a specific part of the facility (called the *material balance area — MBA*) and covering a specified period of time. It is necessary to establish accurately the amount of nuclear material in the MBA and to measure the flows of nuclear materials into and out of it.[23b] In a reprocessing plant, for example, the MBAs are normally the following: the part of the plant into which spent reactor fuel elements are received and stored (the *input section*); the part in which the cladding on the fuel elements is removed and elements dissolved in nitric acid; the part after the dissolver in which the reprocessing chemistry takes place (the *reprocessing section*); and the store in which the separated plutonium is kept. The input section and the reprocessing section are the most difficult MBAs to safeguard.

In practice, material accountancy using MBAs in bulk-handling facilities faces a number of problems.

**1.** The operators of the plants understandably want to operate with as little interruption and intrusion as possible. The inspectors, therefore, have to rely on data supplied by the operator with no possibility of independently checking it.

**2.** Reprocessing and MOX-fabrication are dynamic processes and significant fluctuations in the operations are inevitable. To follow them continually and sufficiently precisely to ensure that diversion has not taken place is, to say the least, exceedingly difficult.

**3.** The plants are largely automated. Because the items and materials involved are normally highly radioactive, they have to be handled with remote-handling equipment. The radiation shielding around much of the plant makes large areas inaccessible while the plant is operating

**4.** The chemical composition of the nuclear materials is complex and there are many changes during the process in the chemical composition and concentrations of the materials. The nuclear materials occur in complex and changing mixtures of nuclear and non-nuclear materials.

If A is the amount of nuclear material going into the MBA, B is the amount leaving the MBA, and R is the total amount of nuclear material removed (legally) from A, then, if no material is lost,

$B = A - R.$

But if an amount, X, has been lost or is otherwise unaccounted for,

$B = A - R - X.$

Hence,

$X = A - B - R.$

If $X = 0$, and the values of A, B, and R given by the operator are authenticated by the IAEA inspector, then the Agency will conclude that no diversion has taken place. A positive value of X indicates that an illegal diversion has occurred or an error has taken place. In theory, the value of X is called the “material unaccounted for” or MUF.

In some cases, it is possible to measure A, B, and R reasonably accurately. For example, if the MBA is the cooling pond of a reactor, then these values are simply numbers of fuel assemblies and X can be determined exactly. But in facilities in which plutonium is handled in large quantities, specifically in reprocessing plants and MOX-fuel fabrication plants, only approximate measurements are possible.

The first measurement of plutonium in a reprocessing plant is made in an accountancy tank. The problem is that the amount of plutonium is not measured directly. A small sample is taken from the tank and, using mass spectrometric methods, the ratio of the amount of plutonium to the amount of uranium is measured. The amount of uranium in the spent reactor fuel elements introduced into the plant is then calculated by the reactor operators from their knowledge of the amount of uranium originally in the reactor fuel elements and of the way in which the reactor was operated (particularly the amount of heat produced by the fuel). From the amount of uranium and the uranium/plutonium ratio, the amount of plutonium is determined. But there is the potential for errors in each step in this operation.

Because of the errors involved, even if no illegal diversion of plutonium has taken place, the value of the MUF will generally not be zero. Its value may be either positive or negative. Put another way, the operator will not know whether or not an amount of plutonium up to the value of the MUF has been illegally removed. Statistical methods must be used to work out the probability that a positive MUF means that plutonium has been illegally diverted or arises because of a chance combination of errors in A and/or B and/or R.

The magnitude of the errors are specified by the square root of the measurement error variance of MUF, o-(MUF), or the measurement error standard deviation. The goal of the IAEA is to verify that for a given period "no significant quantity of nuclear material has been diverted or that no other items subject to safeguards have been misused by the State." A *significant quantity* (SQ) is the amount of nuclear material for which "the possibility of manufacturing a nuclear explosive device cannot be excluded." For plutonium, SQ is defined by the IAEA as 8 kg.

If o-(MUF) is large compared with SQ, then the minimum diversion that can be detected by safeguards measures with high confidence and a low false-alarm probability will be much greater than an SQ. In other words, safeguards will be ineffective.[24]

The THORP reprocessing plant, for example, will separate about 7,000 kg of plutonium a year. The reactor operators that send their spent fuel elements to THORP for reprocessing cannot measure the amount of plutonium in the fuel elements (they are too radioactive to allow measurements to be made); they calculate the amount of plutonium instead. These computer calculations are done from the operator's knowledge of how the reactor operated while the fuel elements were in the core — the heat generated, and so on. The amount of plutonium going into the reprocessing plant (that is, the term A above) is calculated from these computer calculations. The reactor operators do not state the error in their calculations, but independent experts calculate it to be about 5%. Thus, if the material balance is done once a year, as it normally is, then the value of o-(MUF) is 350 kg. The minimum amount of diverted plutonium that could be detected with a false-alarm probability of 5% (that is 95% of diversions would be detected) is 3.3 o-(MUF), or about 1,100 kg.[25] Even if the error in the reactor operator's computer calculations is as low as 1%, the minimum amount of diverted plutonium that could be detected with a probability of 95% and a false-alarm probability of 5% is about 220 kg, equivalent to about

28 SQs. Clearly, the THORP reprocessing plant cannot be effectively safeguarded using current techniques.

Based on such calculations, the Office of Technology Assessment of the US Congress concludes that:

> barring acquisition of additional measurements and use of more sophisticated statistical analysis — many analysts have concluded that measurements are incapable of reliably detecting diversions of one or even several significant quantities of safeguarded material from large reprocessing plants.

The report goes on to say:

> actual IAEA experience in safeguarding large plants is minimal, so that it is not known how well routine measurements will compare with their predicted performance.[26]

Even if the diversion of an SQ could be effectively detected, the IAEA's timeliness goal for plutonium could not be satisfied currently. The IAEA's guidelines for effective safeguards were that the diversion of a significant quantity should be detected, with a 90 to 95% probability and with a false-alarm rate of no more than 5% within a *conversion time*. The concept of a conversion time is based on the time likely to be required to convert diverted fissile material into a form that could be used in a nuclear weapon. For plutonium in the forms of the oxide or nitrate (the products produced in a reprocessing plant), the conversion time is one to three weeks. If the detection of an illegal diversion is to be timely enough to allow action to be taken to prevent the use of the plutonium in a nuclear explosive device, the detection time must be significantly shorter than the conversion time so that a response can be made.

In conventional materials accountancy, to detect an SQ diversion with a 90% to 95% probability, and with a false-alarm rate of no more than 5%, taking the optimistic o-(MUF) value of 1%, a material balance measurement must be made when about 240 kg of plutonium have been separated. For the THORP reprocessing plant, which on average separates about 35 kg of plutonium per working day (assuming it operates for 250 days in the year with the rest of the time being used for routine maintenance), a material balance measurement must be made weekly to detect the diversion of an SQ. But to satisfy the timeliness requirement the period must be significantly shorter than this. This means that, for THORP, a material balance measurement must be made every two days or so, a much greater frequency than that in conventional materials accountancy. Could this be achieved in practice?

Materials accountancy with material balance measurements taken at this sort of frequency is called Near-Real-Time Accountancy (NRTA). Direct measurements using instruments built into the plant, analyses using models of the plant operations, and indirect calculations using computer simulations of the chemical processes are used to provide data.[27] In the case of THORP, direct measurements are taken only in the main buffer tanks and the accountancy tanks. Elsewhere, models have to be used.

NRTA depends on a series of MUF values being obtained when no diversion takes place to calibrate the system. It is assumed that the deviations in this series of MUF values are caused by measurement errors and plant losses, such as plutonium retained in pipes, tanks, and so on. These systematic measurement errors can then be subtracted from a series of MUF values being investigated to see if diversion has taken place.[28] Since the system constantly recalibrates itself, over time, the magnitude of o-(MUF) can be reduced and the detection sensitivity increased. The statistics involved in these sequential tests are very complex. The snag is that no single statistical method can deal effectively with all possible means of diversion.

A problem with NRTA is that small amounts of plutonium may be illegally diverted now and again so that the total diverted over a relatively long period exceeds an SQ. Whether a diversion is a single one or a number of smaller ones is not an issue for conventional materials accountancy because measurements are made over a long period. But because NRTA depends on repeated calibrations, plutonium could be systematically put into or taken out of the plant during a calibration period so that the value of normal MUF values are falsified. This is one example of a way in which a determined diverter could succeed in his purpose even when the most sophisticated safeguards technique available is used.

The Office of Technology Assessment of the US Congress concludes that:

> The conventional "material accountancy" safeguards methods now in use by the IAEA appear unable to assure that the diversion of a bomb's worth of plutonium per year from a large reprocessing facility — e.g., one processing much over about 100 tons of spent fuel per year — would be detected with high confidence.

And goes on to say:

> New techniques such as "near-real-time accountancy" — unproven at this scale by the IAEA — must be adopted for large reprocessing plants, and even these techniques may not be able to measure material flows and inventories accurate enough to detect the absence of one bomb's worth of plutonium per year. In that case, if the IAEA could not demonstrate that safeguards methods other than the material accountancy techniques that form the core of its current safeguards approach can be relied on to detect diversion with a high degree of confidence, it would have to conclude that it could not safeguard such a plant to the same standards it applies at smaller facilities.[29]

## The Disposal of Plutonium

About 20% of the 200 tons or so of civil plutonium reprocessed so far has been used to fuel breeder reactors; about 8% has been used as MOX reactor fuel; and the remainder is in store. Up to the year 2000, according to present plans, a total of about 48 tons will have been used in breeder reactors and a total of about 65 tons will have been used as MOX fuel in ordinary (light water reactors).

A breeder reactor is able, by a clever design, to produce more plutonium than it uses as fuel. This extra plutonium can then be used to fuel new breeder reactors. In theory, a series of breeder reactors eventually becomes self-sufficient in fuel.

But there are two major problems with breeder reactors. One is that the electricity they generate will remain very expensive for the foreseeable future — so expensive that breeder reactors are much less economically viable even than ordinary reactors. Breeder reactors will generate electricity at prices competitive with ordinary reactors only when uranium is five times more expensive than it is today. This will not happen for decades into the future. The other is that the type of plutonium they produce, and the type they prefer as fuel, is the same as the type most suitable for fabricating nuclear weapons. Only Japan and Russia seriously plan to build a series of breeder reactors, but how realistic these Japanese and Russian plans are remains to be seen.

There are also problems with using plutonium to produce MOX fuel. The cost of manufacturing MOX reactor fuel elements is much higher than the cost of producing standard uranium fuel elements. Light water reactors use low-enriched uranium fuel which costs about $750 per kg. A realistic price for MOX fuel today is about $1,500 per kg, excluding the cost of plutonium.[30] The French and British cost for reprocessing spent reactor fuel is about $1,000 a kg. This will produce about 5 grams of plutonium. MOX fuel is, therefore, not economically viable. Nevertheless, the use of MOX fuel in light water reactors is planned in Belgium, France, Germany, Japan, Switzerland, and the United Kingdom. MOX fuel is produced in Belgium, France, and Germany; and the United Kingdom and Russia are planning to produce it.

Other suggested methods of disposing of plutonium include: firing it into the sun using rockets; transmuting it into other elements in special reactors or particle accelerators; and permanently disposing of it in geological repositories. The risk that a rocket might accidentally fall back to earth with its plutonium payload is environmentally unacceptable. Machines for transmuting large amounts of plutonium have not yet been developed.

It can be concluded that commercial facilities for the bulk handling of plutonium — specifically, plants for separating plutonium from unused uranium and fission products in spent nuclear-power reactor fuel elements and for the fabrication of fuel elements from mixed (plutonium and uranium) oxidizes — cannot be effectively safeguarded. Because of measurement uncertainties and the large amount of plutonium (typically about 7,000 or 8,000 kilograms a year) handled in a commercial reprocessing plant, conventional safeguards techniques are not sufficiently precise to ensure, in a timely way, that the diversion of the first few kilograms of plutonium needed to fabricate a nuclear explosive device weapon would be detected. This has nothing to do with inefficiency or incompetence. Even using the best available and foreseeable safeguards technologies and accountancy techniques, the safeguards on plutonium bulk-handling facilities are ineffective.

The disposal of civil and military plutonium would, therefore, be best achieved by permanently disposing of it in geological repositories. A number of countries are putting, or plan to put, high-level radioactive waste into a form suitable for permanent disposal by *glassification* — converting it from liquid to solid form by incorporating it into glass (borosilicate glass, for example, or Pyrex) by a chemical process. Glassified high-level waste is being produced in significant quantities in France, Russia, and the United Kingdom and is planned in Japan and the United States. Plutonium could be included in glassified high-level waste for permanent disposal, with very little extra cost.[31]

The usual justification given by proponents for reprocessing plutonium is that it makes easier the management of the high-level radioactive wastes in spent reactor fuel. But most experts agree that reprocessing does not offer any advantage compared with the storage and direct disposal of spent reactor fuel elements without reprocessing.

Present and planned reprocessing capacity is able to remove only about 20% of the plutonium in discharged reactor fuel elements. The bulk of spent reactor fuel will, therefore, have to be permanently disposed of in suitable geological repositories. Commercial reprocessing is so uneconomical that it is hard to see it surviving for much longer than another decade. The only reason officially given for reprocessing at, for example, the THORP reprocessing plant is to earn foreign currency and to preserve jobs in the area. Given the very real danger that plutonium will be illegally acquired and used to make nuclear explosives, commercial reprocessing should be stopped as soon as practicable.

Until the global stockpile of plutonium is permanently disposed of, large amounts of plutonium will have to be stored. The international community will only be confident that plutonium is being stored securely if the stores are under international safeguards, which could be provided by the IAEA. The international management and storage of plutonium would be preferable to the present chaotic situation of national ownership and storage and would give some confidence that plutonium was not being illegally diverted to military uses or illegally acquired by terrorists or criminals.

# Conclusions

If a relatively limited quantity of either highly-enriched uranium (55 kg), plutonium metal (8 kg), or plutonium oxide (35 kg) is available, the technical barriers to construction of a crude nuclear weapon would be relatively easy to overcome. Depending on the effectiveness of the design, the explosive force of such a device would likely range from a few hundred to several thousand tons of TNT — hundreds to thousands of times larger than the devastating conventional explosions achieved in recent terrorist attacks.

Unless radical changes are urgently made in existing policies about the production and storage of weapons-usable nuclear materials, the likelihood that national or subnational terrorist groups will succeed in devastating cities through a nuclear explosion is dangerously high.

From the tragedies of Oklahoma City and the World Trade Center to the first act of nuclear terrorism requires but one small step. Suppose that, instead of mini-vans filled with hundreds of pounds of the crude explosives used in Oklahoma City and New York, terrorists had acquired a suitcase carrying a grapefruit-sized 100 pounds of highly enriched uranium. Assuming a simple, well-known design, a weapon fashioned from this material would produce a nuclear blast equivalent to 10,000 to 20,000 tons of TNT. Under normal conditions, this would devastate a three-square-mile urban area. Most of the people of Oklahoma City would have disappeared. In the case of New York, the tip of Manhattan, including all of the Wall Street financial district, would have been destroyed.

US Senator Richard Lugar
August 1995

# The Effects of a Crude Plutonium Dispersal Weapon

## Part 2

**Peter Taylor and David Sumner**

## Overview

There is increasing concern that terrorist organizations might obtain sufficient quantities of plutonium for a *radiological* weapon — that is, a device that would disperse radioactive material to create harm and disruption. We are not aware of any studies on the potential impact of such an attack and attempt here to provide an indication of the potential harm using computer simulation of the dispersion of radio-nuclides by fire. The nature and extent of the radiological impact may be indicated using standard computer simulation techniques developed for reactor fires. These models have been used to predict the consequences of radioactive plumes of hot air traveling over great distances and containing dozens of radioactive elements. The simulation encompasses such factors as dispersion characteristics of different weather categories and makes use of site-specific population density and agricultural production. The behavior of the affected population and any countermeasures employed to mitigate the effects, such as timed evacuations, relocation and food bans, can also be modeled. The program arrives at the endpoints relating to the onset of "early" effects which are subject to thresholds in dose, such as death due to pulmonary failure or impairment of bone marrow function, and long-term *stochastic* effects (statistical probability of death or disease) from cancer or hereditary damage, where there is assumed to be no threshold. Thus, the computer models the behavior of the cloud as it spreads, the actions of the affected populace that govern intake of radioactivity, and the disposition of the radioactivity in the various organs of the body (dose per unit intake).

In this study, we use the computer model COSYMA developed by the Commission of the European Communities (CEC). We provide an outline of the consequences of a 35-kg release of plutonium in a major population center by the use of a crude dispersal mechanism such as an incendiary device. This amount has been specified by IPPNW as commissioners of this paper, and we have investigated consequences for 3.5 kg and 350 kg for comparison. The device is assumed to contain plutonium oxide which is dispersed in an aerosol of hot gases generated by the device. We initially compared an oxide of pure Pu-239 with that of a reactor-grade mix of isotopes, with the latter having a marginally lesser impact.

A number of assumptions are made in using the standard radio-nuclide dispersal model that is used primarily for studying the consequences of fires in nuclear reactors which can be expected to burn at very high temperatures for long periods. This study should be treated as indicative only, until such time as appropriate values could be agreed upon for a more accurate simulation of the dispersion characteristics.

Once material has been dispersed by fire there are fewer areas of uncertainty.

Broad agreement exists on plume behavior under various weather conditions and the intake of nuclides through different pathways, as well as on the radiological models of dose per unit intake and health effects per unit dose. When dealing specifically with plutonium, however, there are some important areas of scientific uncertainty that remain unresolved, such as threshold values for the "early" effects of morbidity and mortality due to lung function impairment, and the dose-response factors for plutonium deposited over long time scales on bone surfaces.

With respect to these controversies, we have chosen to stay with the default values of the model and we are in any case constrained by the choices available for the PC (personal computer) version of the software. The values used are drawn from the recommendations of the International Council for Radiological Protection (ICRP) and, in particular, their Report No. 60. Given the approximations necessary in simulating the initial dispersal, there is little to be gained at this stage from adding further complexity with a range of values for the biological effectiveness of the alpha radiation generated by plutonium.

The results of the computer simulations are presented in terms of ground and air concentrations, short-term and long-term doses at specific distances along the center line of the plume, mean doses according to radius and sector, and the health effects that can be expected to occur. Data are presented for the total number of early and late health effects in the areas affected. Different runs can be made under varying "countermeasure" scenarios — for example, sheltering in advance of the plume, evacuation of contaminated zones, and relocation for long periods to uncontaminated areas. We have assumed that the device is used without warning and have studied the consequences of assuming no countermeasures at all (where everyone carries on as normal) and compared this to various feasible or likely responses. The center of London has been chosen for the location and an easterly wind is assumed to carry the plume over the rest of England.

## COSYMA

COSYMA has been developed by the CEC for general use by regulatory authorities, nuclear installations, and research institutes. The PC version has been used here under license to the TERRAMARES Consultancy, an independent group of scientific experts on terrestrial and marine ecosystems. The release of this program has enabled independent experts to undertake consequence studies for aerial releases of radio-nuclides and is a major step toward freedom of information in matters of public interest research. The program enables the user to define the site, the *source term* (how much of any particular nuclide is released), the direction of the release, the weather conditions (including the most unfavorable but less common conditions), and the countermeasures. The mainframe version allows greater flexibility in terms of the dispersal and dose-response models.

The program can generate 10 x 10 km population grids centered upon any site in Europe, as well as agricultural production in the surrounding region. The effects of the plume traveling overhead and of the ground contamination are modeled both in terms of human health and agricultural production that may be interdicted, and there is also an indication of the social impact where evacuation and relocation are necessary in order to limit the long-term health effects. The model allows the user to make varying assumptions with regard to the emergency response of the population, ranging from spontaneous evacuation of contaminated zones, to sheltering and orderly evacuation and relocation according to criteria decided by the responsible authorities.

## The Source Term

We have taken a figure of 35 kg of plutonium as the amount released in the plume and assumed this is bomb-grade plutonium (using the approximation that it is all the Pu-239 isotope). Sensitivity studies using reactor grade isotopic mixtures show the overall long-term health impacts are a few percent lower.

There are a number of key questions with regard to adapting the COSYMA model that provides inputs for inventories designed to model releases from nuclear reactors, and we have not attempted to tackle these. For example, the high release temperatures of a reactor fire convert plutonium metal into insoluble oxide and respirable aerosol. In a crude dispersal device, the fabricator may have access either to weapons-grade plutonium as metal, liquid nitrate or oxide powder, or could use reactor-grade plutonium. These options affect the proportions of the different isotopes and the amount of respirable aerosol in the insoluble form that has maximum residence time in the lungs. We do not have the information or necessary expertise to provide a specific model for these various options. We have assumed that a source term based upon the isotope Pu-239 and utilizing the release model of COSYMA, with zero retention (by the reactor building), will provide a useful approximation and probably represents the most pessimistic assumptions of insoluble small particles of plutonium oxide. Further accuracy could be found by considering the chemical and physical form of the plutonium, appropriate isotopic ratios, and the heat energy of the plume.

The model allows the user to define the release height and the thermal energy of the plume. These factors affect plume rise. In a reactor fire with temperatures as high as 2,000 degrees Celsius, plume rise is significant and it may be some distance before the plume touches the ground and leads to inhalation doses. We have found that our results are not sensitive to release heights of 2-10 meters, and varying the heat input from 0 to 200,000 calories per sec (cal/sec) had no noticeable effects. We have no information on the potential energy of incendiary devices, but assume that the device would have the capacity to reach a sufficiently high temperature and duration to mobilize the plutonium in the way we have modeled. Further detailed study would clarify these factors.

## Dispersion

The dispersion model simulates a plume of hot contaminated air as it travels across the terrain of the chosen site. Some allowance is made for “roughness” caused by buildings. The direction, weather category (Categories), presence or absence of rain, and wind speed can be set for varying conditions. We have assessed consequences for an easterly wind in average conditions (Category D) and 5 m/sec, with no rain. More severe consequences arise in still “inversion” conditions (Category F), or with rain, and we have added consequences for Category F weather in winter, which can occur roughly 20% of the time.

## Health Effects

We have chosen to remain within the generally accepted confines of the recommendations of the ICRP on dose-per-unit intake and the dose-effects model as used in COSYMA. There is considerable uncertainty in the factors relating dose to intake and cancer risk to dose, particularly with regard to long-term effects of doses to bone surfaces. Data on the effectiveness of plutonium in inducing cancer stems almost entirely from animal experiments. Likewise, there is little relevant human data on high doses from insoluble particles trapped in the lungs.

With regard to the transfer of plutonium through food chains, it is generally agreed that the nuclide is not particularly mobile, and the model predicts a small impact via ingestion pathways, with the dose occurring primarily in the colon. Deposited activity, however, can be resuspended in dust and lead to additional inhalation doses.

The presence or absence of countermeasures such as sheltering as the plume passes over, evacuation of contaminated zones (after the plume has passed), and long-term relocation to uncontaminated zones can be modeled. These countermeasures can include decontamination of affected areas and the banning of foodstuffs that breach European Union (EU) legal limits for plutonium contamination. In the latter case, COSYMA presents options relating to doses rather than concentrations.

## Emergency Responses

In the case of most nuclear accidents, the emergency services can be expected to have time to activate emergency plans aimed at limiting public exposure. The first and most effective of these is for people to take cover indoors and to close windows, thus reducing exposure to gamma rays from the plume and to contaminated air that will be inhaled. In the case of plutonium releases, the radiation from the aerosol is not penetrating (it consists of short-range alpha radiation) and constitutes a hazard only when inhaled or ingested. Sheltering indoors can reduce inhalation doses by as much as 50%.

The plume will pass overhead in a time period depending on the duration of the release, wind speed, and dispersion conditions. After passing overhead, the appropriate response is to open windows, and depending upon the risk level from resuspended particles, evacuate the population to uncontaminated areas. If serious contamination persists, it may be necessary to relocate people for periods of time. The time spent under relocation may depend upon how successful decontamination procedures prove to be, and the model allows a range of factors to be used.

Where we have considered a countermeasures model based upon standard emergency response criteria, the results indicate the numbers of people evacuated or relocated and for what time periods. Where agricultural production is concerned, the amounts of food banned (lost production) and the period of the bans are indicated.

## The Results

Integrated air concentration values are given as means for each radius and for each sector at specific distances. For example, at 1.15 km in the worst affected sector these are 2.8 x $10^8$ Bq s /$m^3$ (bequerels per square meter) falling to 9.2 x $10^6$ at 15.5 km for Category D weather and five times higher in Category F inversion conditions.

The predictions of ground contamination in our computer simulation are given in terms of mean concentrations at each distance band. These range from 75,000 Bq/$m^2$ within the first 500 m down to 500 Bq/$m^2$ at 10 km. This mean values, however, reflect a mix of higher and lower concentrations within each distance band because local factors will cause plutonium to be distributed unevenly. Concentrations in the worst affected sectors at 1.15 km and 15.5 km are predicted to be 285,000 and 9,000 Bq/m,$^2$ respectively, in Category D conditions. Concentrations would be three to five times higher under Category F.

## Plutonium Hazards and Evacuation Policies

The main hazard from plutonium aerosol is the dose to the lung from particles retained in the pulmonary system. If the levels are high enough, the resultant dose can lead to fibrosis and collapse of the lung with death occurring within a matter of days or weeks. Long-term lung impairment can leave people disabled and in need of intensive care for the remainder of their lifetime. Below the threshold for “early effects,” alpha irradiation of the lung can lead to lung cancer. Some of the inhaled plutonium will be transferred to the blood via the lymphatic system and become deposited in other organs, notably the liver and on bone surfaces, where it will also produce a cancer risk.

These risks have prompted national authorities to promulgate Emergency Reference Levels (ERLs) for countermeasures. The first of these relates to the air concentration that would precipitate evacuation. After air concentrations have peaked during the passage of the plume, plutonium that has been deposited on the ground will constitute a remaining hazard. In the case of plutonium, the ground contamination hazard arises from resuspension of particles that can be breathed into the lungs and, to a lesser extent, the movement of plutonium into the human food chain.

The air concentration levels out to 15 km are well above the emergency reference levels for both sheltering (7.6 x $10^4$ Bq/$m^3$) and evacuation (4.6 x $10^5$ Bq/$m^3$). In the case of ground contamination, the UK National Radiological Protection Board has recommended ground contamination values for evacuation that for the most restrictive case of insoluble fine particles are 380,000 Bq/$m^2$. This level is not exceeded in areas affected by the projected incidentunder Category D conditions but would be in some areas under Category F. Thus, we might expect that following such an attack, the UK authorities would not advocate long-term evacuation of the contaminated zones.

Short-term evacuation (for example, for 30 days) decisions might be quite different, in part as a precaution during a period when the extent of ground contamination is being assessed. In addition, given the general public fear of radiation exposure, it is likely that large-scale voluntary evacuation will take place independent of any government recommendation.

# Doses Arising From Air and Ground Contamination

## Short-Term Individual Doses

The COSYMA program presents results for the short-term integrated dose in order to assess the likelihood of early deaths due to radiation damage. There is a choice of integration times (for example, 1, 7 or 30 days), and we have integrated doses to the lung over 30 days. The doses are tabled according to selected distances in the worst affected sectors, as well as mean doses for radial distances (over all sectors). There are tables of "early health effects" in terms of deaths and morbidity (long-term intensive care).

The short-term 30-day lung dose at 1 km is 0.3 Sv (Sievert) falling to 0.01 Sv at 15 km in Category D weather and 1.4 Sv and 0.05 Sv respectively for Category F weather. Other organ doses are lower than the lungs. The highest doses (which occur within the first 500 m) are below the threshold for early effects which is assumed to be of the order of several Sv over a few days. In further sensitivity studies, the amount released was increased by a factor of 10 and 100 to test for the threshold of early effects. A factor of ten under Category F did not produce early fatalities, whereas 100 produced 500 early deaths from pulmonary failure and 30 with lifetime morbidity due to lung impairment. This latter amount (3.5 tons) is clearly not an amount of plutonium that would be available for such a weapon.

## Long-Term Doses

When insoluble particles such as plutonium particles are inhaled, they are first deposited in the lung. The amount deposited in different regions depends on the size of the particles. The plutonium then slowly migrates via the lymphatic system to the tracheobronchial lymph nodes. Plutonium entering the lungs and lymph nodes will eventually reach the bloodstream, but the time it takes to do so varies between days and months, depending on the size and chemical composition of the particles. Of the plutonium that finds its way into the blood stream, about 20% is eventually excreted and 80% retained, mainly in the liver and skeleton.

Animal experiments, particularly in Beagle dogs, have indicated that plutonium is a potent carcinogen. Inhaled plutonium can cause lung, bone, and liver cancer. The risk of cancer following exposure to plutonium in humans is uncertain, as there is at present insufficient epidemiological data on which to base an assessment of the risk and estimates have to be based on extrapolation from animal data.

Thus, several organs are at risk of developing cancer from the "committed dose" in the first day which is due entirely to inhalation. There is a further additional risk of producing hereditary defects due to exposure of the gonads. COSYMA provides data on the pathway contribution to this committed dose: the inhalation component is 95% with about 4% due to later resuspension from the ground.

We have examined long-term doses (integrated over 50 years) for all organ systems. The highest doses are to the lung, the bone marrow, bone surfaces, and liver. Lung doses to the most exposed persons at 1 km are 1.6 Sv falling to 0.5 Sv at 15 km.

## Effects of Countermeasures

There are a number of countermeasures that can be modeled and their effects in reducing doses compared. We find that virtually all feasible countermeasures have only a minor effect on doses. This is because 95% of the dose accrues via inhalation in the first few hours of exposure and the model assumes that for a "normal" urbanized population 90% of individuals are indoors. A "shielding factor" of 0.5 is incorporated to reduce these doses in comparison to those in the open. Thus, even if advance warning is given and the extra 10% of people take shelter (cutting their dose by half), this has little overall effect.

In simulations that assume no countermeasures, there is a component of the dose via the ingestion (oral) pathway. This is, however, small in comparison. Plutonium will accumulate in milk, meat, and grain, but it is not readily absorbed into the body by the human digestive system. The ingestion model does, however, generalize with respect to adults and makes no special consideration for children and the fetal population. It is thought that the human fetus may be especially sensitive to alpha irradiation, particularly at the stage where embryonic blood cells are formed in the fetal liver. Given the low rate of plutonium absorption from the mother's digestive track, this effect will not greatly affect the overall figures.

## Collective Doses

The COSYMA program makes use of the population grids centered upon the chosen release point to calculate the collective dose to the affected population. This is the sum total of all the individual doses integrated to 50 years, and the doses are presented with respect to the different organ systems as well as the *effective dose* (whole body dose-equivalent). These are presented in the table below for a computer simulation that includes countermeasures.

**Collective Dose (Person-Sv) Assuming Countermeasures Such As Evacuation and Food Bans**

D = average weather; F = inversion conditions in winter.

| Organ | Collective Dose | |
|---|---|---|
| | D | F |
| Bone Marrow | 39,590 | 202,100 |
| Bone Surface | 494,000 | 2,525,000 |
| Breast | — | — |
| Lung | 190,000 | 971,000 |
| Colon | 28 | 148 |
| Liver | 89,170 | 455,200 |
| Gonads | 7,100 | 36,100 |
| Effective Dose | 38,400 | 196,100 |

**Total Number of Health Effects Assuming Countermeasures and Food Bans to Limit Exposure Following Contamination**

| Organ Cancers | Mortality | | Incidence of | |
|---|---|---|---|---|
| Weather | D | F | D | F |
| Bone Marrow | 197 | 736 | 197 | 736 |
| Bone Surface | 247 | 920 | 247 | 920 |
| Breast | — | — | — | — |
| Lung | 1,618 | 6,030 | 2,157 | 7,920 |
| Stomach | — | — | — | — |
| Colon | — | — | — | — |
| Liver | 133 | 497 | 133 | 497 |
| Pancreas | — | — | — | — |
| Thyroid | — | — | — | — |
| Others | — | — | — | — |
| Hereditaries | 71 | 264 | 71 | 264 |
| Total Number | 2,266 | 8,447 | 2,805 | 10,337 |

These organ doses are then multiplied by the respective risk factors for cancer of that organ and total numbers of cancers (incidence) and deaths (mortality) are presented (see table above).

As can be seen, the collective effective dose is nearly 4 x $10^4$ person-Sv for Category D weather, and with a risk factor of 5 per 100 Sv this will produce approximately 2,000 cancer deaths. Under Category F weather, these figures are five times higher with 10,337 cancers and 8,447 deaths.

# Social Impacts

## Evacuation

The COSYMA program also estimates numbers of those who would need to be evacuated within the contaminated zones according to varying criteria of public protection. We have noted the NRPB criteria for evacuation and sheltering in relation to air and ground concentrations. COSYMA can also present numbers of people affected according to evacuation or sheltering that is either automatic or instigated when certain dose levels are exceeded. Likewise, relocation can be instigated with the return period specified by a dose level not to be exceeded by the returning population.

In these cases, we have used COSYMA's default values (which relate closely to recommended values): 0.5 Sv dose to the lung and 0.05 Sv effective dose for evacuation and relocation; and 0.025 Sv (effective dose) for the return of populations (that is, when the committed dose in a year to those returning would be less than this figure). Under these circumstances, the model predicts that for Category D weather conditions 375,000 people in an area of 900 $km^2$ would require evacuation for a period of 30 days. Under Category F conditions, five times this area and population are affected. This element of our analysis warrants further investigation. The model we used does not take into account possible evacuation prior to the cloud's passage. The health benefits of evacuation are therefore actually quite minimal, since 95% of the exposure arises from inhalation at the time of the cloud's passage, with only 4% of exposure resulting from resuspension of ground contamination. If evacuation takes place following the cloud's passage, then only the latter exposure would be prevented.

The model's prediction of evacuation for 30 days allows for a period of careful assessment of ground contamination, and for the amount of time judged necessary for such mass movement. A significant limitation of the model we used is that it does not fully take into account a number of____ relating to the likelihood of resuspension of ground contamination and subsequent inhalation. More thorough consideration of this issue, as well as different assumptions about the timing and criteria for evacuation and for return, could have significant bearing on the results relating to the size of the population that must be relocated and the period of time that land cannot be inhabited.

When we compare the total health effects of "no countermeasures" with the reduction expected from evacuation, the effect is extremely small; under Category D, a reduction of only a dozen (out of more than 2,000) in total long-term deaths. A greater proportion is saved under Category F conditions with total incidence reducing from approximately 13,600 to approximately 10,300. If the authorities were in a position to assess the risks and benefits from evacuation for 30 days (that is, to compare the potential health damage and social impact of the evacuation process with the health damage it is intended to save), it might well be that evacuation would not be recommended. However, such decisions are not likely to be made on rational criteria. In the event of such a scenario as outlined here, prompt evacuation is unlikely and longer-term decisions will be made by the populace themselves with unspecified and unpredictable regard for scientific cancer-risk or cost-benefit equations.

We have not attempted to assess the potential economic costs of evacuation. Also, the COSYMA program does not contain data relating to the industrial economy other than agriculture, and it can be expected that industrial production in an area such as west London would suffer from even short-term evacuation and the fears from prolonged contamination.

**Table 3**
**Total Quantities of Produce Affected by Food Bans Under Category F Weather**

| Foodstuff | Amount in kg |
|---|---|
| Milk | $4.6 \times 10^7$ |
| Cows meat | $3.4 \times 10^6$ |
| Cows liver | $1.0 \times 10^5$ |
| Sheep meat | $1.7 \times 10^5$ |
| Sheep liver | $7.9 \times 10^3$ |
| Green vegetables | $6.6 \times 10^6$ |
| Potatoes | $1.1 \times 10^7$ |
| Grain | $6.2 \times 10^7$ |

## Food Bans

COSYMA outputs data on food contamination by type (for example, milk, cow meat, cow liver, and sheep meat), distance, and duration of interdiction. The action levels for interdiction can be programmed by the user. We have used the CEC intervention levels of 80 Bq/kg of meat and 20 Bq/l for milk. Produce over these levels is removed from the market. Such bans have a small effect in reducing the dose to the colon via ingestion (and virtually no effect on other organs as absorption is low). The collective dose to the colon is reduced by about 10%, but it represents less than 1/1000th of the total dose and would "save" 0.02 cancers. Nevertheless, these stringent criteria are likely to be adopted and COSYMA outputs the total quantities of produce and areas of land affected. These are presented in Table 3. These data give some indication of the social costs via lost agricultural production. For example, 900 km$^2$ of agricultural land is affected with as much as 3 million kg of cows' meat, 46 million liters of milk, and 62 million kg of grain affected. These amounts can increase between five and tenfold under inversion conditions with 5,000 square kilometers affected. In economic terms, this lost production could amount to between £50 million and £500 million (approximately $75 to $750 million US dollars).

The COSYMA model predicts relatively short-lived bans on foodstuffs — less than one year. These results raise questions, however, about the adequacy of the model used. Plutonium may not be readily absorbed by the human digestive system, but it is long lived and it cannot be expected that significant decontamination of agricultural areas will be feasible. This result therefore seems counter-intuitive, and additional research into this issue is clearly warranted.

## Conclusions

The results of these simulations have indicated that the consequences of a radiological weapon using plutonium in amounts that are potentially available for a terrorist attack are very largely long-term in nature: primarily increased cancer incidence, particularly of lung, bone, and liver cancer. The dramatic early effects of radiation sickness and mortality, which in the case of alpha irradiation of the lung are known as *pulmonary syndrome* are not predicted by the dispersal model, even when the worst weather conditions are combined with ten times the inventory for the weapon.

The numbers of people suffering “late” effects are of the order of 2,000 to 10,000 depending upon population density and weather conditions. The increased incidence and mortality would peak after the usual delay times of 20-30 years for most cancers, and perhaps 5 years for leukemias. Three quarters of the health impact would be due to lung cancer, a relatively common disease, and given the time period and large population in which the excess would occur, it would require sophisticated epidemiological techniques to identify any effect. These predicted cancer rates depend heavily on estimates of the probability of inhalation by humans of particles of the dispersed plutonium, and also on estimates of the likelihood that an inhaled plutonium particle will cause cancer within an individual’s normal lifetime. There is limited empirical data on which to base these estimates, and to the extent that they are in error the actual long-term cancer incidence could be much higher or lower.

Thus, in health effect terms, the impact of such a weapon would be hidden for several decades, and probably would not be dramatic. However, given the public aversion to cancer risk, and the fears engendered by the reputation of plutonium as a potent carcinogen, there are likely to be immediate and dramatic responses by the emergency services. Some of these will be guided by prior Emergency Reference Levels which activate evacuation and relocation, as well as the imposition of food bans. In this respect, runs of the model predict numbers of people requiring evacuation ranging from the order of 300,000 to 1.5 million and covering an area of 900-5000 $km^2$ (in an arc out to 100+ km from the release).

Such mass evacuations appear to have little effect in terms of health damage avoided, but would most likely result either from prompt precautionary action by the authorities or self-evacuation once the public had been made aware of the contaminated zones. Although the program indicates evacuation for a period of 30 days, this is related to assumptions about the minimum period required for mass movements and assessment before return and not related to the actual hazard from ground contamination. Especially after Category F conditions, the risks of resuspension from the ground (with subsequent inhalation) could require longer periods of relocation until the land was sufficiently decontaminated. Because the model we used does not fully assess risks related to

resuspension, it may well be that longer periods of evacuation and relocation would be required until land was sufficiently decontaminated. This issue deserves further study because the problems associated with evacuation and relocation represent, perhaps, the most immediate and dramatic consequences of the weapons in both social and economic terms.

The part of the model that deals with agricultural produce predicts relatively short food bans of less than a year. This could perhaps be explained if the main livestock contamination pathway is via inhalation rather than ingestion, and green vegetables are subject to surface deposition: the plutonium will disperse into the soil and become less available over time. However, the stringent regulations governing concentrations in milk and meat and the long residence times of plutonium in the environment make this a crucial factor in the overall impact and this issue clearly merits further investigation.

It is the conclusion of these authors that despite the fearsome reputation of plutonium, the health impact in physical health of a radiological weapon using plutonium would be undetectable for many years. However, the social impact of emergency responses and public fear of contamination could be very great. It is worth bearing in mind that there are other radio-nuclides more readily available than plutonium, with far greater radioactivity per unit weight and much greater physical health hazards due to either penetrating gamma radiation and/or mobility in the environment.

Terrorists are aware that a nuclear bomb affords the cheapest and biggest bang for the buck. No blackmail would be as compelling as holding an entire city hostage.

Bernard Lown, M.D.
IPPNW Co-Founder

Tracks made by alpha radiation emitted by a particle of plutonium in the lung tissue of an ape, magnified 500 times. *Photo by Robert Del Tredici*.

# Nuclear Terrorism — Prevention Is the Only Cure

## Part 3

**Gururaj Mutalik, MD**

### The Rising Tide of Terrorism

In Tokyo on March 20, 1995, the release of deadly Sarin nerve gas in a subway station killed 12 people and injured 5,000 others. The subway system was closed down for several days, disrupting daily life for Tokyo citizens. In the ensuing terrorist hunt, authorities discovered that the Aum Shinri Kyo religious sect allegedly responsible for the gas attack had plans to produce and store enough of the deadly nerve agent to kill 4.2 million people. The terrorist conspiracy extended beyond Japan to Russia, where Aum Shinri Kyo has 30,000 members and offices in Moscow. Newspapers reported that cult members had plans to obtain nuclear fissile material from Russian sources.

On January 20, 1993, terrorists exploded a truck bomb in the World Trade Center in New York City, shaking the sense of safety and security held by most citizens of the United States. On April 19, 1995, a fertilizer bomb destroyed the Federal Building in Oklahoma City, killing 167 people — many of them children in a daycare center. The explosion left a crater 8 feet deep and 20 feet wide. Terrorist activity is on the rise in many parts of the world: in Palestine, Israel, Ireland, India, Mexico, Saudi Arabia, Pakistan, Sri Lanka, the United Kingdom (UK), and many other countries.

The increase in terrorism has become one of the most pressing problems facing today's governments. Author Jeffrey Simon[32] says worldwide terrorist incidents are becoming more and more deadly and concludes that the rising tide of attacks by religious extremists is changing the very nature of international terrorism.

Aum Shinri Kyo acquired and used a weapon of mass destruction — the nerve gas Sarin. The recipe for nuclear disaster is almost complete. There exists the nefarious designs to commit murder; the knowledge and skills required to produce a crude nuclear bomb; and the necessary components and tools. The key ingredients — fissile materials — are now for sale. The question is no longer whether terrorist groups will acquire them, but when.[33]

## The Reality of a Terrorist Nuclear Threat

The preceding sections of this report have made clear the following:

- A determined sub-national group can fabricate a simple, crude or primitive but highly lethal nuclear device if it can acquire 55-60 kilograms (kg) of highly-enriched uranium or much smaller quantities of plutonium or plutonium oxide.

- Illegal diversion to, or acquisition of, the fissile material needed to produce a crude nuclear device by terrorists, from a number of countries is a very real possibility. The chaotic and ineffective procedures and practices used to safeguard government-owned and stored fissile material permits leakage, theft, and smuggling.
- Ineffective safeguards of fissile material are further complicated by the state of affairs in countries such as Russia and other former Soviet republics, where the prevailing political, economic, and social instability, coupled with the existence of huge quantities of nuclear material, increase the possibility of leakage of nuclear materials.
- Given access to materials to build a bomb, many terrorist or subnational groups would be likely to do so.

This threat prompted US Senator Richard Lugar (R-Indiana) to say:

> From the tragedies of Oklahoma City and the World Trade Center to the first act of nuclear terrorism requires but one small step. Suppose that, instead of mini-vans filled with hundreds of pounds of the crude explosives used in Oklahoma City and New York, terrorists had acquired a suitcase carrying a grapefruit-sized 100 pounds of highly-enriched uranium. Assuming a simple, well-known design, a weapon fashioned from this material would produce a nuclear blast equivalent to 10,000 to 20,000 tons of TNT. Under normal conditions, this would devastate a three-square-mile urban area. Most of the people of Oklahoma City would have disappeared. In the case of New York, the tip of Manhattan, including all the Wall Street financial district, would have been destroyed.[34]

A recent publication, *Avoiding Nuclear Anarchy* (Alison, et al),[35] draws further attention to these dangers. Released on the eve of the March 4, 1996, hearings of the US Senate Permanent Subcommittee on Investigations, the publication cites well-documents instances of illicit nuclear trade and the threat to US security caused by nuclear anarchy. The authors state that the possibility of theft or illicit sale of fissile material has always existed. The result is an emerging nuclear black market, assessible to non-state actors as well as to states. The inherent risk of nuclear terrorism is unprecedented, if under-appreciated. A report prepared specifically by the US General Accounting Office for the Subcommittee Hearings quotes instances of slack security in Russian institutions handling fissile material. The US investigators concluded: "...nuclear material is an easy target for smugglers and terrorists, given the security measures at scores of civilian and military nuclear sites throughout the former Soviet Union, and the United States has little ability to track the material if it is stolen."[36] Another study presented at these hearings cited 11 cases of fissile material diversion from Russian in which at least 7 cases were solidly confirmed.[37]

## The Consequences of Nuclear Terrorism

Fissile material leakage and a nuclear black market may have already enabled terrorist groups to acquire enough material to manufacture a crude weapon. Terrorists could threaten the use of a crude nuclear weapon to intimidate, blackmail, or extort. Whether a radioactive dispersal weapon or an actual nuclear bomb, the consequences of the use of such a device in a metropolitan center could be catastropic: massive casualities, infrastructural destruction, environmental catastrophe, and disruption of political, social, and financial institutions.

Theodore Taylor calculated that a crude low-yield bomb of half-a-kiloton place on the front steps of New York City's World Trade Center would knock the twin centers into the Hudson River. "It would take only a dozen kilos of plutonium oxide powder...to kill 50,000 people."[38] The effects of such an attack could be devastating: public panic would ensue; there would be the need to evacuate a major part of a metropolitan center; and the ambulance, hospital, and other medical services would be overwhelmed by the magnitude of the numbers of people with burns, other injuries, and shock. The consequences would extend far beyond the local level by destroying the world's central financial district and would undermine the trust and sense of security of American citizens. Already in the US, the effects of conventional bombings in New York and Oklahoma have introduced new fear into citizens' lives. This fear replaces the Cold War fear of global thermonuclear war between adversarial superpowers with the dread of uncontrollable, and unpredictable terrorist attack. When the nuclear threat is added to that of terrorism, it can only heighten the public's sense of helplessness. Until now, the nuclear threat has rested solely in the hands of governments who, despite their reliance on nuclear weapons, seem to have at least partially understood the consequences of their use. In the hands of terrorist or sub-national groups, who may disregard any consequences that would prevent them from pressing their agenda, the "security" of current government controls and restraint disappears.

## Coping with the Problem

The tragedies of the World Trade Center bombings, the Tokyo subway Sarin gas attack, and the Federal Building bombing in Oklahoma City have made the reality of terrorism more acute in the public mind. Terrorist attacks by the Irish Republican Army (IRA) in the UK and and the exacerbation of terrorism, including Hamas-sponsored suicide bombings in Israel, have dominated recent news. The result has led to a flurry of activities by the world's governments to devise and enforce the containment of terrorist actions. The March 1996 Middle East Summit on Terrorism, in which US President Clinton, then-Israeli Prime Minister Peres, and all other Middle East government leaders except President Assad of Syria participated, indicates that the pressing urgency of the terrorism issue has at long last led to some action, even if mostly symbolic. President Clinton's immediate commitment of 100 million US dollars to fight terrorism may be the beginning of a long overdue resolve to formulate concerted action to deal with the terrorist threat.[39]

In response to the prospect of domestic nuclear terrorism, the US Department of Energy set up the Nuclear Emergency Search Team (NEST). This high-tech team of volunteer scientists, engineers, technicians, and bomb experts is to develop surveillance and search systems used to pinpoint the location of possible nuclear devices and disable them. New automated techniques designed to deal with terrorist weaponry, such as the Automated Tether-Operated Manipulator (ATOM), are currently in development. Plans are also under way for aerial surveillance aircraft to be used as complementary devices to detect radiation emanating from weapons. Laws such as the Comprehensive Anti-Terrorism Act of 1995 are being tightened in order to assign greater penalties — up to life imprisonment — for illegal procurement of fissile material. The Senate Subcommittee on Investigations held comprehensive hearings on the subject and considered a number of proposals submitted by specially invited experts, scientists, and weapon designers for consideration.[40]

Some of the recommendations either submitted to the Subcommittee or suggested in recent publications include the following:[41]

- Stricter control and safeguard measures at Russian nuclear laboratories and fissile storage facilities.
- Action by the US Congress to fund a variety of Russian anti-leakage measures.
- Re-orientation of the US and Russian political relationship, moving on from programs that only serve US national security interests to those that will also reassure Russian national interests, particularly those that will enlist the cooperation of the Ministry of Atomic Energy of Russia (MINATOM), which controls the Russian nuclear stockpile.
- Involving other nuclear wepaon states and members of the G& to develop a unity of purpose and action in order to prevent nuclear leakage and to make nuclear security one of the highest priorities of their policy concerns with Russia.
- Promote programs that directly address the nuclear leakage threat. These include the following:
  - Expansion and urgent action on the US purchase of Russian highly-enriched uranium and excess plutonium.
  - Assistance to enhance security measures across the entire former Soviet Union.
  - Persuading the Russians to agree to a joint US-Russia nuclear inventory and side-by-side security analysis.

Other recommendations include adequate assistance to Russia for environmental clean-up at key nuclear weapons production and storage sites. For example, in 1992 George Perkovich and William Potter proposed putting Soviet nuclear experts to work cleaning up the enormous environmental damage caused by nearly 50 years of nuclear weapons production.[42] This proposal would take advantage of the considerable expertise of Russian scientists in nuclear clean-up and accident management, establishing a partnership that would benefit both the West and Russia. Others have stressed the urgent need to develop a comprehensive program for longer-term management of fissile material, including accelerated programs to create technology to permanently store plutonium, thus removing huge stocks of fissile material as attractive targets for terrorists. These bilaterial programs could be speedily expanded into effective multilateral collaborations. Other proposals, such as the establishment of an international plutonium bank, the involvement of European and other states, and a nuclear INTERPOL that exclusively deals with nuclear smuggling, terrorism, and proliferation merit attention.[43]

## Are We Working Towards a Comprehensive and Effective Plan?

Increasing terrorism worldwide, combined with the nuclear anarchy caused by the theft and black market trade of fissile materials, have compounded two deadly dangers of our age into the horrific prospect of nuclear terrorism. These developments have prompted new responsive ideas, plans, and actions.

Yet the basic question remains: **Are these proposed responses (or rather, the *potential* for response) adequate enough to lead to an urgent, comprehensive, concerted, and effective plan of action?** Or is it a case of too little, too late? While some of the new initiatives resulting from recent political developments, such as the Terrorism Summit and the ongoing US Senate Subcommittee hearings, deserve commendation, the core issues that must be confronted to effectively deal with the deadly virus of nuclear terrorism have not yet been adequately addressed in the current policy debate.

## What Are the Core Issues?

**1. The existence of fissile material is itself a threat.** The stockpiling and production of fissile material by the military (including those from dismantled nuclear weapons), and waste from civil nuclear-power generation undermines nuclear non-proliferation on the one hand and attracts terrorist exploitation on the other. Current safeguards and verification of fissile materials are inadequate.

Despite univeral recognition of the risks, no determined move has been made to put such material under secure international control so as to hasten its final disposition.[44]

Significant progress in nuclear disarmament has ben illusory given the overall increase in the world's stock of fissile materials. So long as stockpiles exist and increase, the threat of nuclear terrorism cannot be eliminated.

**2. Short-term solutions are not enough.** Despite the threat of nuclear anarchy, the US and its Western partners have not taken the necessary fundamental steps that include confidence-building political and economic measures with Russia, seeking Russian partnership in multilateral programs ensuring nuclear safety and initiating massive technical cooperation that as a by-product might promote democratization in Russia. The urgency of the situation appears to elude decision-makers in the Western nuclear weapon states. In coping with nuclear anarchy, as in the case of nuclear disarmament, rathan than struggling to achieve collective security, they offer only short-term solutions based on unilateral security concerns. Such partial solutions only complicate the situation further.

**3. All aspects of the problem need to be considered.** The trade in black market nuclear materials, much like illicit drug trafficking, is linked to international criminal organizations.[45] To combat that threat, it is vital that all the complex ramifications of the problem be addressed, and not merely the so-called "supply side" equations. Building more jails, stricter sentencing, better detection technology, increased policing and so on are but partial solutions. Just as purposeful efforts to reduce the demand for drugs are important, the global demand for military and civilian fissile materials has to be addressed at its roots. In this context, solutions for dealing with nuclear anarchy overlap with steps for dealing with nuclear proliferation by nations.

**4. International perspectives are required.** Typical expert testimony or governmental policies, including in the United States, is to view the problem from the narrow perspective of national security interests. This obscures the basic fact that the problem is universal and international in scope; national solutions to international problems are doomed to failure. Nuclear terrorism does present a threat to US national security, but preventing nuclear terrorism is not solely in the interest of the US. Viewing this problem in its partial perspective (that is, that the current state of Russia is the root cause of the problem and that resolution of the problem rests with the US), is misleading and simplistic. The threat of nuclear terrorism extends beyond Russia and the former Soviet Republics (even though there are some immediate dangers from the current Russian situation). Wherever fissile material is available, whether civil or military, the threat of it falling into terrorist or malign government hands exists. The US alone cannot provide an answer to this complex problem. No national solutions to such intricate international problems exist.

**5. Nuclear weapons themselves need to be abolished.** The US and its Western partners need to engage in fundamentally new thinking. They must address the problem of nuclear terrorism not as an isolated issue of terrorism, but rather as a predicament that combines the existence of nuclear weapons and a surfeit of weapons-usable material with groups of individuals who are willing to use nuclear weapons for their own political agendas. So long as nuclear weapons and the fissile material from which they are manufactured exist, neither the terrorist threat nor the nuclear ambitions of those the states who covet them can be eradicated. As a result, unprecedented political will and international cooperation must be exercised in order to spark concerted action at the highest levels worldwide. The US could exercise its economic and political strength and lead a comprehensive international effort to deal effectively with nuclear terrorism. The road to abolishing nuclear terrorism is inextricably intertwined with the road to abolition of nuclear weapons themselves. A decisive move towards that end must be made now.

This logic also applies strongly to the waste products of nuclear power generation. Removing weapons production and storage alone does not eliminate the availability of explodable fissile materials generated by power plants or other civilian means.

## A New Opportunity for Accelerated Nuclear Disarmament

In 1994, the International Physicians for the Prevention of Nuclear War (IPPNW) called for worldwide action towards the abolition of nuclear weapons within a fixed time period.[46] This movement aims to unite citizens of the world, through advocacy and education of nuclear decision-makers, to seize the unprecedented opportunities of the post Cold War world to eliminate the continued threat of nuclear proliferation and the dangers of the possible use of nuclear weapons.[47] The movement criticizes the policies of the nuclear weapon states, who have shown scant regard for the fundamental issue of nuclear disarmament and continue to focus on the short-term priorities of nuclear proliferation containment.

The threat of nuclear anarchy finds its roots in a system of nuclear apartheid. The nuclear weapon states believe that the present state of the world necessitates the possession of nuclear weapons while seeking to prevent the acquisition of nuclear weapons by other states. This hegemonic doctrine permeates most arms control and disarmament debates, such as the Nuclear Non Proliferation Treaty (NPT) and the negotiations in the Committee on Disarmament on a Comprehensive Test Ban Treaty (CTBT). The statement made by the French President Jacques Chirac in defense of French nuclear tests conducted in Polynesia soon after the permanent extension of the NPT demonstrates this fact.[48] Such policies and attitudes encourage nuclear proliferation.

Within the nuclear weapons states there is a lack of sufficient motivation and political will or true to alter the status quo. They rationalize that the difficulties of putting in place “fool proof” systems of verification and international controls for weapons and fissile material precludes their progress towards nuclear disarmament. In truth, their lack of motivation and political will to move towards disarmament is the real impediment. There is reluctance even to think in terms of what it takes to abolish nuclear weapons — a reluctance that is shared by many experts and advisors to governments who nevertheless believe in the eventual elimination of nuclear weapons. Ironically, the critical breakthrough in nuclear disarmament brought about by a successful regime of strict international control and verification would provide us with the best means of eliminating nuclear anarchy and its attendant consequences of nuclear terrorism.

## With Political Will, Nuclear Disarmament Can and Must Succeed

Success in fighting nuclear terrorism depends on the success of nuclear disarmament. Currently the world’s governments have an unprecedented opportunity to work toward a breakthrough in this field.

In the wake of French testing and the worldwide indignation that it incited, the Australian Government established the Canberra Commission on the Elimination of Nuclear Weapons, a ground-breaking nuclear disarmament initiative. Comprised of experts in the field of arms control and nuclear disarmament, the Commission's task is to prepare a report for consideration by the governments and people of the world to elimination nuclear weapons. Much attention was given to verification and international controls during initial Commission work. The Commission is also considering the ways and means of drawing worldwide attention, particularly of the nuclear weapon states, to the need to muster the necessary political will to respond to the urgency of these questions.

Expert scientists and military leaders, who previously could not address this question with objectivity and candor because of their ties to nuclear governments, have now begun to address the issue of nuclear weapons abolition, formulating action plans towards this end. A recent report by the Steering Committee of the Project on Eliminating Weapons of Mass Destruction, sponsored by the Henry L. Stimson Center, exemplifies this trend.[49]

The report conceives of the elimination of nuclear weapons as achieved in four phases:

**Phase I:** The US and Russia drastically reduce their nuclear arsenals and lay the foundation for studies on additional cuts and for verification and safeguards.

**Phase II:** Further erosion of the logic of deterrence, leading to reduction of nuclear arsenals in all the nuclear weapon states. De-emphasis of the political role of nuclear weapons in order to bring about significant changes in US defense policy, military strategy and force posture.

**Phase III:** All nuclear weapon states drastically reduce their arsenals to numbers as low as ten.

**Phase IV:** All nuclear weapons eliminated from all countries.

Phase IV of the report contains both the key and the dilemma for the approach needed to ensure ultimate success. "Progress towards the elimination of all weapons of mass destruction would require stringent national and international verification regimes; and companion regimes for biological and chemical weapons would be essential. Most importantly, the international community would have to possess the requisite political will."[50]

The committee has neither spelled out how to mobilize the needed political will nor how to develop and institutionalize stringent national verification regimes. In the past, the nuclear weapon states have shown little motivation or credible commitment to nuclear disarmament.[51] The basic assumptions of these governments must change before such effective regimens become acceptable to all. The crucial point in this debate is not whether stringent international control regimens can be formulated and implemented, thereby paving the way for collective security, but rather what it will take to do so. There are no insurmountable technical barriers. Certainly it will take unprecedented international cooperation and confidence building. It will also require partnership to supplant hegemony. It will take universal awareness that time is running out, and that only concerted action can stave off certain impending disaster. Above all, it will require the political will of a magnitude hitherto unexcercised by nuclear weapon states. The threat of terrorism can serve as an impetus to unite governments and help galvanize global political will.

# The Time is Now For Urgent Action

Nuclear terrorism threatens to strike anywhere, spreading in its wake death, destruction and suffering. So far we have been spared its actual occurrence, but there is no assurance that this will continue. The international community has heard the warning calls in Tokyo, New Delhi, Kashmir, Karachi, London, Tel Aviv, Colombo, New York and Oklahoma City. Nuclear terrorism will not be countered by the piecemeal solutions of increased policing, stricter criminal laws, monetary efforts, or even space-age equipment and gadgetry, even though all of these are valid and necessary ingredients in addressing this peril. The threat of nuclear terrorism will persist so long as terrorism exists and so long as nuclear weapons and the material from which they constructed remain within anyone's reach.

Led by the nuclear weapon states and acting at the highest levels, all states must work together, formulating an urgent plan of action to which they collectively and individually accord their fullest commitment. The elements of steps towards such a plan include:

- Convening a World Summit on Nuclear Terrorism in which all heads of states and governments, citizen groups and international NGOs participate as full-fledged partners.
- The scope of this summit should not include solely terrorism prevention and elimination. It should also include the necessary concomitant means to hasten the process of nuclear weapons elimination within a realistic time frame.
- Resources must be committed to facilitate implementation of the agreed action plan.
- Multi-disciplinary groups of experts from all parts of the world must prepare strategies, regimens and programs for political decision-makers to consider at the summit.
- To coordinate and ensure implementation of the plan of action, an intergovernmental agency exclusively devoted to terrorism should be established. Such a body should have close working links with all inter national entities and agencies connected with disarmament and development.
- Periodical assessment of progress should be made by a high-powered body with representative membership, including representatives from the UN Security Council.

# Dealing with the Mindset

"Since wars begin in the minds of men, it is in the minds of men that defenses of peace must be constructed."[52] In the ultimate analysis, as with war, it is in the minds of men that terrorism must be addressed. A culture of conflict and violence threatens to engulf our societies and our civilization. The massacres in Bosnia, the Hamas bombings in Israel and the killing fields of Rwanda are but symptoms of a deep-seated malaise in our society, the immense magnitude of which we have yet to fully comprehend. It is necessary to make an urgent beginning by involving the best minds of our generation to replace the *culture of violence* with the *culture of peace.* National isolationism, the philosophy of exclusion, and the preoccupation with ones own national security concerns (often at the cost of others) negate the emergence of a holistic remedy that this challenging task demands.

*Boston Globe* columnist James Carroll touched upon this fundamental issue. He said: “No one knows how to change the minds of the sadists who plant bombs in the car parks and in buses, but the mental virus that made them psychopaths is the still sacrosanct niche of ‘absolute and indivisible national sovereignty’ which, to cite only one instance in the United States, prompts talk of an electric fence along the border. Where in the current political campaign is any hint that America should reexamine its exclusivist assumptions as a nations-state? Yet if America does not, why should Hamas or the IRA?”

Mr. Carroll’s essential thesis is unexceptionable. The prevention of terrorism — including nuclear terrorism, which symbolizes the culture of violence in its ultimate form — can only begin when we change the way we think of ourselves and our nations. Nobody knows how to reshape the warped minds of psychopaths, but we can try to reshape the thinking of those who act out of ethnic frenzy or religious fanaticism that is but an extreme form of narrow self-righteousness and intolerance. The change in mindset that Carroll advocates is a fundamental step toward the erradication of such virulent forms of intolerance. We must succeed in changing our own mode of thought, so that we will enbable our children and grandchildren and generations beyond to live and grow in a culture of peace. He goes on to say, “ Indeed to break the cycle of killing, we will take the most extreme measure imaginable: We will change the way we think of our nations and ourselves.”[53, 54]

# APPENDIX A: EFFECTS OF A NUCLEAR EXPLOSION IN A POPULATED AREA

A fundamental precept of preventive medicine is that to motivate the actions necessary to prevent illness it is crucial to help people understand the consequences of failure to take effective preventive action. In Part I of this IPPNW Report, Dr. Frank Barnaby has documented how easily — unless effective preventive action is undertaken urgently — national or sub-national terrorist organizations might build a Hiroshima-type or Nagasaki-type nuclear explosive device. The information provided in this Appendix is intended to allow any citizens to estimate the effects such an attack would have on their local community.

In any presentation, it is important to underscore that estimates of casualties involve a large number of uncertainties, including the actual size (yield) of the nuclear explosion; the location of the explosion (including whether it is a "groundburst" and "airburst"); the weather at the time of the explosion (moist air will absorb more heat and thus reduce the rate of distant fires); the amount, if any, of warning time and the possibility of evacuation; and the availability and effectiveness of any emergency medical and other relief services.

This Appendix is divided into two sections: Section I provides a description and brief explanation of the casualty rates found in Hiroshima and Nagasaki, and Section II provides a step-by-step method for estimating the casualty rates resulting from a Hiroshima-type explosion in any populated area.

## Section I. Casualties in Hiroshima and Nagasaki

Although there are considerable uncertainties in estimating the effects of any explosion on a nearby human population, the experiences of Hiroshima and Nagasaki make it possible to develop reasonable estimates of the casualty rates that would result from the explosion of a crude nuclear weapon in any populated area. These casualties result from three distinct sources of injury: burns, blast, and radiation effects. In the case of burns and radiation, it is important to distinguish immediate from subsequent "secondary" injuries. Initial burn injuries result from the direct thermal radiation from the nuclear explosion — analogous to the heat of sunlight. Secondary burns result when an individual is exposed to the fires that are ignited as a result of the explosion. Analogously, initial radiation doses result from direct exposure to the gamma rays and neutrons released in the fission of the uranium or plutonium of the bomb; subsequent radiation doses result from exposure to the radioactivity of the earth or buildings that is induced by the nuclear explosion, including exposure to radioactive particles in the form of fallout.

If burn, blast, and radiation injuries are each analyzed independently, the following areas of lethal damage would be predicted:

### Table 1
### Areas of Lethal Damage from the Immediate Effects of a Nuclear Explosion, in km $^2$

| Type of Damage | 1-kiloton Yield | 10-kiloton Yield |
|---|---|---|
| Blast | 1.5 (0.7 km radius) | 4.9 (1.2) |
| Initial Heat | 1.3 (0.6) | 11.2 (1.9) |
| Initial Radiation | 2.9 (1.0) | 5.7 (1.3) |

Adapted from Barnaby F, Rotblat J. The effects of nuclear weapons. AMBIO 1982;11:84-93

As we know from Hiroshima and Nagasaki, however, the actual effects of a nuclear explosion are much more extensive. In part, this is because of the added destruction caused by the "secondary" fires described above. The actual destruction of buildings from the combination of blast and fire resulting from the Hiroshima explosion can be seen in Table 2.

### Table 2
### Area of Destruction of Buildings in Hiroshima Following Post-Explosion Fires

| Distance from Explosion | % Buildings Destroyed |
|---|---|
| < 1 km | 100% |
| 1 - 2 km | 98.8% |
| 2 - 3 km | 91.2% |
| 3 - 4 km | 83.2% |
| 4 - 5 km | 66.5% |
| > 5 km | 17.7% |

The actual casualties in these areas are naturally also increased. This is not only because of the added injuries from "secondary" burns and radiation exposure, but also because the health problems resulting from blast, heat, and radiation injuries are synergistic: an individual who is unlikely to die from any one of these three categories of injuries may be extremely likely to die from the combined effects of two or more of these types of injuries. For example, fatalities from burn injuries are frequently a result of overwhelming infection, and one of the most important effects of acute radiation exposure is depression of the bone marrow, with reductions in white blood cells and resulting impaired immune defenses.

The actual casualty rates resulting from the Hiroshima explosion are summarized in Table 3.

Any estimates of the total casualties (deaths plus non-fatal injuries) from Hiroshima and Nagasaki remain controversial, in part because of uncertainty about the numbers of military personnel and refugees present (especially in Hiroshima), and the number of individuals commuting into the city from outside for work. Out of a total of 340-350,000 individuals believed present in Hiroshima at the time of the explosion, a total of 90,000-120,000 deaths likely occurred. According to an official 1951 joint US-Japanese report, by the day

**Table 3**
**Hiroshima Mortality Rates as a Function of Distance from the Explosion**

| Distance from explosion (km) | <0.5 | 0.5 - 1.0 | 1.0 - 1.5 | 1.5 - 2.0 | 2. - 5.0 |
|---|---|---|---|---|---|
| First Day Mortality Rate | 90% | 59% | 20% | 11% | <4% |
| Final Mortality Rate | 98% | 90% | 46% | 23% | <4% |

Adapted from The Impact of the A-Bomb, 1985, p. 90 and Last Aid, p. 175

after the explosion, 91,000 survivors were injured, of whom 19,000 had died within four months. The remaining 72,000 survived beyond four months. (Some of these later died of radiation-related causes, including leukemia, thyroid cancer, breast cancer, and lung cancer.)

For more detailed information on the medical and social consequences of a nuclear explosion, please consult the following references:

1. Committee for the Compilation of Materials on Damage Caused by the Atomic Bombs in Hiroshima and Nagasaki: Hiroshima and Nagasaki -- The Physical, Medical, and Social Effects of the Atomic Bombings. Iwanami Shoten, Tokyo. 1979.

2. IPPNW: Last Aid. Freeman. 1982.

## SECTION II: Estimating the Casualties from a Nuclear Explosion Within Any City

The following simple steps can be used to estimate the results of a Hiroshima-size nuclear explosion in any city.

1. Obtain a map of the city and designate the site of the explosion.

2. Using a compass, draw concentric circles at 0.5 km, 1 km, 1.5 km, 2 km, and 5 km from the site of the explosion.

3. Find out the population density of the area (people per square kilometer) at the presumed time of the explosion. (This may vary tremendously depending on time of day. Business districts, for example, will have a very high population density during working hours and may be almost deserted at night.) The simplest, crude way to do this uses only two easily obtained facts: the city's total population and its area in square kilometers. Dividing the total population number by the number of square kilometers yields the average population density for the entire city.

4. Using the following table, calculate the total population within each band of the concentric rings you have drawn by multiplying the population density by the area in square kilometers. Finally, estimate the total fatalities within each band by multiplying the total population within that band by the fatality rate for that band. The total number of fatalities for the explosion is then the sum of the fatalities within each band. (For band five, the estimated fatality rate in Hiroshima was less than 4%; using a 2% figure for this band is probably reasonable.)

| Concentric Ring | Area (sq. km) | Fatality Rate |
|---|---|---|
| Band One: 0-0.5 km | 0.8 | 98% |
| Band Two: 0.5-1 km | 2.3 | 90% |
| Band Three: 1.0-1.5 km | 4.0 | 46% |
| Band Four: 1.5-2.0 km | 5.5 | 23% |
| Band Five: 2.0-5 km | 65.9 | 2% |

5. To estimate the total casualties in each area, you then need to calculate the number of individuals with injuries that are not fatal. Extrapolating from the Hiroshima experience in 1945 clearly involves tremendous uncertainties, but with estimates (see below) of 90,000-120,000 deaths and 72,000 additional injured, it is probably reasonable to divide the total fatalities by 2 to arrive at a conservative estimate of the number of individuals who will be non-fatally injured.

Additional materials for use in Abolition 2000: The Cities Campaign are currently under preparation by IPPNW. Please contact the IPPNW Central Office for the latest information about available educational resources.

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# Acknowledgements

IPPNW expresses its gratitude to the authors of this books. We sincerely thank Dr. Bernard Lown, IPPNW's Co-Founder, for his inspiring Foreword. We deeply appreciate the untiring efforts of Michael Christ, IPPNW's Program Director, for his editorial work and coordination of this project. We express our thankfulness to Svenska Lakare mot Karnvapens Stodforening and Dr. Ola Schenstrom for financial support for this publication. Our thanks and appreciation also go to Dr. David Rush for reviewing the manuscript. We are especially grateful to Lynn Martin for book design, production, and copyediting.

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1 Allison, Graham T., Owen R. Cote Jr., Richard A. Falkenwrath, and Steven E. Miller, Avoiding Nuclear Anarchy, Center for Science and International Affairs, Harvard University, 1996

2 Ibid

3 Kellen, 1987.

4 Mark et al, 1987.

5 Alvarez, 1987.

6 Hounam and McQuillan, 1995.

7 Imai, 1994.

8 Selden, 1976.

9 Blix, 1990.

10 Office of Technology Assessment, 1977.

11 Mark et al, 1987.

12 The critical mass depends on a number of factors. Firstly, the nuclear properties of the fissile material used - whether it is plutonium or highly-enriched uranium. Secondly, the shape of the material. A sphere is the optimum shape because for a given mass the surface area is minimized which, in turn, minimizes the number of neutrons escaping through the surface per unit time and thereby lost from the fission process. Thirdly, the density of the fissile material. The higher the density, the more likely it is that a product neutron will collide with another nucleus to cause another fission, and therefore the smaller the critical mass. Fourthly, the purity of the fissile material. If materials other than the one used for fission are present, some neutrons may be captured by their nuclei instead of causing fission. Fifthly, the physical surrounding of the material used for fission. If the fissile material is surrounded by a material, such as beryllium, which efficiently reflects neutrons back into the fissile material, neutrons may cause fissions which would otherwise have been lost.

13 IPPNW and Institute for Energy and Environmental Research, Plutonium: Deadly Gold of the Nuclear Age, 1994.

14 For a description of MOX and its implicatications for proliferation, see Kuppers and Sailer.

15 The isotopic composition of reactor-grade plutonium (produced in civil nuclear-power reactor fuel elements exposed to about 33,000 megawatt-days per ton of uranium fuel) is about:

1.4% Pu-238; 56.5% Pu-239; 23.4% Pu-240; 13.9% Pu-241; and 4.8% Pu-242.

Weapons-grade plutonium contains about:

0.05% Pu-238; 93.0% Pu-239; 6.4% Pu-240; 0.5% Pu-241; and 0.05% Pu-242.

The plutonium in typical mixed-oxide (MOX) fuel contains about:

2% Pu-238; 42% Pu-239; 31% Pu-240; 14% Pu-241; and 11% Pu-242.

16 The critical mass of a sphere of reactor-grade plutonium in metal form (in the alpha-phase, density = 19.0 g cm-3) is 13 kg (Mark, 1990).

The critical mass of a sphere of this type of reactor-grade plutonium metal in the delta-phase (density = 15.8 g cm-3) is 20 kg .

For weapons-grade plutonium, the critical mass of a sphere of the alpha-phase metal is 11 kilograms; for the delta-phase metal it is 17 kilograms.

For plutonium produced in the blanket of a breeder reactor, the critical mass for alpha-phase metal is 10 kg; for delta-phase it is 16 kg.

17 Mark, 1990.

18 In a neutron gun, a high voltage is used to accelerate small amounts of deuterium down a cylindrical tube. A zirconium-tritide target is placed at the bottom of the tube. When deuterium nuclei collide with tritium nuclei in the target, they undergo a nuclear fusion reaction, producing high-energy fusion neutrons. When the high voltage is applied, a shower of neutrons penetrates into the compressed plutonium core and initiates the fission chain reaction.

19 The mass of fissile material in the core of the weapon expands at very high speeds when the weapon explodes, initially at speeds of about 1,000 kilometers per second. In much less than a millionth of a second, the size and density of the fissile material have changed so that the mass becomes less than critical and the fission chain reaction stops. The task of the designer is to keep the fissioning material together, against its tendency to fly apart, for long enough to produce a nuclear explosion with an explosive yield appropriate for his purpose.

20 Hansen, Chuck. U.S. Nuclear Weapons. New York: Orion Books, 1988

21 A krytron is a cold-cathode, gas-filled switch using an arc discharge to conduct high peak currents for short times.

22 Cochran and Paine, 1994.

23a Albright et al, 1992.

23b Johnson and Islam, 1991.

24 Office of Technology Assessment, 1995.

25 Miller, 1990.

26 Office of Technology Assessment, 1995.

27 T. Shea and Chitumbo, 1993.

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31 See Makhijani and Makhijani

32 Simon, Jeffrey D., The Terrorist Trap, Indiana University, 1994.

33 Mark, et al, in Preventing Nuclear Terrorism: The Report and Papers of the International Task Force on the Prevention of Nuclear Terrorism, pp. 60-61, eds. Paul Leventhal and Yonah Alexander, Lexington Books, 1987.

34 US Senator Richard Lugas, in a speech to United We Stand, Dallas, August 1995.

35 Center for Science and International Affairs, Kennedy School of Government, Avoiding Nuclear Anarchy — Containing the Threat of Loose Russian Nuclear Weapons and Fissile Material, Chapter 2 and Appendix B, Harvard University, 1996.

36 Shenon, Philip, New York Times, March 13, 1996.

37 Oral testimony by Dr. William Potter, Monterey Institute of International Studies, before the Roth-Nunn Senate Subcommittee, March 13, 1996.

38 Huge, David, When Terrorists Go Nuclear, Popular Mechanics, January 1996.

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41 Ibid. See also note 6.

42 Perkovich, George and Potter, William C. Cleaning Up Russia's Future, Washington Post, January 5, 1992.

43 Alison, Graham, et al., pp. 146-176.

44 IPPNW and Institute for Energy and Environmental Research, Plutonium: Deadly Gold of the Nuclear Age, 1994.

45 Alison, Graham, et. al., pp. 66-67

46 Abolition 2000 is a global movement involving a growing network of over 200 non-governmental organizations and citizens' groups with a membership of over 10 million members. It calls for a convention or treaty by the year 2000 to abolish nuclear weapons so that an agreed timetable towards this is put in place. The call has been endorsed by numerous Nobel Peace Prize winners.

47 IPPNW, Abolition 2000: Handbook for a World Without Nuclear Weapons, 1995.

48 Chirac stated in effect that his country has the sovereign right to bear and use nuclear weapons.

49 Henry L. Stimson Center Project on Eliminating Weapons of Mass Destruction, An Evolving US Nuclear Posture, pp. vii and 35-36, Washington, DC, December 1995. General Andrew J. Goodpaster (USA-Retired) chairs the Steering Committee

50 Ibid.

51 Ibid. The Committee report states: "A more serious commitment to the goal of elimination is necessary to devalue those weapons globally, while signaling to non-nuclear states, that the United States NPT pledge is serious." p. 3G

52 Constitution of the United Nations Educational, Scientific and Cultural Organization, 1946.

53 Carroll, James, Boston Globe editorial, March 12, 1996.

54 Ibid.

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# GLOSSARY

| | |
|---|---|
| **Alpha particle** | Nucleus of the helium atom, consisting of two neutrons and two protons, emitted from radioactive isotopes. |
| **Alpha radiation** | Radiation consisting of a helium ion that is emitted upon the radioactive disintegration of the nuclei of certain heavy elements, such as plutonium-239. |
| **Atomic number** | The number of protons in the nucleus of an atom. All isotopes of a given element have the same atomic number. |
| **Beta radiation** | Radiation consisting of high-speed electrons or positrons. |
| **Bq /$m^2$** | Bequerels per square meter — a measure of the concentration of deposited radioactivity over an area. |
| **Bq s/$m^3$** | A measure of the integrated radioactivity of a cubic meter of air. |
| **CEC** | The Commission of the European Communities. |
| **Chain reaction** | Atomic process in which the products of the reaction assist in promoting the process itself; that is, nuclear fission in which a neutron from one fissioning nucleus produces fission in another nucleus. |
| **COSYMA** | A computer model developed by the Commission of the European Communities. |
| **Critical mass** | The minimum amount of substance that will result in a self-sustaining chain reaction. |
| **Electron** | Elementary particle with a negative electrical charge and a mass of about 1/1836 that of a proton. |
| **Element** | Simple substance which cannot be resolved into simpler substances by normal chemical means. Because of the existence of isotopes of elements, an element is not a substance which has identical atoms but one which has atoms of the same atomic number. |
| **Fissile** | Capable of nuclear fission when certain heavy elements — U-233, U-235, and Pu-239 — capture neutrons of suitable energy. |
| **Fission** | The process whereby the nucleus of a heavy element splits into (usually) two nuclei of lighter elements, with the release of significant amounts of energy. |
| **Fission product** | An isotope of an element created by the fission of a heavy element. |
| **Fission weapon** | Nuclear weapon whose fissile material is uranium or plutonium which is brought to a critical mass under pressure from a chemical explosive detonation to create an explosion. |
| **Gamma radiation** | Electromagnetic radiation with very energetic photons. |
| **Half-life** | The time in which half of a radioactive substance decays away. |
| **ICRP** | International Council for Radiological Protection. |
| **Isotope** | One or more variant forms of an element. Isotopes have the same number of protons in their nucleus, and, therefore, the same chemical properties but different numbers of neutrons, and, therefore, different weights. Various radioactive isotopes of an element have different half-lives. |
| **Kilo-** | The prefix used to denote one thousand. |
| **Kiloton (kt)** | A unit of measure of the explosive yield of a nuclear explosion, equivalent to the explosive energy of one thousand tons of trinitrotoluene (TNT). |
| **Micro-** | The prefix used to denote one-millionth of the unit. |
| **Milli-** | The prefix used to denote one-thousandth of the unit. |
| **Neutron** | An elementary particle which is electrically neutral. Together with protons it forms the nucleus of an element. Neutrons are stable in the nucleus but unstable in free air, decaying into a proton and an electron with a half-life of about 12 minutes. |

**Nuclear weapon** A device in which the explosion results from the energy released by nuclear reactions involving atomic nuclei — fission, fusion or both.

**Nuclide** See radio-nuclide

**Positron** An elementary particle with a positive electrical charge but otherwise identical to an electron.

**Proton** An elementary particle with a positive electrical charge, with a mass slightly less than that of a neutron. Protons and neutrons make up the nuclei of elements.

**Radioactivity** The spontaneous release of energy from the nucleus of an atom, usually in the form of alpha, beta, or gamma radiation.

**Radio-nuclide** A particular radioactive isotope of an element.

**Sv** Siverts — a measure of biological damage caused by absorbed radiation (continually revised with research findings).

**TNT equivalent** The unit most often used to measure the energy released in nuclear explosions. One ton of TNT is equivalent to one thousand million calories of energy.

**Yield** The energy released in an explosion. The energy released in the detonation of a nuclear explosive device is usually measured in terms of the number of kilotons (kt) of TNT required to produce the same energy release.

# Notes