Nuclear Weapons

This book is a history of nuclear weapons. From their initial theoretical development at the start of the twentieth century to the recent tests in North Korea, Jeremy Bernstein seeks to describe the basic science of nuclear weaponry at each point in the narrative. At the same time, he offers accounts and anecdotes of the personalities involved, many of whom he has known firsthand. Dr. Bernstein writes in response to what he sees as a widespread misunderstanding throughout the media and hence among the general public of the basic workings and potential impact of nuclear weaponry. For example, he points out that it has been nearly thirty years since anyone has even seen a nuclear detonation. Likewise, the Nagasaki bomb, primitive when compared to more modern devices, generated an explosion roughly the equivalent of eight thousand copies of the truck bomb used by Timothy McVeigh in Oklahoma City.

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WHAT YOU NEED TO KNOW

Jeremy Bernstein

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore,
São Paulo, Delhi, Dubai, Tokyo

Cambridge University Press
32 Avenue of the Americas, New York, NY 10013-2473, USA

www.cambridge.org
Information on this title: www.cambridge.org/9780521126373

First published 2008
First paperback edition 2010

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication Data

Bernstein, Jeremy, 1929–
Nuclear weapons : what you need to know / Jeremy Bernstein.
p. cm.
Includes bibliographical references and index.
ISBN 978-0-521-88408-2 (hardback)
1. Nuclear weapons. I. Title.
U264.B453 2008
355.02′17–dc22 2007016625

ISBN 978-0-521-88408-2 Hardback
ISBN 978-0-521-12637-3 Paperback

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Cambridge University Press
978-0-521-12637-3 - Nuclear Weapons: What You Need to Know
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ACKNOWLEDGMENTS

I am indebted to a great many friends and colleagues for both criticism and helpful suggestions. Among the commentators were anonymous referees, whom I would like to thank here. The people I can thank personally, and I hope that I have not left anyone out, are Elihu Abrahams, Steve Adler, Norman Dombey, Sid Drell, Freeman Dyson, Richard Garwin, Roy Glauber, Sig Hecker, Walter Isaacson, Rainer Karlsch, Tom Lehrer, Norman Ramsey, Helmut Rechenberg, Cameron Reed, Carey Sublette, Richard Wilson, Herb York, and Peter Zimmerman. I also would like to thank from Cambridge University Press Simina Calin, Shari Chappell, Eric Crahan, Rufus Neal, and Laura Wilmot for their fine editorial work. As I was finishing this book I learned that my friend Francis Low had died. He and I shared an adventure in 1957 without which, as the reader will see, there would have been no book.

UNITS AND SIZES

These are the units and sizes needed for understanding fission and fusion. The "atomic mass unit" (amu) is commonly employed.

Mass Units

- 1 amu $= 1.66 \times 10^{-24}$ gram
- Mass of neutron $=$ 1.00867 amu
- Mass of U-235 nucleus $= 234.9934 \sim 235$ amu $\sim 235 \times 1.66 \times 10^{-24}$ gram $\sim 3.9 \times 10^{-22}$ gram
- Number of U-235 nuclei in a kilogram $= 1{,}000 / 3.9 \times 10^{22} \sim 2.56 \times 10^{24}$
- 1 metric ton (tonne) $= 10^3$ kilograms

Energy Units

- 1 watt second $=$ 1 joule $= 10^7$ ergs
- 1 electron volt $= 1.6 \times 10^{-19}$ joule
- 1 million electron volts (MeV) $= 1.6 \times 10^{-13}$ joule
- 1 kilo calorie $= 4.184 \times 10^3$ joules

It is common to express masses in terms of energy units using $E = mc^2$ with "c" the speed of light ($2.99792458 \times 10^{10}$ cm/sec). In these units the mass of the neutron is 939.573 MeV/c^2.

The average total energy in the uranium fission of one U-235 nucleus is about 200 MeV, which equals about 3.2×10^{-11} joule. The average energy of the fission of one Pu-239 nucleus is about 210 MeV. But the effective energy is about 175 MeV for U-235 or about 2.8×10^{-11} joule per gram.

- 1 kilogram of U-235 completely fissioned produces $2.8 \times 10^{-11} \times 2.56 \times 10^{24}$ joules $\sim 7.2 \times 10^{13}$ joules.
- 1 kilogram of TNT produces about 4.184×10^{6} joules $= 4.18 \times 10^{13}$ ergs.
- 1 metric tonne of TNT produces 4.18×10^{9} joules, so 1 kilotonne produces 4.18×10^{12} joules.

Thus it requires 72/4.2 kilotonnes, which is approximately 17 kilotonnes, or about 19 short kilotons, of TNT to produce an explosion equal to 1 kilogram of fissioned U-235. Timothy McVeigh's Ryder truck bomb gives us a practical unit: it had 2.5 tons of explosives. Therefore 1 kiloton equals about 400 Ryder trucks. McVeigh actually used ammonium nitrate, which has a comparable explosive power. The Nagasaki plutonium bomb had a yield of about 20 kilotons, which is approximately 8,000 Ryder trucks.

Hydrogen bombs obtain their yield by the fusion of light elements – primarily the isotopes of hydrogen of which there are three. The nucleus of ordinary hydrogen has one proton; heavy hydrogen – the deuteron (D) – has one proton and one neutron; and super heavy hydrogen – the triton (T) – has one proton and two neutrons. The most favorable fusion reaction used in hydrogen bombs is

$$D + T \rightarrow He + n + 17.6 \text{ MeV}.$$

In this expression "He" is the nucleus of ordinary helium with two neutrons and two protons and "n" is a neutron. The 17.6 MeV is the energy that is available because of the mass difference between the two sides of the expression. Most of this energy goes into the kinetic energy of the neutron. However, the charged alpha particle does most of the damage. In fission most of the energy goes into the fission fragments and much less to the neutrons, which have average energies of about 2 MeV. Uranium-238 has a neutron energy fission threshold of about 1 MeV. About three fourths of the neutrons produced in the fission of the uranium-235 in natural uranium have energies above this threshold, but only about one fourth are not slowed down below this threshold before the next fission. Hence there are not enough neutrons available above this threshold to fission the U-238 in natural uranium and produce a chain reaction. So natural uranium, which is more than 99 percent U-238 cannot be used to make a bomb. In a so-called hydrogen bomb a good deal of the yield is produced by subsequent fissions caused by the production of energetic neutrons in the fusion reactions.

The Hiroshima bomb, Little Boy, used 64.1 kilograms of about 89 percent enriched uranium and had a 1.4 percent efficiency, which would give about a 15-kiloton yield. The Nagasaki bomb used 6.2 kilograms of plutonium with a 17 percent efficiency, giving about a 20-kiloton yield. Hydrogen bombs produce a thousand times greater yield. In terms of Ryder trucks, the Nagasaki bomb was equivalent to eight thousand and a hydrogen bomb is equivalent to millions.

Cambridge University Press
978-0-521-12637-3 - Nuclear Weapons: What You Need to Know
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PREFACE TO THE PAPERBACK EDITION

The route that led to the Iranian development of nuclear technology began in an unlikely place and time with an unlikely cast of characters. The time was just after the Second World War and the place was a German prisoner of war camp near Sochumi on the Black Sea in Georgia. The camp was a kind of scientific gulag. Its leader was a minor German aristocrat and inventor named Manfred von Ardenne. During the war Ardenne ran a private laboratory on his estate outside Berlin that devoted itself to research on nuclear energy. It is quite unclear whether Ardenne thought in terms of a nuclear weapon. What he did do was invent an electromagnetic method for separating the isotopes of uranium. When the Russians entered Germany, they brought with them a cadre of scientific experts whose mission was to bring back anything the Russians could use to make a nuclear weapon. Apart from a good deal of metallic uranium, the Russians brought back a number of scientists and their equipment. Thus Ardenne landed in Sochumi.

He soon acquired the job of separating the isotopes of uranium. There were three groups. One was headed by the Nobelist Gustav Hertz and devoted itself to separation by means of diffusing gaseous uranium through membranes with tiny pores. Ardenne's group tried electromagnetic separation, and the third group – headed by the physicist Max Steenbeck – took on separation by centrifuge. Ardenne apparently had lists of prisoners in other camps and their scientific backgrounds. He found an Austrian-born physicist named Gernot Zippe and brought him to Sochumi to join Steenbeck. Steenbeck did the theory, and Zippe became head of the experimental part of the effort. Neither man had ever worked on centrifuges. They had available to them some inefficient Russian centrifuges and some review articles by the American physicist Jesse Beams. Nonetheless they managed in the course of a few years to create the best gas centrifuge ever made, which became the prototype of all modern gas centrifuges. They had no idea at the time what they had done.

In 1956, Zippe was allowed to return to Germany. (Ardenne, Hertz, and Steenbeck remained in the east.) Before he died (in May 2008), I had several talks with Zippe. He told me that he had not been allowed to take any papers from Russia but that did not matter because he had all the details of the centrifuge in his head. When he was released he assumed that it was because the Russians had lost interest in using centrifuges for uranium separation. He was surprised when, some decades later, the Russians revealed that they had built tens of thousands of centrifuges along the lines of the designs that Zippe and his collaborators had created. Very soon after returning to Germany jobless, Zippe attended a centrifuge conference in Amsterdam and realized that the "Russian centrifuge," as he called it, was better than anything then on offer. He then began a series of consulting jobs on centrifuge construction. The patent implications of this were entirely unclear, but the Russians never contested it because they would have had to reveal their program.

Later in the book I describe how much of the European centrifuge program became concentrated in a single company – URENCO –

which had branches in Holland. I also describe how a Pakistani metallurgist named Abdul Qadeer Khan came to work for this company, and how he stole the plans for their most advanced centrifuge and turned them over to the Pakistanis. I also describe how Khan created a proliferation network that spanned several continents. I want here to focus on Iran. The Iranian interest in nuclear technology goes back to the shah. After his overthrow in 1979, the program lapsed until the late 1980s. In 1987, the Iranians made their first contact with the Khan network. However, the Ayatollah Khomeni, then the supreme leader, was not enthusiastic about nuclear weapons, for religious reasons. But he died in 1989. His successor, the present Supreme Leader Ayatollah Khamani, was enthusiastic, as was the then-president Rafsanjani. In 1993, for some three million dollars, the Iranians bought part of a whole "menu" of nuclear technology that the Khan network had on offer. This included a design for a centrifuge and some used sample centrifuges, as well as the plans to make uranium metal hemispheres, whose only use would be in a nuclear weapon.

The centrifuges the Iranians bought had been used in the Pakistani nuclear weapons program. This became clear when the United Nations inspectors found traces of highly enriched uranium on them. Whereas the Libyans to whom the Khan network had sold a similar package did not have the infrastructure to make use of what they bought and eventually gave it up, the Iranians were able to reverse-engineer items like the centrifuge and to begin manufacturing their own. There are some accounts of this effort by the Iranians themselves, and it is clear that they put both considerable resources and great effort into this project. This is one of the reasons why they will not give it up readily.

The amount of isotope separation a given centrifuge can perform depends on its size and on the speed of its rotation. The gas is contained in a cylinder whose surface area is proportional to its length. The Russian centrifuges were long and thin. This meant that they were made of shorter cylinders joined together by something called a "bellow." Making these bellows was one of the most technically difficult obstacles the Iranians had to overcome. The most advanced Zippe Russian centrifuge had aluminum cylinders. It achieved a peripheral speed – the speed of a dot on the cylinder – of about 350 meters per second – faster than the speed of sound in air. The first centrifuge model the Iranians built – the P1 – also used aluminum and presumably had similar peripheral speeds. The P1 was succeeded by the P2, which used a special variety of steel. This has been succeeded by a new generation of centrifuges made of carbon fiber. These are capable of peripheral speeds of some 600 meters per second. Hence one can get the same separation with a shorter centrifuge and thus eliminate the need for the bellows. The Iranians have several thousand of these in a cascade and have been able to separate at least a ton of reactor-grade plutonium.

The stated purpose of the reactor-grade plutonium is as fuel in the Iranians' Bushehr reactor, which is designed to produce electric power. One wonders why the Iranians, who, after Russia, have the largest reserve of natural gas in the world – a resource that is barely exploited – would need to bother with this very expensive nuclear program if its purpose was to produce power. Most people who have considered this have come to the conclusion that the reactor is merely a cover for the real intent of the program, which is to produce a nuclear weapon. It may be that we will only know this for certain when and if the Iranians perform their first test. But by then it will be too late to stop the program.