

BIOLOGICAL EFFECTS OF EXTERNAL X AND GAMMA RADIATION

Part I

Edited by

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PREFACE

This volume is one of a series which has been prepared as a record of the research work done under the Manhattan Project and the Atomic Energy Commission. The name Manhattan Project was assigned by the Corps of Engineers, War Department, to the far-flung scientific and engineering activities which had as their objective the utilization of atomic energy for military purposes. In the attainment of this objective, there were many developments in scientific and technical fields which are of general interest. The National Nuclear Energy Series (Manhattan Project Technical Section) is a record of these scientific and technical contributions, as well as of the developments in these fields which are being sponsored by the Atomic Energy Commission.

The declassified portion of the National Nuclear Energy Series, when completed, is expected to consist of some 60 volumes. These will be grouped into eight divisions, as follows:

- Division I — Electromagnetic Separation Project
- Division II — Gaseous Diffusion Project
- Division III — Special Separations Project
- Division IV — Plutonium Project
- Division V — Los Alamos Project
- Division VI — University of Rochester Project
- Division VII — Materials Procurement Project
- Division VIII — Manhattan Project

Soon after the close of the war the Manhattan Project was able to give its attention to the preparation of a complete record of the research work accomplished under Project contracts. Writing programs were authorized at all laboratories, with the object of obtaining complete coverage of Project results. Each major installation was requested to designate one or more representatives to make up a committee, which was first called the Manhattan Project Editorial Advisory Board, and later, after the sponsorship of the Series was assumed by the Atomic Energy Commission, the Project Editorial Advisory Board. This group made plans to coordinate the writing programs at all the installations, and acted as an advisory group in all matters affecting the Project-wide writing program. Its last meeting was held on Feb. 9, 1948, when it recommended the publisher for the Series.

The names of the Board members and of the installations which they represented are as follows:

Atomic Energy Commission Public and Technical Information Service	Alberto F. Thompson
Technical Information Division, Oak Ridge Extension	Brewer F. Boardman
Office of New York Operations	Charles Slessor, J. H. Hayner, W. M. Hearon *
Brookhaven National Laboratory	Richard W. Dodson
Carbide & Carbon Chemicals Corporation (K-25)	R. B. Korsmeyer, W. L. Harwell, D. E. Hull, Ezra Staple
Carbide & Carbon Chemicals Corporation (Y-12) †	Russell Baldock
Clinton Laboratories ‡	J. R. Coe
General Electric Company, Hanford	T. W. Hauff
General Electric Company, Knolls Atomic Power Laboratory	John P. Howe
Kellex Corporation	John F. Hogerton, Jerome Simson, M. Benedict
Los Alamos	R. R. Davis, Ralph Carlisle Smith
National Bureau of Standards	C. J. Rodden
Plutonium Project Argonne National Laboratory	R. S. Mulliken, H. D. Young
Iowa State College	F. H. Spedding
Medical Group	R. E. Zirkle
SAM Laboratories §	G. M. Murphy
Stone & Webster Engineering Corporation	B. W. Whitehurst
University of California	R. K. Wakerling, A. Guthrie
University of Rochester	D. R. Charles, M. J. Wantman

* Represented Madison Square Area of the Manhattan District.

† The Y-12 plant at Oak Ridge was operated by Tennessee Eastman Corporation until May 4, 1947, at which time operations were taken over by Carbide & Carbon Chemicals Corporation.

‡ Clinton Laboratories was the former name of the Oak Ridge National Laboratory.

§ SAM (Substitute Alloy Materials) was the code name for the laboratories operated by Columbia University in New York under the direction of Dr. H. C. Urey, where much of the experimental work on isotope separation was done. On Feb. 1, 1945, the administration of these laboratories became the responsibility of Carbide & Carbon Chemicals Corporation. Research in progress there was transferred to the K-25 plant at Oak Ridge in June, 1946, and the New York laboratories were then closed.

Many difficulties were encountered in preparing a unified account of Atomic Energy Project work. For example, the Project Editorial Advisory Board was the first committee ever organized with representatives from every major installation of the Atomic Energy Project. Compartmentation for security was so rigorous during the war that it had been considered necessary to allow a certain amount of duplication of effort rather than to permit unrestricted circulation of research information between certain installations. As a result, the writing programs of different installations inevitably overlap markedly in many scientific fields. The Editorial Advisory Board has exerted itself to reduce duplication in so far as possible and to eliminate discrepancies in factual data included in the volumes of the NNEs. In particular, unified Project-wide volumes have been prepared on Uranium Chemistry and on the Analysis of Project Materials. Nevertheless, the reader will find many instances of differences in results or conclusions on similar subject matter prepared by different authors. This has not seemed wholly undesirable for several reasons. First of all, such divergencies are not unnatural and stimulate investigation. Second, promptness of publication has seemed more important than the removal of all discrepancies. Finally, many Project scientists completed their contributions some time ago and have become engrossed in other activities so that their time has not been available for a detailed review of their work in relation to similar work done at other installations.

The completion of the various individual volumes of the Series has also been beset with difficulties. Many of the key authors and editors have had important responsibilities in planning the future of atomic energy research. Under these circumstances, the completion of this technical series has been delayed longer than its editors wished. The volumes are being released in their present form in the interest of presenting the material as promptly as possible to those who can make use of it.

The Editorial Advisory Board

PLUTONIUM PROJECT RECORD FOREWORD

This report is a technical account of information collected while developing methods for producing plutonium. Some of the information deals directly with nuclear physics and chemistry. Most of it is related rather to technical processes that needed to be performed in preparation for making the plutonium. These publications represent selections from the great mass of current reports, made on the basis of their value to basic science and technology.

The current technical reports, written during the war years, were essential to the active work of the plutonium project. They supplied needed data and calculations to those who were planning the new processes. Selecting from this mass of records the most reliable data and presenting them in a useful form has been an enormous task, for which the writers and editors of these volumes deserve the sincere thanks of their scientific colleagues. Many fields of science and technology will develop more rapidly because of this knowledge.

The efforts of the men who did this research resulted in the successful production of atomic bombs, which shortened the war and saved the lives of many of their comrades. But in the long view of history it is probable that the major human heritage from their work will not be this quick victory. It may not even be the useful applications of atomic energy, which was first presented as a Promethean gift to man. It is not unlikely that the scientific information in these pages may be the starting point to new reaches of knowledge, which will give to man an understanding that will truly enrich his life.

Arthur H. Compton

INTRODUCTORY NOTE ON THE PLUTONIUM PROJECT RECORD

Organization and Record of the Metallurgical Project. The Plutonium Project Record, which forms Division IV of the National Nuclear Energy Series (NNEs), is the scientific and technical record of the former Metallurgical Project. The project had its origin in work carried on in 1940-1941, mainly at Columbia and Princeton on the development of the chain-reacting pile and at the University of California at Berkeley on the production and chemistry of transuranic elements. In January 1942 this work was concentrated in the newly organized Metallurgical Laboratory at Chicago under the leadership of A. H. Compton. The Metallurgical Project grew out of the Metallurgical Laboratory. The initial objectives of the Metallurgical Laboratory were (1) to develop chain-reacting piles to produce plutonium and (2) to develop fission bombs. Major associated units were organized in 1942 at Iowa State College at Ames, Iowa (chemistry and metallurgy) under F. H. Spedding; at the University of California at Berkeley, Calif. (chemistry) under W. M. Latimer and E. D. Eastman, continuing the previous work there; and at Massachusetts Institute of Technology (metallurgy) under J. Chipman and later M. Cohen. Early in 1943 the work on fission bombs was transferred to an independent project at Los Alamos.

After the successful demonstration of a nuclear chain reaction in the West Stands pile at Chicago in December 1942, the Argonne Laboratory with its experimental pile was built west of Chicago, and the Clinton Laboratories with their pilot-plant pile were built at Oak Ridge, Tenn. — both in 1943. The three major laboratories at Chicago, Argonne, and Clinton, the associated laboratories at Ames, Berkeley, and M.I.T., and some seventy other cooperating groups then constituted the Metallurgical Project, under A. H. Compton as Project Director. Closely cooperating in the transition from laboratory and pilot-plant to large-scale operation was E. I. du Pont de Nemours & Company, which was made responsible for the design and construction of the Clinton pile and for the design, construction, and operation of the Hanford Plutonium Plant. The Project continued as such until June 30, 1945, when it was dissolved.

The Plutonium Project Record (PPR) covers most of the scientific and technical work of the Metallurgical Laboratory and the Metallurgical Project up to the date of the dissolution of the Project, and also

the continuation of this work in the successor laboratories up to approximately Jan. 1, 1946, or in some cases to a later date. In addition, the PPR covers in part the pre-1942 work at Columbia, Princeton, and Berkeley. The record of the work directly leading up to the Los Alamos Project, however, is omitted. Nevertheless the PPR and the Los Alamos Technical Series (Division V of the NNES) cover closely related and in part overlapping subject matter in some of their volumes, particularly in nuclear physics and in chemistry and metallurgy of plutonium.

Important phases of the work of the Metallurgical Project that are not reported in the PPR but will be reported elsewhere in the NNES are as follows: (1) Division VII, the report of the Materials Procurement Project, includes certain early work on process metallurgy, which was initiated largely by the Metallurgical Laboratory. (2) The Division VIII NNES volumes on Analytical Chemistry, which developed from two volumes originally planned as part of the PPR, contain much Metallurgical Project work, including one complete Collected Papers volume. (3) The Division VIII NNES volumes on Uranium Chemistry, which were planned and carried out under the supervision of the PPR editorial group, likewise contain much Metallurgical Project work, including one complete Collected Papers volume.

History and Plan of the Plutonium Project Record. During the war years the scientific and technical work of the Metallurgical Project and its associated laboratories was described currently in a series of reports called the "C reports." The work up to July 1, 1945 was described in some 3,000 reports. After that date the Clinton Laboratories reports became a separate series, but reports of the other units of the former Metallurgical Project continued to be issued as C reports. Most of the C reports were preliminary or semifinal reports. The main consideration during the wartime development was speed of issue and distribution.

As the mass of scientific and technical knowledge obtained on the Project piled up, an increasing need was apparent for its digestion into survey or summary form. In partial answer to this need, an editorial group was set up in the spring of 1943 to organize a Project Handbook. Although never fully completed because of the engrossment of authors in immediately urgent tasks, and because of the transfer of many of them to other sites, enough of the Project Handbook was finished to be of real value.

By the summer of 1944, the Metallurgical Project had largely concluded its major task, that of providing the scientific and pilot-plant know-how for the design of the large-scale Hanford Plutonium Plant. The time seemed ripe to plan a series of volumes in which the Project's fund of accumulated scientific and technical knowledge would be

recorded. These would replace the often sketchy and sometimes mutually contradictory C reports and fill many gaps of unwritten knowledge. In the early planning, Laurence L. Quill as Chief of the Editorial Section of the Project Information Division during the summer of 1944, Eugene Rabinowitch, and H. H. Goldsmith made important contributions. After several committee meetings, a plan for the preparation of a Metallurgical Project Record was approved by the Project Director in the fall of 1944. Later, in 1945, the name was changed to Plutonium Project Report or Record (PPR).

When the PPR was organized, rigid compartmentation was still in effect between the Metallurgical Project and the other Manhattan District projects. Members of each project were in general not supposed to know even the major objectives or main outlines of the other projects. The PPR had therefore to be planned as an independent entity. Nevertheless, at its inception the idea was firmly held that later on the Record should become part of a larger series covering the work of all the atomic energy projects. This idea was repeatedly advocated and led in late 1945 to the plan for the Manhattan Project Technical Series (MPTS), a name which was finally revised to the present designation of National Nuclear Energy Series (NNES).

The general plan of organization of the PPR was that of a series of some twenty Survey volumes, called "A volumes," each documented by a like-numbered Collected Papers volume (or volumes); these were called "B volumes." In general, following somewhat a pattern set by the Project Handbook, a Survey volume was planned for each scientific or technical subject to which the Metallurgical Project had made sufficiently major contributions. Each Survey volume was intended to be a fairly complete review or monograph (or else a collection of review chapters) on the subject field. It was planned to cover work done both within and outside the Metallurgical Project, though with primary emphasis on the former, outside work being included only for the sake of accuracy and completeness.

In contrast to the Survey volumes, each Collected Papers volume was designed to consist of individual papers, mostly from individual laboratories and more or less similar to articles in the scientific journals; they were to include only work done within the Project. In planning the PPR, it was realized that some of the Survey volumes would overlap with possible volumes of other projects, but because of compartmentation restrictions, it was decided to proceed in general with the plan as outlined. An exception was the field of uranium chemistry, where it was obvious that all the major projects were making important contributions. In this field, a Handbook of Uranium Chemistry was planned early in 1944, to be edited and written at the Metallurgical Laboratory at Chicago, but as a cooperative effort of all the

projects, and based on a full interchange of information among them. When the Record was organized, this volume was tentatively included as one of the PPR Survey volumes, to be accompanied by a corresponding Collected Papers volume covering Metallurgical Project work only. Later, when the MPTS (now NNES) was organized, these volumes, with the addition of Collected Papers from the other projects, were transferred to the over-all Division (Division VIII) of the technical series. In the field of analytical chemistry, a Survey volume and a Collected Papers volume were planned for the PPR and were well on their way toward completion. When the MPTS was organized, the content of these volumes was pooled with the work of other projects of the Manhattan District to form Survey and Collected Papers volumes of Division VIII of the MPTS. In certain other fields, pooling of material from the different projects was also considered, but was felt to involve too large a task of reorganization.

Because of the wide variety of subject matter, the organization of the PPR into Survey volumes, each accompanied by one or more Collected Papers volumes, is not always consistently followed. There are a few Collected Papers volumes without corresponding Survey volumes, and the converse is also true. Furthermore, the form of organization varies considerably from one volume to another because of varying subject matter and the preferences of the different volume editors and committees.

When the PPR plans were approved toward the end of 1944, the completion deadline for the manuscripts was set for June 30, 1945, the date of dissolution of the Metallurgical Project. Most of the PPR volumes were organized into three groups: (1) chemistry and metallurgy; (2) physics and related engineering; (3) biology and medicine. The first task was to obtain volume editors and editorial committees for the various volumes, to plan the contents, and to find authors. John C. Warner, as chemistry editor of the PPR and Chief of the Editorial Section of the Project Information Division from December 1944 to June 30, 1945, made decisive contributions to the chemistry and metallurgy volumes and to the general planning of the PPR.

The organization of the volumes on physics and on biology and medicine went more slowly, partly because the subject matter was then less ripe for writing than was that on chemistry and metallurgy, partly because of the demands for continuing research and, in the field of instrumentation, for production of instruments to be used at Los Alamos, Hanford, and other sites. Eugene P. Wigner, Frederick Seitz, and H. H. Goldsmith took an active part in the early organization of the physics volumes. Plans for the volumes on biology and medicine were very effectively organized by Raymond E. Zirkle as PPR editor for these fields, with the backing of Robert S. Stone as Associate

Project Director for Health. Hoylande D. Young entered the PPR program as Technical Editor in charge of final editing and processing of manuscripts, and after June 30, 1946, became General Editor.

After the organization of the PPR, steady progress was made in the work of writing and editing, but at a slower pace than was originally hoped. The dissolution of the Project on June 30, 1945, with the readjustments and administrative problems involved in a 50 per cent cut of total personnel; the end of the war after the bomb was dropped in August and the subsequent deep preoccupation and extensive activities of Project personnel in connection with the social and political implications of atomic energy and atomic warfare; new research and planning directed toward the postwar continuation of the atomic energy program; all these slowed the progress of the PPR writing program. During this difficult period, invaluable encouragement and support of the PPR program came from, among others, Norman Hilberry, Associate Director of the Metallurgical Project up to the time of its dissolution, and Farrington Daniels, Director of the Metallurgical Laboratory in 1945-1946.

Meantime, other projects in the Manhattan District group began the preparation of final accounts of their work. In particular, the Los Alamos Technical Series was begun in 1945. Finally, the MPTS (now the NNES) was organized under the Manhattan District Editorial Advisory Board late in 1945. Under the chairmanship of Alberto F. Thompson, as Chief of the Publications Section of the Research Division of the District, this group began the task of coordinating existing writing activities and filling the gaps in these, with the objective of producing a reasonably well-rounded series of volumes covering the work of the entire District. During early 1946, rules for declassification were set up, and the editors of the MPTS volumes faced the difficult task of dividing the subject matter of their volumes into declassifiable parts, publishable immediately, and classified parts, for which publication must be deferred. In June 1947 the completion of the editorial work of the PPR, as part of the NNES, was taken over by the Technical Information Division of the Atomic Energy Commission, at Oak Ridge, Tenn.

In addition to those named above, many other project members worked together in planning the PPR. After the general plans were made, the actual work of preparing the various volumes was in the hands of the volume editors, volume editorial committees, and authors, as described in the prefaces of the individual volumes.

Robert S. Mulliken
Editor-in-Chief
Plutonium Project Record

ACKNOWLEDGMENT

The Manhattan Project Technical Section of the National Nuclear Energy Series embodies results of work done in the nation's wartime atomic energy program by numerous contractors, including Columbia University. The arrangements for publication of the series volumes were effected by Columbia University, under a contract with the United States Atomic Energy Commission. The Commission, for itself and for the other contractors who contributed to this series, wishes to record here its appreciation of this service of Columbia University in support of the national nuclear energy program.

The Manhattan Project Technical Section of the National Nuclear Energy Series is intended to be a comprehensive account of the scientific and technical achievements of the United States program for the development of atomic energy. It is not intended to be a detailed documentary record of the making of any inventions that happen to be mentioned in it. Therefore, the dates used in the Series should be regarded as a general temporal frame of reference, rather than as establishing dates of conception of inventions, of their reduction to practice, or of occasions of first use. While a reasonable effort has been made to assign credit fairly in the NNEs volumes, this may, in many cases, be given to a group identified by the name of its leader rather than to an individual who was an actual inventor.

PREFACE TO THE HEALTH VOLUMES IN DIVISION IV OF THE NATIONAL NUCLEAR ENERGY SERIES (MPTS)

The health volumes of Division IV contain reports of work done during World War II, under the Manhattan District, as part of the activities of the Metallurgical Project (known as the Plutonium Project after the bombing of Nagasaki). The material is distributed among the various volumes as follows:

Vol. 20	"Industrial Medicine on the Plutonium Project" (Survey and Collected Papers; published 1951)
Vols. 22 B-22 I	Radiobiology (Collected Papers)
Vols. 22 B-22 C	Effects of X and Gamma Rays
Vol. 22 D	Effects of Fast and Slow Neutrons
Vol. 22 E	Effects of External Beta Radiation (published 1951)
Vols. 22 F-22 H	Metabolism and Effects of Internal Emitters
Vol. 22 I	"Histopathology of Irradiation from External and Internal Sources" (published 1948)
Vol. 23	"Toxicology of Uranium" (Survey and Collected Papers; published 1951)

It will be noted that the foregoing outline includes no survey of radiobiology. This was planned as Vol. 22 A. Also, it was originally planned to include two volumes on health physics, one a survey (Vol. 21 A), the other a set of collected papers (Vol. 21 B). These three volumes have been abandoned because personnel who completed the subject research are not presently available as authors.

The work reported in the volumes just listed was mostly done at the Metallurgical Laboratory, University of Chicago; the Crocker Laboratory, University of California, Berkeley; Clinton Laboratories, Oak Ridge, Tenn.; the National Cancer Institute, Bethesda, Md.; and the Hanford Engineer Works, Richland, Wash. It was all under the general supervision of Robert S. Stone, M.D., Associate Director for Health of the Metallurgical Project. Dr. Stone's introduction to this entire set of health volumes appears in Vol. 20.

The medical work was directly supervised by Simeon T. Cantril, M.D. (Chicago, Clinton, Hanford), Leon O. Jacobson, M.D. (Chicago),

John E. Wirth, M.D. (Clinton), and James J. Nickson, M.D. (Chicago). Health Physics was developed under the supervision of Herbert M. Parker (Chicago, Clinton, Hanford), Ernest O. Wollan (Chicago), Karl Z. Morgan (Clinton), and John E. Rose (Chicago). Research in radiobiology was directed by Kenneth S. Cole (Chicago), Joseph G. Hamilton, M.D. (California), Howard J. Curtis (Clinton), and Egon Lorenz (National Cancer Institute). The investigations in uranium toxicology were carried out at Michael Reese Hospital, Chicago, under the direction of Albert Tannenbaum, M.D., as part of the program of the Metallurgical Laboratory.

Practically all the work described in the Health Volumes was done between Sept. 1, 1942, and June 30, 1945. It was subject to the usual disadvantages of wartime research and development—chiefly haste and security regulations. On the other hand, it proceeded under very advantageous financial support. Moreover, the security regulations often had the advantageous effect of preventing publication of research until experiments had been verified by collateral work.

Most of the writing was necessarily done rather hastily because, in the early postwar period, many of the authors were returning to their regular positions in universities and elsewhere. Editing has been done in more leisurely fashion but with a severe shortage of competent manpower. With unlimited editorial personnel, much of the material could have been substantially shortened. Since this seemed impracticable, most of the editorial effort has gone into the correction of major errors and inconsistencies. We hope that not too many of these have eluded us.

Raymond E. Zirkle
Editor, Health Volumes

Volume Editor's Preface

The work reported in this volume was part of a large radiobiological program pursued during World War II at the Metallurgical Laboratory, University of Chicago, and the National Cancer Institute, Bethesda, Md. Although the range of topics may appear quite wide, all these investigations were primarily directed toward an understanding of radiobiological actions on mammals and on man in particular. In editing this material, I have been chiefly concerned to see that the experimental facts are clearly and consistently set forth. The conclusions drawn in each chapter are those of the authors and not necessarily my own.

Much of the editorial detail was handled by Miss Sophia Prior.

Raymond E. Zirkle

PUBLISHER'S NOTE

Although every effort has been made to ensure accuracy in references, at the time of publication of this book some of the other volumes of the Series had not been completed. It is therefore possible that some of the references to other volumes are in error. It is hoped that the extensive cross checking which has been done in the preparation of this volume has resulted in keeping such errors to a minimum.

FOREWORD

Since the discovery of practical means of utilizing the energy of the atomic nucleus, a large and complex atomic energy industry has begun in the United States. As a result of conditions in the world, external to the United States, the requirements of national security have been paramount in our development of this industry thus far. Constant and increasing attention, however, has been given to the problems of economic nuclear power and to the medical and industrial applications of radioactive materials with a view toward "improving the public welfare, increasing the standard of living, strengthening free competition in private enterprise, and promoting world peace." To this end the Atomic Energy Commission has sought the most effective means to accelerate the practical exploitation of nuclear data by American science and industry. The National Nuclear Energy Series is designed to provide for scientists and engineers as comprehensive a source of such data as is possible. The scope of the information presented in these volumes is a measure of American achievements to date in the field of atomic science.

Lewis L. Strauss, Chairman
U. S. Atomic Energy Commission