SAFETY ASPECTS OF NUCLEAR REACTORS

C. ROGERS McCULLOUGH

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Edited by

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SAFETY ASPECTS OF NUCLEAR REACTORS

THE GENEVA SERIES ON THE PEACEFUL USES OF ATOMIC ENERGY

Editor of the Series

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NUCLEAR FUELS
by David H. Gurinsky and G. J. Dienes

EXPLORATION FOR NUCLEAR RAW MATERIALS
by Robert D. Nininger

NUCLEAR REACTORS FOR RESEARCH
by Clifford K. Beck

NUCLEAR POWER REACTORS
by James K. Pickard

SAFETY ASPECTS OF NUCLEAR REACTORS
by C. Rogers McCullough

NUCLEAR RADIATION IN FOOD AND AGRICULTURE
by W. Ralph Singleton

FOREWORD

No matter how the Geneva Conference will be judged by historians of the future, there is one fact which will hardly be forgotten for some time to come: in ten days of August, 1955, an unprecedented volume of technical information on atomic energy was put into the public record. Not all the items of information were of equal value, to be sure, but relatively little was of a trivial nature.

Realizing that a verbatim record of this avalanche of data would be relatively indigestible to a large body of workers in the field, the Publishers requested me to undertake the task of organizing and editing a series of books which would present material of most urgent usefulness. Preprints of many of the conference papers were made available through the courtesy of the United Nations staff.

From a study of these papers it was concluded that six volumes of nominal length would be required. Each would cover a specific subject and include the key papers, suitably edited to eliminate duplication and secondary material, and arranged in a logical manner.

Because of the great interest in finding the raw materials for the growing nuclear appetite, Robert D. Nininger, Deputy Director for Exploration, Division of Raw Materials, United States Atomic Energy Commission, was asked to edit a volume on the geology of and the exploration for uranium and thorium.

All atomic energy projects to date have had research reactors at the base of their technical efforts. Dr. Clifford Beck, Professor of Physics, North Carolina State College, whose foresight and determination put the first research reactor on a university campus, consented to edit a volume on research reactors.

At the center of the stage, particularly for the energy-hungry nations of the world, is the power reactor, a device of many and varied forms. James K. Pickard, now a consultant engineer on atomic energy developments, for many years previously one of the stalwarts of the AEC Reactor Development Division, accepted the task of preparing a nuclear power reactors volume.

Because one of the most difficult and urgent problems in the power reactor program is assessing the hazard and providing safety in reactor operation, it appeared urgent to include a volume devoted exclusively to reactor safety. One of the pioneers in the field, Dr. C. R. McCullough of the Monsanto Chemical Company, has undertaken to edit a volume on the safety aspects of nuclear reactors.

The heart of the power reactor is the nuclear fuel, the energy source and the focal point for intense metallurgical and solid state research efforts. Dr. David H. Gurinsky and Dr. G. J. Dienes of Brookhaven National Laboratory, who have made substantial contributions to these efforts, have edited a volume on nuclear fuels.

In addition to the direct heat energy from fission, the ten per cent or so of reactor energy available as radiation is already exerting profound effect on civilization. One who has probed deeply into what might be termed the interaction of nuclear energy and agriculture, Dr. W. Ralph Singleton, Director of the Blandy Experimental Farm, University of Virginia, has edited a volume on nuclear radiations in food and agriculture.

These six volumes are not intended to cover all the technical areas of the Geneva Conference. Subjects such as radiobiology, nuclear physics, reactor physics, chemical processing—to name but a few—were not included (except where they touch on the subjects chosen) for a variety of reasons. A first consideration was that, if all subjects were properly represented, the series would presume an ungainly large number of volumes. Reducing the number of volumes could only be done by limiting coverage either to a few papers on each subject or to a superficial digest of a large number of papers. It seemed a better choice to cover fewer topics more completely. A secondary consideration was an assessment of the state of the literature—where a subject was rather well represented in the public literature, it could be argued that the need for a corresponding volume was less urgent. Certainly, for example, the literature of nuclear physics does not urgently require amplification. Moreover, although the nuclear physics papers published at Geneva were substantial, they did not disclose any striking new information. (In addition, many of the new nuclear data have been adequately disseminated by the United States Government handbooks.)

In any effort of this kind, arbitrary decisions are made in many places. Material is deleted, rearranged, abbreviated, and new material is added. It is hoped that these decisions have been wise and that the six volumes will be a fundamental reference work for the increasing number of scientists and engineers devoted to the peaceful uses of atomic energy.

The very substantial assistance of John Martens of Argonne National Laboratory in editing the present volume of the Series is gratefully acknowledged.

J. G. Beckerley

PREFACE

This book is an edited collection of papers from the first International Conference on the Peaceful Uses of Atomic Energy at Geneva in 1955 relating to the safety problem. It should be clearly understood that the editor undertook this task as an individual and that the selection of material is based on his judgment. The book represents no official opinion. The editor has been fortunate in having had the opportunity of associating with some of the outstanding authorities in the various fields covered and hopes that this experience has been useful in the proper selection of the material.

As the first International Conference on the Peaceful Uses of Atomic Energy progressed it became apparent that much useful information was being contributed, ranging over the gamut of peaceful applications and, to the delight of those interested in the safety problems of reactors and chemical plants, of value in these fields. The many aspects of the nuclear safety problem were brought together for the first time.

Because of the overwhelming toxicity of fission products and other radioactive materials the possibility of accidents and their consequences have to be examined before attempting to operate—in fact even before completing the design of—any nuclear reactor or other facility. This industrial philosophy was adopted in the early days of atomic energy and has been continued. It has turned out that the general approach to the problems of coping with the potential hazards and of providing the necessary personnel protection is remarkably similar in the various countries even though no general comparison of notes had been made prior to the 1955 Conference.

It was believed that this book should be small enough so that it would be a ready reference work for those needing guidance in the safety aspects of nuclear reactors. The scope was restricted, therefore, to those papers directly applicable to this subject.

The book opens with papers devoted to normal reactor and chemical plant operation. These papers cover the problems both outside and inside the plants and give actual practical experience and data. It is shown that atomic energy can be applied to peaceful purposes without serious hazard to the public or to employees.

The problem of determining the safety standards to be adopted is discussed in the papers selected from leaders in the field. There is a mass of data upon which to base estimates that permit the development of working standards. Means of calculating exposures are covered. There is one rather lengthy paper on the practices in the USSR. It is most illuminating to see how closely these ideas expressed coincide with those held in the United States and the United Kingdom.

The third part of the book deals with the abnormal behavior of reactors and the consequences. The United States and the United Kingdom are in close agreement on these points. It is generally accepted that the main means of dispersing radioactive products is through the air. It may well be that spread of contamination by bird and animal life, by assimilation in crops, and by pollution of water will turn out to be more serious than that spread by meteorological factors. There is practically nothing available on these other dispersing mechanisms, but substantial information on the effect of weather conditions. The theory of dispersion of gases and particles in air is discussed. The problem is important for a variety of industrial wastes, smoke, fumes and noxious gases. The final chapter of the book covers the experiments on the effects of supercriticality of reactors. Although the theory still leaves much to be desired, at least there are experimental data on which to base estimates.

The problem of providing safeguards against accidents with reactors or other atomic energy facilities and evaluating the hazards that may exist has been based largely upon theoretical analysis and hypothesis. There have been accidents with critical facilities but the serious ones were in the very early days. There have been no accidents with regularly operating reactors. As a result there is no practical experience to judge whether the safeguards provided should be more or less complete. However, there is an extensive research program directed toward the problem of reactor safety and valuable data are being obtained. Hopefully, the program will be the main source of information on the adequacy of reactor safeguards.

Despite all the efforts being made to safeguard reactors, and granting that these efforts will continue to be applied, there will be reactor accidents. In machines as complex as these, some parts will fail, a vital point will be overlooked, operators will be negligent or do the wrong things and an accident will result. There will be a demand for more stringent regulation and standardization. Regulation is inevitable and standardization can be very useful in reducing both costs and risks. There is an excellent chance that the making of rules and standards can be kept in the hands of technical people and result in a minimum of interference with technical progress.

It is hoped that this collection of Geneva papers will help reactor designers. In particular it is hoped that by directing attention to the safety aspects of nuclear power the designers will be encouraged to create new, cheaper, more reliable, and safer reactors.

C. Rogers McCullough

Washington, D.C.

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Part I

NORMAL REACTOR AND CHEMICAL PLANT OPERATIONS

Chapter 1

RADIATION EXPOSURE EXPERIENCE WITHIN REACTOR PLANTS*

Radioactive materials became an industrial health problem when radium and mesothorium were used in the dial-painting industry. Unfortunately the toxic nature of these substances was not fully appreciated until they had affected the health of those working with them. Within the last decade the industrial health problem has grown considerably as a result of the production, from nuclear reactors, of large amounts of radioactive nuclides.

There has also grown a philosophy that the occupational damage which occurred in the past from ionizing radiation should not be repeated. This poses the following questions:

1. How can workers handle large radiation sources without suffering harmful radiation exposures?
2. How can work be carried out with large amounts of radioactive materials without getting harmful amounts into the body by ingestion and inhalation?
3. How can one work with loose radioactive material and not contaminate the working environment so there is ultimately a health hazard?
4. How can one deal with radioactive effluent so that the safety of the surrounding population is ensured?

The exposure of workers to radiation levels above the natural background is now an accepted situation in nuclear energy plants. The prevention of overexposure to radiation is a function of proper plant design, the existence of an adequate system of hazard control, and adherence to a proper code of prac-

* The introductory paragraph and the section on Chalk River experience is from Geneva Conference Paper 8, "Health and Safety Activities in Reactor Operations and Chemical Processing Plants" (Vol. 13) by A. J. Cipriani of Canada. The section on Hanford Works experience is from Paper 240, "Radiation Exposure Experience in a Major Atomic Energy Facility" (Vol. 13) by H. M. Parker of the United States. The last section on BEPO experience is from Paper 452, "Control of Radiation Hazards in the Operation of Medium-powered Experimental Reactors" (Vol. 13) by W. G. Marley and B. S. Smith of the United Kingdom.

tice—in this case the recommendations of the International Commission on Radiological Protection.[1] * Experience shows that exposure to radiation can be controlled within acceptable limits even under emergency conditions.[2]

Experience at Chalk River

External radiation exposure. External exposure data for the Chalk River Project of Atomic Energy of Canada is presented as a guide to what may be expected in practice in atomic energy work. The frequency of occurrence of annual total exposures is tabulated in terms of class of work and for a three-year period. The figures for 1952 and 1954 represent normal operations while those for 1953 represent an abnormal emergency period wherein a considerable effort was directed towards decontaminating and rebuilding a seriously damaged reactor.

During the period covered by Table 1.1, the total employment averaged 1800 persons. Certain observations are pertinent. Despite work in high-radiation fields (in several cases involving entry of personnel into fields greater than 50 r/hr) only one person received more than the recommended upper limit of 15 r/year. This exposure of 16.1 r occurred accidentally to an individual lacking any experience in active work and under supervision which also had little experience with radiation.

The abnorm al situation in 1953 involving the restoration of N.R.X. shows the value of careful planning. The experienced reactor personnel were kept working throughout the year with relatively modest exposures by calling on personnel normally in inactive work to carry out the tasks involving the higher radiation exposures. As a result, the figures for 1953 show that the moderately high exposures were distributed widely among all plant personnel. It is interesting to note that chemical operations personnel who were not directly involved in pile restoration were responsible for the majority of exposures over 10 r/year, although the pile restoration work involved five times the total exposure received in all other work combined. This in part could be a result of concentration of protective measures and attention on pile restoration with relaxation of supervision in areas considered less critical.

Since this plant is of early design and has suffered from some "growing up," the problem should be more easily dealt with in better designed installations, which would have the benefit of past experience.

At Chalk River it has been found that in order to preserve adequate Radiation Hazard Control standards, it is necessary to keep the organization of the control personnel separate from that of the operation groups. A similar situation exists at all other places in Canada where radiation workers receive this service, at the moment, from the Department of National Health.

* See the numbered references at ends of chapters.

TABLE 1.1. FREQUENCY OF EXPOSURE LEVELS AT CHALK RIVER

Class of Work (Normal)	Year	Exposure Range in Roentgens/Year				
		1–3	3–5	5–10	10–15	>15
High activity						
Reactors	1952	14	6	14	—	—
	1953	11	13	25	2	—
	1954	23	4	1	—	—
Chemical process	1952	38	16	5	—	—
	1953	35	34	62	8	—
	1954	34	34	18	—	—
Maintenance	1952	59	5	2	—	—
	1953	68	57	64	3	—
	1954	78	24	14	—	—
Moderate activity						
Research	1952	25	—	—	—	—
	1953	6	2	2	—	—
	1954	6	3	—	—	—
Others	1952	17	—	—	—	—
	1953	88	39	20	—	—
	1954	18	5	2	—	—
Low activity	1952	17	—	—	—	—
	1953	61	22	14	—	1
	1954	19	—	—	—	—
Total	1952	170	27	21	—	—
	1953	269	167	187	13	1
	1954	169	70	35	—	—

In general, the figures presented justify the belief that an efficient radiation protection service, well integrated into the over-all project organization, can result in a large output of work in high-radiation fields with no need for serious overexposure.

Internal radiation exposure. The entry of radioactive materials into the human body where they might remain and irradiate specific tissues with adverse effects presents a more complex problem. A great deal of provisional information exists on what amounts of the various radioactive nuclides may exist in the body without harmful effects.[3] From these figures are derived maximum permissible amounts of radioactive materials in air and water for continuous intake; but this information is of a form more useful to the plant designer than to those working with health hazards. In practice, the first indication of internal contamination is often the presence of radioactive material in the excreta of the worker, without a knowledge of the exposure conditions. Since the correlation between excretion levels and hazard estimation is at present unsatisfactory and since there are at present no good methods of usefully increasing excretion of the wide range of elements involved, a conservative approach is taken. This involves very strict measures to prevent intake and the removal of internally contaminated individuals from working areas when the activity of their urine reaches arbitrary low levels.

Urinary assays are carried out by the Medical Division at Chalk River. The samples are collected at home because it is not practicable to collect them during working hours and not desirable owing to the strong possibility of contamination. Since the daily creatinine excretion is relatively constant and related to body weight, this is used in estimating the 24-hr excretion of radioactive material from that measured in the partial sample of urine. The practice is to treat internal radioactive contamination conservatively and to rotate personnel who have radioactive materials in the urine. Workers are removed from contact with loose radioactive substances when the urine activity reaches the following levels:

Material	*Removed from Work*
Mixed fission products	150 dpm in a 24-hr sample
Plutonium	3–4 dpm

The arbitrary level for mixed fission products is chosen on the following bases: (*a*) It is a level which can be easily measured. It is usually not measured immediately after exposure since samples are not done daily and the time of exposure is not usually known. At this time the urine level would be much higher. (*b*) The contaminant is presumed to be strontium, in all cases, a presumption based on the results of many spot analytical checks. It can be said that mixed fission products in the urine is the most frequent cause of urinary contamination which has been encountered.

Urine tests are carried out on all personnel in certain critical areas every three months. Spot checks are done on some of these individuals every week. Additional tests are done promptly on individuals suspected of being accidentally exposed. Table 1.2 presents results from the bioassay laboratory for the year 1953–4.

With this conservative policy regarding internal contamination, a serious attempt is made to prevent such occurrences. This in brief involves the control of air-borne contamination by installation of proper ventilation systems and the prompt cleaning up of spilt radioactive material. Filtration of potentially contaminated air is an important consideration. At Chalk River the Cambridge absolute filter or its equivalent is used for filtering out the fine