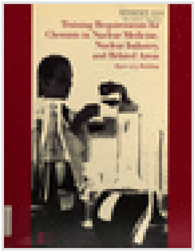

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Training Requirements for Chemists in Nuclear Medicine, Nuclear Industry, and Related Areas

Report of a Workshop

BOARD ON CHEMICAL SCIENCES AND TECHNOLOGY
COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND RESOURCES
NATIONAL RESEARCH COUNCIL

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

This report summarizes the deliberations and conclusions of participants in the Workshop on Training Requirements for Chemists in Nuclear Medicine, Nuclear Industry, and Related Areas, held in Washington, D.C., February 4-6, 1988. The workshop was organized by the Board on Chemical Sciences and Technology at the suggestion of and with the cooperation of the Committee on Nuclear and Radiochemistry (CNR). The workshop was supported by the Department of Energy (DOE), the National Institutes of Health, and the Electric Power Research Institute.

In 1978 the American Chemical Society's Division of Nuclear Chemistry and Technology conducted a survey of the nuclear and radiochemical community to determine the need for chemically trained personnel. That survey indicated a serious discrepancy between the demand for and the supply of trained nuclear and radiochemists; the survey also predicted that the discrepancy would increase over the next decade. A subsequent survey in 1984 proved the earlier predictions to be valid.

The CNR recognized a need to bring together experts from the user community—the practitioners of nuclear medicine, the radiopharmaceutical industry, DOE national laboratories, and the nuclear power industry—to focus on training requirements for chemists in these fields.

The workshop participants were chosen from these fields plus academic institutions and government administration. The workshop discussion was conducted by five panels, which addressed the following topics: nuclear and radiochemistry (particularly, education in academic institutions); nuclear and radiochemistry in other fields (particularly, contributions of nuclear and radiochemists to other sciences and applied fields); national laboratories (particularly, weapons effect diagnostics, waste management, environmental science, fission studies, isotope production, and nuclear fuel cycle research); nuclear medicine applications (particularly, basic and clinical research, the radiopharmaceutical industry, design of new radionuclide generators, optimization of radionuclide production at accelerators, and development of new applications); and the nuclear power industry (particularly, the nuclear power and process industry and support activities, e.g., environmental effects, severe accident analysis, and waste management).

Rosalyn S. Yalow of the Veterans Administration Medical Center, Bronx, New York, provided the keynote address. Jan Rydberg of Chalmers University of Technology, Gothenburg, Sweden, spoke about the European approaches to training chemists for nuclear chemistry activities. Background papers related to each panel's topic were distributed to participants prior to the workshop. During the workshop the authors presented highlights of these papers. The presentations of Yalow and Rydberg, as well as the background papers, are included as appendixes to this report. In contrast to the steering committee's report, which was reviewed by the National Research Council, the background papers are reproduced as submitted, and the views expressed by their authors do not necessarily reflect those of the steering committee.

On behalf of the entire committee, we would like to thank our colleagues who participated in the workshop for their assistance in preparing this report. Thanks, too, to Peggy J. Posey and her assistants, Victoria Phillips and Maria P. Jones, for providing staff support in organizing the workshop and in preparing this report.

Gregory R. Choppin
Michael J. Welch
Co-Chairmen

OVERVIEW AND RECOMMENDATIONS

ROLE OF NUCLEAR AND RADIOCHEMISTRY IN THE UNITED STATES

Over the past four decades, nuclear science has been a significant and necessary factor in an extraordinary number of facets of American national life. During this period there have been exceptional developments in the use of radioactive isotopes in nuclear medicine, the radiopharmaceutical industry, and the ethical drug industry. The value to the health of the American population of the diagnostic and therapeutic uses of radioisotope-labeled compounds would be difficult to overestimate. Essentially every hospital in the country uses nuclear medicine to some degree. One of three hospital patients receives one or more nuclear medicine procedures, and the use of such procedures will continue to grow as new and even better methods of treatment and diagnosis are developed.

Radioisotopes are used in diverse areas of research and technology. Some of the most sensitive analytical methods are based on radioactivation. Radionuclides are used widely by industry in inexpensive and reliable thickness gauges, flow meters, and smoke detectors, and in the development and verification of separation processes, studies of environmental pollution, and agricultural, chemical, biological, and geological research.

Since World War II, the national security of the United States has been dependent on nuclear weapons. Even with new treaties limiting nuclear weapons, they will remain the primary shield to protect the United States from foreign aggression.

Application of nuclear technology to harness the energy produced by the splitting of the atom has also played a strong role in the production of useful energy in the form of electricity. Although the nuclear power industry is not growing at present, a significant fraction of the electrical power in the United States is now and will for decades to come be produced by nuclear reactors. Furthermore, as Frank Press, president of the National Academy of Sciences, stated in a recent interview on national research and development priorities, ". . . now is the time to do the R&D for a whole new generation of nuclear reactors . . ." (*Science & Government Report*, Vol. XVIII, No. 1, January 15, 1988).

Regardless of the eventual fate of both the weapons program and the nuclear power industry, we must dispose of the nuclear waste that has accumulated thus far from these sources. Development of the optimal mode for containment and isolation of nuclear waste for hundreds of thousands of years is vital to the long-term well-being of this country and the world.

The future vigor and prosperity of American medicine, science, technology, and national defense thus clearly depend on continued use and development of nuclear techniques and use of radioactive nuclides. Loss of know-how in this field or failure to develop new uses for the technology could seriously and adversely affect this country's economic competitiveness in many technological and industrial areas.

In nearly all the areas mentioned, there is a clear need for scientists who are well versed in both chemistry and nuclear science. There have been strong indications that the supply of such people has been increasingly inadequate to meet national needs in the several sectors of medicine, science, and technology. This workshop was held to examine whether there is indeed such a mismatch between supply and demand and, if so, to recommend corrective measures.

ORIGIN OF THE WORKSHOP

In 1978, at the request of the National Research Council's Subcommittee on Nuclear and Radiochemistry (later renamed the Committee on Nuclear and Radiochemistry (CNR)), the American Chemical Society's Division of Nuclear Chemistry and Technology (DNCT) conducted a survey of the needs of the nuclear community for chemically trained personnel. The results of the survey, which did not include the health care industry, indicated a serious shortage of appropriately trained personnel to meet the projected demand. The survey cited three problem areas that have contributed significantly to a decrease in the supply of personnel trained in nuclear and radiochemistry:

1. Student reluctance to enter the field because of negative public perception.

2. A decline in faculty at academic institutions qualified to train students.

3. A decrease in research funding.

Since 1984, the DNCT has addressed the first problem area by sponsoring a Summer School in Nuclear Chemistry. This undergraduate fellowship program has proven to be a successful start toward increasing student interest in and awareness of applications of nuclear and radiochemistry and of career opportunities in the field.

To focus on the specific needs of the user community, i.e., practitioners of nuclear medicine, the radiopharmaceutical industry, Department of Energy (DOE) national laboratories, and the nuclear power industry, for personnel trained in nuclear and radiochemistry, the Board on Chemical Sciences and Technology, in cooperation with its Committee on Nuclear and Radiochemistry, organized a workshop aimed at identifying the requirements for training such personnel.

ORGANIZATION OF THE WORKSHOP

The workshop followed the pattern of previously successful workshops organized by the CNR. The participants were chosen from academic institutions, national laboratories, the nuclear power industry, the nuclear medicine community, the pharmaceutical industry, and government administration. A chairman and rapporteur were responsible for the final report and conclusions from each panel. In addition, for each of the panel subjects, position papers were prepared prior to the workshop by experts in the field. These position papers reflect the opinions of the individual authors and served to provide the necessary historical and technical background to direct the panels in their deliberations. They are appended to this document.

The panels' reports and conclusions formed the basis for the steering committee's recommendations included in this overview. The participants in the workshop have reviewed and concurred with these recommendations.

SUMMARY OF THE WORKSHOP

The panel reports (Chapters 1 through 5) should be read in their entirety for a detailed discussion of the issues and the conclusions reached. However, the committee briefly summarizes the most relevant points brought out by the panels in order to give a rationale for the recommendations that follow.

The Panel on Nuclear and Radiochemistry (Chapter 1) was concerned with the current state and trends of nuclear chemistry and radiochemistry education in academic institutions and with possible mechanisms for meeting the present and foreseeable needs for people trained in nuclear and radiochemistry. Among the important observations of this panel, based on surveys conducted in 1978 and 1987, are a decrease by over 60 percent in radiochemical faculty over this period and a 57 percent drop in nuclear and radiochemistry courses offered in Ph.D.-granting departments. Yet all the other panels concluded that there is a clear and growing need for scientists thoroughly trained in radiochemistry.

The Panel on Nuclear and Radiochemistry in Other Fields (Chapter 2) addressed the important contributions that scientists with nuclear and radiochemistry backgrounds have made and are continuing to make to other sciences and to various applied fields. Among the areas discussed are environmental studies, life sciences, materials science, separations technology, hot atom chemistry, and cosmochemistry. Numerous examples of vital contributions and major breakthroughs in these fields, resulting from the use of nuclear techniques, are cited in the panel report.

The Panel on National Laboratories (Chapter 3) dealt with the training needs in the national laboratories, where nuclear and radiochemists have always played a vital role. Their particular training and experience will continue to be required in many areas, including, for example, weapons effect diagnostics, waste management, environmental science, fission studies, isotope production, and nuclear fuel cycle research. The panel estimated that the DOE national laboratories currently employ between 575 and 850 nuclear and radiochemists (with one-third of these at the Ph.D.

level) and concluded that there will be a continuing need for approximately these numbers for the foreseeable future. In addition, they estimated that for about 1,200 M.S./Ph.D. chemists working in related areas, some radiochemical training is highly desirable. Assuming a turnover of 5 percent per year, these estimates translate into an annual need for 10 to 20 Ph.D.'s who are experts in nuclear and radiochemistry, as well as 20 to 40 B.S. chemists and about 60 advanced-degree chemists who have had at least a lecture-and-laboratory course in radiochemistry.

The Panel on Nuclear Medicine Applications (Chapter 4) considered nuclear and radiochemical training required in areas related to nuclear medicine. Two types of needs were identified. In most instances what is needed in basic and clinical research as well as in the radiopharmaceutical industry and in nuclear pharmacies are people whose primary specialization may be in organic synthesis, analytical chemistry, or biochemistry but who also have a sound background in radiochemical techniques and instrumentation. In addition, there is a need for a smaller number of bona fide nuclear and radiochemists to work in such areas as design of new radionuclide generators, optimization of radionuclide production at accelerators, and development of new applications. The panel listed 120 positions that are currently open for chemists and pharmacists with advanced degrees and that require knowledge of radiochemistry. It is estimated that by 1993 there will be 225 such openings.

The Panel on the Nuclear Power Industry (Chapter 5) addressed the needs of the nuclear power and process industry. Annual needs for chemists with radiochemical training were estimated to be 2 at the Ph.D. level and 25 to 30 at the B.S. level for the utilities (power plants) themselves, and 10 to 20 with Ph.D.'s and 40 to 50 with B.S. degrees for support activities (e.g, environmental effects, severe accident analysis, and waste management). Because of the lack of trained radiochemists, the industries have in recent years relied largely on in-house training of people with other educational backgrounds.

It was gratifying to find that all the panels, despite their different perspectives, came to similar conclusions regarding the remedial measures required to alleviate the current serious shortage and to ensure a future adequate supply of scientists with nuclear and radiochemical backgrounds and knowledge. On the basis of their findings, the workshop participants conclude that there is a need for:

- ensuring that all B.A./B.S.-level chemists have a rudimentary understanding of nuclear and radiochemical concepts and techniques;
- stimulating interest in the field among students and making them aware of career opportunities;
- maintaining and strengthening a small number of academic centers of excellence in nuclear and radiochemistry, where future leaders in the field can obtain their graduate education; and
- establishing mechanisms for providing the training needed by the various user constituencies.

To these ends, the steering committee makes the following specific recommendations:

1. Nuclear and radiochemical concepts and techniques should receive sufficient coverage in undergraduate courses to provide chemists with a basic understanding of this field and its applications to science and technology.
2. A program of Young Investigator Awards for tenure-track faculty at universities should be established, with at least five such awards to be given, each for a 5-year period.
3. A program of training grants and postdoctoral fellowships should be established.
4. A small number of training centers should be established at universities and/or national laboratories for short courses in nuclear and radiochemistry and for retraining scientists and technologists with backgrounds in other areas. The training centers should be supported in part by the industries and enterprises dependent on the trained personnel.

5. A second summer school for undergraduates, similar to the one that has been successfully conducted at San Jose State University, should be established at an eastern U.S. site.

6. Adequate funding for research should be assured from the DOE, National Institutes of Health (NIH), National Science Foundation (NSF), Department of Defense (DOD), and other federal agencies to maintain the continued vigor of the field of nuclear and radiochemistry at universities and national laboratories. In particular, it is suggested that the NSF identify a specific program to receive proposals in the field of nuclear and radiochemistry and that the NSF adequately publicize this step in the appropriate divisional announcements.

PANEL REPORTS

1

NUCLEAR AND RADIOCHEMISTRY

SUMMARY

Nuclear and radiochemistry is a field of extraordinarily broad scope. Its continued health and vigor are vital to a number of major areas of national need. Because the academic component is small and is decreasing, the projected need for professionals trained in this field is not being met and cannot be expected to be met through existing mechanisms. Both immediate and long-term solutions are necessary. The personnel requirements are discussed and documented in the other panel reports and in the resource papers presented in the appendixes. This panel confines itself to suggesting mechanisms for meeting the needs. The following steps should be promptly initiated:

- establish Young Faculty Investigator Awards in nuclear and radiochemistry;
- establish postdoctoral fellowship programs;
- expand the summer program for undergraduates;
- establish fellowship programs for training of faculty from other fields in the theory and practice of nuclear and radiochemistry;
- establish training centers;
- increase student recruiting activities;
- promote inclusion of material on nuclear and radiochemistry in undergraduate chemistry courses; and
- broaden the funding base for research in nuclear and radiochemistry.

None of these urgent steps will be taken unless a number of funding agencies (e.g., DOE, NIH, Air Force Office of Scientific Research (AFOSR), Army Research Office (ARO), Office of Naval Research (ONR), and NSF) can be brought to recognize their responsibilities to support the training of the nation's future nuclear and radiochemists. In particular, it is suggested that the NSF identify a specific program to receive proposals in the

field of nuclear and radiochemistry and that the NSF adequately publicize this step in the appropriate divisional announcements.

INTRODUCTION

A number of areas of major national need depend critically on scientists trained in nuclear and radiochemistry as well as on the results of research in nuclear and radiochemistry. Among these areas are:

1. Health care, including nuclear medicine, the radiopharmaceutical industry, and radioactive tracer studies in the ethical drug industry.
2. National security, specifically the nuclear weapons program.
3. Nuclear energy, which currently provides 17 percent of U.S. electric power.
4. Nuclear waste isolation, an important issue even if all nuclear power plants were to be shut down immediately, because there is a 40-year accumulation of waste from the defense and power plants.
5. Monitoring and management of the environment.
6. Fundamental nuclear science, including chemical effects of nuclear transformations.

Thus the welfare and competitive strength of the nation demand that the future of the field of nuclear and radiochemistry be assured. In spite of the importance of nuclear and radiochemistry, the National Research Council's *Summary Report 1986: Doctorate Recipients from United States Universities* (Washington, D.C.: National Academy Press, 1987) shows that only 10 to 12 Ph.D. students are graduating each year and that that number is dropping. Twenty percent are not U.S. citizens.

The panel recognizes that nuclear and radiochemistry is a relatively small field in terms of numbers of practitioners, but its scope is extraordinarily broad. A common thread that runs through it is the use of radioactivity and nuclear techniques combined with the knowledge and methodology of chemistry. As a scientific field with a small population, nuclear and radiochemistry is particularly vulnerable to extinction. That concern is the motivation behind this workshop.

NUCLEAR AND RADIOCHEMISTRY AT ACADEMIC INSTITUTIONS

In 1978, because of widespread concern that fewer scientists in nuclear and radiochemistry were being produced by educational institutions than would be required over the next decade, a survey of the need for chemically trained nuclear personnel was conducted by the Division of Nuclear Chemistry and Technology (DNCT) of the American Chemical Society (ACS) at the request of the National Research Council's Subcommittee on Nuclear and Radiochemistry (later renamed the Committee on Nuclear and Radiochemistry (CNR)). Indeed, the survey indicated that over the next decade there would be a serious gap between the supply of and demand for nuclear and radiochemists.

Recently, it was perceived that the problem is even more severe than previously anticipated. In order to investigate the current situation, E.S. Macias and G. Friedlander in 1987 circulated a questionnaire similar to one used in 1978. The results of this survey are given in detail in the attached paper, "Nuclear and Radiochemistry Education in U.S. Universities and Colleges" (Appendix E). It confirms the rather dire predictions about supply presented in the 1978 survey.

Because of the current and projected future demand for personnel trained in nuclear and radiochemistry, the United States is faced with a critical situation. The total number of nuclear and radiochemistry faculty at Ph.D.-granting institutions has decreased dramatically in the past decade, and the number of separate departments in which they reside has dropped by about one-third. Although the number of faculty working in fundamental nuclear chemistry decreased by only 10 percent between 1978 and 1987, there was a decrease of 64 percent in the number of academic radiochemists! There was an increase of 8 years in the average age of the radiochemists compared to an increase of only 2 years in the average age of all nuclear and radiochemistry faculty. Further, no new radiochemistry faculty were added. Yet it is in the radiochemistry area that the workshop panels have projected the greatest need for trained personnel. The survey further showed that only 42 (22 percent) of all Ph.D.-granting institutions offered courses in nuclear and radiochemistry, compared to 70 in the 1978 survey. The statistic that most dramatically illustrates the anemic state of academic nuclear and radiochemistry instruction in the United States today was that the total of 66 courses offered at Ph.D.-granting institutions in 1987 is a 57 percent decrease from the 153 courses offered in 1978. The widely held view that the opportunity for academic training in nuclear and radiochemistry is declining in the United States is certainly substantiated by the current survey. Yet each of the panels addressing national needs lists education as a top priority action item.

In order to meet the demand for Ph.D.'s in nuclear and radiochemistry, it is absolutely essential not only to maintain but also to increase the number of faculty and graduate students in this discipline in the chemistry departments of Ph.D.-granting institutions. In a given chemistry department, there is probably a "critical mass" of two to three professors required in order to provide a viable program of research and course offerings. To accomplish this, funding must be available for new assistant professors in the field. Although there appears to be a resurgence in graduate student interest in the field, currently no responsibility for funding research in nuclear and radiochemistry is recognized explicitly by either DOE or NSF. A substantial amount of nuclear chemistry (identified as type 1 in Appendix E) is funded by DOE's Office of Energy Research, Division of High Energy and Nuclear Physics; the division's activity is increasingly oriented toward higher-energy physics, with less emphasis on traditional nuclear chemistry approaches. Some studies of actinide and separations chemistry are funded by DOE's Office of Basic Energy Sciences, Division of Chemical Sciences. However, there is no real "home" in the funding agencies for nuclear and radiochemistry as such despite continued interest in pure research on high-energy reactions, heavy-ion reactions, studies of nuclear and chemical properties of the heaviest elements, the search for superheavy elements, cosmochemistry, hot atom chemistry, and the separation sciences, to name a few.

Although the requirements, identified by the other panels, for what amounts annually to several hundred "professionals with training in nuclear and radiochemistry" can perhaps be met for the short term by specific training courses, this is not a sufficient solution for the long term. What will be the source of the more broadly knowledgeable scientists to conduct the training if university and college chemistry departments do not replace retiring professors in nuclear and radiochemistry?

The intellectual challenges of nuclear and radiochemistry have a resoundingly successful history, giving a basis for confidence that future activities with similar vitality are probable. These intellectual challenges have actually attracted an increased number of graduate students (+32 percent) over the period since the 1978 survey in spite of the decreased number of nuclear and radiochemistry faculty at Ph.D.-granting institutions.

A further concern is raised as a consequence of the survey discussed in Appendix E. About one-third of the current nuclear and radiochemistry graduate students are enrolled at institutions that do not offer any courses in nuclear and radiochemistry. This is particularly evident for students who are entering the fields of nuclear medicine and radiopharmaceutical chemistry.

The inescapable conclusion is that the United States must take prompt action to ensure the vigor of nuclear and radiochemistry in the chemistry departments of Ph.D.-granting institutions. This is necessary in order to fill the projected needs for (1) Ph.D. nuclear and radiochemists and (2) training in nuclear and radiochemistry for professionals in related disciplines and applied areas.

In the following sections the panel presents some concrete suggestions that would help to ensure the viability of nuclear and radiochemistry at U.S. universities and colleges.

YOUNG INVESTIGATOR AWARDS

The number of chemistry departments with strong, active programs in nuclear and radiochemistry is small and is shrinking, an unacceptable situation. A program of Young Investigator Awards for tenure-track faculty at universities should be established to provide incentive to university chemistry departments to hire nuclear and radiochemistry professors and to support these young faculty with sufficient funding to develop viable research and educational programs for the future. The panel suggests that:

1. Support be sought for the establishment of Young Investigator Awards (YIA) to fund assistant professors in nuclear and radiochemistry.
2. Five such awards be given to chemistry departments over a 5-year period under a competitive scheme. The basis of the competition shall include the department's current strength in nuclear and radiochemistry, the caliber of the candidate, and the commitment of support for the position.
3. The budget for each YIA include start-up funds of $250,000 and $50,000 of annual support for 5 years.
4. Support for these YIAs be provided by the DOE, possibly by other federal agencies, and by industries requiring persons trained in this field.

POSTDOCTORAL TRAINING PROGRAMS

There is a substantial and unmet need for chemists with radiochemistry training to fill positions in nuclear medicine programs in medical schools, hospitals, and the radiopharmaceutical industry. A few (approximately 8 per year) of these positions must be filled by individuals having a Ph.D. degree in nuclear and radiochemistry. Most of these positions (approximately 25 per year) require individuals with degrees in other disciplines, most frequently synthetic chemistry, but some will hold degrees in other areas of the physical and life sciences. They will, however, all have career interests in using radioisotopes for important research problems. This need should be met through support from NIH for a few training grants to support postdoctoral fellows in radiochemistry. These training grants would be most effective at universities that include nuclear and radiochemists in the chemistry department and in the medical and pharmacy schools. The fellows should take at least one formal course in nuclear and radiochemistry, including both lectures and laboratory experience, as well as engage in at least one year of research on applications of radiochemistry to experimental problems of their interest.

In addition, there is a projected shortfall of at least 10 Ph.D. nuclear chemists per year in the national laboratories. To alleviate this shortage, it is necessary to establish postdoctoral fellowships to prepare chemists who have received graduate education in other areas of chemistry for careers in nuclear or radiochemistry.

SUMMER PROGRAMS FOR UNDERGRADUATES

There is a perceived and urgent need to attract talented and motivated students to nuclear and radiochemistry and to academically related areas such as nuclear medicine. The current and anticipated opportunities for such graduates far exceed the number of available candidates. Most undergraduate schools give no introduction to such topics in their B.A./B.S. chemistry programs. This obvious need is being met, in part, by a special undergraduate fellowship program sponsored by the Division of Nuclear Chemistry and Technology of the American Chemical Society. The program is a 6-week Summer School in Nuclear and Radiochemistry, funded by the Department of Energy and taught at the undergraduate nuclear science teaching facility at San Jose State University. This summer school, held for the past four summers, has attracted several hundred applicants, from whom 47 students were selected and have participated to date. Twenty-six of these 47 students have now graduated from their respective colleges and universities, 8 are studying in areas of nuclear chemistry in graduate school, and all but 2 or 3 of the remainder are in graduate or medical schools. The success of this summer school program has led to the proposal to expand this concept by funding a second, similar program in the eastern United States.

FACULTY FELLOWSHIP PROGRAM

A recent survey by the Educational Testing Service of the content of freshman chemistry courses in leading U.S. universities and colleges found that only 2 percent of such a course is devoted to nuclear and radiochemistry. More than 20 percent of the respondents provided no coverage of nuclear stability, decay, or reactions.

In order to foster knowledge in nuclear and radiochemistry among college chemistry faculties in general, it is proposed that funds be budgeted to allow for the establishment of a summer and sabbatical leave fellowship program for college and university faculty members. Such a program will allow interested college faculty members to participate in a training or research experience in nuclear and radiochemistry. These faculty can be expected to transfer their newly acquired knowledge to their home institutions and to provide a background for the development and teaching of courses and programs in nuclear and radiochemistry at such locations.

The panel recognizes that only a very limited number of students will have the opportunity to take a course in nuclear and radiochemistry. Due to the importance and significance of radioactivity in public health and in the environment, the panel strongly suggests that all chemistry students receive at least a minimum education in radioactivity. This minimum requirement could be met by including two to four lectures on radioactivity, including appropriate discussion of risks and benefits, in general chemistry.

TRAINING CENTERS FOR NUCLEAR AND RADIOCHEMISTRY

There is a need for a center, or centers, that can provide an appropriate introduction to nuclear and radiochemical topics for scientists switching into the field. Such centers would serve the needs of many segments of the scientific community and would provide basic laboratory and practical training, in addition to lecture material. Such centers could be located at universities, hospitals, or national laboratories and could provide short courses in various formats to suit the diverse requirements in these fields.

STUDENT RECRUITMENT

In addition to the recruitment of students into nuclear and radiochemistry careers and training at the collegiate level (see the section on summer programs for undergraduates), the panel urges that an effort be made to inform high school students of the excitement and career opportunities in nuclear and radiochemistry and related nuclear sciences. One mechanism to accomplish this goal is to meet with local high school students and their teachers in a special evening session during each national American Chemical Society meeting. This should be arranged by the ACS Divisions of Chemical Education and Nuclear Chemistry and Technology.

Another avenue for reaching a much larger audience of high school and junior high school students is through an interactive video laser disc based exhibit that could circulate among science museums. Themes of current interest to students could be developed. This would be an effective way to show students the important roles of chemists and to give information on the training necessary for pursuing a career in the field.

FUNDING

Although the focus of this workshop is on training requirements, it is clear that students and postdoctoral researchers cannot be trained in nuclear and radiochemistry if there are no exciting and adequately supported research activities in these fields in at least a few universities and in the national laboratories. Continued research funding from the DOE and NIH is absolutely essential in order to support faculty, postdoctoral research associates, and graduate students in nuclear and radiochemistry.

In view of the national needs identified in this report and the central role of nuclear and radiochemistry in a number of fields of fundamental scientific research, NSF must accept a share of the responsibility for supporting research and graduate studies in this field. In particular, it is suggested that the NSF identify a specific program to receive proposals in the field of nuclear and radiochemistry and that the NSF adequately publicize this step in the appropriate divisional announcements.

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NUCLEAR AND RADIOCHEMISTRY IN OTHER FIELDS

SUMMARY

Nuclear and radiochemistry theory and techniques have contributed significantly to such diverse endeavors as high-sensitivity analyses of extremely pure electronic materials, determinations of movements of nuclear and non-nuclear hazardous wastes in the geo- and biospheres, studies relating to "nuclear winter" and the "greenhouse effect," and the counting of neutrinos from the sun to test theories about the reactions that sustain its heat and light. These examples are part of a broader spectrum of contributions of nuclear and radiochemistry to the earth and cosmological sciences, life sciences, materials science, and separations science. Appropriate training for students of such disciplines is required if the full potential of these fields is to be realized, yet it is clear from the experience of the workshop participants that most practitioners in other fields who use nuclear and radiochemistry are not receiving the proper training. For such individuals, a lecture course plus laboratory training in nuclear and radiochemistry would be adequate. New textbooks and new curricula must be developed. Funding for radiochemistry teaching equipment must be made available by appropriate federal and state agencies since most universities do not have such equipment now. For personnel who already use nuclear and radiochemistry in other fields, or who wish to begin such work, short courses given under the auspices of a university, the American Chemical Society, or other organizations such as Oak Ridge Associated Universities would suffice.

INTRODUCTION

Over the past several decades, developments in nuclear and radiochemistry have greatly altered and enhanced U.S. industrial, defense, agricultural, educational, and numerous other activities. In order for the nation to maintain economic and political competitiveness in the international arena, strong support for teaching and research in nuclear and radiochemistry in universities and colleges is essential, not only for nuclear and radiochemists but also for workers in many other fields. Unfortunately, much of the present teaching equipment and instrumentation is outmoded and inadequate. Existing textbooks have not kept pace with the expanding information base or with the increasingly diverse group of scientists working in other fields who make extensive use of the theories and techniques that have been developed by nuclear and radiochemists. Despite the contributions that nuclear and radiochemistry have made to the evolution of other sciences, there is no "home" for much of the research in any of the funding agencies, and relatively few universities are equipped to provide adequate training in nuclear and radiochemistry to students specializing in other areas. A strong commitment to investments in such university programs is needed if progress in nuclear and radiochemistry is to continue to pay off in advances in the life sciences, materials science, industry, separation science, environmental science, agriculture, and other theoretical and applied related fields.

CHEMISTRY OF THE NATURAL AND PERTURBED ENVIRONMENT

The environmental sciences were revolutionized after World War II by the development of techniques for measuring very small amounts of radionuclides and the isotopic compositions of elements. Nuclear methods, such as radiocarbon dating, were used to determine the time frames of environmental systems (geochronologies) and to trace the movements of natural materials within and among the various geospheres (i.e., the atmosphere, hydrosphere, and biosphere). Today, stable isotope geochemistry and nuclear geochemistry are integral parts of earth and planetary sciences. Nuclear analytical chemistry, especially neutron activation analysis, has been an essential tool for determining trace element concentrations in the rocks and minerals of the solid earth and in the atmosphere and hydrosphere.

In the early 1950s, a new parameter was introduced into natural systems: artificially produced transuranic, fission-product, and activation-product radionuclides from weapons testing. These radionuclides extended our ability to study the movements of materials, both natural and man-made, in the environment. Today there is a continuous release of a small amount of artificial radionuclides into the environment from nuclear energy facilities and weapons testing (now mostly underground). These releases present an opportunity to learn more about the movement of various species in the environment (allowing us to predict the fate of both nuclear and non-nuclear hazardous materials) and a challenge for us to identify any radionuclide that may be detrimental to human health. Thus there is a crucial need for a cadre of environmental chemists trained in nuclear and radiochemistry to improve our understanding of the disposition of radionuclides in the biosphere and to guide surveillance programs. Further, even the small possibility of accidents with large releases requires quick responses from experts who understand these kinds of problems in order to minimize damage to public health and to the environment.

The federal government has placed a high priority on understanding the long-term changes in global climate that are produced by natural causes, such as volcanic activity and solar cycles, and by man-made changes, such as the buildup of carbon dioxide from the burning of fossil fuels (the "greenhouse effect") or the release of chlorofluorocarbons. These changes can have enormous consequences, and our ability to understand, predict, and perhaps control these effects requires a detailed knowledge of the mixing of materials within the geospheres, and the exchange of energy and materials between them. Much of our present knowledge in these areas has come from studies of the movement of natural and artificial radionuclides. However, much more knowledge is needed for the development and testing of global models that successfully account for the sources, transportation, and deposition of airborne materials on a global basis. This research requires the assay of radionuclides and the determination of isotopic ratios in the various environmental compartments and the measurement of trace elements characteristic of certain sources or regions on samples collected at sites remote from extensive human activities. Many other significant results, such as a better understanding of the "nuclear winter" following nuclear explosions, the flow of groundwaters, the ages of geological formations, and the permeability of soils, will derive from these kinds of studies. The information obtained from these fundamental studies will also be important for control of practical problems, such as the management of hazardous and radioactive wastes.

Nearly all university departments dedicated to environmental studies (geological, hydrological, oceanic, and atmospheric sciences) use nuclear chemistry techniques that usually require sophisticated instruments. These departments, as well as their counterparts in national and private laboratories, need a steady supply of investigators trained in nuclear chemistry to expand and enhance current research. An appropriate and effective way to meet the need for a continuing supply of environmental scientists trained in nuclear and radiochemistry would be for relevant agencies, such as the DOE, the Environmental Protection Agency (EPA), and the U.S. Nuclear Regulatory Commission (U.S. NRC), to provide sustained support to investigators who also direct graduate student research and teach in the universities. Such support would achieve the multiple goals of meeting the missions of the respective agencies, providing the needed research to solve the fundamental and applied challenges in the environmental sciences, and training the next generation of environmental scientists in the areas of nuclear and radiochemical science and technology that have become an integral part of many specialties.

APPLICATIONS OF NUCLEAR AND RADIOCHEMISTRY IN THE LIFE SCIENCES

The term "life science" in this context is intended to include topics relating to human and animal health science and agriculture but not to the field of nuclear medicine, which is discussed in Chapter 4 of this report. The current activities and future needs of these disciplines are similar in terms of educational objectives relating to fundamentals in nuclear science and its applications.

Current applications of nuclear science and technology in the life sciences include qualitative and quantitative analyses of the molecular and elemental components of biological fluids by methods such as radioimmunoassay

(RIA), radioisotope dilution, and neutron or charged-particle activation, and the use of radiotracers or stable isotopes for metabolic studies, biosynthetic pathway studies, and nucleotide sequencing. Other applications involve characterization of the structures of biologically important molecules through techniques such as ^{252}Cf mass spectrometry and the use of ionizing radiation for food preservation and sterilization. Nuclear and radiochemical techniques have been used to identify appropriate nuclides for use in these applications and to develop methods for the production, isolation, and purification of a variety of radiolabeled and nonlabled biological materials. Nuclear chemists have also contributed to the development of detection technology (new detectors and low-level counting techniques) for methods used in the life sciences.

Many future advances in the life sciences will be aided by the continuing development of nuclear technology. For example, the use of RIA will be expanded to applications in fields outside nuclear medicine, which will require the development of more sensitive detection techniques. The response of the nuclear chemistry community to the needs of the life sciences must also include the production and characterization of a wider spectrum of radioisotopes than is currently available. The field of biotechnology, particularly in such areas as protein sequencing by synthetic means and recombinant DNA methodology, could be advanced by further development of the mass range and sensitivity of nuclear-based analytical methods such as ^{252}Cf mass spectrometry. Nuclear chemists must also provide expertise for improving the use of ionizing radiation for food preservation and sterilization and for understanding the microscopic effects of ionizing radiation in this application. In addition, many life scientists will require training in the use of the materials and techniques that have been and will be developed by the nuclear and radiochemical community.

MATERIALS SCIENCE

Nuclear and radiochemistry has contributed in a number of areas of materials science, and further application of this technology is vital to future progress in a number of significant research and development problems. For example, a major requirement in electronics is ultrahigh-purity materials, such as silicon and germanium. Activation analysis, using a high flux of neutrons from a reactor or charged-particle beams from accelerators, has been useful in these analyses and is sometimes uniquely capable of solving specific problems, such as the determination of uranium impurities too small to be assayed by any other method. Similarly, very low levels of boron have been measured in high-purity semiconductor materials by a new nuclear analytical method called neutron-capture prompt gamma ray activation analysis (PGAA), in which prompt gamma rays are observed while samples are irradiated in a beam of neutrons from a reactor. Since ultrahigh-purity materials are critical to further improvements in solid-state electronic devices, continued improvements are needed in these nuclear analytical techniques.

One of the most exciting prospects in nuclear analytical chemistry is the use of PGAA with beams of cold neutrons from the National Bureau of Standards research reactor. The cold (cryogenic-temperature) neutrons will be conducted in a beam tube far from the background radiation around the reactor with little loss of flux. This facility (which will be available to outside users) will improve the sensitivity of PGAA by at least 2 orders of magnitude. Among other things, it will be extremely valuable for the analysis of materials, such as the determination of very low hydrogen levels in metals. If this facility proves to be as valuable as anticipated, similar ones will be installed at other U.S. reactors. Obviously, researchers trained in materials science as well as nuclear and radiochemistry will be needed if the full potential of the facility is to be realized. Several such facilities are already operating in Europe.

Studies of radiation damage for fission and fusion reactors are carried out in high-flux reactors, but they are also carried out at accelerators by such methods as implanting alpha particles and other nuclides to create voids and dislocations. These types of studies use the tools and techniques originally developed in nuclear chemistry and nuclear physics. Another area of great success in materials science is ion implantation, which has a similar accelerator-based background.

Another technique that originated in nuclear science is Mössbauer spectroscopy. This technique has had a great impact in many areas, including materials science. For example, the analysis of radiation damage in Nb_3Sn-type superconductors was done with ^{119}Sn Mössbauer spectroscopy. Current research is seeking information on the new ceramic high-temperature superconductors by substituting ^{119}Sn for copper.

Thus it is clear that continued improvement in accelerators, reactors, nuclear instrumentation, and nuclear and radiochemical techniques is of considerable importance to materials science. Materials scientists working in many areas will need training in nuclear and radiochemical theory and technology if they are to remain at the forefront of research in their specialties.

SEPARATION SCIENCE

Future progress in fields as diverse as biotechnology, hazardous and radioactive waste management, electronics, nuclear power, materials science, and medicine depends heavily on the development of new separation technologies. These developments, in turn, often depend on or can be greatly simplified by the use of nuclear and radiochemical methods. Thus scientists, engineers, and technicians who are involved in the development and use of new separation methods (or the improvement of established methods such as solvent extraction, ion exchange, absorption, and precipitation) must also be skilled in the use of nuclear and radiochemical techniques.

The nuclear fuel cycle is perhaps the most obvious marriage of separation science with nuclear and radiochemistry. Uranium is mined and then refined by solvent extraction methods. The uranium must be isotopically enriched for use as fuel, and the spent fuel then reprocessed to recover unburned uranium, other fissile materials, and fission products. The fission material and useful byproducts may be recovered for use, and the remaining material must be properly disposed of as radioactive waste. A number of aqueous and nonaqueous separation technologies, such as solvent extraction, ion exchange, gaseous diffusion, atomic vapor laser isotope separation, and various pyrochemical processes, are used in the fuel cycle for various applications. Clearly, any scientist working to improve the safety and efficiency of the nuclear fuel cycle needs a thorough understanding of many aspects of both separation science and technology and nuclear and radiochemistry.

Nuclear reactors are also used to produce the transuranium elements for fundamental research in physics and nuclear chemistry, as well as various radioisotopes of other elements for use in nuclear medicine and other applications. The cost and rate of production of these materials are often controlled by the separation processes that are used to recover and purify them. Separation scientists attempting to develop improved methods for the production of these materials must understand the special problems—such as the charring of ion exchange resins in high-radiation fields—that occur when intensely radioactive samples are handled.

The need for ultrahigh-purity materials in the electronics industry is discussed in the materials science section. The nuclear power, biotechnology, pharmaceutical, and food industries (among others) also have special needs for materials that are ultrapurified with respect to one or more components. Radiotracer methods are well suited for use in the development of new purification methods, and only nuclear analytical techniques are sensitive enough to assay some species at levels low enough to meet process and regulatory requirements.

In general, radiotracer techniques are very useful in the development of separation methods and also in the elucidation of the mechanisms of the separations. Unfortunately, most separations chemists receive little or no training in radiochemical techniques and so rely on wet chemical or instrumental techniques that are more time consuming and expensive. This hampers the progress of separation science as well as the progress of fields that rely on improved separation technology for their development.

CHEMISTRY OF ENERGETIC ATOMS (HOT ATOM CHEMISTRY)

Hot atom chemistry is the study of the chemical effects associated with nuclear transformations, whether produced by nuclear-reactor or cyclotron irradiation, or by radioactive decay of electron capture or isomeric transition nuclides. Since its discovery by Szilard and Chalmers in 1934, one of the fundamental goals of hot atom chemistry has been to understand the chemistry of energetic radioactive atoms in gas and condensed-phase environments. Hot atom chemistry is a specialty area of physical chemistry, and most of the research has been conducted in universities and national laboratories. These programs have proven to be excellent training grounds for doctoral candidates in radiochemistry, and they have provided results that have had major impacts in many other areas of science. For example, carbon-14 radiocarbon dating, the discovery of stratospheric ozone depletion by chlorofluorocarbons, and various applications in nuclear medicine were all derived from hot atom chemistry research. In addition to employment at universities and the national laboratories, Ph.D. graduates trained in hot atom chemistry have found careers in nuclear medicine, state or federal health, energy, and environmental sciences laboratories, and nuclear power plants. There are various unique advantages to receiving training as a hot atom chemist; because of their research and formal course training, these scientists can make an immediate impact in areas requiring in-depth expertise in radiochemistry.

COSMOCHEMISTRY

In this context, cosmochemistry refers to the chemical and nuclear aspects of questions relating to the origin, structure, and future of the universe. It seeks to understand the origin of the elements, the "Big Bang," and the reactions in stars, quasars, and other extraterrestrial bodies. Such studies are vital to testing the "Grand Unified Theories" as well as the intermediate theories that have been developed in the search for a "Grand Unified Theory." Nuclear and radiochemical techniques often play a critical role in confirming, disproving, or refining these theories.

An excellent example of the use of nuclear and radiochemistry to solve cosmochemical questions is the experiments to study the neutrino flux from the sun, which were begun over 20 years ago at Brookhaven National Laboratory. The results of these experiments will tell us much about a hotly debated question in particle physics, namely, whether or not the neutrino has mass. In the first experiment, neutrinos were detected through reaction with chlorine-37 in a tank located in a deep mine that contained many tons of a chlorocarbon. The reaction produced a very small amount of argon-37, which was swept out of the tank and counted. Only a fraction of the neutrinos expected from the standard solar model were detected. For that reason, a second experiment is now being mounted using gallium-71. The reaction of this isotope with neutrinos produces germanium-71. Thirty metric tons of natural gallium is expected to produce about one germanium-71 atom per day. The threshold of the gallium-71 reaction with neutrinos is only about 200 keV versus about 800 keV for chlorine-37, so more neutrinos should be detected and less dependence on the details of the model of the sun is expected. The germanium chloride produced in an 8-molar solution of gallium chloride in 2-molar hydrochloric acid will be swept out, converted to the hydride, and counted. This experiment is a classic example of the ability of the nuclear chemist to handle very low-production-rate problems in order to solve some of the most fundamental questions of the structure of the universe.

Other areas in which nuclear chemists make contributions to cosmochemistry include the measurement of cross sections needed for nucleosyntheses calculations and the study of isotopic ratios of elements and cosmic-ray-induced radioactivity in meteorites for cosmic-ray and other outer-space information. The development of small-production-rate chemistry, such as "one-atom-at-a-time" chemistry in the heaviest actinides and in the transactinides, and of ultrasensitive mass spectrometry techniques has contributed greatly to resolving the questions raised by cosmochemists.

NEED FOR TRAINING IN NUCLEAR AND RADIOCHEMISTRY FOR WORKERS IN OTHER FIELDS

As has been shown, workers in many sciences require training in the following areas if they are to make effective use of nuclear and radiochemical methods: the biological effects of radiation, the detection and analysis of ionizing radiation, the interaction of radiation with matter, the chemistry and methodology of radiotracers (with and without the use of carriers), radiation monitoring, nuclear and radiochemical analytical techniques (especially activation analysis), the handling of radioactive waste materials, and basic health physics. In some cases, special topics, such as actinide chemistry, radiodating methods, hot atom chemistry, the production of radionuclides and labeled compounds, and chemical aspects of the nuclear fuel cycle, are important. A textbook and curriculum must be developed that address the needs of students who are majoring in other disciplines but who need some knowledge of nuclear and radiochemistry. This curriculum should be available to upper-level undergraduate and entering graduate students as part of a formal lecture and laboratory course in radiochemistry.

However, it is neither practical nor desirable for every university to provide courses in nuclear and radiochemistry. Thus alternative sources for education and training in nuclear and radiochemistry are necessary. The American Chemical Society (ACS) Summer School in Nuclear and Radiochemistry offers most of the needed information and should be offered at two or three sites each year. Courses in nuclear and radiochemistry that have been offered sporadically by the national laboratories, the ACS, and various universities or university consortia (e.g., Oak Ridge Associated Universities) could also provide the necessary training.

It should be especially noted that a theoretical knowledge of nuclear and radiochemistry is inadequate in sciences that require the actual use of a method or process in the laboratory, plant, or field. Thus adequate laboratory courses are an essential part of a curriculum provided for workers in other disciplines. Administrators and funding agencies must recognize that budgets for the purchase, maintenance, and replacement of the specialized equipment used for research and teaching in nuclear and radiochemistry are essential.

CONCLUSIONS

1. An upper-division or graduate lecture course in nuclear and radiochemistry plus a 1- to 2-hour laboratory course would be appropriate and sufficient for scientists in other disciplines who make use of nuclear and radiochemical science and technology.

2. Appropriate agencies (e.g., DOE, EPA, NSF, NIH, and the U.S. NRC) should fund radiochemistry teaching equipment for university courses.

3. For personnel already involved in or seeking to enter disciplines that require specialized training in nuclear and radiochemistry, short courses are appropriate. These include university continuing education courses, ACS courses, and courses given by consultants or by centers such as Oak Ridge Associated Universities.

4. Communication among universities, national laboratories, the nuclear utilities, and other industries must be enhanced to ensure adequate, relevant training opportunities in nuclear and radiochemistry for workers in other fields.

5. Industry and the national laboratories should play an active role in supporting the universities, the ACS, and other institutions that provide specialized training in nuclear and radiochemistry. Such support should include providing information on career opportunities, guest lecturers, suggestions on course content, direct funding, and equipment grants.

6. A new textbook is needed on applied nuclear and radiochemistry for workers in other fields.

3

NATIONAL LABORATORIES

SUMMARY

It is anticipated that the national laboratories will continue to have major research and development programs supported by the DOE. In addition to the basic research programs, applied programs have promoted the development of nuclear and other forms of energy, nuclear medicine, and nuclear weapons. Radiochemists and nuclear chemists have played, and continue to play, important roles in many aspects of these programs. Also, trained radiochemists are involved in a number of programs in which radiochemical techniques are applied. Although possible changes in national policy regarding these laboratory programs contribute some uncertainty to projected needs for personnel, trained radiochemists will continue to be needed in several important long-range programs. Because of the increasing average age of nuclear and radiochemistry staff members at the national laboratories and the corresponding increase in retirement rates, the panel believes that the needs summarized below for trained new staff members are realistic, even considering potentially significant changes in program funding.

The panel's estimates of the national laboratories' needs for researchers are as follows:

1. Ten to twenty Ph.D.'s per year who are expert in nuclear and radiochemistry, have had formal course training in the field, including training in laboratory practices, and have done their thesis research in an area involving radioactivity.
2. Sixty advanced-degree chemists, working in related fields, whose training includes at least one course in radiochemistry that also requires laboratory work.
3. Twenty to forty B.S.-degree chemists whose training includes one course in radiochemistry, including laboratory practice.

To ensure that scientists with these qualifications are available in the future, the panel is unanimous in its opinion that:

1. The Summer School in Nuclear Chemistry, which has been held at San Jose State University for the past four summers, should continue to be supported. The panel regards this school as one of the most positive solutions to the problem of providing chemists trained in nuclear and radiochemistry to work on national programs in the coming years. The panel encourages the present plans to expand this activity by organizing a second summer school at Brookhaven National Laboratory.

2. Instruction in nuclear and radiochemistry should be required for every B.S.-level student in chemistry, because the principles and methods of nuclear and radiochemistry are used extensively in a wide variety of research and industrial institutions. Knowledge of radiation, radioactivity, and nuclear energy has become an important component of a scientific education.

3. Young Investigator Awards should be established for junior chemistry faculty specializing in nuclear and radiochemistry. These awards could be supported by organizations such as the NSF, NIH, and DOE and by industry to provide several multiyear, tenure-track faculty appointments.

4. Regional training centers for the study of nuclear and radiochemistry should be developed at selected universities. Such centers would offer courses specifically designed to meet, in addition to other objectives, the training needs of the national laboratories, so that DOE support of the centers would be appropriate. Alternatively, DOE should be encouraged to establish training courses at one or more of the national laboratories.

In conclusion, the panel stresses that the national laboratories' needs for such trained personnel are much greater than the foreseeable future supply. This imbalance is rapidly approaching a critical state and must be corrected very soon if the traditional excellence of the national laboratories is to be maintained in matters relating to nuclear and radiochemistry.

INTRODUCTION

Organizations that later became the national laboratories were bases for the development and use of nuclear and radiochemistry during World War II. A broad range of activities was pursued, including the discovery and characterization of the nuclear properties of fission products and heavy elements (actinides), the study of the process of nuclear fission, the development of detectors and counting techniques, tracer chemistry, chemical separation processes, and radioanalytical chemistry. After the war, many nuclear scientists trained during the Manhattan Project established active research and instructional programs at universities. Basic research programs in high-energy nuclear reactions, heavy-ion reactions, nuclear spectroscopy, fission, and identification of new elements were particularly prominent. Moreover, the use of radioactivity and radiochemical techniques expanded into almost every field of scientific investigation as well as into many industrial processes. The allied fields (e.g., nuclear medicine, geo- and cosmochemistry, analytical chemistry, environmental science, radioactive waste disposal, and national defense programs) have further expanded the historic range of national laboratory activities that involve radioactivity and radiochemical techniques, both in programmatic and basic research.

Although some basic research is currently being conducted in nuclear and radiochemistry, the emphasis at the national laboratories has shifted largely to basic studies in nuclear physics and to applied areas, i.e., the use of radioactivity in chemistry and related disciplines. (The areas of particular importance to the national laboratories are listed in Table 1.) Universities are not now training an adequate number of personnel required for these programs. The number of professionals in nuclear and radiochemistry is decreasing, and student interest is not high. This situation is rapidly approaching a critical state, and steps must be taken soon to ensure an adequate future supply of researchers and technical staff at the national laboratories who are trained in the safe handling and effective use of radioactivity.

REQUIREMENTS OF THE NATIONAL LABORATORIES FOR PERSONNEL TRAINED IN NUCLEAR AND RADIOCHEMISTRY

An informal survey of the number of staff members at national laboratories who currently use radiochemical techniques is summarized in Table 1 and is presented in terms of the categories designated by C. Gatrousis and R. Wymer in Appendix G. The current staff numbers represent the estimated totals for all DOE laboratories (Argonne National Laboratory, Brookhaven National Laboratory, Savannah River, Rocky Flats, and so on).

The panel's prediction is that the total (575 to 850) will remain constant but that the needs in categories *I* and *VI* may decline somewhat, whereas those in categories *III*, *IV*, and *V* will increase. Category *II* is decreasing as an identifiable area, but personnel trained in analytical chemistry are increasingly needed in categories *III*, *IV*, and *V*.

Based on a 5 percent annual rate of turnover and a ratio of Ph.D. to B.S. staff of 1:2, the panel estimates that there is an **annual need for 10 to 20 Ph.D. staff** and **20 to 40 B.S.-degree staff** integrated over the entire DOE complex, including the production facilities. The Ph.D. staff

TABLE 1 Number of Staff Members at National Laboratories Who Currently Use Radiochemical Techniques

Area of Study Requiring Knowledge of Nuclear and Radiochemistry		Nuclear and Radiochemistry Staff with Advanced Degrees	
I	Basic Research	100-200	(20%)
II	Analytical Chemistry	200-300	(35%)
III	Process Applications Research and Development	100	(15%)
IV	Health-Related Applications	50-100	(10%)
V	Environmental Applications	25-50	(5%)
VI	Nuclear Weapons Application	100	(15%)
	TOTAL	575-850	(100%)

represents specialists in nuclear and radiochemistry, while the B.S. staff represents chemists with some training in the field (e.g., a lecture-and-laboratory course).

In addition, the panel estimates that a total of approximately 1,200 M.S./Ph.D. chemists are currently working in related areas at the national laboratories for whom some radiochemical training is highly desirable. With the same 5 percent turnover rate, this translates to about **60 additional people per year who will require radiochemical training.**

POTENTIAL SOLUTIONS

To satisfy the needs of the national laboratories for chemists trained in nuclear and radiochemistry, both short- and long-term actions are required. To satisfy immediate needs, the national laboratories require ways to train employees who will be working with radioactivity but have no formal training in the field. At present, these needs are satisfied through on-the-job training, which is necessarily limited in scope. A more satisfactory approach might be to establish training centers at nearby universities to which employees of the national laboratories could be sent for instruction. The training course would be appropriate for all levels of degreed personnel and would teach use of radiochemical techniques, including basic skills in the safe handling of radioactive materials. One important advantage of using universities with existing capabilities is avoiding both the considerable cost of infrastructure components (e.g., instructional laboratories, health and safety technicians, and waste disposal facilities) and the licensing needed for a comprehensive laboratory program.

The training provided at such university centers would serve the immediate needs of the national laboratories as well as the requirements of other government agencies, medical centers, and industrial laboratories. Since DOE-operated facilities are to be the direct beneficiaries of training centers, the DOE is encouraged to provide financial support for this endeavor, and participation by experts from the national laboratories is anticipated.

Establishing training centers could be coupled with making Young Investigator Awards (see below) available for faculty at universities, thereby allowing support of the centers to serve additional purposes. The funding would support creating or upgrading radiochemistry teaching laboratories that would also be available for teaching undergraduate and graduate students in chemistry and related disciplines that require the use of radiochemical techniques.

If these university-based training centers cannot be established, the DOE should meet current training needs by providing its own broad training courses at centralized facilities in one or more of the national laboratories. In addition to the DOE, agencies such as the EPA and the NIH should recognize the need for personnel trained in nuclear and radiochemistry and should provide support for the necessary training.

The national laboratories' future needs for chemists trained in nuclear and radiochemistry can be alleviated over a longer period by carefully planning long-term programs that focus on education and support of faculties. Several approachs would be useful, including the following:

1. Expanding the Summer School in Nuclear Chemistry for Undergraduates sponsored by the American Chemical Society and supported by the DOE, as discussed in Chapter 1 by the panel on nuclear and radiochemistry.

2. Establishing the Young Investigator Awards first proposed in this report by the panel on nuclear and radiochemistry.

3. Supporting the faculty fellowship program suggested by the panel.

4. Encouraging promising college graduates to continue their education, by promoting excellence in the faculties that interact with the students and by providing financial support. The needs of the national laboratories and universities would be served by making available **graduate and postdoctoral fellowship grants** supported by various sources, including the DOE, NSF, Congress, and private industry.

4

NUCLEAR MEDICINE APPLICATIONS

SUMMARY

Nuclear medicine is currently facing a desperate shortage of organic and inorganic chemists and nuclear pharmacists who also have advanced training in nuclear and radiochemistry. Ironically, this professional and technical personnel deficit is occurring in the face of rapid growth and technological advances that have made the practice of nuclear medicine an integral part of the modern health care system. Approximately 120 chemists and pharmacists are needed to fill vacant positions that exist now in medical centers, industry, universities, and national laboratories, and it is estimated that 225 such positions will have to be filled by 1993. This shortage of qualified professionals threatens to limit the availability of radiopharmaceuticals required in routine hospital procedures and to impede the development of new diagnostic and therapeutic agents. To redress this deficiency and prevent a similar shortfall in the future, this panel urges immediate action on, and a long-term commitment to, the following: educating the public on the benefits of nuclear medicine; informing undergraduate and graduate chemistry students about career opportunities in nuclear medicine; offering upper-level university courses in nuclear and radiochemistry, including laboratory work; and establishing training centers and postgraduate fellowships to support specialized education in those aspects of nuclear and radiochemistry required by the nuclear medicine profession.

The panel's conclusions are summarized at the end of this chapter.

INTRODUCTION

The Pimentel Report (*Opportunities in Chemistry*, National Academy Press, Washington, D.C., 1985, page 265) described the application of nuclear and radiochemistry in the practice of medicine and in biomedical research as one of the intellectual frontiers of chemistry related to the national well-being. The report listed the "chemistry of life processes" as one of the five frontiers deserving high priority. Because nuclear medicine, medical research, and related activities require the use of radioactive materials, it is clear that nuclear and radiochemistry play a vital role in the continued growth of these fields. It follows that the need for training in radiochemistry is an imperative. It is a matter of great concern to this panel that while the demand is increasing for people knowledgeable in nuclear and radiochemistry, the supply from U.S. educational facilities is decreasing.

DISCUSSION

Because research in nuclear medicine is not a common interest of faculty members in universities with graduate programs in chemistry, there is a problem in attracting chemists to this field. In addition, public concern about, indeed even fear of, nuclear matters is regrettably real, yet few patients will deny themselves needed medical care that involves use of radioactive materials. Therefore it is necessary to inform people of the opportunities in nuclear medicine and of its benefits to the public in order to stimulate greater interest in and awareness of the field in university chemistry departments.

Stimulating interest in careers in chemistry related to nuclear medicine can be effected in several ways: by promoting nuclear medicine in lectures to undergraduates and graduates, perhaps as part of a course or in career seminars with solid scientific content; by contributing more articles on nuclear medicine to the popular scientific literature, e.g., *Science*, *Accounts of Chemical Research*, *Chemical Reviews*, and *Quarterly Reviews*; by holding symposia at national and local meetings of the American Chemical Society on topics related to nuclear medicine; and by attempting to dispel the myths surrounding radioactivity and the biological effects of radiation. Such efforts could be particularly effective in promoting nuclear medicine because its positive societal benefits are easily documented.

An examinination of the needs of medical centers and the radiopharmaceutical industry suggests some specific areas in which training and knowledge of nuclear and radiochemistry are necessary:

Medical centers. One of the modalities at the frontier of new medical technologies is exemplified by positron emission tomography (PET) centers. In the past 12 years the number of PET centers in the United States has grown from 4 to 24. At present most are centers for basic and clinical research. Clinical application of PET is just beginning. Future growth will require chemists trained principally in organic and inorganic chemistry who also have the training in radiochemistry needed to develop and provide the required radionuclides and labeled compounds. Knowledge and appreciation of radiation and radiochemistry are essential for such work.

The increasing sophistication of labeled drugs makes training in radiochemistry essential to the mission of nuclear pharmacists, trained professionals who work in many major health care delivery centers and commercial nuclear pharmacies. Additional educational requirements will be placed on the nuclear pharmacist, especially as the number of clinical PET centers increases.

Radiopharmaceutical industry. There will be a large and continuing need for chemists, primarily for research and development but also to staff key positions in such areas as manufacturing, waste disposal, and radiation protection in the radiopharmaceutical industry. Although their primary field of chemical specialization may be organic or inorganic synthesis, analytical chemistry, or biochemistry, a background in radiochemical methods and instrumentation is essential for chemists working in these areas.

While no necessary connection exists between nuclear medicine and ethical drugs, radiolabeled drugs are used extensively in the study of drug metabolism, pharmacokinetics, drug biodistribution, drug delivery systems, bioavailability, and molecular pharmacology. These studies, intrinsic to drug discovery, development, and approval, require the expertise of synthetic chemists and pharmaceutical scientists who are knowledgeable in radiolabeling, radioanalytical techniques, and the basic properties of radioactive materials. Future demands on these researchers will be even greater due to increased sophistication of pharmacologic studies requiring isotopic methods and new approaches by PET or single photon emission computed tomography (SPECT) in the study of dynamic factors in drug activity. Thus, training of these researchers must impart knowledge of positron-emitting nuclides as well as the traditional radionuclides of pharmaceutical research—tritium, carbon-14, and iodine-125.

Radioimmunoassay (RIA) is another area in the radiopharmaceutical industry that requires knowledge of radiochemistry. While RIA is limited primarily to radioligands labeled with tritium and iodine-125, development and purification of these materials have been the province of biochemists and immunochemists with backgrounds in radiotracer synthesis and development. RIA will remain a vital part of the in vitro diagnostic field and will have a modest but very real need for chemists trained in radiochemical techniques.

Involvement by specialists in nuclear and radiochemistry is also required for accurate measurement of nuclear reaction cross sections, optimization of target design, production of radionuclides for diagnosis and therapy, design of new radionuclide generators, and cyclotron or other accelerator technology for radionuclide production, which are areas beyond the normal purview of synthetic or analytical chemists. For example, development of therapeutic applications, particularly of radioimmunotherapy of cancer with labeled monoclonal antibodies, is an area of current intense research interest and effort. Selecting appropriate nuclides for therapy and developing an adequate supply for clinical use are major needs that will require the efforts of a significant number of highly trained nuclear and radiochemists at national laboratories and universities, and in industry.

The increasing need for chemists trained as nuclear and radiochemists or with some training in this field as a part of their education is indicated in Table 2, which gives (1) the number of positions currently available for chemists and pharmacists in nuclear medicine and in related disciplines that require a knowledge of radiochemistry and (2) an estimate of the number of such positions that will be available in each area in 1993. Details of requirements for radiochemical training for professionals working in nuclear medicine and related areas are given in Appendixes H-K.

TABLE 2 Need for Advanced-Degree Personnel With Training in Nuclear and Radiochemistry

	1988[a]	1993[b]
Medical Centers		
Imaging and related fields	15	40
Nuclear pharmacy	10	30
Industry		
Radiopharmaceutical manufacture	40	60
Ethical drugs	40	80
Radioimmunoassay	5	5
Universities and National Laboratories	10	10
TOTAL	120	225

[a]The numbers in this column are based primarily on open positions gleaned from classified advertisements. Needs and openings personally known by members of the panel were also included.
[b]The numbers in this column are based on panel members' projections of positions to become available in 1993.

CONCLUSIONS

In summarizing its position on nuclear and radiochemistry training for chemists who provide the basic research and clinical effort necessary to support the field of nuclear medicine, the panel presents the following conclusions:

1. Increasing public awareness of the significance of radioactive materials in public health and in other areas affecting society's welfare is of prime importance.
2. Chemistry departments should be encouraged to provide, where possible, an upper-level course in nuclear and radiochemistry to their students and to allow faculty from other departments to take the course.

3. Specialized application of nuclear and radiochemistry can best be accomplished by postgraduate education offered at a select number of centers, perhaps five to seven, that have the necessary faculty, infrastructure, and equipment. Extended, in-depth training could be supported with fellowships for some individuals following completion of the course. Such courses might not be uniform in content but would be specific and would be designed to meet the needs of those who work in nuclear medicine and health-related fields.

4. The panel wishes to underscore as a national priority the desperate need for professionals trained in radiochemistry to support the continued vitality of an important segment of the health care delivery system. Quality of care and the ability to deliver such care will not only be impaired but will also continue to decline in the next decade without some redress of this need.

5
NUCLEAR POWER INDUSTRY

SUMMARY

Utilities currently meet their needs for personnel skilled in nuclear and radiochemistry by providing in-house training. The power industry's supporting organizations meet such needs largely by retraining other professionals. To enhance present training programs and ensure the quality and quantity of personnel well versed in nuclear and radiochemistry, the panel proposes the following actions:

1. Add courses in nuclear and radiochemistry to university undergraduate chemistry curricula.
2. Facilitate cooperative agreements and ventures among research and educational organizations and utilities to meet objectives in training and research.

INTRODUCTION

This section reviews the chemistry-related staffing needs and sources of personnel for the civilian nuclear power industry. Two distinct areas of need are identified and analyzed: the first concerns the chemical and radiochemical-related requirements of operating a nuclear power plant; the second involves the technical support activities necessary for continued assurance of safety, environmental control, and compliance with licensing requirements. Compliance includes auxiliary activities, such as developing high-level radioactive waste repositories and instituting environmental standards and controls, that are paid for with utility funds but are not performed or directly controlled by the utilities. Other support activities include the research and development and analysis connected with safety, licensing, and other generic issues.

REQUIREMENTS FOR SKILLED PERSONNEL

Personnel Operating Nuclear Power Plants

At present in the United States, 54 utilities own 110 licensed nuclear power reactors that are located at 76 separate sites and generate about 5×10^{11} kW-h/yr (over one-sixth of all the electric power generated in the United States and over 50 percent in some regions). Based on a March 1987 survey, an estimate is given in Table 3 of the current and projected number of individuals directly involved in chemistry functions related to the operation of U.S. nuclear power plants.

Although the nuclear power industry typically hires chemical engineers and chemists with degrees, they may lack nuclear and radiochemistry training, which is then supplied in specialized courses provided by universities or private industry. Chemistry technicians may or may not have college degrees, depending on the hiring practices of the utility; entry-level requirements vary from high school graduation with a strong math/science background, to prior nuclear experience in the Navy, to a B.S. or B.A. degree in chemistry, biology or a related science.

TABLE 3 Chemistry Personnel Needed to Operate U.S. Nuclear Power Plants—10-Year Projection (1987-1997)

	Current Filled Positions	Current Vacancies	Needed for Growth	Replacements	Total Hiring Requirements
Chemical engineers	305 (0.3)*	12	3	88	103
Chemists	261 (0.3)*	22	8	136	166
Chemistry technicians	1,538 (1.7)*	65	49	492	606

*As a percent of total work force.

SOURCE: Survey of Nuclear-Related Employment in United States Electric Utilities, INPO 87-017 (1987).

INPO's Role in Promoting Excellence of Personnel. Before the Three Mile Island accident, the quality and scope of training programs for power plant personnel varied greatly. As a result of that accident, the Institute of Nuclear Power Operations (INPO) was established by the power industry to assist it in achieving excellence in the safe operation of nuclear power plants. INPO helps the industry to develop highly qualified, well-trained professionals to operate, maintain, and support the nation's nuclear power plants: the Institute develops training guidelines, evaluates the quality and effectiveness of training provided by utilities, assists member utilities in developing performance-based training programs, and provides financial aid to a limited number of college students who are considering a career in the nuclear power industry.

INPO's assistance to utilities extends to accreditation and plant evaluations. The accreditation program is intended to systematically evaluate and subsequently improve individual utility training programs. INPO plant evaluations, which focus more directly on the performance of personnel in the plant, are meant to ensure that training is producing the desired results and that plants are being operated safely.

One Example of a Well-Staffed Nuclear Utility. Duke Power Company, one of the largest U.S. nuclear utilities, is an example of a utility that has successfully met the need for personnel trained in nuclear and radiochemistry. A three-station, seven-unit nuclear utility with a generation mix that is approximately 53 percent nuclear, 46 percent fossil, and 1 percent hydroelectric and outside purchase, Duke Power is heavily staffed with professionals in the general office and at the plants.

Duke Power is both similar and dissimilar to other nuclear power companies in its need for chemistry personnel. The company does not now hire degreed chemists for technician-level positions in chemistry sections at the plants or in the corporate office. Chemical engineers, chemists, or individuals with a background in health physics may fill positions that, in many companies, are only chemistry's domain. Consequently, Duke Power's training programs may be much broader in scope than similar programs at other companies, as well as more specific to nuclear power plant requirements than is training received from conventional schools.

Requirements of Nuclear Power Plant Personnel for Specialized Knowledge. "Radiochemistry" is usually a misnomer for many of the studies conducted on samples at a nuclear power plant, where chemical analyses are performed on samples that just happen to be radioactive. Radioactive samples have to be handled differently from nonradioactive samples simply because they are radioactive. Also, most (>95 percent) of the radioactive analysis is done instrumentally rather than by classical radiochemistry separation and counting. Only tritium, strontium, and a rare alpha count are chemically separated and counted. Nuclear (gamma) spectroscopy plays a leading role in isotope identification and in qualitative analysis. However, a capability for doing classical radiochemistry is important for the small number of samples that require diagnostic analyses.

There is a strong interdependence between control of the chemistry variables in a nuclear power plant and their radiochemistry behavior. For example, pH, total ionic content, organic content, and oxidation potential (parts per billion of oxygen) affect rates of corrosion, stress corrosion cracking, and radiation levels at various locations around the plant. Basic knowledge of corrosion and transport in high-temperature water systems is an important asset to nuclear power plant chemists, radiochemists, and health physics professionals in interpreting radiochemistry data.

Other activities of a power plant chemistry technician that demonstrate the requirement for specific knowledge of chemistry and of nuclear and radiochemical techniques are listed below:

1. An average of 2,000 radioactive samples are analyzed per month to determine the radionuclides present. These may be broken down as follows:

- Technical specifications and release samples,* 35 percent
- Health physics job coverage,† 29 percent
- Chemistry and radioactive waste, 23 percent
- Miscellaneous, 13 percent

2. The disintegration rate (dps) varies from 0.3 dps (for environmental samples) to approximately 10^6 dps (for reactor coolant). The chemist is prepared to count several orders of magnitude higher if an accident involving fuel damage should occur.

3. An average of more than 1,000 radioactive samples per month are analyzed to determine the pH, Cl^-, F^-, B, conductivity, Li^+, suspended solids, O_2, H_2, Al, SiO_2, Ca, Mg, and total gas.

4. An average of over 5,000 nonradioactive samples per month are analyzed to determine the pH, turbidity, biological oxygen demand, conductivity, Cl^-, SiO_2, Ca, Mg, Na^+, K^+, N_2H_4, NH_3, O_2, total organic carbon, nitrite, chromate, B, Fe, and so on.

5. An average of 300 thermoluminescence dosimeters (TLDs) per month are processed to determine the amount of radiation exposure received by workers.

6. An average of 360 individuals per month are analyzed to determine the amount of internally deposited radioactive material.

7. An average of 150 environmental samples per month are analyzed to determine the amount of radioactivity present.

The courses needed to bring power plant personnel to the level of expertise required are now, for the most part, given in-house by the

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*These are samples taken to determine whether allowable regulatory limits variables are being met, including limits on liquid or airborne releases.

†Health physics samples include wipes taken to identify low-level contamination and adequacy of decontamination, samples from air-sample filters, and urine samples.

utility or by a service company. It could be more cost-effective in some cases if this training were done at universities. The need for extensive retraining by the utilities indicates that universities in regions near nuclear power plants should address more adequately the educational needs of the nuclear power industry.

Education to Promote Excellence of Nuclear Power Plant Personnel. Some of the concepts and topics that should be included in undergraduate as well as in advanced degree programs, in addition to the traditional content of nuclear and radiochemistry courses, include:

1. Appreciation and understanding of the goals, objectives, and constraints of a "working" nuclear power utility.
2. Nuclear power plant operations and design from a chemistry perspective.
3. Basic engineering principles involved in power plant operation.
4. Applications of modern instrumentation in plant operation.
5. Extensive laboratory experience in radiochemistry as well as instrumentation in order to develop skill levels and discipline in the handling of higher-level radioactive samples; laboratory experience in nuclear instrumental methods.
6. Training for radioactive waste management.
7. Training in the requirements and procedures for radiochemists in radioactive waste management areas, to assure compliance and safety in a cost-effective manner.

Early exposure to career opportunities in radiochemistry is suggested as a means to recruit undergraduate chemistry majors for the radiochemistry field. Comprehensive, one-semester, elective courses at the junior/senior level would provide the necessary stimulus and training to fulfill the nuclear power industry's need for professionals at the B.S. level. A possible curriculum is one that parallels the program at San Jose State University, where chemistry graduates can receive a B.S. in chemistry with a specialization in radiochemistry. This type of curriculum can also produce some of the graduate students who will provide the core of nuclear and radiochemistry Ph.D.'s.

Table 4 suggests a range of options (not necessarily complete) that may coexist in a university program that provides for training in nuclear and radiochemistry. Such options, which include short modules inserted in more general courses, are desirable to keep the university community up to date in this field of science.

Personnel Responsible for Technical Support Activities

There are thousands of technologists whose primary function is radioactive waste management, a responsibility of every user of radioactive nuclides.* A significant number of chemists work for suppliers of waste-treatment processes and equipment. These chemists are involved with the design and operation of low-level waste disposal sites, and with the large technical efforts associated with the design of facilities and site evaluations of federal repositories such as the Waste Isolation Pilot Project, the Basalt Waste Isolation Project, and Yucca Flats. The magnitude of these efforts can be appreciated when one considers the funds generated by the tax of $0.001 per kilowatt-hour assessed on all nuclear-generated electrical energy ($455 million in 1987). Six to ten low-level waste sites are to be built under the state compacts (Radioactive Waste Policy Act, P.L. 96-573, 94 Stat. 3347; amended by the Low-Level Radioactive Waste Policy Amendments Act, P.L. 99-240, 99 Stat. 1843).

Although most of these work efforts are by nonchemists, chemical process development for volume reduction and immobilization of low-level waste, chemical processing of high-level and transuranic waste, evaluation of potential or measured ion migration away from disposal sites, and radioactive species identification and decay calculations all involve radiochemical techniques and methods.

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*State and federal agencies and government laboratories also employ substantial numbers of chemically trained people, including some radiochemists.

TABLE 4 Introduction to Nuclear and Radiochemistry—Matrix of Options

Type of Course	All Students	Any Science and Engineering Students	Chemistry, Physics, Biology Majors	Nuclear and Radio-chemistry Majors	Nuclear Engi-neering Majors
General survey module[a] Nonprofessional courses	✓	✓			
Basic nuclear science module[b] in physics or engineering physics or inorganic chemistry course		✓	✓		
Nuclear and Radiochemistry					
Short course[c]			✓		
Module[d]		✓	✓		✓
Semester[e]			✓	✓	✓
Year[f]				✓	✓

[a]Module equals 1-hour course in elementary nuclear science and demonstration of radioactivity and detection.
[b]Module equals 1- to 2-hour lecture plus demonstration. Elementary calculus required.
[c]Short course equals 10- to 80-hour course on specific nuclear and radiochemistry techniques, oriented to specific applications (power, biology, medicine, research).
[d]Module equals chemical science and engineering courses beyond freshman level (5 to 20 hours).
[e]Intensive 4- or 5-unit course for potential graduate students.
[f]For potential accredited nuclear and radiochemistry major at the B.S. or M.S. level. Professional courses are offered to the nuclear engineering majors. In most universities, it can be suggested that these courses be at least electives in a general chemistry curriculum. They may be treated as mandatory for students who wish to have a specialty in nuclear and radiochemistry. Accreditation of such courses is a logical further step.

TABLE 5 Annual Needs for Personnel Skilled in Chemistry and Radiochemistry for Operation of Nuclear Power Plants and for Support Activities

Segment of Nuclear Industry	Level of Personnel		
	Ph.D.	B.S.	Technicians (nondegree)
Utilities (power plants)	2 (60)*	25-30 (570)*	60 (1,500)*
Support activities (including environmental and severe accident analysis, and waste management)	10-20 (100-200)*	40-50 (600-700)*	50 (1,000)*

*Estimated totals as of 1987.

SUGGESTIONS FOR TRAINING QUALIFIED PERSONNEL

Table 5 gives estimated annual needs for personnel working in nuclear power plants and in technical support activities. The values shown are estimates of annual replacement needs based on steady-state values shown in parentheses below each number. The average number of individuals needed annually to operate nuclear power plants is derived from the INPO survey of needs over the next decade (see Table 3), except for the estimated number of Ph.D.'s, which is an estimate by this panel. For personnel for nuclear industry support activities, estimates are based on replacement rates of 10 percent, 7 percent, and 5 percent per year for Ph.D., B.S., and technician levels, respectively.

General Suggestions

To ensure an adequate supply of workers trained in nuclear and radiochemistry to meet the needs of the nuclear power industry, the panel suggests the following:

1. Improve coverage of nuclear and radiochemical topics in undergraduate chemistry courses to provide all chemistry students with an understanding of the concepts and techniques of nuclear science and technology and a balanced perspective on relative risks.

2. Establish a program of Young Investigator Awards to halt the present trend of a decreasing number of faculty in nuclear and radiochemistry.

3. Establish a number of centers for short courses to prepare those scientists and technologists who require knowledge and skills in nuclear and radiochemistry.

4. Replicate the national summer school program to include an eastern site, and develop similar programs to meet the needs of a wide spectrum of participants

5. Establish a program of training grants and postdoctoral fellowships.

6. Encourage cooperative agreements between utilities and educational institutions to meet mutual objectives in training and research.

Suggestion for Nuclear Utility and University Collaboration

The licenses for operation of nuclear reactors require the continued objective assurance that the reactors are operated in a safe and environmentally acceptable manner. This depends, in part, on the availability of personnel with knowledge and skills in nuclear and radiochemistry. A cooperative or collaborative effort is desirable for technical training conducted at universities and supported by the utilities. Taught by professional educators (including adjunct professors from industry), courses with content agreed to by the utilities could be offered by universities either on-site or as summer institute courses on campus. Such courses, with content appropriately adjusted to meet special needs, could be modeled after the American Chemical Society undergraduate audio radiochemistry module. Courses with continuing education credit should be offered and uniformity in content and quality achieved so as to meet standards for accreditation. These courses should be directed to several audiences: technicians, professionals, entry-level employees,

employees seeking continuing education at all levels, and individuals concerned with special topics.

It is suggested that universities, colleges, and nuclear utilities, and in some locations interested government laboratories, establish cooperative agreements in areas of mutual interest to solve existing problems. Included in such cooperative agreements, as appropriate, could be the education, continuing education, and training of personnel; the mutual availability and use of essential equipment and facilities; and the solution of problems through research or through technical assistance. Models do exist, for example, the Arizona State University program in environmental monitoring and the Pennsylvania State University program in nuclear engineering.

To implement cooperative programs between industry and academia, the utilities should be encouraged to:

1. Communicate to the university community information concerning the need for power, the economics of nuclear power versus other power sources, environmental concerns associated with various power sources, and political implications of such situations as the growing U.S. dependency on foreign supplies of oil.
2. Communicate to chemistry department chairs the need for special courses and degrees in nuclear and radiochemistry.
3. Assist universities in upgrading instrumentation, facilities, and equipment for teaching and laboratory work in nuclear and radiochemistry. This can be done through grants, shared costs, donation of used equipment, and joint, in-plant measurements.
4. Give the staff in utility plants time off to lecture, teach, demonstrate a laboratory technique, or interact in other ways with students.
5. Employ faculty during a semester or a sabbatical.
6. Hold open house for faculty, students, and the public.
7. Provide summer job opportunities for students.
8. Establish co-op arrangements with neighboring universities.
9. Recruit on university campuses.

Universities should also take the initiative by approaching utilities with offers to:

1. Design or modify courses to meet the needs of the utilities.
2. Teach credit nuclear and radiochemistry courses at utility training facilities to upgrade the knowledge of staff members or to meet a specific need.
3. Include nuclear and radiochemistry segments in freshman general chemistry courses or use other means to stimulate student awareness of the many applications for nuclear and radiochemistry.
4. Have nuclear utility staff members speak at career days, or serve as adjunct lecturers or professors.
5. Require nuclear and radiochemistry courses for all chemistry majors.

APPENDIXES

APPENDIX A

WORKSHOP AGENDA
Training Requirements for Chemists in Nuclear Medicine, Nuclear Industry, and Related Areas

Thursday, February 4

8:00 a.m.	Registration - North Lounge
8:30	Opening Session - Room 130 Welcome by Co-Chairmen of Organizing Committee - Gregory R. Choppin, Florida State University - Michael J. Welch, Washington University Medical School
8:45	"Radiation and Society" - Rosalyn S. Yalow, Veterans Administration Medical Center
9:30	Discussion
9:45	Nuclear and Radiochemistry "Nuclear Chemistry Education in U.S. Universities and Colleges" - Edward S. Macias, Washington University
10:15	Discussion
10:30	Coffee Break - North Lounge
10:45	Related Research Disciplines "Training Requirements for Chemists in Related Research Disciplines" - Glen E. Gordon, University of Maryland
11:15	Discussion
11:30	National Laboratories "The Need for Nuclear and Radiochemists at the National Laboratories" - Christopher Gatrousis, Lawrence Livermore National Laboratory
11:50	Discussion
12:05 p.m.	Lunch - North Lounge
12:45	Nuclear Medical Applications - "Training Requirements for Chemists in Radiotracer Development for Nuclear Medicine" - Ronald D. Finn, National Institutes of Health "Radiopharmaceutical Industry" - Maria P. Liteplo, E. I. Du Pont de Nemours & Co. Inc. "Training Requirements, Credentialing and Standards of Practice for Pharmacists in Nuclear Medicine" - Ronald J. Callahan, Harvard Medical School "Radiochemistry in the Pharmaceutical Industry" - Scott Landvatter, Smith Kline & French Laboratories
1:45	Discussion

2:05	Nuclear Power and Process Industry "Training Needs for Chemists in Nuclear Power Industry" - William A. Haller, Duke Power
2:25	Discussion
2:40	"European Approaches to Training Chemists for Nuclear Activities"- Jan Rydberg, Chalmers University of Technology
3:25	Discussion
3:40	Organization of and Charge to Panels
4:00	Panel Meetings
6:00	Reception and Dinner - South Lounge (Rooms 113 & 114)
7:30	Panel Meetings continued
9:30	Adjournment

Friday, February 5

9:00 a.m.	Plenary Session - brief status reports from Panels Room 130
11:00	Panel Meetings - report drafting, North Lounge Area
12:30 p.m.	Lunch - North Lounge
1:30	Panel Meetings - report drafting continued
7:30	Plenary Session - presentation and review of panel deliberations - Room 130
10:00	Adjournment - deadline for draft reports

Saturday, February 6

9:00 a.m.	Panel Meetings - revision of reports North Lounge Area
11:00	Plenary Session to discuss overall conclusions and possible recommendations
12:30 p.m.	Workshop Adjourned
	Steering Committee, Panel Chairmen, and Rapporteurs will remain to discuss report outline and preparation—group will adjourn no later than 2:00 p.m.

APPENDIX B

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Rapporteur	Paul J. Karol, Carnegie-Mellon University
Discussants	Gerhart Friedlander Rolfe H. Herber Günter Herrmann John R. Huizenga Kenneth A. Krohn Alan C. Ling Edward S. Macias Joseph R. Peterson Norbert T. Porile Jan Rydberg
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Rapporteur	David J. Pruett, Oak Ridge National Laboratory
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Rapporteur	David C. Moody, Los Alamos National Laboratory
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Rapporteur	Alfred P. Wolf, Brookhaven National Laboratory
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Discussants	Jack Berga Michael E. Burns William A. Haller Chester Harris Roy G. Post Ivor L. Preiss Forrest J. Remick Barry D. Stewart

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Guests	Anne Anderson John L. Burnett June S. Chewning Cyrelle K. Gerson Irwin Goodwin Samuel Kavruck Steven M. Larson Elliot S. Pierce James S. Robertson

APPENDIX C

United States
Environmental Protection
Agency

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February 1985

Research and Development

EPA

Distinguished Lecturer Series

Rosalyn S. Yalow: Biologic Effects of Low-Level Ionizing Radiation

The following is the first of a planned series of lectures to be sponsored by the Office of Research and Development, U.S. Environmental Protection Agency. The views expressed in this lecture are the speaker's own, not to be construed as the Agency's. This material has not been subject to the normal Agency peer and administrative review procedures and, therefore, does not necessarily reflect the Agency's position on any aspect of the issue discussed.

As the scientific arm of the Agency, the Office of Research and Development has the responsibility to advance the state of scientific knowledge about the environment. Highlighting emerging issues and providing scientific perspectives on current problems is an important part of our responsibility. We intend that our lecture series will present a range of perspectives on various aspects of health and environmental research, from the vantage points of well-known and distinguished scientists. The points of view represented in our lectures will be varied, perhaps conflicting, and not necessarily in agreement with Agency policy. But scientific progress depends upon the free exchange of diverse opinions.

Biologic Effects of Low-Level Ionizing Radiation*

By Rosalyn S. Yalow

ROSALYN S. YALOW, of the Veterans Administration Medical Center and Montifore Hospital in the Bronx, is a distinguished researcher in the field of medical physics. She won the Nobel Prize in 1977 for her work in radioimmunoassay development. Her recent publications include "Radioactivity in the Service of Man;" "Disposal of Low-Level Radioactive Biomedical Wastes: A Problem in Regulation, Not Science;" and "Reappraisal of Potential Risks Associated with Low-Level Radiation."

We live in a world in which the perception of reality is too often confused with reality and there are few fields in which more confusion exists than in the popular perception of the hazards of exposure to low level radiation and low level radioactive wastes. Much of the fear of radiation has been generated by the association of radiation and radioactivity with nuclear explosions and nuclear war. So phobic is the fear that the new medical imaging modality "nuclear magnetic resonance" or NMR has been renamed Magnetic Resonance or MR to avoid the bad word "nuclear." What I would like to discuss today is not philosophy but science—what do we know about health effects, and in particular, the carcinogenic effects associated with low doses of lightly ionizing radiation. Since there are tens of thousands of papers in this field, I have obviously had to be selective in choosing studies to discuss.

Before discussing radiation effects, let me define some units. A rad is a unit of absorbed dose or energy absorbed per unit mass from ionizing radiation and corresponds to 100 ergs/gram. Densely ionizing radiation such as that associated with α particles, protons or fast neutrons is more effective in producing deleterious biologic effects than is the lightly ionizing radiation associated with β, γ- or X-radiation. A rem is a unit that takes into account the relative biologic effectiveness (RBE) of lightly (low linear energy transfer, LET) and densely (high LET) ionizing radiation. A rem is an absorbed dose that produces the same biologic effect as 1 rad of low LET radiation. Rad and rem can be used interchangeably for low LET radiation. The RBE is not a constant for any ionizing particle but depends to some extent both on its energy and the biologic effect under observation.

The question to be addressed "How low is low" or are there levels of radiation below which one cannot discern deleterious effects. Much of what is known about the biologic effects of ionizing radiation has been obtained from epidemiologic studies of humans exposed to high doses and/or at high dose rates. Over about the past three decades national and international standard-setting bodies concerned with establishing radiation protection guidelines have accepted the hypothesis of a linear dose-effect extrapolation with no threshold, on the assumption that this provided a generous safety factor for predicting possible radiation-induced deleterious effects. According to this hypothesis, there would be the same number of radiation-related cancers or other biologic effects, among a 100 thousand people each receiving 100 rem as among 100 million people each receiving 100

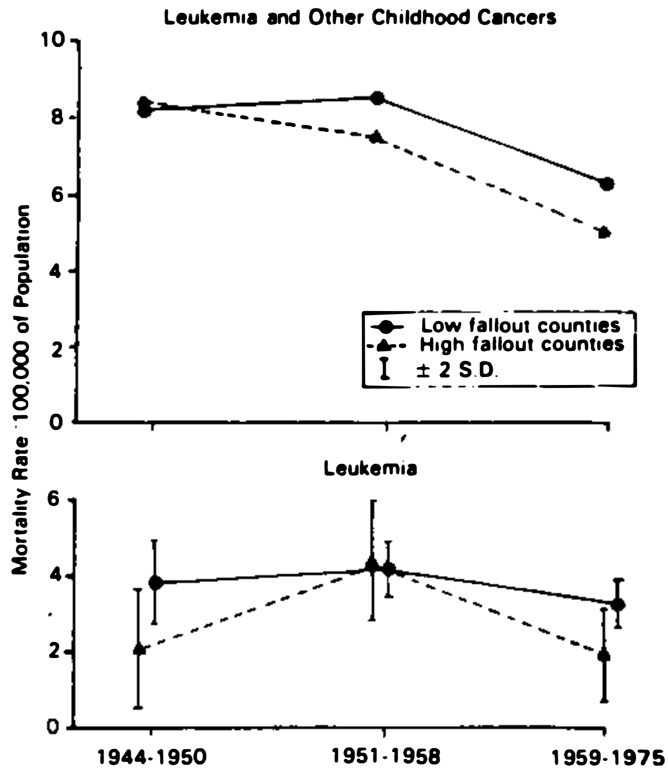
*Presented at the Environmental Protection Agency, Washington, DC, on August 17, 1984 mrem. Can this hypothesis be tested? To put this concept into the proper perspective let us consider that there were about 80000 survivors of the Hiroshima-Nagasaki bombings. The survivors received doses less than 400 rems. To deal in round numbers one can treat this group as 100 thousand people receiving about 100 rem. In almost three decades the excess radiation-related deaths in this group were less than 200. Natural background radiation in most of the United States is 100 mrem/year, due to cosmic rays, natural radioactivity of the soil and building materials and the self-contained radioactivity in all living things, each contributing about one-third. If the linear extrapolation hypothesis were valid, based on the Japanese experience, one would expect about 200 deaths due to background radiation. Since among 100 million Americans there are about 200 thousand cancer deaths per year, natural variations in this death rate would not permit ascertainment of the few hundred deaths that might be attributable to background radiation. This rough calculation points out the absurdity of Public Law 97-414 that requires "the Secretary of Health and Human Services to devise and publish radioepidemiologic tables . . . These tables shall show a probability of developing each radiation cancer associated with receipt of doses ranging from 1 mrad to 1000 rads . . . ." It must be appreciated that 1 mrad is about 1% of natural yearly background and that a round trip flight from Washington to Los Angeles increases radiation exposure by 5 mrad. Most of us would accept that the probability of causation of cancer at dosages in the mrad range is obviously zero to many significant figures. As a member of the committee attempting to construct these tables, I can assure you that the uncertainties even at doses of many rads are subject to such controversy that one should not "require" attention to exposure in the mrad range. However, such legislation creates a mind-set in the public that radiation at the mrad level is a cause for concern.

There have been a number of studies attempting to detect deleterious health effects in regions of the world where natural background radiation is increased. One such study was performed in China by examining 150,000 Han peasants with essentially the same genetic background and same life style. Half of them lived in a region where they received an almost three-fold higher radiation exposure because of radioactive soil (1). More than 90% of the progenitors of the more highly exposed group had lived in the same region for more than 6 generations. The investigation included determination of radiation level by direct dosimetry and evaluation of a number of possible radiation-related health effects including chromosomal aberrations of peripheral lymphocytes, frequencies of hereditary diseases and deformities, frequency of malignancies, growth and development of children and status of spontaneous abortions. This study failed to find any discernible difference between the inhabitants of the two areas. The authors of this study concluded that either there may be a practical threshold for radiation effects or that any effect is so small that the cumulative radiation exposure to three times the usual natural background resulted in no measureable harm after six or more successive generations.

There are regions in the United States where natural background radiation is also increased. In the Rocky Mountain States the average radiation exposure is about twice that on the East and West coasts because of increased cosmic rays at their higher elevations and natural radioactivity of the soil. However, death rates due to cancer in these states are among the lowest in the country. It is possible that an appropriate statistical analysis would reveal that the racial, ethnic, age distribution or other factors might account for the lower cancer death rates in these states. However, when Mason and Miller (2) compared the age-adjusted risk ratio for mortality from malignancies for Caucasians in Denver and Salt Lake City with those in San Francisco and Seattle-King County, Washington, they observed that the leukemia incidence was slightly but not significantly lower and the incidence of other cancers was significantly lower in the higher radiation exposure cities. An inverse relationship between elevation (hence higher radiation exposure) and mortality from leukemias and lymphomas has also been reported (3). Others have concluded (4) that in the United States there is no relation between increased background radiation and leukemia. There are regions of the world in India and in Brazil where natural background radiation is up to 10-fold higher than usual (~1 rem/year) and deleterious health effects have been looked for and not found (5-9). This is not surprising since even were the linear extrapolation hypothesis valid, the populations involved are too small to detect increased malignancies above the natural variation in the incidence of the diseases. However, these studies emphasize the difficulties in assessing probablity of causation at low doses and dose rates.

Senator Hatch was undoubtedly stimulated to sponsor Public Law 97-414 mandating the radioepidemiological tables in response to several widely publicized reports asserting that the cancer risks from low radiation exposures are much higher than those estimated according to the linear extrapolation hypothesis. One report that was of particular concern to his constituents was that of Lyon et al. (10) who reported that leukemia mortality in children was increased in those counties in Utah receiving high levels of fall-out from the atmospheric nuclear testing conducted in 1951-1958 compared to the mortality in low fall-out counties and in the rest of the United States. Let us examine the original data. In Figure 1 are shown the mortality rates for leukemia and for all cancers, including leukemia, for children in high and low fall-out counties in Utah. The 1944-1950 period represents the pre-fallout control low-exposure cohort. The 1951-1958 group was considered to be the high-exposure cohort, that is, those born during the period of maximum above-ground nuclear bomb testing in Nevada. The second low-exposure cohort was the group born after most, but not all, of the above-ground testing had ended. From a perusal of Lyon's data it could reasonably be concluded that on the average during the entire 30-year period the high fall-out counties might have had a lower incidence of leukemia than the low fall-out counties, but that the uncertainties in the determinations are so large that one cannot reliably conclude whether or not there is a trend. If one considers the sum of childhood malignancies (leukemia plus other cancer deaths) there appears to be a generally downward trend, with the drop in the high-fallout counties being somewhat greater than in the low-fallout counties, although if the standard deviations had been included the differences would not have been significant. The news headlines following interviews with Dr. Lyon would have been less sensational if he had stated that his data had shown no relation between the totality of childhood malignancies and the atomic tests of the 1950's rather than selectively reporting what would appear to me, as an experimental scientist whose results do not depend on marginal p-values, to be an inconclusive study of the relation between leukemia and fall-out. Lyon's paper in the New England Journal of Medicine was criticized in the same and later issues of the Journal by several biostatisticians (11-13). In general, their criticisms were related to the apparent under-reporting or misdiagnosis in the earlier cohort and to errors in small sample analysis. For instance, Bader (12) presented a year-by-year listing of leukemia cases in Seattle-King County, which has a larger population than the Southern Utah counties, and noted that there were only two cases in 1959 and 20 in 1963 among the 217 cases reported from 1950 to 1972. Thus, a ten-fold difference in annual incidence rates when the number of cases is small simply represents statistical variation. Although the yearly distribution of leukemia cases had not been reported in any of Lyon's papers or in the associated publicity, it was however tabulated in the Government Accounting Office Report on the Problems in Assessing the Cancer Risks of Low-Level Ionizing Radiation Exposure (14). Table 1 is taken from that report. It is to be noted that the so-

Figure 1. Data reproduced in graphical form from (10). Total childhood malignancies including leukemia (top) and childhood leukemia in high fall-out and low fall-out regions of Utah according to study of Lyon et al.



called excess leukemia cases reported by Lyon et al. (10) was due to a clustering of 13 cases in 1959 and 1960. In fact, 22 of the 32 leukemia cases occurred in 1951-1960, i.e., during the first 10 years of testing. Since there is a several year latency period between radiation exposure and induction of leukemia, were the excess leukemia deaths a consequence of nuclear testing in the 1950's; they would have been more likely to occur after 1960 rather than before.

Furthermore, a new estimate of external radiation exposure of the Utah population based on residual levels of ^{137}Cs in the soils has shown that the mean individual exposure in what Lyon deemed to be the "high fall-out counties" was 0.86±0.14 rad compared to 1.3±0.3 rad in the "low fall-out counties" (15). Even in Washington County, the region in which the fall-out arrived the earliest (less than 5 hours after the test) the estimated exposure to its 10,000 population averaged only 3.5±0.7 rads—quite comparable to natural background radiation in that region over a 20-30 year period. Thus on the basis of the Japanese experience the exposure from fall-out was too low to expect an

Table 1. Year of Bomb Testing in Nevada[a] and Year of Death from Leukemia for the Southern Utah High-Exposure Cohort[b]

	Test Yield (kilotons)	Number of Deaths Southern Utah High-Exposure Cohort
51	112	0
52	104	3
53	252	2
54	—	0
55	167	2
56	?	2
57	343	0
58	38	0
59	—	7
60	—	6
61	—	2
62	101	1
63	<20	1
64	<20	0
65	<80	1
66	<60	1
67	20-200	2
68	<60	1
69	20-200	1

[a]Data taken from reference 10.
[b]From data supplied by Dr. Lyon for the report in reference 14, pages XVIII-43.

increase in leukemia and a careful perusal of the raw data would suggest that none was found.

Another report that has received publicity far beyond its scientific merit is the Mancuso study of workers at the Hanford Laboratories, the site of several of the then AEC's reactors. The history of this study dates back to 1964 when Dr. Mancuso was awarded a contract to investigate for the AEC the health of these workers. Dr. Barkev Sanders, a statistician, and Dr. Allen Brodsky, a health physicist, were co-investigators in this project. Annual project reports for many years suggested only that there were negative findings regarding a link between cancer and radiation and Drs. Sanders and Brodsky left the project. There were no papers published during the period in which they were involved in the analysis of the data. In about 1976, Mancuso was joined by the pediatrician Stewart and the statistician Kneale who had acquired a reputation for their studies on relationships between diagnostic X-rays and childhood cancers. Together they wrote a controversial paper purporting to show that workers at Hanford had a statistically significant increase in the incidence of two types of cancer, multiple myeloma and cancer of the pancreas (16). According to Table 10 of their paper the mean cumulative radiation dose for Hanford workers who subsequently died from cardiovascular disease was 1.05 rads; for solid tumors 1.3 rads; for leukemias and lymphomas 2.2 rads. This excess radiation exposure is quite comparable to the excess received by living in Colorado for 10 to 20 years—and Colorado has a low cancer death rate. The evidence in the Mancuso report that has not been widely publicized was that Hanford workers receiving the highest radiation doses (greater than 15 rem) had a lower death rate from all causes and from all malignant neoplasms than expected in a control population. However, because of the small numbers of workers who received this exposure and the small number of cancer deaths in this group, (a total of 14 cancer deaths compared to 24 expected) the distribution among the different malignancies appeared to have a pattern not identical with that found in much larger groups. Subsequently, both Dr. Brodsky and Dr. Sanders, who initially collaborated with Dr. Mancuso, have been highly critical of the Mancuso paper. An independent analysis by Gilbert and Marks is most revealing (17). The positive correlation purported to be demonstrated in the Mancuso report appears to be due to 3 deaths from pancreatic cancer in workers receiving more than 15 rem cumulative exposure. However, according to Gilbert and Marks (17) this diagnosis had been confirmed only in 1 case. Furthermore, it should also be noted that the Atomic Bomb Casualty Committee report described a much larger cohort with much higher radiation exposures (up to 400 rads) and found no positive link between pancreatic neoplasms and radiation (18). The second category of excess cancer deaths was reported to be multiple myeloma, which included 3 cases compared to an expected number of 0.6 (16). Whether this excess of 2 deaths in this category represents a statistical variation or the effect of another carcinogen cannot be determined. Nonetheless, since among those receiving a cumulative exposure of 15 rems, the observed number of subjects with malignancies was only 14 compared to an expected 24 in a control population, one could be tempted to conclude that radiation at this level is protective against malignancies.

To demonstrate how legislation is sponsored in response to special interest groups rather than rational analysis, let me pose the following problem. Let us assume that there are two groups who received exposure to radiation. Group A consists of 6500 people who were not badged but who received radiation exposures probably in the range of 10-50 rems, or perhaps more; Group B consisted of 39 who received more than 25 rem, 1400 who received between 5 and 25 rem and another 5000 who received between 3 and 5 rem. Which of the two groups should have been favored with respect to compensatory legislation concerning possible radiation-related health effects? The logical answer would be the Group A who received the larger radiation exposure. Now let me identify for you Groups A and B, the legislative act and the known health effects. Group A was a group who were trained during World War II as radiology technicians and who subsequently served in that role for a median period of 24 months. Description of their training (19) included the statement that "During the remaining two hours of this period the students occupy themselves by taking radiographs of each other in the positions taught them that day." It was noted (19) that the students did not receive a skin erythema dose nor did they show a drop in white count—monitoring procedures that are insensitive to acute doses less than 100 rem. The cumulative exposures of these radiology technicians were not monitored. However, the radiation exposure of technologists at a more modern installation, Cleveland Clinic, was monitored in 1953 and found to be in range of 5-15 rad/year (20). Army technologists a decade earlier probably received greater exposures. Hence my estimate of 10-50 rem during their period of service. Yet, a followup of these 6500 radiology technicians (21, 22) for a period of 29 years revealed no increase in malignancies when compared with a control group of similar size consisting of Army medical, laboratory or pharmacy technicians.

Who was Group B? This group consists of those who entered Hiroshima and Nagasaki after the bombing and who received less than 0.1 rem during the occupation and the 220,000 Department of Defense (DOD) personnel involved in the atmospheric nuclear testing in the Pacific Ocean and Nevada. Among this large group only 1400 received more than 5 rem (23). Among these 1400 were 39 who received over 25 rem as a result of a wind shift during the 1954 Bikini testing. A follow-up of these 39 men almost 30 years later revealed that 4 were dead from causes not associated with radiation (trauma, heart attacks). Of the 35 who were notified, only 18 desired medical examinations, 7 refused and 10 failed to reply. No adverse health effects associated with radiation were found in those examined.

Further to put in proper perspective the cumulative radiation exposure among Armed Services personnel associated with nuclear testing, it should be appreciated that in the early years of the draft those accepted into the Armed Forces, and many of those rejected on medical grounds, a group numbering over 12 million persons, received chest photoroentgenograms. Unlike ordinary X-ray examinations of the chest, these deliver 1 to 5 rad skin dose (24). In addition, some of the Armed Services received considerable X-ray exposure secondary to service-related injuries and of course there were the higly exposed radiology technicians. None of these are included in Public Law 97-72 (25) which provides that "a veteran who the (Veterans Administration) Administrator finds was exposed while serving on active duty to ionizing radiation from the detonation of a nuclear device in connection with such veteran's participation in the test of such a device or with the American occupation of Hiroshima and Nagasaki, Japan, during the period beginning on September 11, 1945, and ending on July 1, 1946, may be furnished hospital care or nursing home care for any disability notwithstanding that there is insufficient medical evidence to conclude that such disability may be associated with such exposure."

There is no logic in giving special privileges to some veterans who received radiation exposure and not to all receiving equivalent exposure. Perhaps this legislation was in response to another highly publicized report concerning 9 cases of leukemia among 3200 men who participated in a nuclear test explosion in 1957 (26). The radiation exposures of 8 of the 9 men were monitored; 3 received between 1 and 3 rem; 3 received less than 0.1 rem. Since the 20,000 people exposed in Hiroshima-Nagasaki to doses between 1 and 9 rads showed no increase in malignancies, including leukemia, the study by Caldwell et al. (26) concerning only 3200 people exposed in this dose range is obviously flawed; the most probable reason is once again the error inherent in small number statistics. By the time of diagnosis all the leukemia cases had received more radiation from natural background than from Operation Smoky.

Can epidemiologic studies permit testing of the validity of the linear extrapolation hypothesis in estimating effects at low doses and dose rates? The answer is unequivocally no. As Land has pointed out (27) to test this hypothesis, for instance in radiation-induced breast cancer, a sample size of 100 million women would be required to be certain of an increased radiologic incidence following an acute exposure of 1 rem to both breasts at age 35. Such a sample is hardly practical. Therefore, a case-control approach, in which the sample consists of a fixed number of cancer cases and a fixed number of matched non-cases or controls, is used. Land has calculated (27) that using this cohort approach only 1,000,000 women would be required to be certain of a radiation effect from 1 rem. Of course, in the case-control approach to evaluation of radiation and other carcinogens, a sufficient number of subjects are never included and there is not random selection of cases and controls. Hence, the data presented simply do not have statistical significance and subtle sources of bias could well account for purported observed effects. For instance, MacMahon has reported (28) that children born after their mothers had received one to six pelvic radiographs (average dose per radiograph was 1 rad) were 42% more likely to die of cancer in the first 10 years of life then were children not irradiated *in utero*. Using the same case-control method of analysis MacMahon et al. (29) also reported that drinking 1 to 2 cups of coffee a day introduced a relative risk of 2.6 in developing cancer of the pancreas and further suggested that coffee drinking at this level can account for more than 50% of the cases of pancreatic cancer. However, since coffee drinking is familiar and radiation is not, most people would discount that his case-control analysis proves that such modest coffee drinking is a risk factor for pancreatic cancer, particularly since the effect did not appear to be dose-related in men—the risk factor was the same, 2.6, whether consumption was 1-2 cups or greater than 5 cups a day. There are other reasons for reluctance in accepting his analysis. For instance, the risk factor was twice as great for ex-smokers compared to current smokers drinking 1 to 2 cups of coffee per day, a rather unlikely finding since it is commonly accepted that smoking is a carcinogen or promoter of other carcinogens. The MacMahon et al. (29) report on the association between coffee drinking and cancer of the pancreas is, however, in a sense less-flawed than his earlier report (28) on the association between prenatal radiation and early cancer death. In the latter study there was clearly a bias in that no account was taken of the fact that the exposed mothers had medical conditions that prompted the diagnostic X-rays.

Webster has provided a simple demonstration of the problem of small number observations by determining the counting rate from a weakly radioactive source (30). Such a counting rate, like cancer events, follows Poisson statistics. In 20 successive periods the counting rate varied from 0 to 8 counts per unit time, with an average of 4. As shown in Table 2 the actual occurrence of a particular counting rate to the probability of its occurrence ranges from 0.6 to 2.8—these ratios are equivalent to the "relative risk" ratio using the case-control approach in epidemiologic studies—except that there was no bias introduced in the "control" or Poisson probability distribution.

For almost 30 years committees concerned with radiologic protection accepted the linear extrapolation hypothesis without correction for dose rate on the basis that it overestimated potential radiation-related risks. This has left the impression that it is an established fact that any level of radiation, no matter how small, carries some risk even if that risk is not measurable. In the latest report of the National Academy of Sciences Committee on the Biologic Effects of Ionizing Radiation (BEIR III Report) (31), it was concluded that a linear-quadratic extrapolation was to be preferred although it was also stated that the scientific basis for making estimates of the

Table 2. Poisson Statistics: The Problem of Small Number Observations*

	No. Observed	Probability (%)	Occurrence Probability
Actual counts observed during 20 consecutive counting periods	6,3,5,4,2,2,4,4,7,3,8,6,6,2,0,5,2,3,6,1		
Theoretical expectations with Poisson distribution	0	1.8	2.8
	1	7.3	0.63
	2	14.6	1.37
	3	19.5	0.77
	4	19.5	0.77
	5	15.6	0.64
	6	10.4	1.90
	7	5.9	0.85
	8	3.0	1.60

*Taken from Reference 30.

carcinogenic risk of low-dose low-LET whole body radiation is inadequate. The data are simply not available that would permit determination as to whether there is any risk associated with radiation at doses below 10 rads.

There is one large group of subjects with total body exposures in this dose range, i.e., patients treated with radioactive iodine, ^{131}I for hyperthyroidism. As of 1968 it was estimated that 200,000 people were so treated and the number has probably since doubled. A study of 36000 hyperthyroid patients from 26 medical centers of whom 22000 were treated with a single dose of ^{131}I and most of the rest with surgery revealed no difference in the incidence of leukemia between the two groups (32). The average bone-marrow dose was about 8 to 10 rads, about half of which was delivered within one week. The follow-up for the ^{131}I-treated group averaged 7 years, quite long enough to have reached the peak incidence, as determined from the Hiroshima-Nagasaki experience. A subsequent follow-up three years later again revealed no differences in the leukemia rate between the two groups (33). This study emphasizes the importance of having an appropriate control group. Earlier studies had suggested that the occurrence of leukemia in hyperthyroid patients following ^{131}I therapy was 50% greater than that of the natural population (34, 35). However, it appears from this study that there is an increased incidence of leukemia in hyperthyroidism, irrespective of the type of treatment (32).

The question may be addressed as to whether a large epidemiologic study could or should be undertaken to follow-up the several hundred thousand who have been treated with ^{131}I for hyperthyroidism. I believe the feasibility of such a study should be examined. It has the potential for answering the question as to whether general body exposure in the 10 rad range delivered at a relatively low dose rate is carcinogenic. However, since it appears that hyperthyroidism *per se* may be associated with leukemia, the appropriate control group should be, as in the study of Saenger et al. (32), patients treated with surgery. I doubt if it is currently possible to obtain an age-matched surgically treated group since ^{131}I has certainly become the treatment of choice for definitive therapy. In evaluating whether hyperthyroid patients treated with anti-thyroid drugs until remission would be suitable as a control group, the potential of these drugs for inducing leukemia must also be considered.

There have been several other negative studies in which induction of leukemia as a consequence of radiation was sought for and not found. The BEIR III Report did not consider early papers (36, 37) that observed no increase in leukemia in women treated for cervical cancer with either intercavitary radium, external radiation or both. Perhaps the reasons for neglecting consideration of these papers was the incomplete patient follow-up in these earlier studies. However, a recent report (38) of an international collaborative study of 31,219 women with cervical cancer, of whom 28,490 received radiation therapy and 2729 did not, revealed that in the irradiated group 15.5 cases of leukemia were expected and 13 were observed (relative risk=0.8) (95% confidence levels 0.4-1.4) and in the non-irradiated group 2 cases of leukemia were observed as compared with the 1.0 expected. The follow-up was long enough to have included the 4 to 8 year period of leukemia peaking observed with the Japanese atom bomb survivors. The consistency of these studies (36-38) would suggest that there is no detectable leukemogenic effect in patients with cervical cancer following radiotherapy. The cohort size of this study is quite comparable to the Court-Brown and Doll study showing increased incidence of leukemia in patients irradiated for ankylosing spondylitis (39, 40). It does remain a mystery as to why radiotherapy would appear to be leukemogenic in one disease and not in another when the therapeutic doses are in the same range although not delivered to the same body region.

It is commonly accepted that early radiation workers had an increased incidence of malignancies. For the most part, their radiation exposures cannot be estimated. The classical picture of the Curies working in their shed for 4 years while separating and purifying radium and polonium is one which will never be repeated. It is not surprising that Marie Curie died from aplastic anemia, probably secondary to the radiation exposure she received in her laboratory and during her experiences in World War I when she personally provided X-ray services just behind the front lines, trained X-ray technicians and installed 200 radiologic rooms. What is surprising is that she did not die until 1934 at the age of 66 in spite of cumulative exposures that must have been thousands of rems. What about more recent radiation workers with lesser exposures? A recent report of the mortality from cancer and other causes among 1338 British radiologists who joined radiologic societies between 1897 and 1954 revealed that in those who entered the profession before 1921 the cancer death rate was 75% higher than that of other physicians but that those entering the profession after 1921 had cancer death rates comparable to other professionals (41). Although the exposure of the radiologists was not monitored, it is estimated that those who entered between 1920 and 1945 could have received an accumulated whole-body dose of the order of 100 to 500 rad.

It seems obvious from these sampling of reports that human studies in the low dose, low-dose rate range are complicated by the biases introduced by the case-control methodology, the limitations of small number statistics and the natural variation in disease patterns in a heterogeneous human population. Because of these inherent limitations, it seems unlikely that human studies will ever answer definitively the question as to whether there is a threshold for radiation-induced carcinogenesis.

Animal studies have certain advantages: the animals are inbred and are not subject to the genetic and environmental variability of a human population; at present it is possible to expose animals but not humans to graded radiation doses at different dose rates. The inherent limitation of such studies is that it would be enormously expensive to maintain the large groups of animals that would be required to evaluate effects at truly low doses and dose rates. The conclusion of many studies of different tumors in different animals is that for a given total dose there was generally decreased tumorigenesis when the radiation was delivered at a lower dose rate, but that the reduction factor was dependent on the tumor and the species of animals (42). None of these studies have been performed at truly low dose rates. The studies by Ulrich and Storer (43) on tumorigenesis in RFM mice revealed that the ^{137}Cs gamma-ray irradiation is delivered at 8.3 rad/day, i.e., 25,000 times natural background, there is a threshold of about 50 rads before an increased incidence of ovarian tumors or thymic lymphomas is observed. The threshold appeared to be no more than a few rads when the irradiation dose rate was 45 rad/min. Studies at even lower dose rates, for instance at about 100 times natural background, would require an enormous number of animals and are really not practical.

Without developing a detailed theoretical model for radiation carcinogenesis, it can be expected that, since human beings are more than 75% water, low-LET ionizing radiation is probably largely absorbed in the water with production of free radicals. Thus many of the biochemical changes initiated in the cell and, in particular, damage to cellular DNA, are probably a consequence of the indirect action of the products of water radiolysis. If molecules which scavenge radicals and which are normally present in tissue exceed the concentration of free radicals generated at low dose rates, there may well be no initiating event, i.e., damage to DNA. The threshold could be the dose rate at which the free radicals overwhelm the scavengers—and this may be dependent on species of animals and specific tissue. This is a tenable hypothesis but one that is not readily verifiable.

In addition to concerns with carcinogenesis, there is considerable fear of the risks of genetic effects from radiation. This was considered extensively in the BEIR III report (31) and it was concluded that since radiation-induced transmitted genetic effects have not been demonstrated in man, estimates of genetic risks must be based on laboratory data obtained at high dose rates. Schull et al. (44) have concluded on the basis of studies of the children born to survivors of the Hiroshima-Nagasaki bombings, that the estimated doubling dose for genetic changes would be about 150 rem, a value some four-fold higher than the results from experimental studies on mice. Furthermore, this represents simply an estimate since they reported that in *no* instance was there a statistically significant effect of parental exposure. It should be noted also that many investigators have found that chronic irradiation in mice is about three-fold less effective than acute irradiation. This would effectively raise the doubling dose for prolonged exposure in man to about 500 rem. Furthermore, since none of the studies in mice were performed at truly low dose rates, one cannot really determine what the doubling rate would be for background radiation.

In my introduction to this presentation I raised the question "How low is low?" or are there levels of radiation below which one cannot discern deleterious effects of radiation. The answer to that question is YES. The GAO report concludes (14) that "there is as yet no way to determine precisely the cancer risks of low-level ionizing radiation exposure, and it is unlikely that this question will be resolved soon." Stating that there are levels below which one cannot discern harmful effects of radiation is not the same as reaching conclusions concerning the existence of a threshold below which radiation effects in man does not occur. In science we can only accept as valid those laws that are subject to experimental proof. We can hypothesize, but we should not confuse hypothesis with reality. There is a problem in determining what kinds of studies should be funded in radiologic research. It is evident that epidemiologic studies cannot produce meaningful data about the existence of a threshold for radiation effects. Molecular and cellular studies may or may not give some insight about molecular or cellular effects but cannot answer important questions about repair mechanisms in the intact animal or man when radiation is delivered at low dose-rates. At present there are no really good ideas that would permit a breakthrough in the field of low-level radiation effects. Therefore, good scientists with imagination and insight are unlikely to work in a field in which the studies, at best, are pedantic and, at worst, are inevitably flawed. Thus, this field of research which is now primarily generated not by scientific interest but by Federal concern and Congressional mandate is not likely to attract investigators seeking to open new frontiers in science. It is essential to communicate to the public and through them to our government that each of us loses when scientific talent and funding is diverted from scientifically important and socially desirable investigations to predictably negative experimentation because of irrational fears generated by well-intentioned or ill-intentioned but often uninformed Cassandras.

Let me turn now, for a moment, from science to philosophy. Science, unlike religion, is not influenced by belief or divine revelation. In science we observe, hypothesize and reobserve in an attempt to determine whether the hypothesis is consistent with the observations. Scientists are not Aristotelians—if we want to determine the number of teeth in a horse's mouth we open its mouth and count the teeth. Sometimes the critical experiments cannot be performed with available tools. Thus, Newton's Laws, which were dogma for over two centuries, could not predict behavior at high velocities or atomic or subatomic dimensions. But this is simple compared to predicting the laws governing the much more complex interrelations in biologic systems including man. With respect to effects of low-level radiation, there is a consensus that there are no reproducible studies demonstrating unequivocally that such effects are demonstrable. The disagreement concerns how to extrapolate from higher dose rates and total doses to the non-measurable range. The BEIR III Report (31) concluded that a linear-quadratic extrapolation is the one most consistent with available data; Radford dissented and contended that the linear extrapolation hypothesis was appropriately conservative; Rossi claimed that a quadratic extrapolation should be employed. There are those who hold that there is no evidence which would exclude the possibility that there is a threshold below which there are no radiation effects. After all, with what we have learned in recent years through studies in molecular biology there is every reason to believe we have repair mechanisms hitherto undreamed of. The disagreement in the low-level radiation field is about hypothesis—not observable facts. One could not determine the validity of Newton's Laws at sub-atomic dimensions until the tools became available. However, in that case there was no need to make policy decisions based on extrapolation. In the case of low-level radiation effects, public policy decisions need to be made in the absence of scientific evidence. It should be appreciated that these are arbitrary decisions based on philosophy not fact and may well change because of political or other considerations.

In conclusion let me quote from the National Council (NCRP) Report No. 43 on Radiation Protection Philosophy. "The indications of a significant dose rate influence on radiation effects would make completely inappropriate the current practice of summing of doses at all levels of dose and dose rate in the form of total person-rem for purposes of calculating risks to the population on the basis of extrapolation of risk estimates derived from data at high doses and dose rates. . . . The NCRP wishes to caution governmental policy-making agencies of the unreasonableness of interpreting or assuming "upper limit" estimates of carcinogenic risks at low radiation levels, derived by linear extrapolation from data obtained at high doses and dose rates, as actual risks, and of basing unduly restrictive policies on such an interpretation or assumption. Undue concern, as well as carelessness with regard to radiation hazards, is considered detrimental to the public interest." Would that all legislators and regulators would pay heed to these words!

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APPENDIX D

EUROPEAN APPROACHES TO TRAINING CHEMISTS FOR NUCLEAR ACTIVITIES

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1. INTRODUCTION

The Austrian psychologist and Nobel Prize winner Konrad Lorenz has pointed out that, like animals, humans have a strong "Revier Instinkt" ("territorial instinct"), i.e., we always tend to strongly defend our own territory. Nuclear chemistry is such a Revier, and we can see a threat against it by anti-nuclear forces in society. However, this meeting has not been arranged only to defend this territory, but rather because of a general concern about the present trends in the whole nuclear field, not only in nuclear chemistry but also in nuclear medicine and other applications of nuclear science. Nuclear science has given great contributions to the society, and there are still large benefits to reap.

Many of us here matured during the decades after World War II, when nuclear science attracted the best young brains in the country, when every university gave courses in nuclear chemistry, when new elements were synthesized almost every year, when the nuclear submarine N/S Nautilus cruise under the North Pole was hailed as a bold venture, when nuclear power plants were considered the height of technology with a promise of unlimited and cheap electric energy.

Two events broke this "nuclear elation": the Vietnam war and the associated student revolution in 1968, and the energy crisis in 1973. Looking back we remember an earlier beginning of an anti-nuclear movement. Rachel Carson wrote "Silent Spring" in 1962. The shadow of the atomic bombs over Japan was never possible to shake off. Yet, one ought to remember that already in 1940 the two French scientists, J. Perrin and F. Joliot, obtained patents on a nuclear power reactor as well as a nuclear bomb. Thus, even without the U.S. Manhattan Project we would have had these things—but the world might have been different today!

During the last 10-20 years we have seen a decreasing interest among students in taking courses in nuclear chemistry, and a decreasing interest among university faculties in continuing to teach nuclear chemistry and in replacing retiring professors in nuclear chemistry. The reason for this is certainly multifold.

Nuclear chemistry per se no longer offers great intellectual challenges: we know so much about the nucleus, the nuclear reactions and decay modes, the chemistry of the heavy elements, etc., that whatever more there is to learn seems to be of limited interest. For the student, the "freshness" or "charisma" of the field is gone. There are also so many new challenging areas like biochemistry and solid state chemistry, not to mention that environmental research is highly in vogue. Last but not least, the word "nuclear" has achieved a bad taste, among students as well as the public; this is a product of the anti-nuclear movement.

This report describes **nuclear chemistry teaching in some European countries**. It not only reports present teaching, and especially conditions for professorships in nuclear chemistry, but also tries to analyze how the situation has developed as well as to suggest some actions to improve conditions in the future.

This subject has been treated before (to various extents). In 1966 the Council of Europe (Strasbourg) made a survey of the resources in nuclear chemistry, which is now being up-dated by an IUPAC committee headed by Professor J. P. Adloff in Strasbourg. You certainly also remember that in 1969 this Society reviewed the status of nuclear chemistry in the U.S. The latter report contains much material, which still is topical.

In 1980 the International Atomic Energy Agency (IAEA) in Vienna published a report on "Manpower development for nuclear power," in which, however, the academic situation was not well covered. On the suggestion by Professor G. Choppin and myself, they appointed a new committee to study the academic resources. The outcome of this was another IAEA report, "Engineering and Science Education for Nuclear Power," published in 1986. Unfortunately, even this report avoided the question of the university manpower situation. Instead it focused on the skills required to assure safety and reliability of nuclear power programs, and on providing undergraduate and graduate programs (especially for the developing countries) at engineering schools and in health physics.*

2. WHAT IS NUCLEAR CHEMISTRY?

In judging the resources for education in nuclear science, it is necessary to offer some definition of the fields of interest. It is not a question of semantics if we call these fields **nuclear chemistry** or **radiochemistry**, or **nuclear medicine** or **health physics**, and so on, but a matter of understanding what we are really talking about.

Nuclear chemistry can be defined—or better, described—in many ways, some of which are illustrated in Figure 1: its relation to other fields of science, its connection to other areas of chemistry, and its content in technical terms. A more detailed description can be found in subsequent Sections. Figure 1 does not indicate areas of application, which are dealt with in Section 7. In my presentation I shall use the term **nuclear chemistry**, meaning **nuclear and radiochemistry** in the sense of Figure 1.

3. FORMALIZED NUCLEAR EDUCATION (ACADEMIC CURRICULUM)

Formal nuclear courses are given as a part of the undergraduate or graduate curriculum at:

(1) (Classical) Universities in the Schools of Physics, Chemistry, Medicine
(2) Technological Universities** in the Schools of Mechanical Engineering, Electrical Engineering, Chemical Engineering, Nuclear Engineering
(3) Special Government Schools.

*The IAEA report contains "National Experiences in Engineering and Science Education for Nuclear Power" of the following countries: Argentina, Brazil, Czechoslovakia, France, Federal Republic of Germany, India, Republic of Korea, Spain, Sweden, United States of America, and Yugoslavia.
** These schools have various names; see the Appendix to this paper.

Here and in the following sections the reader should consult the Appendix to this paper for an explanation of the academic system and terminology; the terms used here may sometimes differ from customary U.S. terms.

3.1 Nuclear Chemistry Curriculum at (Classical) Universities

European universities require on the average 3-4 years of full-time studies for a B.S. degree after the high school diploma. A M.S. degree requires 4-5 years, about 75% of which is spent on formal courses and the rest on diploma work. An additional 4-5 years is required for a Ph.D. degree, of which about 25% may be spent on formal (advanced) courses.

The nuclear chemistry courses offered by universities in Europe differ considerably in name, content, and size. Some will be presented under respective countries (Section 8). In general one can say that they emphasize either the analytical, biomedical, or nuclear energy aspects.

Université de Paris XI (Orsay) offers a very comprehensive course in nuclear chemistry, which is summarized below (see Table 1 for details):

Basic course: Radioelements-Radiations-Radiochemistry

Ch. 1 Radioelements-Radiations-Radiochemistry
- -- Radioactivity
- -- Radiochemistry
- -- Radioelements
- -- Health physics

Ch. 2 Radiation, Detection and Production of Radionuclides
- -- Interaction of radiation with matter
- -- Detection of nuclear radiations
- -- Production of radionuclides

Ch. 3 Data Acquisition and Data Treatment
- -- Introduction
- -- Analysis of α, β, γ, and x-ray spectra
- -- Introduction to automatic treatment in spectrometry
- -- Data treatment in neutron activation

Special course:

Ch. 1 Nuclear Analytical Methods
- -- Methods based on nuclear radiations (gauges, etc.)
- -- Misc. methods (activation, x-ray fluorescence)

Ch. 2 Radiochemistry and Isotope Chemistry
- -- Chemistry and methodology at tracer scale
- -- Analysis based on mixture of isotopes
- -- Radioactive sources
- -- Isotope effects and separation of isotopes

Ch. 3 Actinides
- -- Generalities (chemical systematics, electronic structure, etc.)
- -- Thermodynamic properties and kinetics in solution
- -- Spectroscopic properties of actinides
- -- Magnetic properties of actinides

Ch. 4 Radioelements and Radiations In Other Fields
- -- Hot atom chemistry and chemical effects of ionizing radiation
- -- Biological behavior of radioelements and health physics
- -- Production of radionuclides and labelled compounds
- -- Chemical aspects of the nuclear fuel cycle
- -- Radwaste and radioelements in the geosphere

In 1987 sixteen students took this course. This course will be further commented upon in Section 8.1.

At some universities the students are free to elect the courses they feel are needed, although some courses may have an entrance examination or other prerequisites. Many of these courses are open to and taken by students majoring in other fields (geology, archeology, medicine, etc.).

3.2 Nuclear Chemistry Curriculum at Technological Universities

An undergraduate student in chemical engineering needs 4-5 years to complete all courses and the diploma work (Master's Thesis) in order to become an accredited M.S. Chemical Engineer. For the doctor's degree (D. Techn.) an additional 4-5 years are needed, of which 1 year may be spent on compulsory courses.

The IAEA Report 266 gives typical undergraduate and graduate curricula at universities with nuclear-oriented engineering schools and health physics programs.

The following example is taken from a typical 4.5-year undergraduate program in chemical engineering.* It comprises 3,700 lecture and laboratory hours (about 40 hours/week for 2 x 16 weeks per year); these hours do not include homework or diploma work (4-6 months). The undergraduate program contains 150 hours (1/3 exercises, 1/3 laboratory) of "Nuclear Chemistry and Radiation Protection" and 120 hours (1/2 exercises) of "Nuclear Power Plant Engineering." The content of the former course follows closely the text by Choppin and Rydberg, see Tables 11 and 12.

The postgraduate compulsory chemical engineering curriculum comprises courses amounting to about 1,000 hours (1 year). It contains the following nuclear oriented courses:

- -- Reactor theory and control (120 hours)
- -- Nuclear chemistry and radiochemistry (150 hours)
- -- Radiological protection and environmental effects (80 hours)
- -- Water chemistry (50 hours)
- -- Solvent extraction chemistry (100 hours)
- -- Work science (hazards) in chemical process industry (50 hours)
- -- Introduction to the nuclear fuel cycle (60 hours)
- -- Radioactive waste management (80 hours)

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* See IAEA Report 266. The program is believed to be representative for most chemical engineering schools.

In these courses, except for the first one, the students are taught by nuclear chemists.

The postgraduate courses emphasize the responsibility of nuclear chemists for a safe nuclear energy program. They also illustrate the usefulness of the special knowledge acquired by nuclear chemical engineers for other fields of chemistry (water chemistry, solvent extraction). Of particular importance, recently often pointed out, is the transfer of the experience of nuclear chemical engineers in work safety (radiochemical hazards, glove box work, remote control, etc.) to other fields of chemistry.

3.3 Special Government Schools

Some countries (France, U.K., West Germany) have large national nuclear energy research centers. The researchers at these centers usually collaborate with those of neighboring universities, providing an important teaching and research resource for the university, which often has chronic funding problems. Courses may be given at the research center, at a special school (see France, Section 8.1), or at the university by teachers accredited by the university but employed either by the research center or the university. These courses carry full university credit. The student may wish to later become employed by the research center—thus filling its manpower needs, or by the university, or industry. The joint courses so arranged are both basic and applied, and cover various areas like physics, chemistry, medicine, and technology; such collaboration will be discussed for each nation covered in Section 8.

4. EXTRAMURAL (NONACADEMIC) NUCLEAR EDUCATION

Extramural (nonacademic) nuclear education is usually "profit based", i.e., it is not free or heavily subsidized as at national laboratories or state universities. Such education is provided by the Reactor Schools for training reactor operators, the expenses of the student being paid to the school by the nuclear power industry. These courses include nuclear power operations, nuclear safety, regulations, leadership, and on-the-job training. They may also include basic nuclear chemistry (the atomic nucleus, radioactive decay, etc.), health physics, waste handling, and so on, for shift operators and technical personnel. The teachers may or may not be academically trained, and the courses carry no university credit (although the industry sometimes asks for that). These courses are mentioned here not only for completeness, but also because they are in competition with some university courses. Also, they may lead to a kind of inbreeding without insight.

The industry regularly needs to reeducate its own personnel. This can be done by sending personnel to the university teaching institutions or by providing intramural courses. It is the author's opinion that it is particularly unwise for the industry to provide all intramural (by themselves) reeducation.

On-the-job training in the industry is often combined with the type of courses mentioned above. It is not of particular interest for this presentation.

5. HEALTH PHYSICS

The picture will be incomplete unless a few words are said about teaching health physics. Knowledge in this subject is needed wherever man is confronted with large sources of radiation, especially at nuclear power plants and at hospitals. Health physics at the university may be given by the School of Physics, School of Chemistry, or School of Medicine (all cases exist). The IAEA Report 266 gives a detailed 4-year program of undergraduate (about 4,000 hours) courses in health physics, as well as 2-year postgraduate courses. While the IAEA courses (some also given by IAEA) focus on nuclear power plant problems, the university courses usually focus on hospital demands. Thus the latter courses, some being compulsory, are taken by medical students. Many non-medical students taking these courses get employed by the hospitals. In Sweden many students in nuclear chemistry supplement their education with health physics courses; they have become employed both by hospitals and in the nuclear industry, in the latter case becoming responsible for plant safety, waste handling, etc.

In Sweden the Institutes of Health Physics at the universities also provide courses at several levels for nurses specializing in that area.

It is interesting to note that most curricula in health physics do not include—or require—any chemical knowledge, although much of the nuclear hazard is related to the transportation in the environment of radioactive chemical compounds. This has been somewhat remedied in the IAEA course mentioned above. It may be worth considering introducing chemistry (nuclear chemistry) into all health physics courses.

6. ACCREDITATION OF FORMAL NUCLEAR EDUCATION

At the Vienna meetings leading to IAEA Report 266, the safe operation of nuclear power plants was the main concern. It was discovered that in many countries no formal education was required for the plant Head Manager or for the responsible Health Officer, who were the only two who had (independent) authority to shut down the plant in case of emergency. It was pointed out that in some countries (the U.S.?) the responsible Health Officer had to be an accredited health physicist, but that this was not so in other countries (e.g., Sweden). The working group at the meeting found it surprising that the authorities granted the industry permission to operate a nuclear power plant, with no requirement for any formal education for the Head Manager or Health Officer.

Special accreditation for nuclear power plant managers and Health Officers may be worth considering; of this, nuclear chemistry should be an integral part.

7. APPLICATIONS OF NUCLEAR CHEMISTRY

Fundamental research, carried out for pure scientific curiosity, would probably not be funded by society if it did not believe that it would pay off in the future. Does anyone remember an important scientific discovery that has not had any application? It is worth remembering the words in the will of Alfred Nobel, ". . . to those who have made mankind the greatest benefit." Nuclear chemistry will be judged by the benefits of its applications. These are many. A few are summarized below.

When we look at areas of application of nuclear chemistry, and employment for the nuclear chemist, it is practical to make a distinction between (i) what chemists can do in nuclear activities and (ii) what nuclear chemists can do in other disciplines. In this connection it is important to remember that nuclear chemists are basically chemists.

7.1 Chemists in Nuclear Activities

The "nuclear activities" can be divided into four main groups, dealing with nuclear physics, nuclear energy, the production of radiochemicals, and the use of radiation and radioisotopes in hospitals.

7.1.1 Nuclear Physics

- target chemistry (e.g., preparation, separation)
- excitation functions (e.g., reaction paths, yields)
- decay schemes (e.g., correlation to structure)

7.1.2 Nuclear Energy

Front-end fuel cycle:

- uranium production (refining, waste handling)
- isotope separation
- fuel element fabrication (including MOX)

Reactor operation:

- reactor chemistry (radiolysis, water purification [before and on-line], radioactive leaks [aqueous, gaseous], filtering)
- reactor accident studies (source term, aerosol transport)
- decontamination and decommissioning

Back-end fuel cycle:

- spent fuel handling
- reprocessing (decanning, separation, process waste, analysis)
- waste handling
- waste storage (technology, risk analysis, materials testing, ecology, public relations)
- research on improvements of the nuclear fuel cycle

Radiological protection:

- radionuclide analysis
- handling large amounts of radionuclides ("health chemistry")
- radiobiology

7.1.3 Production of Radiochemicals

- accelerator and reactor technology
- target chemistry
- labelling
- radiochemical purity
- radioactive self-destruction of labelled compounds
- production of milking pairs

7.1.4 Hospitals (closely related to Section 7.1.3 and 7.2)

- o understanding production of radionuclides
- o handling large radionuclide sources
- o handling milking pairs
- o diagnostic uses
- o sophisticated scanning techniques (gamma and positron tomography)
- o radioimmunoassay
- o therapeutic uses (large doses) of radionuclides
- o dose calculations

7.2 Nuclear Chemists in Life Sciences (closely related to Sections 7.1.3 and 7.1.4)

- o cyclotron production of short-lived nuclides
- o rapid labelling
- o non-carrier techniques
- o automatization of synthesis
- o tracer kinetics in vivo
- o tracer work with ^{3}T, ^{14}C, etc.
- o radiation chemistry (for understanding radiation biology)
- o studies of metabolic rates
- o analytical chemistry of environmental samples (in soil, water and air)
- o (Maybe one should add "understanding man's world", because of the information about this planet and the universe obtained from nuclear and radiochemical research.)

7.3 Nuclear Chemists in Chemistry

- o Analysis
  - -- elementary: activation (neutron, proton; prompt, delayed; instrumental, etc.)
  - -- molecular: isotope dilution labelling, tracing
- o Chemical reactions
  - -- tracers in inorganic, organic, biochemical, etc. equilibrium constants, kinetics
  - -- separations yield determinations (isotopic exchange)
  - -- hyperfine interactions (chemical environment effects as Mössbauer spectroscopy, isomeric transitions, intensity of conversion electrons, etc.)
  - -- positronium chemistry
  - -- hot atom chemistry (extreme valency states)
- o Radiation chemistry
  - -- materials treatment
  - -- food sterilization
- o Chemical industry
  - -- chemical tracers, physical tracers
  - -- gauges for level, thickness, etc.

7.4 Nuclear Chemistry in Other Disciplines

- o Dating research
  - -- archeology (usually now at specialized labs)
  - -- geology
  - -- mineral prospecting
- o Environmental research and control -- use of sensitive radiotracer and radioanalytical techniques

7.5 Employment of Nuclear Chemists

The following areas can be discerned:

- teachers at universities
- experts at authorities (federal, state, county), Radiation protection; Nuclear Inspectorate; Ministries (Health, Energy, Environment); Defense
- nuclear power plants (see above for responsibilities)
- nuclear fuel cycle (see above for responsibilities)
- mining industry (geological research)

Experience in the U.K. indicates that those graduating in nuclear chemistry have been employed in (i) hospitals and medical research, (ii) the industry, (iii) analytical applications and dating, (iv) environmental studies and radiological protection (most rapidly growing in the U.K.), and (v) a small number of universities.

A study in Sweden of students graduating in nuclear chemistry gives the following fields of employment: university and hospitals (28), nuclear industry (11), authorities (control) (10), nuclear consulting (6), patent offices (4), and non-nuclear industry (8). It should be noted that the selection of these persons was through "friends-to-friends" information and does not represent a good statistical selection.

A more comprehensive study is presented in Table 2, which shows how nuclear chemists compete in the nuclear energy field with other academically trained groups.

8. NATIONAL PROGRAMS FOR NUCLEAR CHEMISTRY EDUCATION

Three events have formed the nuclear science of today: the discovery of natural radioactivity in 1896-1898, the discovery of artificial radioactivity in 1934, and the discovery of fission and n-producing chain reactions in 1939-42. Chemists were deeply involved in all of these events.

The early pioneers of radioactivity established world famous laboratories for research in nuclear chemistry: the Curies and Joliots in Paris, Rutherford and his collaborators in Cambridge, Hahn and collaborators in Berlin, and Niels Bohr and co-workers in Copenhagen, to mention a few. Other locations for early work were Strasbourg, Vienna, Rome, Oslo, Uppsala, Berkeley, Montreal, etc. Although the discovery of artificial radioactivity opened up a completely new field for the nuclear chemists, it was not until nuclear energy became a reality that nuclear chemistry was introduced as a subject into the undergraduate curriculum at universities.

This paper will not present the history of teaching nuclear chemistry. It will only deal with the present situation, and only for a few selected countries. These countries have been chosen partly because of easily available information, and partly because they form a representative pattern of "extremes" in the nuclear energy policy field. Table 3 provides some statistics about these countries: population density, GNP, electric energy consumption per capita, nuclear energy production, etc.

8.1 France

Teaching in nuclear chemistry is conducted at (i) the universities, (ii) the National Institute of Nuclear Science and Technology, and (iii) the National School of Arts and Crafts.

The latter only offers evening courses for technicians. The presentation below will only deal with (i) and (ii). Because France is somewhat unique in the nuclear field, it is suitable to begin with a short presentation of the French nuclear policy and public attitude.

8.1.1 Nuclear Energy in France

France is the most nuclear energy intensive country in the world, 70% of its electricity being produced by nuclear power (see Table 3). It is also the only non-communist country with a complete fuel cycle: mining uranium ores in the Massif Central (though most is purchased from former French colonies), uranium purification plants, isotope separation plants (gaseous diffusion and ultracentrifugation; solvent extraction is being given up, while laser separation is being developed), gas-cooled reactors for weapons production at Marcoule and about 50 PWR reactors for energy production, the (international) Super-Phoenix 1 power-producing (1,200 MWe) breeder reactor at Creys-Malville, reprocessing (Marcoule and La Hague), production of MOX (4% Pu) and breeder (15%-25% in core) fuel elements, waste handling (2 vitrification plants for high-level waste), and final deposition techniques are being vigorously developed. The program, run by the Commissariat a l'Energie Atomique (CEA) through a number of subsidiary companies, includes development of nuclear weapons. About 9,000 people work in the fuel cycle. The CEA functions as an independent Government ministry, sorting directly under the Prime Minister.

On the educational side, the French have developed their own programs, without much glancing at other countries. It is interesting to study the background of this development.

8.1.2 Public Attitude Towards Nuclear Energy*

In order to understand the public attitude towards nuclear energy in France, one must try to grasp the French national character. The French are very individualistic and critical, and rapid to rise emotionally to defend an important cause. Still they easily follow a "good" leader and neglect misconduct ("humans are humans"). The French Revolution changed an authoritarian regime into a democracy (though not overnight), and the student revolution, most intense in Paris, split the powerful 800-year-old Paris university into 13 less powerful (semi-independent) universities; it also gave students considerable power (there is a reverse tendency at the present). Still, France is a very centralized society, and the French have great respect for authority. Politicians are highly regarded in France. The French admire their great men of the past—military leaders, politicians, artists, and scientists—even though they constantly debate them. This "contradictory character" has an important effect on the nuclear energy policy.

*The author's personal opinion.

In this connection three names are mentioned with deepest respect: Curie, Joliot, and de Gaulle. Marie Curie spent the later part of her life working for peace and the poor. Her discoveries were used in the treatment of the sick and disabled. Paris University VI is named Université- Pierre et Marie Curie. Institut Curie runs research, the most famous cancer hospital in France, etc. To people, "radioactivity and radiation"— Marie Curie's "discoveries"—are something good. Every weekday, school classes, and individuals of every class, come to the Laboratoire Curie to see Marie Curie's laboratory, handwritings, photos, and Nobel Prizes. Irène Curie (daughter to Pierre and Marie) received the Nobel Prize in chemistry (together with her husband Frederic Joliot) in 1935 and became the first Minister of Scientific Research in 1937. Frederic Joliot worked during the war for the underground movement and joined the communist party. After the war he became responsible for reorganizing French science and was head of the Atomic Energy Commission. He and Irène strongly supported nuclear energy but were against nuclear weapons. They are still highly regarded, especially by the young. De Gaulle is the founder of the Fifth Republic. He rebuilt France from the ruins after the war and restored self-confidence in the French people. He told the French only to trust themselves. Thus they had to have a strong defense ("military" has always been respectable in France), including nuclear weapons (Force de Frappe). In this he was supported by the communist party and Joliot.

As a consequence of this, the French public favors both nuclear energy and a nuclear weapons program. All political parties support this policy. Nevertheless, there is a small anti-nuclear group in France, which seems to get more publicity than public support. (One may ask if this is a "Dreyfus-syndrome", a continuation of the classical struggle in France between the military and the press.) The anti-nuclear group refers to the pro-nuclears as "electro-fascists".

The Chernobyl accident took the French people by surprise. It is claimed that the nuclear authorities tried to hide the fall-out over France. As experts, we know that the fall-out was small, less than 1% of the fall-out over Sweden. Nevertheless, the French seem more upset than the Swedes are. The news media appear to make efforts to worry people. Recent polls indicate that people now regard the large number of nuclear power plants in France (at 19 places) with increasing suspicion. For example, the plant at Nogent-sur-Seine, located 60 miles (100 km) up River Seine from Paris, would seriously menace the drinking water of Paris in case of an accident.

In conclusion, while the French are for nuclear energy by tradition, their support is likely to weaken in the future. On the question "Shall we continue to build nuclear power plants?" 58% of the people voted "No" (and 37% "Yes"), according to a recent poll by the L'Express. To this picture one has to add the pressure from abroad. The French nuclear power plants at Gravelines, Choose, Cattenom, and Fessenheim are not only localized at highly industrialized parts of Europe, where there is a great demand for electricity, but they are also located at the border to Belgium, Luxembourg, and West Germany, causing great opposition in these countries. This opposition seems to be spreading to France.

8.1.3 University Organization

Higher education in France is conducted at the universities and technological institutes (Grand Ecole). The educational system is illustrated in Figure 2 (the example for Orsay can differ slightly). For comparison with the U.S. system, see Figures 3 and 4. After a high school diploma (Baccalauréat) 2 years lead to a Diplôme d'Etudes Universitaire General (DEUG), Diplôme d'Etudes Universitaire de Science et Technique (DEUST, for science students), or Diplôme Universitaire Technique (DUT, for technicians; for this group there are higher possibilites, BTS). After DEUG further studies lead, after 2 years, to a Master's degree (Maîtrises) or to Diplôme d'Etudes Approfondis (DEA, "diploma allowing advanced studies"), the latter compulsory for graduate students who want to obtain a Ph.D.; the graduate studies are 4-5 years (the 2-3 years shown in Figure 2 do not hold in practice). The French refer to this scheme as "1:e cycle" (to DEUG), "2:eme cycle" (to maîtrise) and "3:eme cycle" (graduate work). On most levels there are exit points for special professions. In 1985/6, at the Université d'Orsay the number of applicants in chemistry was 199 for DEUG and 105 for DEA.

The engineering education (Formations ingenieurs) is formally 5 years but in practice about 6 years. This is considered a good education and jobs are "guaranteed". A Ph.D. is considered equally qualified (but after about 8 years!).

8.1.4 Universities Teaching Nuclear Chemistry

Nuclear chemistry is taught at 9 universities (3 of which are in Paris) and at the CEA organization, INSTN. Research in nuclear chemistry is carried out by the universities, the CEA, and at IN2P3. Table 4 summarizes the status of these laboratories, excluding CEA. Although all universities can grant a Ph.D. degree, only the universities in Table 4 can grant the Ph.D. in nuclear chemistry; all DEA courses are compulsory for those registering for DEA. The courses at Orsay are indicated in Tables 5 (general survey) and 1 (course content).

The full Orsay DEA course is quite comprehensive. The title of the main course is "Radioéléments-Rayonnements-Radiochimie". It is given by the Institut de Physique Nucléaire (IPN) at Orsay. A few years ago a similar course was offered by M. Lefort, who formally was Professor of Nuclear Chemistry at Orsay. At his retirement, no new professor was appointed in nuclear chemistry; instead R. Guillaumont was appointed Professor of Chemistry with the responsibility to teach nuclear chemistry. This is further commented on in Section 10.2.

Student interest in nuclear courses is decreasing. Also employment is difficult, at the present, because of the closing of the solvent extraction isotope separation plant, freeing about 250 chemists; during 1987, only one new chemist was hired by CEA. However, in coming years retirees must be replaced, and the outlook for getting a job within CEA will improve. It is believed that this situation may lead to a demand exceeding available manpower.

8.1.5 Institut National des Sciences et Techniques Nucleaires (INSTN)

In the 1950s the French authorities decided to develop nuclear power on the bases of CO_2 cooled graphite reactors (Magnox). Many years later it was decided to switch over to a Westinghouse PWR type as being more economical. In this situation a demand developed for engineers and scientists knowledgeable in the new system. Because this demand could not be met by the universities, a special school was created in 1956 by the CEA at Saclay (Paris): INSTN. The institute sorts under a committee with representatives of the Ministry of Research and Technology, the Ministry of Education, the CEA, and private industry (the chairman is the Rector of the Academy of Paris). Teachers are recruited from the universities, from industry, and from CEA. Also, foreign students are admitted. INSTN is integrated into the Saclay Nuclear Research Center, which offers research resources.

The INSTN has large resources for education: 6-8 lecture halls for 30-50 students (total capacity: 300 students); a large number of student laboratories for mechanics, electronics, chemistry, biomedicine, and computer science; a large reactor simulator, and a 100-kW research reactor.

Courses are of two kinds: (i) Special courses, "Sessions d'etudes", which are for people from industry (e.g., Electricité de France) and hospitals who pay for the course, covering a large number of subjects related to the nuclear industry (metal corrosion, radiation protection, biological uses of radioisotopes, etc.), and (ii) formal university teaching courses, "Ensignements," in nuclear science and technology for the DEA and DESS degrees (Figure 2). INSTN is trying to be "all-covering" in nuclear education, although this seems to be opposed by some universities. For example, a medical doctor who intends to use radioisotopes has to take comprehensive courses at INSTN; no such teaching is offered by the hospitals or universities. Each year about 300 students take courses in radiochemistry; however, for some types of students, the course is short, only 3-6 hours, whereas it is much more comprehensive, e.g., for chemical engineers. In 1987, the number of DEA students in nuclear chemistry amounted to 15-20.

The INSTN feels that it covers the whole French demand for nuclear education. They claim that their courses are always full (15-20 students per course, except for about 50 for computer science). The number of applicants to the courses in nuclear chemistry has increased 20% this year.

8.1.6 Nuclear Research and Education Outside Universities and CEA

The Centre National de Recherches Scientifique (CNRS) is the largest research organization in France, with over 30,000 employed. It sorts under the Ministry of Education and deals only with fundamental research. They can autonomously open or close their own laboratories. A subdivision is the Institut National de Physique Nucleaire et de Physique des Particules ("IN2P3"), which employes about 500 scientists, of which 45 work at the Laboratoire de Chimie Nucleaire in Strasbourg (Professor J.P. Adloff). The CNRS employees have no teaching responsibilities. However, many of the laboratories collaborate with a local university, e.g. in Strasbourg with the Université Louis Pasteur, and there offer some teaching, mostly on the graduate level.

8.2 The Federal Republic of Germany

See Table 3 for some statistical data related to nuclear energy.

8.2.1 Background

The Federal Republic of Germany has large indigenous (brown and hard) coal resources but little water power. Most of the electricity is produced from coal, while about 30% comes from nuclear fuels. Nuclear industry is private. The present large unemployment among coal miners hampers the expansion of nuclear energy. The anti-nuclear movement is led by the Greens (though split into fundamentalists and realists, the latter "may accept" existing nuclear plants), which have about 7% of the votes. "Teachers and women" are said to favor the Greens.

Two large research centers, at Julich (KFA) and Karlsruhe (KFZ), provide most of the R & D needed for the nuclear energy program: this comprises use of MOX fuel, development of a high-temperature gas-cooled thorium-fueled graphite reactor (THTR 300 at Hamm), breeder reactors (SN 300 at Kalkar; collaboration on the French Super-Phoenix), reprocessing (to be built at Wackersdorf), and waste storage (Asse, Konrad, Gorleben). As in other countries, the nuclear research centers move away from nuclear energy to energy in general and to environmental research.

Several federal ministries are engaged in nuclear energy:

o the Federal Ministry of Research and Technology (BMFT)
o the Federal Ministry of Interior (safety)
o the Federal Ministry of Environment (BMU).

The ministries only fund large research projects.

The individual state governments are responsible for schools and universities. The universities are fairly independent and differ considerably between the 10 states (Ländern). The funding from the Landesregierung is limited and is not enough for research. Small-scale funding mainly comes from the National Research Council (Deutsche Forschungsgemeinschaft).

8.2.2 Universities Teaching Nuclear Chemistry

Some universities still have "chairs", while others only have "professorships". There are 3 ranks of professors: C4 professor (full), C3 professor (associate), and C2 professor (assistant). All professors are appointed by the minister of cultural affairs of the Landesregierung, and all receive a budget. A C4 professor cannot be replaced by a C3 or C2, or vice versa, by pure university decision. Vacant positions are publicly advertised. The number of applicants may be 20-30; applicants from other universities are preferred. During the 1960s, C2 professors were appointed without a selection procedure. Figure 5 shows the FRG educational system. Four years are required to obtain a Diploma degree. Diploma work in nuclear chemistry can only be carried out at universities that have a chair in the subject. Below, TU refers to Technical University; all faculty are C4 or C3/C2 (marked*) professors in nuclear and/or radiochemistry, except as specified.

- Aachen (TU), E. Merz (Nuclear Technology)
- Berlin (Freie Universität), G. Marx*
- Bonn (University), Aumann (at Department of Physical Chemistry)
- Cologne (University), G. Stöcklin (Director of Nuclear Chemistry at Julich, Professor at Cologne University)
- Darmstadt (TU), K. H. Lieser, H. Munzel*, K. Bächmann* (Inorganic and Nuclear Chemistry; Lieser soon retiring, uncertain replacement)
- Hamburg (University), A. Knöchel*
- Karlsruhe (TU),H.-J. Aache (Analytical Chemistry; head of Institute of Radiochemistry at KFZ Karlsruhe)
- Mainz (Univ.), G. Herrmann, J. Kratz, O. Denschlag*, N. Kaffrell*
- Marburg, R. Brandt*, Patzelt*
- Munich (TU), F. Baumgätner, Heusinger*, F. Lux*, J. Kim* (Institute of Radiochemistry)
- Saarbrucken (vacant, uncertain replacement)

Several factors make the future of nuclear chemistry in the FRG dim: there is no expansion of nuclear energy, nuclear chemistry is not needed by the industry any more, and the subject is not considered very important by colleagues.

8.2.3 Johannes Gutenberg Universität Mainz

The School of Chemistry includes rather large Institutes: Inorganic and Analytical, Nuclear, Organic, Physical Chemistry, Biochemistry and Pharmacy. The Institute für Kernchemie has about 80 people, 4 professors (see above), 8 research group leaders, and about 25 graduate students. The experimental resources are very good and include a 100-kW Triga reactor (pulsed to 250 MW). The adjoining Institute of Nuclear Physics has a 300-MeV electron LINAC.

Nuclear chemistry is taught at the 200 level. Annually 13 different courses are offered for one semester of 13 weeks:

<u>For chemistry students</u>:

Kernchemie I (3 hours/week, 13 weeks/semester, 2 semesters; 30 students per year)

- o Weshalb Kernchemie (Why nuclear chemistry?)
- o Radioactivity
- o The nucleus
- o Spontaneous transformations
- o Induced transformations
- o Nuclear models
- o Nuclear processes in geology and astrophysics

Kernchemisches Practikum I, Ferienkurs (2 full weeks; 100 students)
Kernchemisches Practikum II (4 full weeks)

<u>For non-chemistry students</u>:

Lectures in nuclear chemistry for science teachers (3 hours/week)
    Experimental course for d:o (2 full weeks)
Lectures in nuclear chemistry for physicists (2 hours/week)
    Experimental course for d:o (1 hour/week)
6 Advanced courses: Nuclear reactions with heavy ions (2 hours/week)
    Selected topics (1 hour/week every 2nd week)
    Seminars in nuclear and cosmochemistry (d:o)

Seminars by research groups of the Institute (d:o)
Reactor practicum (1 full week)
Seminars (preparations) for Ph.D. works

The research activities are directed into the following areas: production and structure of short-lived nuclei, heavy ion reactions, fission yields, superheavy elements, laser spectroscopy of actinides, and detection of very small amounts of actinides in nature. Close collaboration with GSI in Darmstadt (see Section 8.2.7).

8.2.4 Universität zu Köln (University of Cologne)

After the retirement a few years ago of Professor W. Herr as the head of the Institute of Nuclear Chemistry, no C4 professor has been formally appointed. However, there is now an Abteilung Nuklearchemie (Nuklearchemie = Kernchemie + Radiochimie) at the Institute of Biochemistry with Professor G. Stöcklin as scientific leader; at the same time he is head of the Institut für Nuclearchemie at the large Kernforschungsanlage (KFA) Julich. Thus the "Abteilung (Department) Nuklearchemie" has 1 C4 professor "on leave of absence to KEA Julich," 1 senior staff member, 2 technicians, and several graduate students. While the research interests during the time of Professor Herr were much directed towards isotopes and radiation applications in geo- and cosmochemistry, and radiation effects on materials, the interest is now directed towards nuclear chemistry applications in the life sciences field.

The Nuklearchemie postgraduate option leading to Diploma (1 year after a B.S.), or Dissertation, contains the following courses:

- o Basic lectures (2 hours/week for 2 semesters)
- o Special lectures (for nuclear chemistry majors)
  Chemistry of the radioelements (1 hour/week, 1 semester)
  Chemical aspects of nuclear energy technology (1 hour/week, 1 semester)
  Radionuclide techniques applied to chemistry and life sciences (1 hour/week, 1 semester)
- o Experimental course in radiochemistry (full time for 1 semester; see Table 6 for content)
- o Experimental course in radiochemistry for advanced students (for nuclear chemistry majors) (full time for 2 weeks)
- o Tutorial exercises (seminars)

The number of students taking these courses is shown in Table 7. The numbers for Cologne are said to be rather stable and seem to be independent of political fluctuations.

8.2.5 Universität Karlsruhe

The Institute of Radiochemistry is headed by Professor H.-J. Ache. It is an integral part of the large Kernforschungszentrum (KFZ) Karlsruhe. The research is directed towards analytical uses of nuclear techniques, and areas of importance for KFZ. The following program is offered for the M.S. or Ph.D. in the course on Instrumental Analysis and Radiochemistry:

- o Introduction to nuclear chemistry (2 hours/week, 1 semester for undergraduate and graduate studies; about 35 students/year)

- o Special topics (1 hour/week, 2 semesters), e.g., chemistry of nuclear fuel cycle, transuranium elements, radioisotopes in life sciences, etc.
- o Introductory laboratory course (3 full weeks; offered 4 times per year)
- o Advanced laboratory course in instrumental analysis (3 or 6 full weeks; offered twice a year)
- o Lectures in instrumental analysis (2 hours/week, 1 semester; for undergraduate and graduate students)
- o Colloquium in instrumental analysis and radiochemistry (1.5 hours/week, each semester).

8.2.6 Technische Universität München

The Institut für Radiochemie der Technischen Universität München at Garching is headed by Professor F. Baumgärtner with the assistance of Professors Heusinger, Lux, and Kim. The Institute is affiliated with the faculty of chemistry, biology, and geosciences and is responsible for research and teaching in radiochemistry, nuclear, and radiation chemistry. It offers Master's (Diploma) and Ph.D. degrees for students in chemistry and physics. The doctorate work requires, on the average, three years after the completion of the diploma courses, altogether 5-6 years. Each year 3-4 students finish their dissertation work.

In the course Instrumental Analysis of Elements and Chemical Structure (one semester with lectures and practicum), which is compulsory for all chemistry students, nuclear methods of analysis and analysis of nuclear materials are included (2 weeks). Over 70 students take this course each semester.

Special (elected) courses are offered to advanced students of chemistry and physics. The teaching comprises a wide variety of subjects:

- Introduction to Nuclear Chemistry and Radiochemistry
- Introduction to Radiation Chemistry
- Chemistry of Nuclear Fuel Cycle
- Chemical Reactions of Ionizing Radiations
- Chemistry of Radionuclides in Nature
- Chemistry of Actinides
- Nuclear Methods of Radiation Detection
- Technical Chemistry of Nuclear Waste Treatment
- Nuclear Methods of Analysis
- Modern Instrumental Analysis: Element and Surface Analysis

Four subjects are in cycle in each semester. There are 15-20 students attending each course. Depending on the subjects chosen, the chemistry student may add a radiochemistry laboratory course; there are three different kinds of basic training in handling radioactivity. Each practicum lasts 2-4 weeks, with subsequent completion of a written report. On the average, 40 students per year take these practical courses.

The institute members are composed of 4 professors, 1 of whom is chairman and director (F. Baumgärtner), 1 academic manager, 3 guest lecturers, about 35 scientific staff members, about 30 technical personnel, and about 10 other supporting personnel.

The major research areas of the institute are:

- Aerosol generation in nuclear technical processes
- Thermodynamics and spectroscopy of actinides
- Solution chemistry of TRU-elements in natural aquatic systems
- Tritium and iodine chemistry in nature
- Radiation chemistry in solid and liquid phases
- Modern spectroscopic methods of analysis
- Chemical speciation and detection of trace elements in nuclear technology, high purity science, and environmental science.

The institute has extensive research facilities:

- 3 hot cells; α-tight, up to 1,000 Ci activity
- Co-source: 70 kCi
- Irradiation facilities at the reactor (4 MW power)
- α–laboratories with over 30 glove boxes
- β–γ–laboratories
- 4 separate counting rooms with 20 different α, β, γ spectrometers
- Modern instrumentation: SEM-EDX, TEM-EDX, AES, XPS, SIMS, HPIC, HPLC, TC-Analyzer, ICP-AES (2 x), MS-GC, ESR, IR/UV-Spec. (6x).

8.2.7 Darmstadt: Technische Hochschule and GSI

The head of the Institute of Inorganic and Nuclear Chemistry at the TU is Professor K.H. Lieser. Teaching is by Professors Lieser, Munzel, and Bächmann. Annually 12 different courses are offered (hours/week during 13 week semester):

<u>For chemistry students</u>:

o Introduction to nuclear chemistry (3 hours/week)
o Practical course (1 full week, 10 times per year)
o Nuclear fuel cycle (2 hours/week)
o Radioanalytical chemistry (2 hours/week)
o Radiation chemistry (2 hours/week)

<u>For non-chemistry students</u>:

- Practical courses (1 full week, twice a year)
- Application of nuclear chemistry techniques (2 hours/week)

<u>Advanced courses</u>:

o Advanced practical course (4 full weeks, twice a year)
o 3 seminars on various topics (2 hours/week, twice a year)
o Seminars in inorganic and nuclear chemistry

The main topics of the practical courses are Radioactivity in Nature, Radioactive Decay, Nuclear Reactions, Applications in Analytical Chemistry, and Applications in Kinetics. The main topics of the advanced practical courses are Activity and Counting Rate, Measurement of Low-energy Beta-emitters, Low-level Radioactivity, Gamma Spectrometry, and Radiochemical Separations.

The research activities in nuclear chemistry are chemistry of radioelements, chemistry of radionuclides in the nuclear fuel cycle, chemistry of radionuclides in the hydrosphere and the geosphere, radioanalytical chemistry (mainly neutron activation analysis), tritium in nuclear fuel elements, corrosion of zirconium, low-level radioactivity in the environment, and measurement of small amounts of actinides in nature.

Darmstadt is the center for the Gesellschaft für Schwerionen Forschung (Society for Heavy Ion Research), the main instrument being the large heavy ion linear accelerator (UNILAC) by which several of the heaviest nuclides have been synthesized.

8.2.8 University of Freiburg

There is an Abteilung Radiochemie, headed by Professor Horst Muller, at the Institut für Anorganische und Analytische Chemie. Of the 80 or so students who take courses at the Institute, 20-30 take Radiochemie, 2 hours/week for 11 (summer) or 14 (winter) weeks. The courses are offered twice per 3 years. There is no experimental course.

8.3 The United Kingdom

Although the U.K. has a substantial nuclear power program (see Table 3) teaching in nuclear and radiochemistry is minimal (at least formally). This is because the subject is integrated in the "main topics" at the teacher's choice, i.e., chemistry of the radioelements in inorganic chemistry, isotope separation in statistical mechanics in physical (or theoretical) chemistry, etc. For example, research and some teaching in nuclear chemistry is conducted at the Department of Inorganic Chemistry (Professor A. Maddock) at Cambridge University. In general there are only four kinds of professors at the university: Physical, Organic, Inorganic, and Theoretical; there are no professors of Nuclear or Radiochemistry. At the Technical Universities (Colleges), courses are sometimes given in radiochemistry, commonly oriented towards applications in hospitals or industry. The Isotope School at the Atomic Energy Research Establishment (AERE) at Harwell is now closed. (A prominent professor of chemistry recently stated, "Nuclear chemistry in the U.K. is dead!")

Research is conducted at several places:

1) At the Scottish Universities Reactor Center in Glasgow about 20 scientists are involved in applied radiochemical problems.
2) The Imperial College Reactor Centre at Ascot has about 12 scientists mainly engaged in activation analysis, but the Nuclear Technology Group has disappeared.
3) The Manchester and 4) Salford Universities use both the Universities' Research Reactor at Risley and the Synchrotron at Daresbury Laboratory for nuclear and radiation chemistry research (5 people).
5) At the University of Wales at Cardiff a small group is engaged in nuclear waste studies (speciation, solubilities, etc.).

In addition to this should be pointed out the use of dating techniques at earth science departments, of radioanalytical techniques at environmental departments, and of radiotracer techniques at biochemical departments.

Outside the universities, radiochemical work is done at AERE laboratories at Harwell, Dounreay, Sellafield, etc., at the Ministry of Environment laboratories (waste studies), and at the National Radiological Protection Board Laboratory at Didcot.

The number of nuclear and radiochemistry scientists presently employed in the U.K. is estimated to be about 400. The teaching demand is estimated at 40-50 persons/annually, corresponding to an actual annual job demand for about 15 trained nuclear and radiochemists.

8.4 The Scandinavian Countries

The Scandinavian countries of Sweden, Finland, Norway, Denmark, and Iceland form a cultural and linguistic unity, if one includes the large Swedish-speaking population in Finland. They have a joint population of 23 million people.

They also form an interesting group from the energy resource viewpoint. Iceland (0.2 million people) has large geothermal and water power resources, and Norway (4.1 million people) large water power and oil resources. Thus neither needs nuclear energy. Sweden (8.4 million people) and Finland (4.8 million people) have large water power resources, although insufficient for their industry, and thus have a nuclear power industry. Denmark (5.2 million people) has no energy resources at all but has decided not to build any nuclear power plants, using instead imported coal or imported electricity.

8.4.1 Sweden

Nuclear power comprises 12 600- to 1,000-MW reactors (9 BWR, 3 PWR) located at 4 different sites, with a total installed power of 9.5 GW. This provides > 50% of Swedish electricity consumption. The electricity price is the lowest in the world next to those of Norway and Canada, about 0.30 SEK/kWh; about 0.02 SEK is reserved for a fund for covering all expenses of the back end of the nuclear fuel cycle. In 1980 it was decided by the Parliament, after a referendum, that nuclear energy should be phased out at the latest in the year 2010. It has not yet been decided what shall replace it. (SEK = Swedish equivalent crowns; 1 U.S. $ = 6 SEK.)

Sweden has five classical and five technological universities. Chairs in nuclear chemistry were established at the technological universities in Stockholm (KTH) and Göteborg (CTH) in 1962/63. A few years later a chair in nuclear chemistry and nuclear physics was established in Uppsala (though located at Studsvik, see below), and an associate professorship in nuclear chemistry at Stockholm University (now defunct). The chairs in nuclear-related subjects are now being critically reviewed, as the professors approach pension age. So far, it has only been decided to renew the chairs of reactor safety in Stockholm and nuclear chemistry in Gothenburg. At the time of writing it is believed that most of the chairs will be renewed, among them nuclear chemistry in Uppsala and at KTH in Stockholm. By 1989-91 a completely "new set" of nuclear professors will have taken over.

A complete picture of all nuclear teaching in Sweden is presented in Table 8. These courses are offered at the universities for teachers and researchers, at the technical universities for engineers, at the university hospitals for medical students and for nurses, and by nonacademic organizations for nuclear power plant operators and shift personnel.

There are presently only two full-scale conventional "Nuclear Chemistry Departments" (institutions) in Sweden: the technological universities in Stockholm (KTH; Professor T. Westermark) and Gothenburg (CTH; Professor J. Rydberg). These departments are described in Tables 9A and 9B. The courses are also open to students at the (classical) universities in Stockholm (SU) and Gothenburg (GU). The situation at Uppsala/Studsvik is special (see above and below).

Figure 6 illustrates the number of students taking nuclear chemistry in Gothenburg since 1964; these courses are all in the 3rd (GU) to 4th (CTH) year. The downward trend began at a time when criticism against nuclear energy became more intensive. The upward trend after 1980-82 could be explained by the start a few years earlier of a very small compulsory **Introduction to Nuclear Chemistry** course for the first-year students (6 hours in the Inorganic Chemistry lecture course). If this is the true explanation, then the qualification of the teacher giving this introduction course is of utmost importance (cf. Section 10)!

The Studsvik Energy Technology Center (former The Atomic Energy Co.) has shifted research activities away from nuclear energy towards energy problems in general. Still, the nuclear research resources are good, a 50 MW research reactor, VdG accelerator, etc. These are used by the National Neutron Research Laboratory (reorganized in 1986) and the Department of Neutron Research of the Uppsala University (Head of both: Professor G. Rudstam). The nuclear chemistry/physics group of the department comprises 4 senior scientists, 3 graduate students, and 3 technicians. The two laboratories have a total of 31 personnel. The nuclear chemistry research activities are directed towards high energy nuclear reactions using ISOLDE and OSIRIS separation and identification techniques. Research is also conducted on radiation chemistry. Teaching is in a state of organization.

8.4.2 Finland

About one-third of the electricity in Finland is produced by nuclear power. Two of the plants were built by the Swedish company ASEA-Atom (now ASEA-Brown-Bovery) and two are of Russian design (PWR-type with Finnish improvements). The public attitude towards nuclear energy seems to be a slight favoring of nuclear energy. However, expansion plans have been shelved.

The University of Helsinki has a Department of Radiochemistry. The number of graduate students is 10-15. Main research interests are in the field of applications in the life sciences and on nuclear waste disposal. The previous head, Professor J. Miettinen, is now retiring; the appointment procedure for his successor has commenced.

8.4.3 Norway

Norway has large domestic gas and oil resources (the North Sea and

Continental Shelf) and extensive water power. Plans have been made for introducing nuclear power, but it is not considered to be needed at the present. The electricity consumption per capita in Norway (15.6 MWh/cap) is the largest in the world, and also the cheapest; electricity is the main source of domestic heating. Nevertheless, there is a Department of Nuclear Chemistry at the Oslo University. Nuclear chemistry research was introduced in Norway in 1913 by Ellen Gleditsch (Professor in 1929), a student of Marie Curie. In 1950 Alexis Pappas became professor of nuclear chemistry, but was replaced (after retirement) in 1986 by J.O. Liljenzin.

Almost all chemistry at the university level in Norway is taught at Oslo University, as it is also for students majoring in other fields like medicine and veterinary medicine. Graduate studies leading to Cand. Mag. take 3.5 years, and to Cand. Sci. (or M.S. in Chemical Engineering), 5 years. The Dr. Scientist (Ph.D.) is obtained after >7 years. A higher degree is the Dr. Philosophy (about equal to Docent). Courses and the number of students are given below:

Level	Name of course	Course hours	Students
203	Environmental Chemistry	(6 h on radioactive and nuclear energy)	
250	Radiochemistry	3 lec, 15 ex (1 sem.) 75 lab	10
251	Nuclear Chemistry, Higher Course I (nuclear properties & spectroscopy)	20 lec, 10 ex (half sem.)	4
339	Solvent Extraction and Ion Exchange	30 lec	
355	Radioactivity and Nuclear Reactions, Higher Course II	32 lec, 15 ex (half sem.)	4
356	Radiation Hygiene (radiation properties, biological effects, protection)	15 lec, 15 ex	5
Nuclear chemistry for medical students (2 weeks)			150

A special course in radiotracer applications is given twice a year (3 full days plus examination); participants (maximum 8 per course) are from industry, hospitals, pharmacies, etc. Research activities are focused on nuclear structure, short-lived fission products, and applied aspects.

8.4.4 Denmark

Denmark lacks domestic energy resources. Electricity is produced in coal-fired plants or is imported. Domestic heating is achieved by oil, coal, or electricity. Although detailed plans have been made for introducing nuclear energy, public opinion seems to be strongly anti-nuclear. Political parties have requested that Sweden close down a nuclear plant that is located only 30 km (20 miles) from the capital, Copenhagen.

No formal teaching in nuclear chemistry occurs, but graduate work in nuclear chemistry can be carried out at the research station at Risö, where two research reactors are located.

8.5 Belgium

From Table 3 it can be seen that Belgium is a comparatively "nuclear power intensive" country. Historically Belgium was the world's largest uranium producer for decades, the uranium being mined in the Belgian Congo (now Zaire); the uranium ore was shipped to Belgium and purified at the Metallurgie Hoboken. Belgium has a large number of nuclear institutions, among them a reprocessing plant at Mol (Geel), which also is a center for nuclear waste research.

Although discussions have been carried out about a national center for nuclear education, presently nuclear chemistry is included as part of other university courses in chemistry (inorganic, analytical, etc.). Professor J. Hoste at the Institute for Nuclear Science at the Rijksuniversiteit te Ghent (Ghent State University) offers the following courses:

	Course	Hours
1.	Nuclear instrumentation and statistics	10
2.	Radioprotection	8
3.	Sources of elementary particles	10
4.	Structure and nuclear reactions	5
5.	Radiation chemistry	12
6.	Radiochemical analysis	5
7.	Activation analysis	8
8.	Analysis via prompt reaction products	4
9.	Separation methods	4
10.	Actinides	10
11.	Fission and fuel cycle	10
12.	Preparation of radioisotopes	10
13.	Dating, radiogeo- and cosmochemistry	10
14.	Computer applications and in the future	5
15.	Radiopharmacy and radioimmunoassay	
16.	Positron tomography	
17.	Environmental measurements	

The whole program amounts to about half a day per week over a whole year. At present there are 3-4 graduate students in nuclear chemistry. The main areas of interest are analytical and medical applications.

9. SUMMARY OF THE EUROPEAN SCENE

Nuclear chemistry (under various names) is being taught in 24 countries in Europe, almost exclusively on the graduate level. In general, the courses are rather similar, although the emphasis shifts somewhat. Institutes of Nuclear Chemistry exist only in countries with an extensive nuclear energy program, although not in all. These institutes are usually located on or close to a university campus, although they may not be funded by the university (Ministry of Education). Such funding is never enough to cover research; grants are obtained from research councils or industry.

There seems to be a trend away from "Professors of Nuclear Chemistry", partly due to the fact that "specialized chairs" are no longer established (see

Section 10.2). However, teaching is still conducted simply because there is a demand for formally trained nuclear chemists. Also, the students seem to continue to be reasonably attracted to graduate work in nuclear chemistry.

10. A STRATEGY FOR THE FUTURE*

10.1 Public Opinion on Nuclear Science and Technology

The public's opinion on nuclear energy is closely related to its confidence in the various institutions of society. In a poll carried out in a number of countries by the French news magazine L'Express, the public was asked in which institution (government, parliament, courts, police, army, church, school, news media, large companies, and small business groups) they had the highest confidence (for telling the truth, defending their rights, and opposing excess power). The replies were as follows (+ % confidence, - % distrust):

U.S.		France		W. Germany		U.K.		Spain	
Police	+76	School	+68	School	+65	Army	+63	School	+24
Supr.court	+73	Police	+45	Governm.	+61	Police	+60	Governm.	- 5
Army	+73	Governm.	+37	Police	+60	Business	+21	News media	- 5
....		......		......		......		......	
News media	+39	News media	- 1	News media	-18	News media	-22	Parliam.	-31

It is interesting to note that the institutions of physical power (Police, Army, and Court) are met with the highest confidence in the U.S., and also enjoy relatively high confidence in the other countries, but not in Spain. The schools receive very high confidence in all countries (+65% also in the U.S.); in Spain the schools are the only institution met with trust. The news media inspires low confidence in all countries except the U.S. (+39%). The Government is generally more believed than members of the Parliament, the relative figures for the latter being +67, +23, +28, +6 (U.K.) and -31, respectively. The great confidence in politicians in the U.S. is quite interesting, and the distrust in Spain perhaps understandable.

In a poll in Sweden in 1987, people were questioned: Which group do you think gives the most correct information on nuclear energy? The replies were 70% for scientists, 45% for environmental groups, 30% for the authorities and for the nuclear industry, and about 15% for journalists.

Several years ago an investigation in Sweden showed that people got their opinion on nuclear energy mainly from the news media. This is probably the same for all countries in Europe even today. Television, especially, has a large impact on public opinion. We thus see that the group that is least believed has the largest public influence. This may not be a surprise. The situation is typical for our democratic society. Maybe this situation first developed in the U.S.—Oscar Wilde said, "In America the President reigns, but the journalists have the power."

* The author's personal opinion.

Because the news media are—or, at least appear to be—opposed to nuclear power, the public becomes anti-nuclear. In a recent investigation in Sweden (J. Westerståhl and F. Johansson), 70%-80% of researchers at science faculties were found to be receptive to a continuation/expansion of nuclear energy, while at the same time the public believed that the majority of these scientists were against nuclear energy. The news media obviously deliver a false picture to the public. Why is it so? There may be two explanations:

1. An analysis of all news material presented by the Swedish press or TV on nuclear power just after the TMI-accident revealed that for "news decided by the media" (i.e., by the journalists), the anti-nuclear material dominated, while "news decided by the actor" (e.g., official statements, personal comments, etc.) mainly was pro-nuclear; taking both groups together, the anti-nuclear material strongly dominated. About 10 years ago it was said that 60% of the teachers at the Schools of Journalism in Sweden voted for the communist party, compared to only 4% for the whole population. Yet newspapers in Sweden are mainly "conservative" (political color of owner), while the State TV Monopoly is supposed to be non-political.

2. Even if the "news media" as such are not anti-nuclear, I believe they appear so to the public because of the larger amount of anti-nuclear material published. This may well be due to the intense activities of the anti-nuclear groups, through demonstrations, violent activities against nuclear installations, upsetting public statements, etc. This could well be part of a clever scheme of these groups, who know how to get public attention, because these demonstrations make excellent news on the TV screen*. Compare them with a lecture by a scientist on the benefits of nuclear energy!

Of course, the relation between the common man and the various institutions in the society differs among different countries as well as between individuals. Maybe there is no common national denominator. Nevertheless, I believe that there are three levels on which one should act to improve the image of nuclear science:

1) Most important is to provide factual information on nuclear energy to and by the schools. Especially, **science teachers at high schools must become better informed** on benefits as well as risks. This information must cover alternative energy sources.

2) **Nuclear science must be taught at the universities**, otherwise there will be neither any expertise to teach high school teachers nor any expertise to judge nuclear activities in surrounding countries. Further, of course, the societal value of nuclear science must be preserved (as described in Section 7).

3) **The proponents of nuclear science must become more public** and especially try to reach out to the journalists to provide them with factual information.

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* These groups may generally be termed anti-nuclear, because this is the common denominator, although they appear under a large number of names such as Friends of the Earth, Union of Concerned Scientists, Greenpeace, The Environmental Party, Save ET (for EveryThing), etc. They all modestly refer to themselves as only being concerned about saving the environment.

10.2 Professorships in Nuclear Chemistry

The break-through of nuclear power after World War II led to the establishment of chairs ("professorships") in nuclear science and technology at many universities in Europe. Some teaching in nuclear science became compulsory at most science universities.

This occurred almost 40 years ago, and in the last decade many of these early pioneers of nuclear chemistry have reached retirement age. The question of replacement of these chairs has become acute at a time when political groups (see footnote, previous page) in the society make big efforts to stop nuclear energy and related activities. As a consequence of this we see in some places a declining interest among students for taking nuclear courses. In many countries anti-nuclear groups have "infiltrated" the educational system, from ministries to faculties, leading to an "administrative" resistance both to continuing courses in nuclear science and replacing old "nuclear chairs."

A student elects a course for several reasons: to fill the study quota, either because it is easy (many points for little work), because of scientific curiosity, or because he believes he will need the knowledge in future research or a job, or because **the teacher has a good reputation**, or the course is prestigious, etc. In this connection it is important that the courses in nuclear chemistry be given by (preferably full) professors. One of our concerns today is that the number of full professors teaching nuclear chemistry is declining, which may lead to a reduced number of students taking nuclear chemistry courses, and—in the extension—cancellation of such courses. Therefore, the **renewal of professorships (chairs) in nuclear chemistry becomes an important issue from the viewpoint of attracting students to the field.**

A professor represents the highest rank in a university. As such he also still has a fairly high status in society. For the public he not only represents science ("the expert") but also—to a large extent—he is the most believable person ("the truth"), according to public polls. Thus, it is important to nuclear chemistry that the subject is represented by a professor both for internal (university) and for external (authorities, society in general) reasons.

Some years ago a poll was carried out in Sweden on the question, "What value is it to have a professorship in nuclear technology?" The reply is given in Table 10. The response to professors in nuclear chemistry is more than satisfactory. If we find it important to renew professorships in nuclear chemistry, we must analyze what the formal conditions for renewal are today, so that we can develop proper strategies.

10.2.1 The U.S. System

While the renewal procedure varies between the European countries from more "traditional" to more "radical", there seems to be a slow change towards a system similar to that in the United States.

Usually the U.S. universities have Schools of Chemistry. The all-academic Chemistry Faculty decides the number of professors of all ranks within the economic frame set by the university, and appoints (without appeal) a new Professor of Chemistry with no specialization indicated. The Faculty decides if and by whom nuclear chemistry courses shall be given. Faculty are free to abandon any course they decide should not be offered, due to the retirement of a teacher or for other reasons. The new professor is completely free to choose whatever research field he wants to pursue, because his research funding comes from resources outside the University.

10.2.2 The Traditional European System

On the recommendation of the Chemistry Faculty, the University suggested to the Ministry of Education that a new chair should be established in a specific subject, e.g., in nuclear chemistry. If the Ministry decided accordingly, which usually took 2-3 years, the chair was publicly announced as vacant with specified teaching and research responsibilities. A special evaluation committee (sometimes international) was then appointed to evaluate the applicants. On their advice, the Faculty recommended one person to become the holder of the chair, after which the Ministry decided. Time was given for complaints and—if necessary—reevaluations. This whole procedure usually took 1-2 years. This very formal system was favored in the Scandinavian countries, while in France the Faculty itself made the selection and appointment.

The appointment was for the holder's life-time (retirement age, 65-70 years), and the professor became head of a fairly independent Department or Institute (e.g., Department/Institute of Nuclear Chemistry). The professor had to teach and conduct research within the announced subject; some research funding was provided by the University. At retirement age the chair was "automatically" declared open for reappointment.

10.2.3 The New European System

The prewar university system survived in the non-communist countries until the student revolution in 1968. A number of changes have since then been made, both with regard to appointment procedure and to internal responsibilities. When a chair becomes vacant, the Faculty and University must indicate to the Ministry why they want to reestablish the chair in the same field in preference to other chemistry fields. In Sweden, this suggestion is sent out (by the Ministry) to Sector organizations, industry, etc. for comments (the Swedish "remittance" system). Then, on "the full picture," the Ministry makes its decision. If renewed, the open chair is announced publicly. The applicants are then evaluated by experts (as before), but the Faculty now has a "democratic selection committee" (at some universities), which includes laymen and representatives for the students and technical workers within the Faculty personnel.

10.2.4 Practical Consequences

Whereas in the U.S. the appointment of a professor to teach nuclear chemistry is an all intrafaculty affair, in many European countries, sector as well as nonacademic organizations (representatives for the community, industry, and even unions) now have their voice. The reestablishment of a chair is also more scrutinized by Faculty than before.

Thus (i) it will be easier to replace a chair after the retirement of a professor with an established reputation, because the faculty confidence in him is likely to be reflected in a confidence in the chair and a need for teaching the subject; (ii) in renewing the chair it is important to point out the societal value (i.e., value for environment, health, or industry), because groups with such interests have an influence on the renewal procedure; (iii) at universities where the election committee contains nonacademic people, it is important for the applicant to show societal and social qualities in addition to a good scientific reputation.

These are important changes from the traditional system, in which the only important qualities were scientific. These aspects, with due modification for national differences, must be remembered in strategies for renewal of professorships in nuclear chemistry.

10.3 Definition of "Nuclear Chemistry"

In the book "Radioactivité", published in 1910 and in a second edition in 1934, Marie Curie describes all physical and chemical studies related to the radioactive elements, including everything known about the nucleus. The term "radiochemistry" was introduced around 1935 in analogy to "photochemistry", but sometimes used with the meaning "radiation chemistry". In 1946 Irene Joliot-Curie published the book "La Chimie des Radioelements Naturels", while her successor, M. Haissinsky, in 1957 wrote the textbook "La Chimie Nucleair et ses Applications".

In 1935 Otto Hahn published the book "Applied Radiochemistry", but two years later when Frederick Joliot was appointed professor at College de France, he had his chair named "Chimie Nucleaire".

It may suffice to say that many of these books covered almost the same areas of knowledge, independent of whether it was labeled "radiochemistry" or "nuclear chemistry". In Table 12, contents of more recent texts in "nuclear chemistry" are presented; the contents are summarized in Table 11. In more recent books there seems to be a trend to include chemical aspects of nuclear power.

In a survey of the Nobel Prizes awarded to nuclear scientists, it is interesting to see that about one-half have gone to chemists (see Table 13). It may not be unfair to label these scientists as "nuclear chemists."

The purpose of this exercise is to show the fleeting use of the terms radiochemistry and nuclear chemistry.* Thus the field described in this paper may be labelled either.

10.4 Nuclear Chemistry: a Discipline or Specialty?

From discussions with European colleagues, there seem to be two opinions about the content and name of the field we have here discussed under the label nuclear

*The French and German languages have two words for nuclear (nucleaire et noyau, and nuklear und kern), which can be defined differently if desired.

chemistry. According to one school, "nuclear chemistry" and "radiochemistry" are two different areas, **nuclear chemistry** dealing with nuclear reactions and **radiochemistry** dealing with radioisotopes. **Isotope chemistry** and **radiation chemistry** are left outside, according to the proponents of this division, who usually label themselves "radiochemists". The "nuclear reaction chemists" (the only "true" nuclear chemists) seem to think the same: isotope chemistry and radiation chemistry are outside their field. If we look at the textbooks in nuclear chemistry, or radiochemistry, we find, however, that both isotope and radiation chemistry are often included.

One may state that each one of the areas mentioned is a specialty; as such they are part of larger subjects. This may lead to the following equivalences:

1. Isotope separation and effects is —Physical chemistry
2. Nuclear reaction chemistry is —Nuclear physics
3. Radiochemistry is —A technique
4. Actinide chemistry is —Inorganic chemistry
5. Radiation and hot atom chemistry is —Physical chemistry
6. Chemistry of nuclear fuel cycle is —Chemical engineering

In this manner, only radiochemistry survives as an independent subject, but is—as many of us certainly have heard from colleagues in other fields of chemistry—only a technique. The chance that a technique shall be able to survive as an independent discipline is small. It is more likely that the specialty will be swallowed up by a larger discipline—this has also occurred!

One can look at this from another point, stating that **the nuclear specialities together form a discipline in its own right**. I believe it is important—if we want to keep this as an independent Revier—that we include all the specialities, without regard for the name (see next Section). This can be supported—if one so wants—with reference both to Nobel Prize winners and to current textbooks.

10.5 The "Name Problem"

At the meeting in Munich in September 1987 arranged by IAEA on "Training requirements in modern aspects of radiochemistry", professors in nuclear and radiochemistry from seven countries briefly discussed the name of the field but could not reach an agreement on how to define it. Because the teaching and research activities partly overlapped each other, it was decided to refer to all the different subjects under the heading **Nuclear and Radiochemistry**.

One may question if there really is a "name problem"?

To the embarrassment of many of us, the world "nuclear" is being dropped even in its most positive connections: e.g., when nuclear magnetic resonance tomography now is being introduced in hospitals, it is referred to only as "magnetic resonance tomography". No doubt the word "nuclear" has obtained a bad sound, as has "atom," as shown by the recent newspaper headline "TT shipping company refuses to transport atomic wastes". This problem may be worth analyzing. Can "nuclear and radio-chemistry" be replaced by one single covering name without any stigma? Can a consensus be reached on this issue?

"Nuclear and radiochemistry" (suggested by G. Friedlander in 1955) is a conjunction of nuclear chemistry and radiochemistry. The term is difficult to explain to the layman, the student, and even sometimes to faculty. Nowadays "nuclear chemistry" and "radiochemistry" are used by many people to cover almost identical areas, in textbooks as well as for professorship chairs.

An indication of the name difficulty comes from the following example: the 1952 Nobel Prize in chemistry was awarded for "discoveries in the chemistry of the transuranium elements". This involved the synthesis of the elements through nuclear reactions, studies of their physical and chemical properties at trace concentrations, sometimes in solutions, which continually changed due to the intense radiation field from the actinides and fission products present. These studies were of essential importance to the practical use of nuclear energy, and all the various "areas" still engage "nuclear chemists" today. The content of the award work could probably best be covered by the term "nuclear and radiochemistry".

The interest in the field has changed with time: before World War II it focused on natural radioactivity and a beginning use of radiochemical tracers. Just after World War II interest focused on actinide elements, their nuclear synthesis and properties, and later on studies of yields and properties of nuclides produced through high-energy reactions, while at present interest is shifting away from nuclear reactions to applications for a sensitive analytical technique (NAA, IAR, PIXE, etc.), medical applications (radiopharmaceutical scanning, PET, etc.), and nuclear waste management. From the National Research Council's panel reports it is seen that the discipline now encompasses a high number of areas of considerable importance to society.

This shift in interest away from nuclear reactions ("nuclear chemistry") has led to the "nuclear" part in "nuclear and radiochemistry" being dropped, the name "radiochemistry" being retained for the university chair (professorship). Such a change of name (from nuclear chemistry to radiochemistry) has already occurred, e.g., at the universities in Paris (Orsay) and Cologne.

A change of the name of the chair/professorship/department/etc. from nuclear chemistry, or nuclear and radiochemistry, to only radiochemistry will have effects (for logical reasons) on the curricula offered. Thus nuclear structure and nuclear reactions will be de-emphasized while the production, properties, and use of radiochemicals get increasing attention. Isotope effects and separation may be excluded from the curriculum, but some of these aspects should be retained in dealing with the nuclear fuel cycle. Radiation health aspects become of greater importance, which may lead to an increased interest in the underlying radiation chemical effects.

Such changes will not be difficult to adjust to. Overall, the very fundamental aspects on radioactive decay, the interaction of radiation with matter, and its detection must be strongly emphasized so that the students graduating from the course have sufficient knowledge to safely, accurately, and successfully use radioisotopes and radiation in nuclear medicine, geochemistry, the nuclear fuel cycle, environmental studies, and other fields of importance to the society.

11. CONCLUDING REMARKS

This report has been written fairly rapidly and the material covers a large field. Only a few countries have been reviewed and those not very comprehensively. There may be errors or misunderstanding in the text. Further, the language has not been corrected. The author asks the reader to forgive him all these limitations. Also, many personal viewpoints are expressed, which serve as "explanations" to the present situation and as discussion background for possible actions.

It is hoped that the information shall be useful and shall further research and training in nuclear chemistry. The author thanks all colleagues who so kindly offered their time trying to explain the special conditions in their countries.

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Appendix
Explanation and Use of Terms

Although the academic hierarchy is ancient and well established, the terminology used to describe this varies extensively between countries, often leading to considerable confusion in international discussions of these matters. Thus in this Appendix an attempt is made to explain some of these terms and their common international translations in an hierarchical order to simplify understanding; the boldface words are those which are primarily used in that sense in the main text, even if this does not always agree with U.S. custom.

(Federal) **Government**	Headed by a President or Prime Minister.
(Federal) Department	Executive division of Federal Government, headed by a **Minister** (Bundes-Minister), or Secretary.
Ministry	Same as above, e.g., Ministry of Education; may have separate organizations for Basic (Primary and Secondary) Schools, High Schools (Gymnasium) and University; the Head of all Universities is called **University Chancellor.**
University (classical)	Higher teaching organization (private, state, or federal) incl. humanities and natural science, headed by a **Rector**, President, etc.
Technological University	Higher teaching organization in the technical field. Other terms are Inst. of Engineering, Inst. of Technology, Technische Hochschule, Institut Polytechnique, Grand Ecole, Engineering Univ., etc.
Faculty	A subdivision of a University; e.g., Faculty of Sociology, Faculty of Science, Faculty of Engineering; Faculty is headed by a **Chairman** or Dean; Faculty may be subdivided into **Schools** (Departments, Institutes, Abteilung, etc.), e.g., School of Physics, School of Chemistry, etc.
School	Subdivision of Faculty, e.g., School of Chemistry, headed by a **Dean** (Rector, etc.); School may be subdivided into Institutions (Departments, etc.) of individual subjects as, e.g., Analytical Chemistry, Molecular Physics, Nuclear Chemistry, and Reactor Engineering.
Institute	Smallest academic subdivision dealing with a specialized field; sometimes called Department.
Department	Sometimes used for Institute; term to be avoided because of risk of misconception.

Professor	University teacher of highest rank, usually requiring a degree of Ph.D. or D.Sci. **Associate Professor** (Lecturer, Maitre, Docent, etc.) is a slightly lower university teaching rank. **Assistant professor** is a professor of lowest rank; may not have a Ph.D. and may not be head of an Institute (Department).
Professorship	The office (Institute, Department) headed by a professor; also called **Chair**.
B.S.	**Bachelor of Sciences** (or B.A., **Bachelor of** Arts), lowest academic degree, requiring 3-4 years of undergraduate studies. The French **Baccalaureat** means High School Diploma.
M.S.	**Master of Science**, usually requiring a B.S. + 1 more year, includes a **Master's Thesis**. At Eng. Univ. an engineering degree (Diploma) is awarded, e.g., M.S. Chem. Eng.
Diploma	Corresponds to Master's degree.
Ph.D.	**Doctor of Philosphy**. Highest academic degree at classical university. Requires 4-5 years of graduate studies (after a B.S.), incl. a Ph.D. **Thesis**, which is publicly defended.
D.Sci.	(i) Equivalent to above at science school of classical univ., or at techn. univ. (ii) At some univ. a degree granted to a Ph.D. after additional (commonly >5 years) scientific work; equivalent to (honorary—awarded without any requirements for teaching)* Docent.
D.Techn.	**Doctor of Technology**; equiv. to Ph.D. at a techn. univ.
Dozent, Docent	See D.Sci. At some univ. an academic teacher (must have Ph.D. or equiv.).
Lecturer	An academic teacher (Maitre), usually just below professor in rank (equiv. to associate professor).
Semester	In Germany, 12-13 weeks; in Sweden, 2 x 7 weeks + 2 x 1 weeks for examination.

National Research Foundations (NRF)	These are "sector organizations", i.e., they support research and development (R&D) only within a certain sector. Therefore they also sort under different Ministries. A typical example is the following (not related to any special country): fundamental research sorts under Ministry of Education, industrial research under Ministry of Industry, nuclear research either under Ministry of Industry, or of Energy, or of Defence, biological and medical research under Ministry of Health (and Welfare), environmental/pollution research under Ministry of Environment, etc.

TABLE 1 DEA "RADIOELEMENTS - RADIATIONS - RADIOCHEMISTRY"

Paris - Orsay

Chairman : Prof. R. GUILLAUMONT

Duration	Course
	Basic course
4 weeks	weekly : lectures 6h exercices 6h practicum 1 day
	Special courses
9 weeks	weekly : lectures + exercices 9 - 12h practicum 1 day
13 weeks	Training in Laboratory and Conferences

submission of report

DEA 3R (BASIC COURSE : three chapters) - Chapter one

I - RADIOACTIVITY, RADIOCHEMISTRY, RADIOELEMENTS

1. Radioactivity
   1.1. Time-dependent properties (decay modes, decay probabilities, statistics, growth and decay)
   1.2. Time-independent properties (spherical and deformed nuclei, laws of conservation, decay schemes, nuclear systematics)

2. Radiochemistry
   2.1. Weighable and non-weighable amounts of radioactive matter
   2.2. Principles of radiochemical methods

3. Radioelements
   3.1. Natural and artificial radioelements
   3.2. Nuclear and chemical characteristics of radioelements

4. Health physics

DEA 3R (BASIC COURSE) - Chapter two

II - RADIATION, DETECTION and PRODUCTION OF RADIONUCLIDES

1. Interaction of radiation with matter
   - 1.1. Slowing down of charged particles (electrons, particles, heavy ions, energy loss, range, use of Tables)
   - 1.2. Absorption of photons (main processes, role of Z and E)
   - 1.3. Slowing down of neutrons (collision theory, log energy decrement, diffusion length)

2. Detection of nuclear radiations
   - 2.1. General principles of radiation detection
   - 2.2. Types of detectors (ionization detectors, scintillators, semiconductors, neutron detectors)
   - 2.3. Choice and response of detectors for α, β, γ spectroscopy
   - 2.4. Measurement procedure (efficiency, signal analysis)

3. Production of radionuclides
   - 3.1. Cross section, reaction threshold, activation
   - 3.2. Nuclear reactions via compound nucleus (induced by neutrons and charged particles ; cross section of compound nucleus formation)
   - 3.3. Principles types of accelerators and reactors

DEA 3R (BASIC COURSE) - Chapter three

III - DATA ACQUISITION AND DATA TREATMENT

1. Introduction (utilization of MCA ; calibration channel/energy ; identification of radioelements ; background correction)

2. Analysis of α, β, γ and X spectra (deconvolution of complex spectra, resolution, efficiency calibration, correction terms : window, self-absorption, sum peaks, interference peaks, solid angle, detection limit.

3. Introduction to automatic treatment in spectrometry (peak search, background subtraction, separation of multiplets, qualitative and quantitative analysis)

4. Data treatement in neutron activation (constant or time-dependent flux, cross section and fission yields calculation)
   Exercices on microcomputers (simulation)

<u>DEA 3R</u> (SPECIAL COURSE : 4 Chapters) - Chapter one

A) <u>NUCLEAR ANALYTICAL METHODS</u>

I. <u>Methods based on nuclear radiations</u>

1. General considerations on analytical methods
2. Use of radioactive sources (applications of gauges, of positrons)

II. <u>Miscellaneous methods</u>

1. X-ray fluorescence (X-ray tubes, synchrotron radiation, PIXE)
2. Activation (neutrons, charged particles)
3. Backscattering
4. Direct observation of nuclear reactions and resonance reactions

<u>DEA 3R</u> (SPECIAL COURSE) - Chapter two

B) <u>RADIOCHEMISTRY AND ISOTOPE CHEMISTRY</u>

I. <u>Chemistry and methodology at tracer scale</u>

1. Qualitative and quantitative radiochemical methods (autoradiography, migration and separation techniques)
2. Qualitative and quantitative identification
   - 2.1. Qualitative (aqueous/solid and solid/solid systems, distribution between phases, reaction kinetics)
   - 2.2. Quantitative (chromatography, electrophoresis, applications : control of radioactive solutions, speciation)
3. Radiochemical separations (chromatography, solvent extraction, distillation, speciation)
4. Analytical radiochemistry (control and calibration, reaction kinetics, labelling and isotope dilution, distribution coefficient, successive extractions)

II. <u>Analysis based on mixture of isotopes</u>

1. Analytical techniques using mixture of isotopes (labelling, dilution, isotopic mixtures)
2. Procedure (homogeneization, valence cycle, chemical equilibrium, filiation)

Chapter two (continued)

III. Radioactive sources

1. Source characteristics (α, β, γ, n)
2. Preparation of sources (direct deposit, electrodeposition, electrospraying, vacuum deposit
3. Choice of techniques vs objective

IV. Isotope effects and separation of isotopes

1. Isotope effects (differences in physical and chemical properties of isotopic compounds, origin of isotope effects, use of enriched compounds)
2. Definition of separation work, SWU (application to uranium, role in separation procedure)
3. Non-statistical procedures for isotope enrichment : laser chemistry (number of stages ; procedure with atoms and molecules)
4. Statistical procedures for isotope enrichment (chemical exchange reactions, ultracentrifugation, gaseous diffusion)

DEA 3R (SPECIAL COURSE) - Chapter three

C) ACTINIDES

I. Generalities

1. The actinide elements (position in the periodic chart, main isotopes in weighable amounts and availability, oxydation state and ions)
2. Systematic chemical properties (atomic properties, elements, halides and oxihalides, oxides, behaviour in aqueous solutions)
3. Electronic properties (configuration, terms and state in various symetries)
4. Delocalization of f electrons (metals, semi-metallic compounds, ionic compounds, molecular units)

II. Thermodynamic properties and kinetics in solution

1. Thermodynamics

1.1. Homogeneous aqueous phases (ions in aq.solution : thermodynamic and structural data, redox potentials and electrochemistry : intensity/potential curves and radiopolarography ; hydrolysis and complexation : inorganic ligands, cations, organic ligands ; Eh/pH diagrams)

1.2. Distribution between two phases (precipitation : oxalates, fluorides, peroxides, carbonate ; liquid-liquid extraction ; extraction chromatography, ion exchange resins, application to chemical separation)

2. Kinetics

2.1. General considerations (redox reactions of actinides)

2.2. Reactions between ions of a same element (excluding isotope exchange)
(disproportionation of M(IV), M(V), M(VI) ;
M(III) + M(VI) = M(IV) + M(V)

2.3. Reactions between ions of different elements

2.4. Reactions with ionic reagents : cations, anions

2.5. Reactions with other reagents : H_2O_2, NO_x, N_2H_2, NH_2OH...

III. Spectroscopic properties of actinides

1. Recording optical and magnetic-optical spectra (ff, fd and charge transfer spectra ; experimental methods : absorption, emission, Zeeman, MCD, data analysis)
2. Systematics of absorption spectra (actinides in various oxidation states ; comparison solid state and solution ; comparison with 4f ions)
3. Spectroscopic parameters (naked ions, determination of F_k, ϕ and B_q ; trends of these parameters).
4. Optical properties and analytical methods at low concentrations (fluorescence, thermal lensing, photoacoustic spectroscopy, multiphoton excitation)

IV. Magnetic properties of actinides

1. Experimental methods (problems specific to actinides : purity, radioactivity ; magnetic phenomena : magnetic susceptibility ; neutron diffraction ; Mössbauer : hyperfine interactions, application to ^{237}Np)
2. Results and interpretation (localized or/and itinerant magnetism, metals, alloys and semi-metallic compounds, ionic compounds)
3. Outlook

DEA 3R (SPECIAL COURSE) - Chapter four

D) RADIOELEMENTS AND RADIATIONS IN OTHER FIELDS

I. HOT ATOM CHEMISTRY AND CHEMICAL EFFECTS OF IONIZING RADIATIONS

1. Hot atom chemistry (recoil energy, effect on ionization, types of recoil, positonium and applications)
2. Chemical effects of ionizing radiations
   - 2.1. Experimental techniques (sources ; G ; dosimetry ; sample preparation, analysis of chemical changes)
   - 2.2. Experimental results (γ - irradiated water and aqueous solutions)
   - 2.3. Interpretation (indirect effect, solvated electron, molecular product)
   - 2.4. Determination of radicalar and molecular yields
   - 2.5. Properties of radiolytic free radicals from water (thermodynamic and kinetic)
   - 2.6. Influence of various parameters on γ radiolysis of aq. solutions (solute concentration, dose rate, type and energy of radiation)
   - 2.7. Radiolysis of transuranium elements in water
   - 2.8. Radiolysis of solvents other than water
   - 2.9. Radiolysis in solid state (ionic crystals, graphites, polymers)
   - 2.10. Relation with other fields (electrochemistry, kinetic, organic and inorganic chemistry, radiobiology, biogenesis, technology)

Chapter four (continued)

II. BIOLOGICAL BEHAVIOUR OF RADIOELEMENTS AND HEALTH PHYSICS

1. Methodology (metabolism, transfer coefficient, dose, dose commitment, relation dose/effect, annual incorporation limit)
2. Group ^3H, ^{14}C, labelled molecules
3. Group fission products and activation
4. Group α emitters - actinides

III. PRODUCTION OF RADIONUCLIDES AND LABELLED COMPOUNDS

1. Production of radionuclides (reactor, accelerator, separation of fission products)
2. Radionuclides generators
3. Preparation of labelled molecules (total and partial synthesis, isotope exchange, labelling with heteroatom)

IV. CHEMICAL ASPECTS OF THE NUCLEAR FUEL CYCLE

1. Fuel cycle of electronuclear reactors (reactor systems, nuclear fuels ; fuel cycle : open and closed cycles ; important stages in the cycle with emphasis on the chemical aspects)
2. Survey of a few chemical engineering steps in the fuel cycle
   - 2.1. Liquid-liquid extraction (principles, successive equilibria, co-current and counter-current ; MaC Cabe and Thiele diagrams, practical procedure)
   - 2.2. Distillation (liquid-vapour equilibrium, flash distillation, columns)
   - 2.3. Chromatography on ion-exchange resins (properties of resins, column separation)

3. Ore processing and production of concentrate
   3.1. Treatment of ores (U rich and U poor ores, leaching or dissolution : sulf. acid, carbonate
   3.2. Treatment of the uraniferous solutions (liquid-liquid extraction : tertiary amines, TBP ; ion exchange resins; recovery of U from phosphates)
   3.3. Obtention of the yellow cake
4. Purification of U and conversion to metal or to UF_6
   (purification of yellow cake, conversion to UF_4, conversion $UF_4 \longrightarrow UF_6$; obtention of U metal)
5. Elaboration of nuclear fuels for electronuclear reactors
   NUGG : uranium based alloys
   PWR : conversion $UF_6 \longrightarrow UO_2$; mixed fuels (U, Pu) O_2
   FBR : mixed fuels (U, Pu) ; core, blanket
6. Fuel reprocessing
   Objective, principles, Purex process, elaboration of end products : U and PuO_2
   Recycling HNO_3 and solvent
7. Treatment of effluents and wastes
   Effluents : vitrification for high specific activity
   Solid wastes : incineration, aqueous decontamination
8. Extended reprocessing
   Separation of α emitters and FP ; separation actinides lanthanides

IV. RADWASTES AND RADIOELEMENTS IN THE GEOSPHERE
1. Wastes
   Origin and radiochemical composition ; classification vs storage ; methods of incorporation : concrete, bitumen, polymers, glasses
2. Migration
   Leaching ; K_d-R_d ; species encountered in various media ; Eh-pH diagrams, carbonates, natural organic acids, colloids
3. Storage sites
   Surface storage, geological storage, sea-bed, subsea-bed

TABLE 2 UNIVERSITY TRAINED PEOPLE IN SWEDISH NUCLEAR SCIENCE AND INDUSTRY

	Number	Ann. Replac.	TPh	M	E	Ch
1. Nuclear manuf. industry[a]	300	15-30	30	30	20	20
2. Nuclear power companies[b]	260	<10	30	30	25	20
3. Nuclear research centers	80	5-10				
4. Authorities[c]	70	5-15	27	27	27	19

a) About 6,000 employees. No uranium production, isotope separation or reprocessing.
b) About 4,000 employees.
c) Nuclear Power Inspectorate, Radiation Protection Inst., etc.
Sixteen (16) organizations were questioned, representing >10,000 employees. Figures to right refer to relative importance of education (in percentage) in technical physics and in mechanical, electrical and chemical engineering for each group of replies to questionnaire. Sweden's population is 8 million. Figures estimated for 1986. See Sect. 8.4.1 and Table 3.

TABLE 3 STATISTICS (1987) ON NUCLEAR ENERGY IN SOME COUNTRIES

	U.S.	France	F.R.G.	U.K.	Belgium	Sweden
Population, M	235	55	62	56	10.0	8.4
Pop. dens., M/km^2	26	100	250	230	320	19
G.N.P. (1982), k$/pers.	13.1	10.0	10.7	8.5	8.6	11.9
Elec. energy prod., MWh/pers.	12	6.3	6.5	6.0	5.5	15.6
Installed nuclear power, GW	100.3	46.7	18.9	12.8	5.5	9.7
Nucl. energy prod., MWh/pers.	1.8	4.4	1.9	0.4	3.7	7.7
Percent nuclear electricity	16.6	69.8	29.4	18.4	66.9	50.3
Reactors in operation	109	49	21	38	7	12
Reactors under construct.	13	14	4	5	(1)	0
Reactors per M population	0.46	0.9	0.34	0.68	0.7	1.4

TABLE 4 POPULATION OF RADIOCHEMICAL LABORATORIES (OUTSIDE CEA): (STATUS JANUARY 1987)

Laboratory	Researchers (CNRS)	Academic staff	Technical staff	Research students
Bordeaux	6	3	5	3
Orsay	7	5	3.5	4
Nice	-	7	1	3
Vitry	1	-	3	3
Lyon	4	4	4.5	8
Saclay (P. Sue)	1	-	10	2
Paris Lab Curie	4	1	2.5	-
Orléans	4	3	18	4
Strasbourg	5	4	13	10
TOTAL	32	27	60.5	37

TABLE 5 UNIVERSITY CURRICULUM

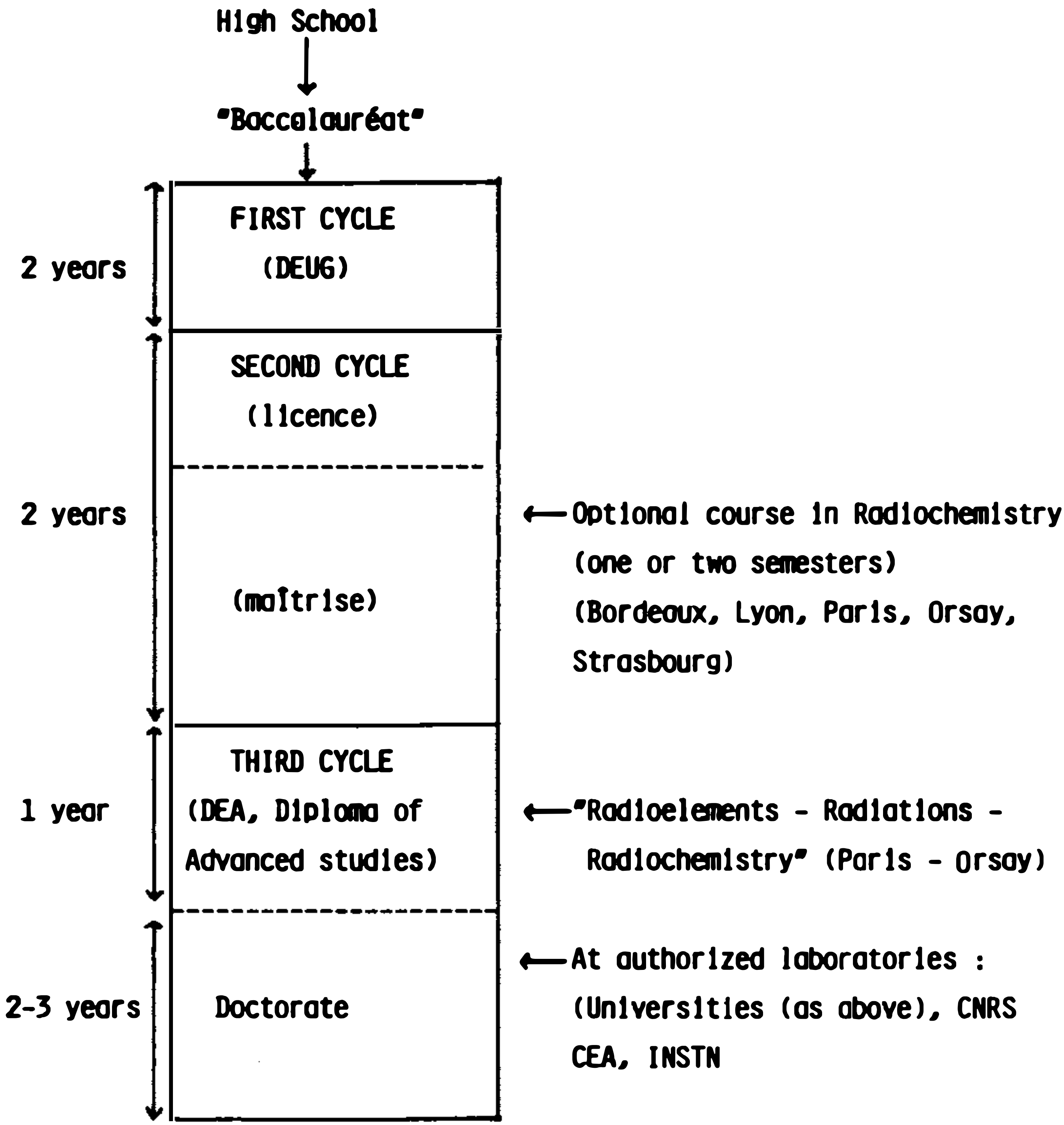

TABLE 6 EXPERIMENTAL COURSE IN RADIOCHEMISTRY

Physics	– Radioactive decay – Statistics – Radiation detection – Spectroscopy
Chemistry	– Activation analysis – Isotope dilution analysis – Extraction – Ion exchange – Chromatographic separation – Isotope exchange – Szilard-Chalmers separation
Exercises:	enlarge and complete studies by accompanying lectures and courses.
Tutorial exercises:	students review a scientific problem, give a lecture on this topic and put it in writing.
Book used:	Herforth, L. and Koch, H., Praktikum der Radioaktivität und der Radiochemie, Deutscher Verlag der Wissenschaften, Berlin.

TABLE 7 STATISTICS OF STUDENTS IN NUCLEAR CHEMISTRY

University	Cologne Class. Univ.	Gothenburg Techn. Univ.	Gothenburg Class. Univ.
All students	50,000	3,900	20,000***
Undergrad. chem. students	1,165	410*	305**
Grad. chem. students	206	130	100
Grad. students taking nucl. chem. courses		21	4
Grad. students in nucl. chem.	20	5	4
Nucl. chem. dissertations/year	2 - 3	1 - 2	

*Students at all levels; 4.5 years to obtain Master's of Chem. Eng.; 4 years minimum to obtain Ph.D. in Chem. Eng. (D.Tech.) at Chalmers University of Technology or Ph.D. (Chemistry) at University of Gothenburg
**Formally 3 (normally 4) years to obtain a B.Sc.
***1,930 students at the Mat. National Science Faculty

TABLE 8A NUCLEAR AND RADIATION TEACHING IN SWEDEN AT ALL ACADEMIC CENTERS (Number of students given within parenthesis)

A.1. STOCKHOLM

1. Stockholm University (SU)
   School of Physics (incl. nuclear physics*)
   Dept. of Radiation Physics (6 in 1987)
   " Radiobiology (28 in 1987)
   " Oncology (14 in 1987)
   (Nuclear Chemistry taught at KTH)
2. Royal Institute of Technology (KTH)
   Reactor Physics
   " Materials
   " Technology
   " Safety
   Nuclear Chemistry (13 people in 1987, includes SU students)

A.2. GÖTEBORG (GOTHENBURG)

1. Gothenburg University (GU)
   School of Physics (incl. nuclear physics)
   Dept. of Radiation Physics (9 in 1984)
   (Nuclear chemistry taught at CTH)
2. Chalmers University of Technology
   Reactor Physics (14 people in 1987)
   " Technology (3 people in 1987)
   Nuclear Chemistry (23 people in 1987; also for GU students)

A.3. UPPSALA

1. Uppsala University
   School of Physics (incl. nuclear physics*)
   Dept. of Neutron Research; professor located at and also Head of the National Neutron Research Laboratory at Studsvik Energy Research Center; in total about 30 people; in nuclear chemistry/physics about 10 people; recently formal courses.
2. Gustaf Werner Institute
   (Accelerator and radiation research center, with nuclear physics, nuclear chemistry, radiation biology, etc.; employs several nuclear chemists, but no teaching)

A.4. LUND

1. University of Lund
   School of Physics (incl. nuclear physics*)
   Radiation Physics
   (No nuclear chemistry)

A.5. UMEÅ

1. University of Umeå
   School of Physics (incl. nuclear physics)

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* The large nuclear physics groups employ some nuclear chemists, but no teaching.

TABLE 8B NUCLEAR ENERGY TEACHING AT NON-ACADEMIC CENTERS IN SWEDEN

1. Nuclear Power Safety and Education
   (Jointly owned by the nuclear power industry; associated with the Institute for Nuclear Power Operations, Atlanta; operates 3 full-scale reactor simulators; about 100 people, but no chemists.) Courses for nuclear power plant operators.

2. ASEA-ATOM CO*
   (A commercial company offering complete services within the whole fuel cycle: fuel element manufacturing—reactor construction—waste handling.) Offers internal courses for own needs and for nuclear power industry personnel, also covering nuclear chemistry.

3. Studsvik Energy Research Company
   (Reactor research center conducting research in nuclear and radiation chemistry; about 500 people.) At same place is the National Neutron Research Laboratory, and the Department of Nuclear Research of the Uppsala University; courses normally at Uppsala.

4. Nuclear Power Plants
   (Extensive internal specialist training, usually on shift-engineer level.) Courses usually bought from 1-3 above. Courses include radiation protection, contamination/decontamination, waste handling, radiochemical analyses, etc.

*Recently restructured to ASEA-BROWN-BOVERY

TABLE 9A DEPARTMENT OF NUCLEAR CHEMISTRY, CHALMERS UNIVERSITY OF TECHNOLOGY, GOTHENBURG, SWEDEN

Courses

1. Fundamentals of nuclear chemistry,	1st year, 12 lec + 12 lab
2. Nuclear chemistry, general course,	4th year, 70 lec + 28 lab
3. Applied nuclear chemistry,	4th year, 42 lec + 28 lab
4. Solvent extraction chemistry,	4th year, 42 lec + 14 lab

Major research projects

1. Chemistry of actinides and comparable metals
2. Techniques of solvent extraction research
3. Separation and identification of short-lived nuclei (SISAK)
4. Nuclear waste in geologic media

Special equipment: Radiometric equipment for spectrometry, several AKUFVE units (full size and mini), glove box laboratory for high-level work (6 boxes), gamma cave with manipulators (max. 10 Ci), ^{60}Co source.

Personnel: 3 senior scientists (incl. professor), 9 graduate students, 6 laboratory technicians, 5 administrative and workshop personnel.

Budget: For 1986/87, 4.96 M Skr (1 US$ = 6 Skr), of which 3.06 M Skr was for salaries.

TABLE 9B DEPARTMENT OF NUCLEAR CHEMISTRY, ROYAL INSTITUTE OF TECHNOLOGY, STOCKHOLM, SWEDEN

Courses

1. Nuclear chemistry I (general course), 4th year, 28 lec + 42 lab (5 p)
2. Nuclear chemistry II (nuclear energy), 4th year, 22 lec + 14 lab (3 p)
3. Radiation chemistry I, >4th year, 120 lec + lab (6 p)
4. Radiation chemistry II, >4th year, (4 p)

Major research projects

1. Radiation chemistry (radical chemistry, bleaching of paper pulp, radiolysis effects on radionuclide migration in ground, etc.)
2. Nuclear waste (ceramic canning [megalite], radionuclide migration)
3. Dating (mussel shells, etc.)

Personnel: 5 senior scientists (incl. professor), 4 graduate students in 87/88, 4 technicians/administrative personnel.

Budget: For 86/87 a total of 3.24 M Skr

TABLE 10 WHAT VALUE IS IT TO HAVE A PROFESSORSHIP IN NUCLEAR TECHNOLOGY?
(Reply from industries and authorities to a questionnaire)

Choice of reply:

A) They produce essential research.

B) They provide education in research methods.

C) They promote recruitment to the field.

D) The professor is an independent authority.

Chairs evaluated by industries and authorities	Replies			
	A	B	C	D
1) Reactor technology	5	8	12	8
2) Reactor physics	4	9	8	7
3) Reactor safety	5	5	6	13
4) Nuclear chemistry	12	12	10	9
5) Reactor materials	4	5	9	6

TABLE 11 COMPARISON OF TEXTBOOKS* IN NUCLEAR AND RADIOCHEMISTRY

	RRW 1950	H 64	ML 68	Y 68	L 69	MC 71	CR 80	FKMM 81	BPL 81	VK 87
NUCLEAR PHYSICS										
o fundamental particles		+	+	+	(+)	(+)	(+)	+		+
o nuclear structure	(+)	(+)	+	+	(+)	+	+	+		+
o nuclear spectroscopy		(+)	+	+	(+)	(+)	+	+		(+)
o nuclear reactions	+	+	+	+	+	+	+	+	+	+
o radioact. decay	+	+	+	+	+	+	+	+	+	+
o radiation absorpt.	+	+		+	+	+	+	+		+
o radiation detection	+	+		+	+	+	+	+		+
o accelerators	+	+		+	+	+	+	+		
o (target chemistry)		+		+	+	+	+	+		
RADIATION CHEMISTRY										
o eff. on inorg. matter	+	+		+	+	+	+		+	+
o eff. on biosystems	+	+			+	+	+			
o hot atom chemistry		+		+	+	+	(+)	+		+
o large scale uses		(+)					+			
RADIATION PROTECTION	(+)	(+)			(+)		+	(+)		
RADIOCHEMISTRY										
o radiochemical tech. including tracer methods	+	+		+	+	+	+	+		+
o labelling		+			+	+	+	+		(+)
o isotope exchange	+	+			+	+	+	+	+	+
o isotope dilution	+	+			+	+	+	+		+
o analytical uses	+	+			+	+	+	+		+
o tracers in chemical research and technique	+	+			+	+	+	+		+
o radioactive elements	+	+			+	(+)	+		+	
ISOTOPES										
o isotopic effects	+	+			+	+	+	+	+	+
o separation	+	+			+	+	+		+	+
COSMOLOGICAL APPLICATIONS										
o nucleosynthesis		+			(+)	+	+	+		
o natural radioact., dating	+	+		+	+	+	+	+		(+)
MEDICAL APPLICATIONS										
o radiopharmacy		+			(+)		(+)			
o diagnostic uses		+					+	(+)		
o immunoassay							+			
o use of short-lived nuclei								(+)		
o therapeutic uses		+					+			
NUCLEAR POWER										
o reactor design and safety		(+)			(+)		+	+	+	+
o reactor chemistry					+		+	+	+	(+)
o fuel cycle		(+)			(+)		+	(+)	+	
o waste handling							+	(+)	+	
o environmental contamination							+			
o fusion energy							+	+		

*The textbooks are identified in the head by last initial(s) of author(s) and by year of publication. Full titles and a listing of contents for each textbook are given in Table 12.

TABLE 12 CONTENTS OF SOME TEXTBOOKS IN NUCLEAR AND RADIOCHEMISTRY

R.R. Williams Principles of Nuclear Chemistry, Van Nostrand Co., 1950.
The atomic nucleus, physical and chemical manifestations of nuclear mass, Devices for preparation and detection of unstable nuclides, Nuclear decay reaction, Nuclear bombardment reactions, Chemical operations with unstable nuclides, Chemical consequences of nuclear reactions, Chemical and biological effects of nuclear radiations, Applied nuclear chemistry.

M. Haissinsky Nuclear Chemistry and its Applications, Addison-Wesley, 1964.
The development of radioactivity, nuclear physics and nuclear chemistry, The fundamental particles, The nucleus, Spontaneous radioactive transformations, Nuclear reactions, Fission and nuclear reactors, The natural radioelements, The transuranium elements, Isotope effects and separation of isotopes, The geochemical, geological, and astrophysical applications of radioactivity, Dissipation of the energy of radiations in matter, The chemical effects of ionizing radiations: introduction and reactions in the gas phase, The radiolysis of water and of aqueous solutions, The radiolysis of organic compounds and the biological effects of radiation, The effects of radiations on solids, Fluorescence and colorations produced by radiation, The chemical effects of nuclear transformations, Radioactive indicators, Isotope exchange, Electrochemical applications, The distribution of a micro component between two phases, Applications of radioactivity in analytical chemistry, Tracers in the study of the mechanism of chemical reactions, The biochemical, physiological, and medical applications of isotopic tracers, Technological and industrial applications.

M. Lefort Nuclear Chemistry, Van Nostrand Co., 1968.
Spontaneous disintegration and radioactive decay, Types of nuclear disintegration, Fundamentals of nuclear reactions, The compound nucleus reaction mechanism, High energy spallation reactions—direct interactions followed by particle evaporation, Direct transfer of nucleons or clusters of nucleons in nuclear reactions, Nuclear fission at low energies, High-energy fission, Experimental methods in nuclear chemistry, Applications of nuclear chemistry.

L. Yaffe Nuclear Chemistry, Academic Press, 1968.
Nuclear models, Low-energy nuclear reactions, High-energy nuclear reactions, Studies of nuclear reactions by recoil techniques, Experimental nuclear spectroscopy, Heavy-ion induced nuclear reactions, Nuclear fission, The chemical effects of nuclear transformations, Modern rapid radiochemical separations, Electromagnetic separator and associated techniques, Computers applied to nuclear chemistry, geo-, and cosmochemistry.

K. H. Lieser Einfuhrung in die Kernchemie, Verlag Chemie GmbH, 1969.
Periodensystem der Elemente und Nuklidkarte, Eigenschaften der Atomkerne, Isotopieeffekte, Isotopentrennung, Radioaktiver Zerfall, Radioaktive Strahlung, Zerfallsprozesse, Kernreaktionen, Chemische Effekte von Kernreaktionen, Strahlenchemische Reaktionen, Kernbrennstoffe und Reaktorchemie, Grossgeräte (nuclear reactors, accelerators, etc.), Gewinnung und Chemie der Radionuklide, Kunstliche Elemente, Anwendungen.

TABLE 12 (continued)

H.A.C. McKay Principles of Radiochemistry, Butterworths, London, 1971.
The nucleus and radioactivity, Rates and energies of radioactive decay, Nuclear reactions, The occurrence and preparation of radioactive substances, Radiotracer principles and analytical applications, Physicochemical applications of radiotracers, Radiotracers in the study of chemical reactions, Chemical effects of nuclear transformations.

G. Choppin and J. Rydberg Nuclear Chemistry, Theory and Applications, Pergamon Press, 1980.
Beginnings of nuclear science, Nuclei and isotopes, Nuclear mass and stability, Radioactive decay, Cosmic radiation and elementary particles, Nuclear structure, Nuclear reactions I (Energetics), Accelerators and neutron sources, Nuclear reactions II (Mechanisms and Models), Production of radionuclides, Thermonuclear reactions and nucleogenesis, Naturally occurring radioactive elements and extinct radioactivity, Synthetic elements, Absorption of nuclear radiation, Radiation effects on matter, Radiation biology and radiation hazards, Detection and measurement of nuclear radiation, Applications of radioactive tracers, Nuclear chain reactions, Treatment of spent nuclear fuel, Nuclear power: problems and promise.

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TABLE 13 NOBEL PRIZES IN THE FIELD OF NUCLEAR SCIENCE

"...TO THOSE WHO HAVE MADE MANKIND THE GREATEST BENEFIT"

Year	Field	Name(s)	Discovery of /Work on /Development of
1901	Physics	W C Röntgen	-- X-rays (first Nobel Prize ever)
1903	Physics	H Becquerel, P Curie, M Curie	-- radioactivity
1908	Chemistry	E Rutherford	-- the disintegration of elements
1911	Chemistry	M Curie	-- elements radium and polonium
1921	Chemistry	F Soddy	-- the origin and nature of isotopes
1922	Chemistry	F W Aston	-- isotopes in non-radioactive elements and ... of the whole number rule
1934	Chemistry	H C Urey	-- heavy hydrogen
1935	Physics	J Chadwick	-- the neutron
1935	Chemistry	I and F Joliot-Curie	-- for synthesis of new radioactive elements
1938	Physics	E Fermi	-- nuclear reactions effected by slow neutrons
1939	Physics	E O Lawrence	-- development of the cyclotron
1943	Chemistry	G de Hevesy	-- use of isotopes as indicators
1944	Chemistry	O Hahn	-- for work on atomic fission
1951	Physics	J D Cockroft, E T S Walton	-- work in 1932 on transmutation of atomic nuclei
1951	Chemistry	E M McMillan, G T Seaborg	-- plutonium
1957	Physics	T D Lee, C N Yang	-- non-conservation of parity
1958	Physics	P A Cherenkov, I M Frank, I E Tamm	-- cosmic-ray counter
1959	Physics	E Segre, O Chamberlain	-- existence of the anti-proton
1960	Chemistry	W Libby	-- "atomic time clock"
1960	Physics	D A Glaser	-- bubble chamber
1961	Physics	R Hofstadter	-- shape and size of atomic nucleus
		R Mössbauer	-- recoil-free gamma-rays
1961	Chemistry	M Calvin	-- photosynthesis (ext. use of ^{14}C)*
1963	Physics	E P Wigner, M Goeppert-Mayer, J H D Jensen	-- nuclear structure
1967	Physics	H Bethe	-- energy production in stars
1975	Physics	J Rainwater, B Mottelsen, A N Bohr	-- asymmetrical atomic nuclei
1977	Physiology /Medicine	R S Yalow	-- hormone research (radioimmunology)*

* Closely related to nuclear science.

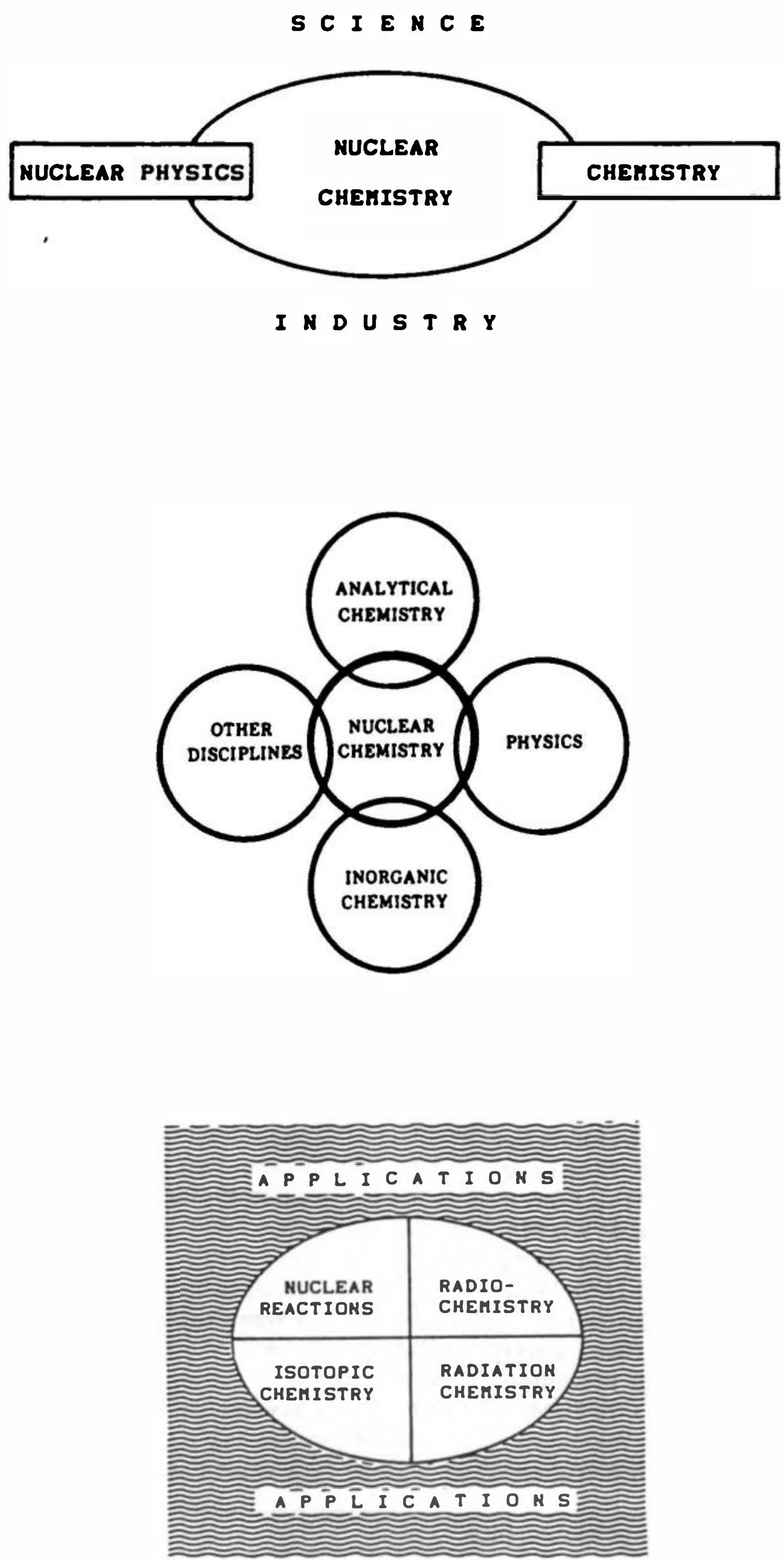

FIGURE 1 VARIOUS DESCRIPTIONS OF NUCLEAR CHEMISTRY

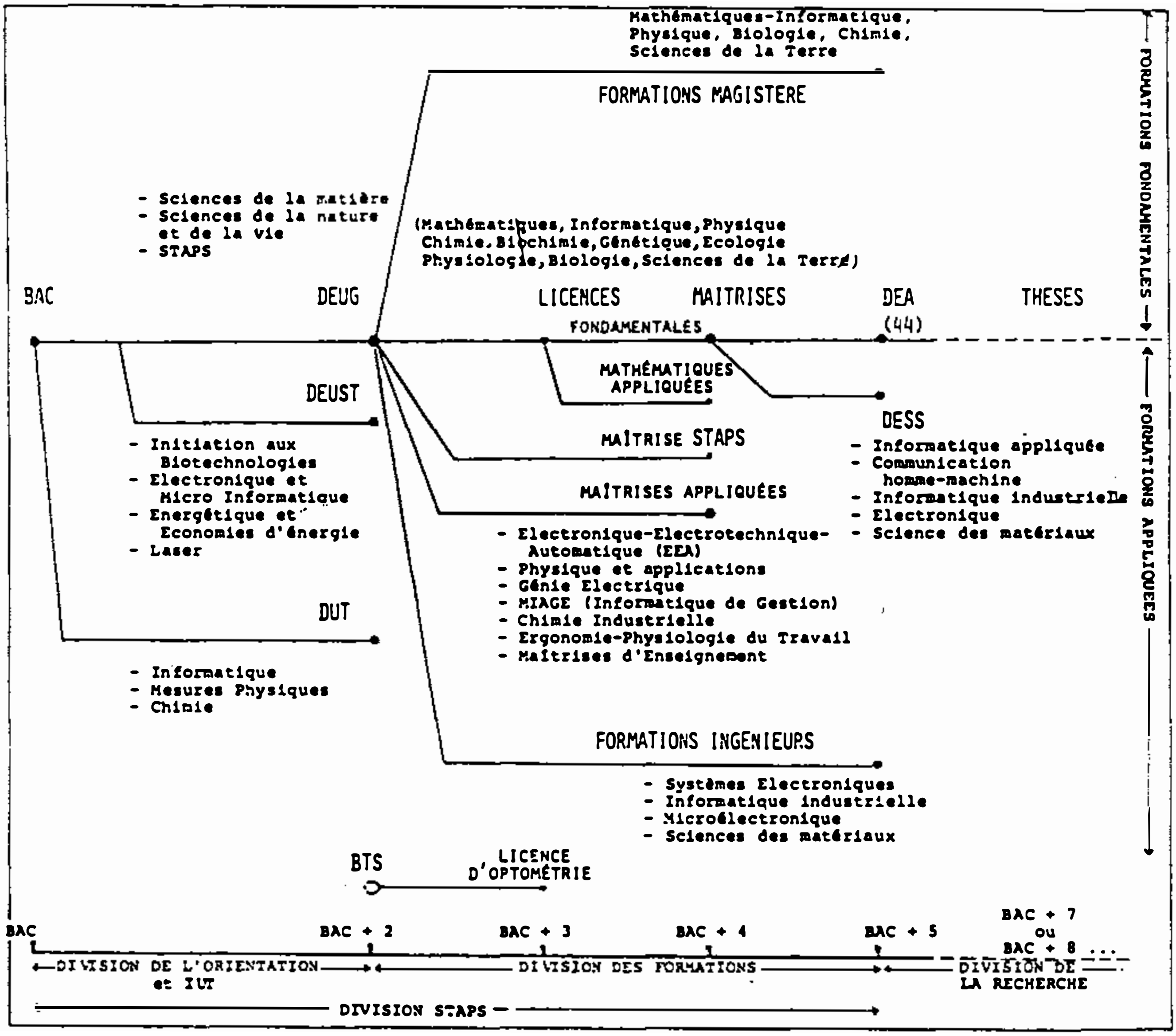

FIGURE 2 UNIVERSITY EDUCATIONAL SYSTEM IN FRANCE

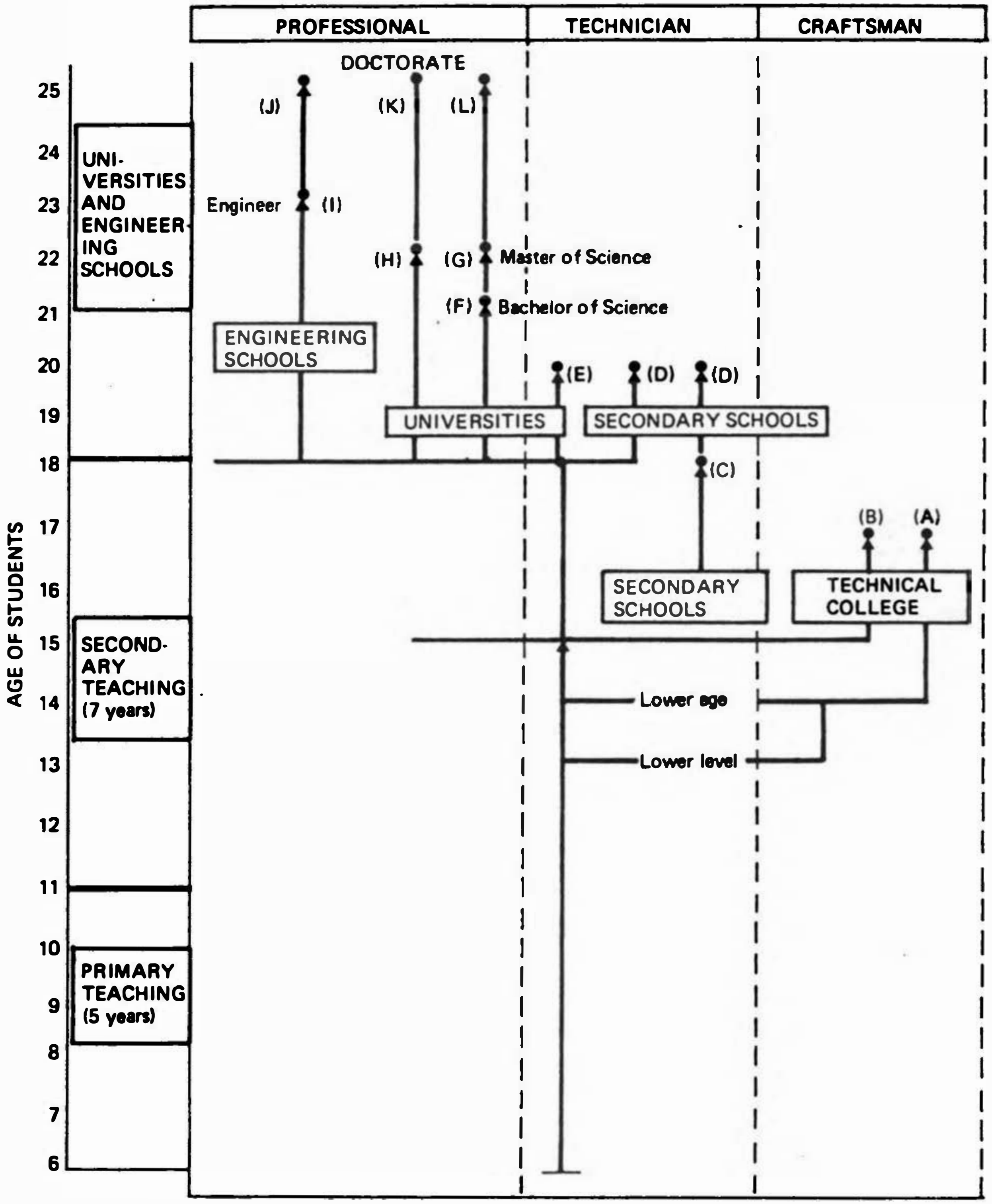

FIGURE 3 TECHNICAL EDUCATION AND TRAINING SYSTEM IN FRANCE

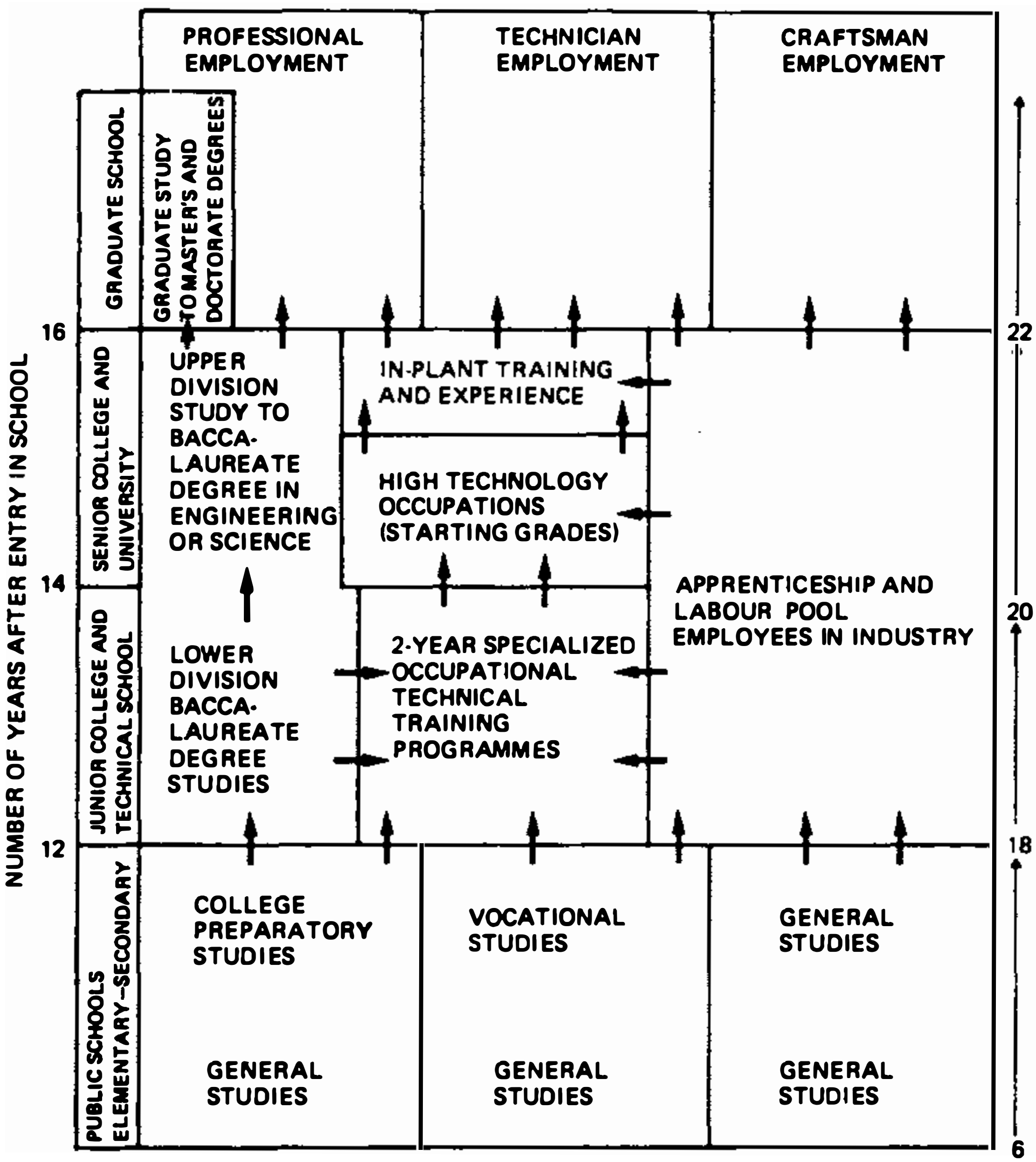

FIGURE 4 TECHNICAL EDUCATION AND TRAINING SYSTEM IN THE UNITED STATES OF AMERICA

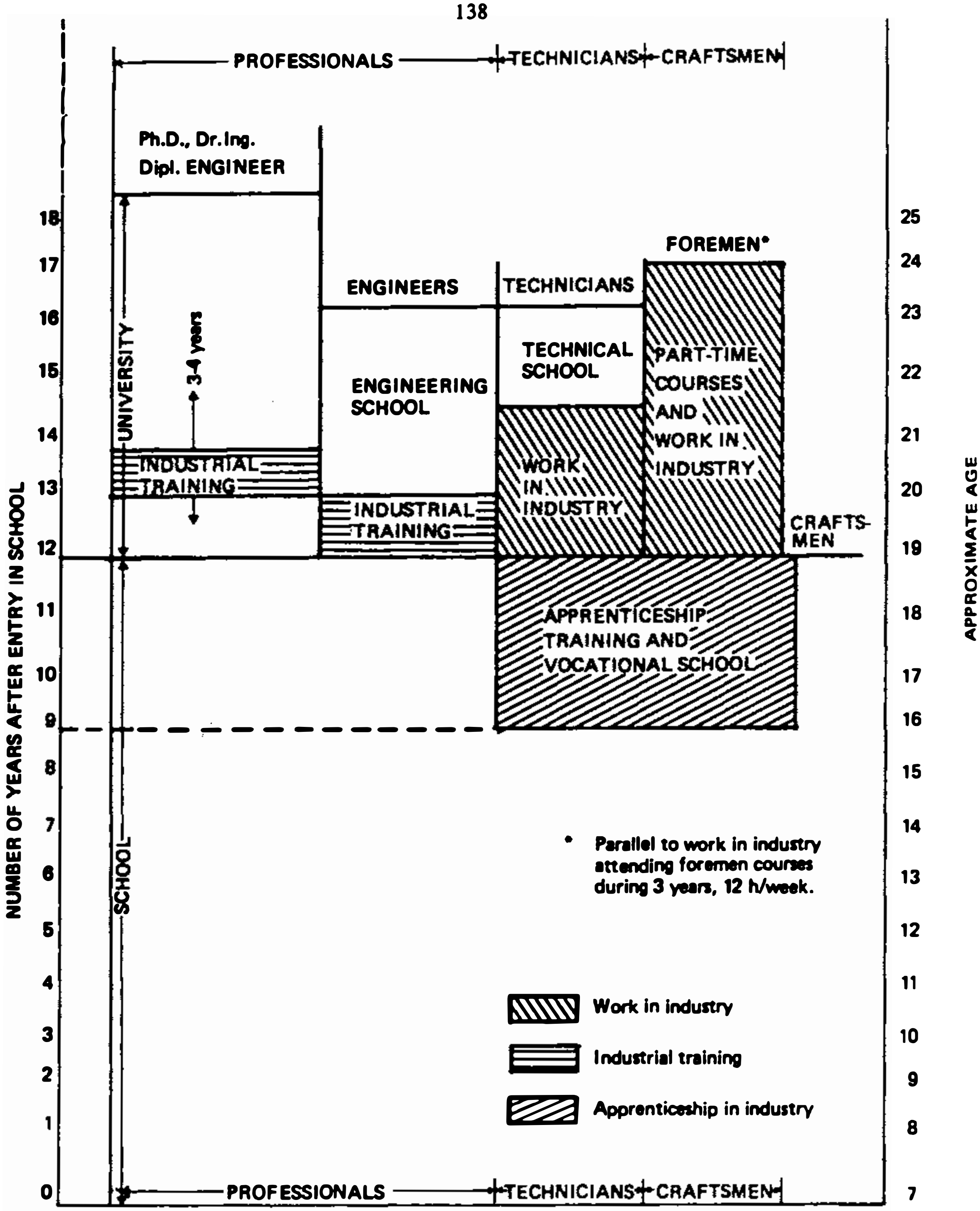

FIGURE 5 TECHNICAL EDUCATION AND TRAINING SYSTEM IN THE FEDERAL REPUBLIC OF GERMANY

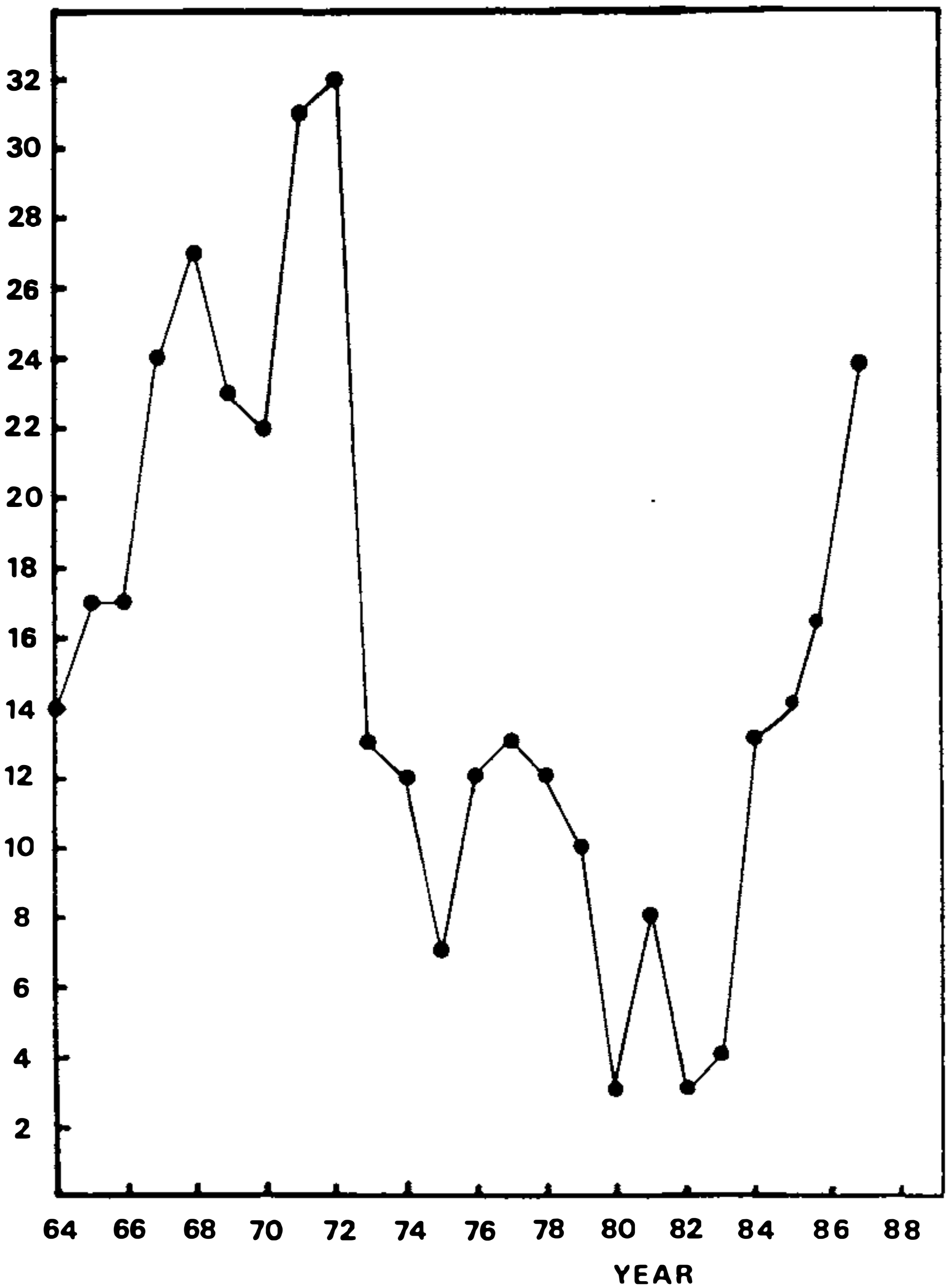

FIGURE 6 STUDENTS IN NUCLEAR CHEMISTRY (OPTIONAL COURSES) AT CHALMERS UNIVERSITY OF TECHNOLOGY (CTH) AND UNIVERSITY OF GOTHENBURG (GU) SWEDEN

APPENDIX E

Nuclear and Radiochemistry Education in U.S. Universities and Colleges

Edward S. Macias
Washington University, St. Louis, MO

Gerhart Friedlander
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INTRODUCTION

Beginning with the pioneering work of the Curies, chemistry has been a vital ingredient in the study of radioactivity and nuclear phenomena and, throughout the last 90 years, chemists have made key contributions to advancing our knowledge in these fields. One needs only to recall names like Frederick Soddy, Kasimir Fajans, Otto Hahn, Georg von Hevesy, Fritz Strassmann, Glenn Seaborg to back up that statement.

The present state of knowledge about atomic nuclei and their interactions has indeed been acquired through the combined efforts of people trained as physicists and chemists and right up to the present their different backgrounds and complementary skills and approaches continue to be important in advancing the field.

To give some examples: Nuclear chemists have played a particularly important role in achieving detailed understanding of the fission process, e.g. through studies of charge, mass, and kinetic energy distributions in the fission of various nuclei under a variety of conditions. Another fruitful domain of nuclear chemical research has been the exploration and characterization of nuclei further and further from the region of nuclear stability, both to the neutron-rich and to the neutron-deficient side of the valley of stability and particularly to new elements beyond those occurring in nature. Such studies have been important in advancing our understanding of the factors that govern nuclear stability. Investigations of complex nuclear reactions (such as high-energy spallation reactions) have usually been pioneered by nuclear chemists, perhaps because in their complexity, they are somewhat akin to chemical reactions. Nuclear chemists are actively involved in the current, very intensive pursuit of relativistic heavy ion reactions, aimed at discovering and characterizing states of nuclear matter at extremely high densities and pressures believed to have existed in the earliest stages of the universe.

Even more important, in the context of the Workshop on Training Requirements, than chemists' role in nuclear research per se is the fact that people trained in nuclear chemistry have been extraordinarily successful in fruitfully applying their backgrounds and knowledge to other fields and in developing imaginative new techniques for the solution of many problems.

The whole field of radioactive (and stable isotope) tracer applications grew out of nuclear chemistry (Hevesy being recorded as the first practitioner when he used RaB tracer to establish that, in the boarding house in which he took his meals, table scraps from one day appeared in next day's meal). Isotopic tracer techniques have, of course, come into common use in many fields including physics, chemistry, biology, agriculture, geology, and archaeology. These widespread applications certainly owe a great deal to the pioneering contributions of nuclear chemists.

The same can surely be said of the various specialized and sometimes ultrasensitive analytical techniques that are based on nuclear processes and phenomena. Principal among these is neutron and charged particle activation analysis. But one can also mention isotope dilution, ESCA, EXAFS, and others. Starting with the first publications on neutron (1) and charged particle (2) activation, the applications of these techniques in diverse fields - archaeometry, criminology, atmospheric science, oceanography, art history, biochemistry, process control, to name just a few - have often been initiated and developed by chemists with a nuclear or radiochemical background.

Exponential radioactive decay provides a natural tool for various forms of chronometry, and many applications along these lines were pioneered by nuclear chemists. W.F.Libby's carbon-14 dating method has had enormous impact on archaeology, climatology, and related fields. Geology was revolutionized by the arsenal of dating techniques that are based on naturally occurring radionuclides and their daughters (e.g. the U/Pb, Th/Pb, Rb/Sr, K/Ar, Re/Os methods). What we know about the early history of our solar system is derived from these same chronometers as applied not only to terrestrial rocks but also to meteorites and the surface of the moon. In the development, refinement and applications of each of the techniques mentioned, nuclear chemists and radiochemists have been seminally involved.

As a final example we mention the important role that radiochemistry plays in the advancement of nuclear medicine, which has become such a vital component of medical practice. The development of methods for producing specifically labelled radiopharmaceuticals of high specific activity and requisite radiochemical purity requires the skills and experience of nuclear or radiochemists.

From the sketchy examples given, it should be clear that a combination of chemical and nuclear training and education has proved to be excellent preparation for branching out into other fields and for bringing that background to bear on a great variety of problems, both in other basic sciences and in applied areas. There is every reason to believe that this will also be true in the future, provided that such education and training continues to be sufficiently available. This is a most important proviso. Opportunities for graduate study in nuclear chemistry have been declining in the US and in Western Europe and, if this trend is allowed to continue, there will very soon be a dearth of people with that combination of skills that has proven to be so valuable, unless new mechanisms for developing them can be put in place. It is this concern that motivates this workshop.

In this paper we have assessed the status of academic training in the area of nuclear and radiochemistry, broadly defined, as indicated from a survey we conducted of U.S. college and university chemistry departments. We present data from this survey on the numbers of faculty and graduate students involved in various aspects of nuclear chemistry teaching and research and on the numbers of courses all or in part devoted to nuclear and radiochemistry. To put these data in the proper perspective we have compared our results to similar surveys conducted over the last two decades (3-5). It is our intention to examine the commonly held view in the nuclear and radiochemistry community that the availability of academic training in the field is decreasing.

SURVEY

The questionnaire (Appendix 1) was quite similar to those used in previous surveys to allow us to examine the trends over the past two decades. It was mailed to Chairs of 728 academic chemistry departments including the 199 departments which grant PhD degrees in chemistry as listed in the 1985 American Chemical Society (ACS) Directory of Graduate Research. Replies were received from 482 institutions (66%) with a similar fraction of returns from PhD and non-PhD granting institutions (69% and 65%, respectively) as given in Table 1. This reply percentage is quite similar to that of the 1978 survey in which 68% of 188 PhD granting institutions returned the questionnaire. Most of the comparisons in this paper are made to that 1978 survey.

To estimate if a significant number of non-replying institutions have faculty and courses in nuclear and radiochemistry, we reviewed faculty research interests at all non-replying PhD granting institutions in the ACS Directory of Graduate Research. We found only two non-replying institutions with a faculty member who indicated a research interest in nuclear and radiochemistry. Therefore, we feel confident that at least for PhD granting institutions, our survey covers essentially all of the relevant chemistry departments.

RESULTS

Faculty

Only a modest fraction of the responding institutions have nuclear and radiochemistry faculty (40% and 24% at PhD and non-PhD granting institutions, respectively). In fact, those percentages are too high because most of the non-responding schools have no nuclear and radiochemistry faculty. For example, we estimate that the percentage of all PhD granting institutions that have nuclear and radiochemistry faculty is closer to 28%.

This survey asked for the primary and secondary interests of faculty broken down into six areas (Figure 1). Type 1 faculty, interested in fundamental nuclear chemistry, are traditional nuclear chemists while type 2 faculty are traditional radiochemists. Type 3 through 6 faculty are involved

TABLE 1

Summary of Responses

All Institutions	
Surveys sent	728
Surveys received	482 (66%)
Ph.D. Granting Institutions	
Surveys sent	199
Surveys received	138 (69%)
Institutions with nuclear and radiochemistry faculty (all types)	55 (40%)
Institutions with nuclear and radiochemistry courses	42 (30%)
Institutions with nuclear and radiochemistry content in other courses:	
in general chem	102 (74%)
in physical chem	11 (8%)
in other courses	15 (11%)
Non-Ph.D. Granting Institutions	
Surveys sent	529
Surveys received	344 (65%)
Institutions with nuclear and radiochemistry faculty (all types)	81 (24%)
Institutions with nuclear and radiochemitry courses	75 (22%)
Institutions with nuclear and radiochemistry content in other courses:	
in general chem	276 (80%)
in physical chem	36 (10%)
in other courses	56 (16%)

Percentages refer to the fraction of responding institutions.

in most of the applications of nuclear and radiochemistry to other scientific fields. We are particularly interested in types 1-4 when considering education, because these are the faculty who normally teach the core courses in nuclear and radiochemistry. Type 5 faculty, users of tracers and labelled compounds, were included in the survey in order to allow direct comparisons with the results of the 1978 survey, but this is actually a very diverse group which is often far removed from teaching and research in nuclear and radiochemistry. In retrospect, we realized that more definition of this group is needed to make the survey results for type 5 chemists meaningful.

It is clear from Table 2 and Figure 3 that the total nuclear and radiochemistry faculty at PhD granting institutions has decreased dramatically in the past decade. There has also been a drop by about one-third in the number of type 1-4 faculty and in the number of separate departments in which they reside from the 70's to the 80's. This comes after essentially no change in their numbers during the 1970's.

Faculty involved in nuclear medicine and radiopharmaceutical chemistry (type 6), an area of research of particular interest to this workshop, were not specifically identified in a separate subdivision in any of the earlier studies. Therefore, no trends in the numbers of faculty in this subdivision can be determined. No comparable information was requested from non-PhD granting institutions in the earlier studies and thus we present no trends for these schools.

Table 2
Nuclear and Radiochemistry Faculty
at PhD Granting Institutions

	1960	1973	1978	1987
Total Faculty (All Types)	106		180	108(55)
Faculty (Types 1,2,3,4)	67(37)	117(64)	121(69)	81(46)

Numbers in parentheses indicate number of separate departments in which these faculty reside.

During the past decade there has been a decrease in all areas of the field as shown in Table 3 and Figure 3. By contrast, in the period between 1973 and 1978 there was very little change in the number of nuclear and radiochemistry faculty of type 1-4 in PhD granting institutions but there was a big increase in the number of faculty working with tracers and labelled compounds (type 5). Only the number of faculty working in fundamental nuclear chemistry were relatively constant from 1978 to 1987 with only a 10% decrease. By contrast, academic radiochemists decreased by 64%!

TABLE 3

Faculty by Research Type and Age

Granting Type	PhD Granting Institutions: Interests, Primary 1987	Primary 1978	Secondary 1987	Secondary 1978	Ave Age[a] 1987	Ave Age[a] 1978	Non-PhD: Primary Interest 1987
1 Fundamental Nuclear Chemistry	34	38	7	12	50	47	21
2 Chem of Radioactive Elements	4	11	8	18	60	52	6
3 Analytical Applications	33	45	20	30	49	48	45
4 Nuclear Probes for Chemical Studies	6	27	9	10	51	47	2
5 Tracer Techniques and Labelled Compounds	23	59	11	28	49	47	19
6 Nuclear Medicine and Radiopharmaceutical Chem	8		5		49		1
Totals 1987	108	180	60	98			94
Average Age					50	48	

[a] Average age tabulated according to faculty member's primary interest.

It is worth noting that in addition to the 108 nuclear and radiochemistry faculty at PhD granting institutions there are also 94 nuclear and radiochemistry faculty at non-PhD granting institutions.

From 1978 to 1987 the average age of all nuclear and radiochemistry faculty increased by two years to 50 years which indicates some replacements of retiring faculty. This is not drastically different from an average age of 49 years for a random sampling of some 1300 U.S. chemistry faculty taken from the 1987 ACS Directory of Graduate Research. However, there was a smaller proportion of young nuclear and radiochemistry faculty than for the sample of all academic chemists as can be seen in Figure 4. The extreme in the aging trend was for type 2 radiochemists whose average age increased eight years in the past nine with no new faculty added. It should be noted that there are only four academic radiochemists remaining in PhD granting institutions in this country and a total of 10 in all schools.

There are only 9 chemists working in nuclear medicine and radiopharmaceutical chemistry (type 6) overall. Although this is a small group, it is not older than the average chemist. We have not counted the number of faculty in this field working in medical and pharmacy schools.

The diversity of nuclear and radiochemistry research makes clusters of faculty within a single department quite important for cross fertilization of ideas and for the teaching of core concepts to students in applied and peripheral areas. Unfortunately the number of departments with more than one faculty member in nuclear and radiochemistry has decreased since 1978 as can be seen in Figure 5.

Courses

The number of institutions that teach nuclear and radiochemistry courses is quite small (30% and 22% for responding PhD and non-PhD granting institutions, respectively) and we estimate that only 22% of all PhD granting institutions offer such courses. In this survey only 42 PhD granting institutions indicated nuclear and radiochemistry course offerings as compared to 70 and 86 institutions in the 1978 and 1973 surveys, respectively. The details of these course offerings are given in Table 4.

TABLE 4

Nuclear and Radiochemistry Courses
(number of courses)

Course Level[a]	With lab	Without Lab	Lab only
At PhD Granting Institutions			
Lower Level UG	1	0	0
Upper Level UG	7	11	1
UG and Grad	4	8	1
Grad	10	23	0
Total Courses	22	42	2
At non-PhD Granting Institutions			
Lower Level UG	4	4	0
Upper Level UG	38	14	2
UG and Grad	5	5	2
Grad	5	12	0
Total Courses	52	35	4

These nuclear and radiochemistry courses are offered at 42 PhD granting institutions and at 75 non-PhD granting institutions.

[a] UG - Undergraduate level course
Grad - Graduate level course

The total of 66 courses at PhD granting institutions is a sharp 57% decrease from the 153 courses offered in 1978. This is perhaps the statistic which most dramatically illustrates the anemic state of academic Nuclear and Radiochemistry instruction in the U.S. today.

Although there are fewer faculty at non-PhD granting institutions, they offer a larger number of nuclear and radiochemistry courses (91) than the PhD granting institutions.

Nuclear and radiochemistry fares best in general chemistry courses as tabulated in Table 1. Overall, 78% of the replying institutions devote part of that course to nuclear and radiochemistry topics although the extent of coverage is generally less than 10% and often as little as one lecture. Only a very small percentage (<10%) of institutions have any coverage of nuclear and radiochemistry in their physical chemistry courses.

Graduate Students

The survey indicates that the number of graduate students in the field has increased since 1978 as shown in Table 5. However, these data are somewhat misleading because there are a large number of students working with tracers and labelled compounds (type 5) whose main research project is in a field other than nuclear and radiochemistry. We estimated a lower limit of the number of type 5 students by counting the number of students at institutions which had only type 5 faculty. In a similar way we were also able to estimate the number of chemistry students working in nuclear medicine and radiopharmaceutical chemistry. The only meaningful comparison with previous studies can be made with students working in type 1-4 research areas. We can only give an upper limit for that category, since after subtracting the graduate students in departments with only type 5 and 6 faculty, we are still left with a mixture of types 1-6. That upper limit for types 1-4 is 32% above the 1978 number.

In contrast the data from the National Research Council on numbers of PhDs granted per year since 1976 (Figure 6) indicate that the number of graduate students in the field has been decreasing over the past decade. The NRC survey presumably reflects a narrower definition of nuclear and radiochemistry, corresponding roughly to types 1-4.

TABLE 5

Nuclear and Radiochemistry Graduate Students
At PhD Granting Institutions

	1960	1973	1978	1987
Types 1-4 only (upper limit)			96	127(29)
Type 5 only (lower limit)				71(29)
Type 6 only				25(18)
Total Graduate Students	213	281	102	223(76)

Numbers in parentheses indicate the number of students in that category who are at institutions where no nuclear and radiochemistry courses offered.

One surprising result of our survey is the large number of nuclear and radiochemistry graduate students who are enrolled at institutions which do not offer any nuclear and radiochemistry courses. This is particularly evident for type 6 students.

There are an additional 63 graduate students (presumably working for a masters degree) at non-PhD granting institutions. However, 20 of those students are at institutions which offer no nuclear and radiochemistry courses and may be working in a peripheral research area.

CONCLUSIONS

This survey confirms the commonly held view that the opportunities for academic training in nuclear and radiochemistry in this country are decreasing. We found that the number of faculty and courses of instruction in nuclear and radiochemistry at U.S. colleges and universities is very small and at least for PhD granting institutions has decreased dramatically over the past decade. Contrary to this trend, the number of graduate students appears to have increased somewhat over this same time period, but this increase has probably not been in the core areas of the field.

The average age of nuclear and radiochemistry faculty is only slightly older than the average age of all chemistry faculty in the U.S. However, only a few retiring nuclear and radiochemistry faculty are being replaced with young nuclear and radiochemistry faculty. This is most evident for radiochemists who are now an endangered species in U.S. chemistry departments.

There are very few faculty working in nuclear medicine and radiopharmaceutical chemistry in U.S. chemistry departments. The present faculty in this area, however, are not a particularly old group and are relatively successful in attracting graduate students to the field. It should also be noted that we surveyed only chemistry departments and that some faculty educated as nuclear and radiochemists very likely reside in other departments, e.g. in medical schools and nuclear engineering departments.

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Appendix

FACULTY AND COURSE SURVEY

American Departments of Chemistry

Return to: Prof. Edward S. Macias, Department of Chemistry, Washington University, St. Louis, MO 63130

A. Does your Department offer courses which are devoted all or in part to nuclear and/or radiochemistry?

Yes No (circle one)

1. Course title ________________

Level: (circle one)

Lower Div. Upper Div. Grad.

Typical enrollment _________

Lab work included? Yes No

If broader course, about what % devoted to nucl/radiochem?

____

2. Course title ________________

Level: (circle one)

Lower Div. Upper Div. Grad.

Typical enrollment _________

Lab work included? Yes No

If broader course, about what % devoted to nucl/radiochem?

____

B. Is nuclear/radiochemistry material included in general lecture or lab courses?

Course title __________________

Approximately what fraction of the course lecture or lab time is devoted to nuclear/radiochemistry? ________

Cont.

Faculty and Course Survey, Cont.

C. Does your Department faculty include nuclear and/or radiochemists? If so, please provide their names and areas of interests specified according to the following designations:

1. Fundamental nuclear chemistry - interest in nuclear properties (structures, reactions, fission, etc.)
2. Chemistry of radioactive elements - actinide and lanthanide chemistry, other elements such as Tc, Ra, Po, etc.
3. Analytical Applications - uses activation analysis, tracers, etc. to measure elemental concentrations in geochem, environmental, biological applications.
4. Nuclear probes for chemical studies - e.g., Mössbauer effect, nuclear orientation experiments, perturbed angular correlations.
5. User of tracer techniques and labelled compounds.
6. Nuclear medicine and radiopharmaceutical chemistry.

Faculty Name	Primary Field (circle)	Second Area (circle)	Directs grant Research (circle)
______________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
______________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
______________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
______________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
______________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
______________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No
______________	1 2 3 4 5 6	1 2 3 4 5 6	Yes No

D. The number of faculty in these areas in 1978 (date of the last survey was ______________.

E. 1) The number of graduate students in research in these areas presently:

______________.

2) In 1978 ______________.

Please return by September 15, 1987

TYPES OF NUCLEAR AND RADIOCHEMISTS
Research Interests

1. Fundamental nuclear chemistry
2. Chemistry of radioactive elements
3. Analytical applications
4. Nuclear probes for chemical studies
5. Tracer techniques and labelled compounds
6. Nuclear medicine and radiopharmaceutical chem

Figure 1. Categories of nuclear and radiochemistry research interests used in the survey of colleges and universities.

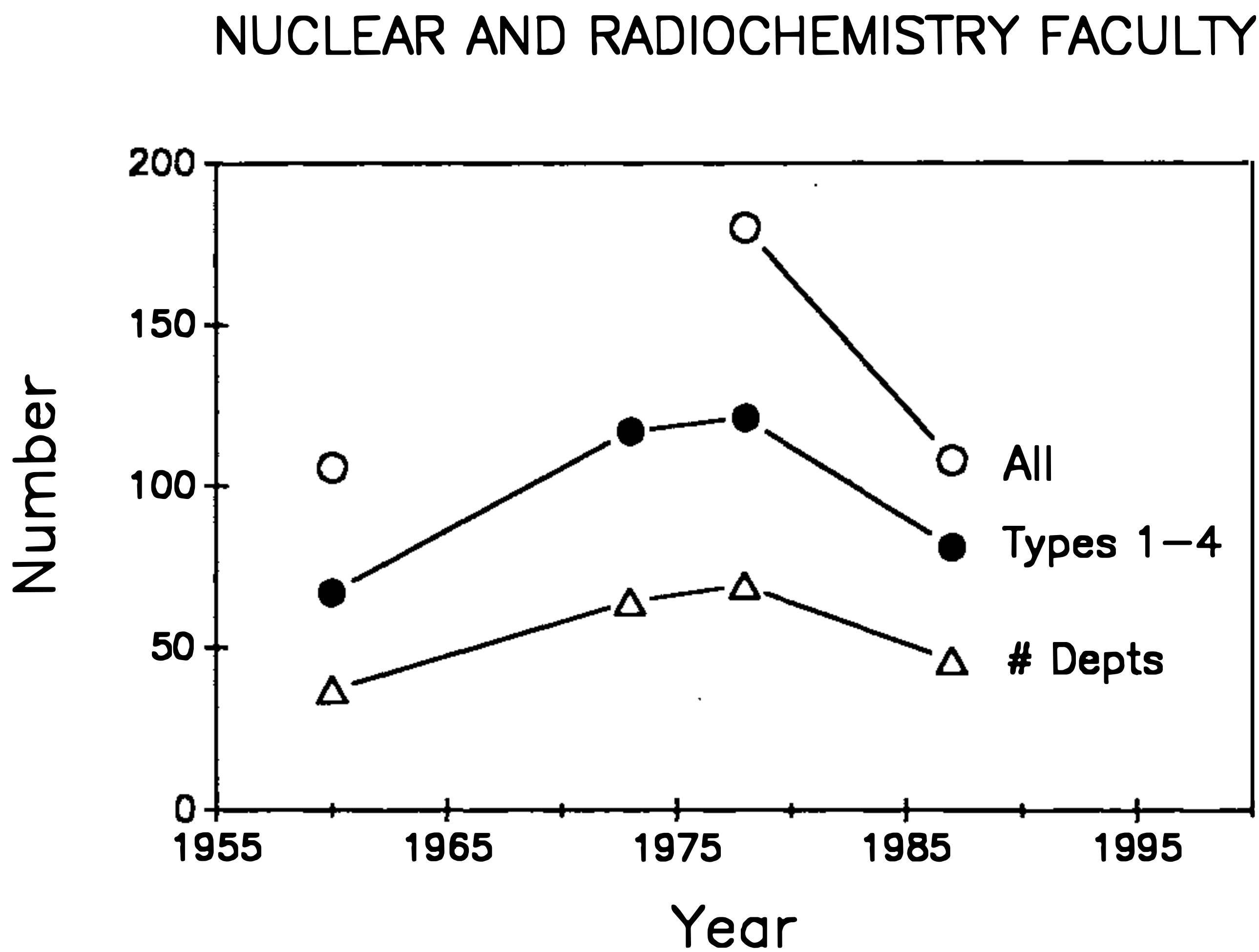

Figure 2. Trends in numbers of nuclear and radiochemistry faculty in U.S. PhD granting institutions since 1960. Data prior to 1987 were taken from references 3-5. The open triangles indicate the number of separate departments of chemistry in which these faculty reside.

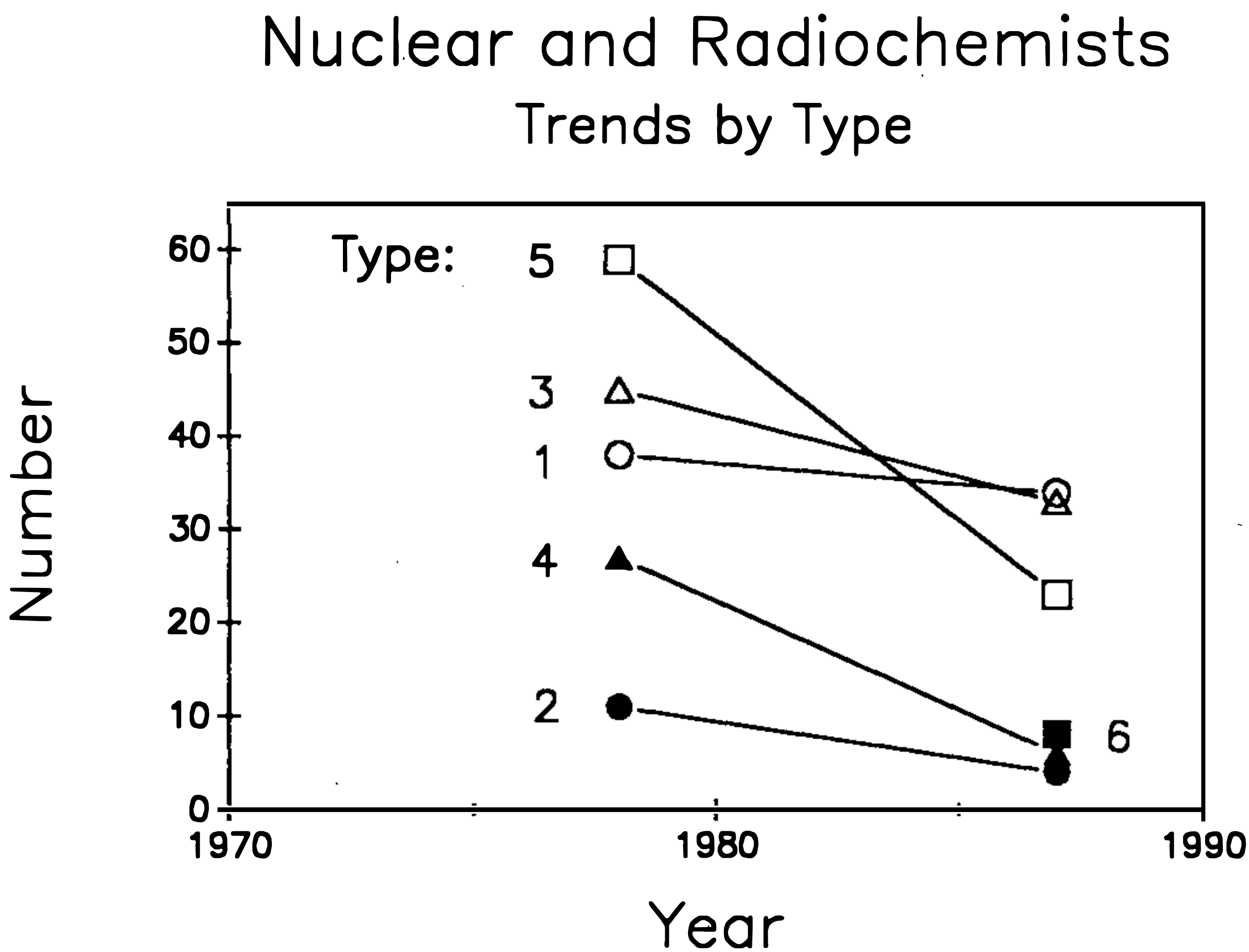

Figure 3. Number of nuclear and radiochemistry faculty subdivided by research category. No data exist for type 6 chemists prior to 1987. The data for 1978 were taken from reference 3.

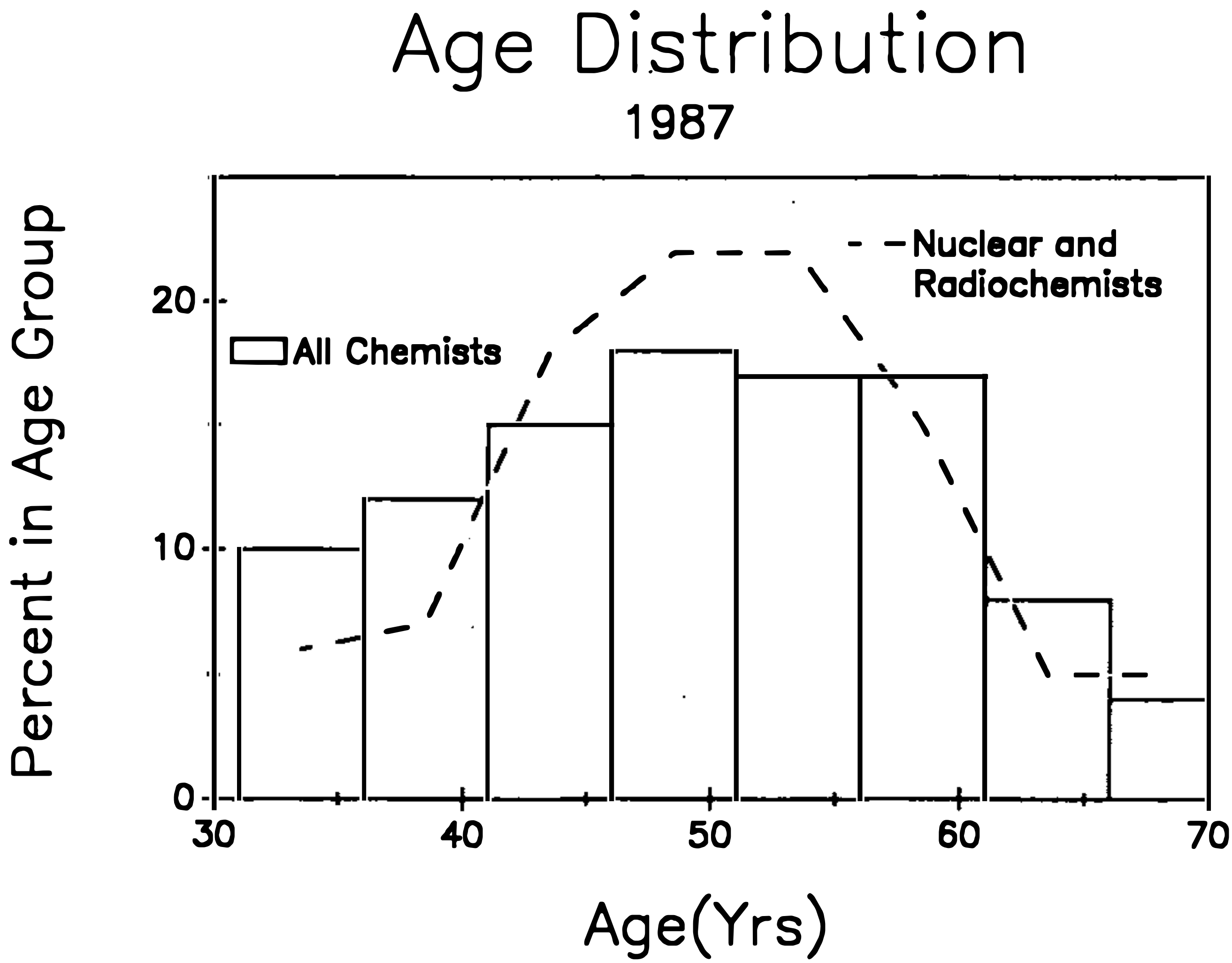

Figure 4. Age distribution of faculty in PhD degree granting institutions in the U.S. in 1987. The histogram represents a random sampling of 1400 chemistry professors. The dashed line is the age distribution of all nuclear and radiochemists.

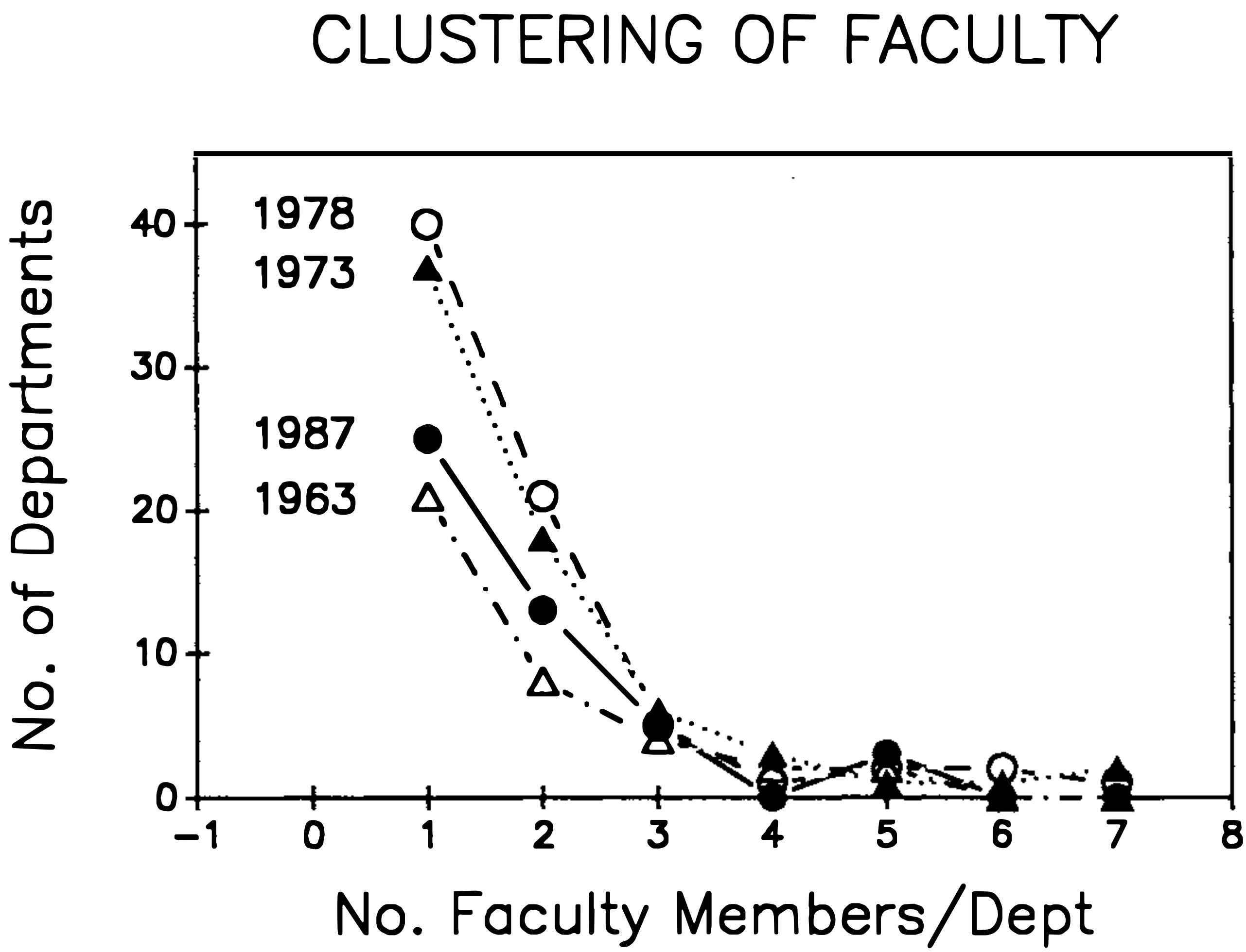

Figure 5. The number of nuclear and radiochemistry faculty per chemistry department in PhD granting institutions. Data prior to 1987 were taken from references 3-5.

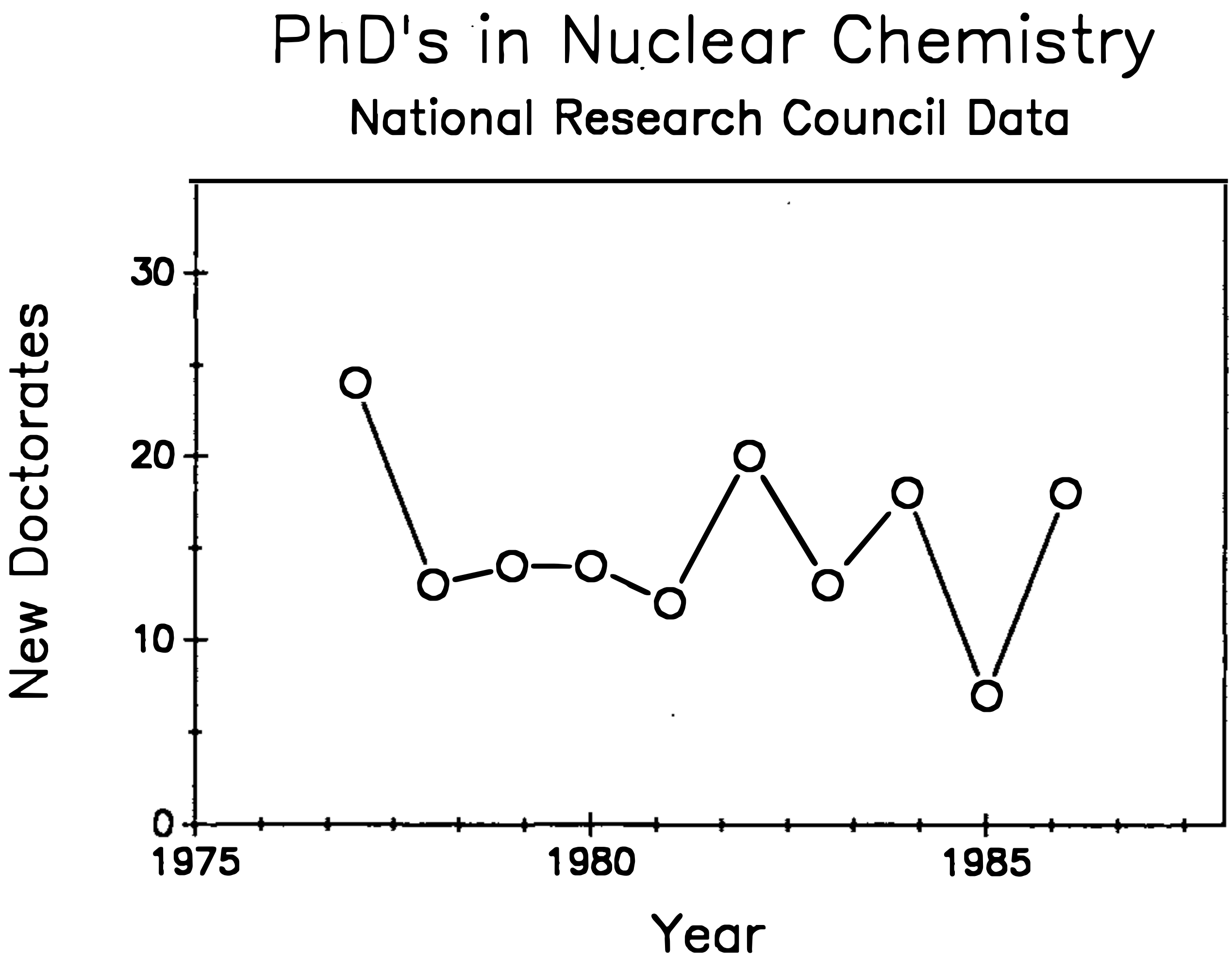

Figure 6. The number of PhDs in nuclear chemistry granted per year since 1976 as compiled by the National Research Council (private communication, 1988).

APPENDIX F

TRAINING REQUIREMENTS FOR CHEMISTS IN RELATED RESEARCH DISCIPLINES

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I. Introduction

Nuclear methods have proven to be of great value in applications in many fields. Since at least the mid-1930s, chemists have used radioactive tracers to observe the behavior of minute quantities of various elements, e.g., to determine the absorption and movement of essential trace elements in human bodies and in plants, to follow the metabolism of certain sugars or amino acids labelled with ^{14}C, or to measure the abrasion of Fe from the cylinder of an engine into the oil. Other groups of investigators have used nuclear methods of analysis, especially neutron activation analysis, to determine concentrations of a wide range of elements in samples, mostly from the "real" world, that are so complex and/or difficult to dissolve that they are almost impossible to analyze by conventional analytical methods. Nuclear analyses have been especially useful in the analyses of rocks, meteorites and lunar samples by geochemists or cosmochemists and of airborne particles and air-pollution source materials such as soil, coal, oil, fly ash, etc. by atmospheric environmental chemists. Activation analyses are also used for trace elements in natural waters by marine geochemists and in biological tissue and fluids by nutrition researchers; however, neutron activation analysis suffers from severe interference from elements such as Na, K, Cl, Br and P in these media, so nuclear methods have not, in general, been as important in these fields as those noted above.

Over the past ten years, another nuclear-related technique has come into wide use in many applications in these fields, i.e., Accelerator Mass Spectrometry (AMS). Although AMS essentially uses van de Graaff accelerators as highly selective, sensitive mass spectrometers, the method allows one to make measurements of isotopic ratios with much smaller quantities of material than was ever before possible. For example, the measurement of $^{14}C/^{12}C$ ratios can be done with orders of magnitude less carbon than that required by β proportional counting of ^{14}C (*1*).

How should chemists be trained to use these nuclear methods in research and applications? There is no single answer to that question, as there are several levels of sophistication to which people may aspire.

II. Training for Researchers of the Nuclear Methods

First, I consider the training of students whose major objective is improvment of nuclear methods themselves. Because of my familiarity with nuclear analytical methods, I will focus most of my attention on them, but the considerations surely apply in the other areas noted. Most breakthroughs in the techniques have resulted from the research of people who were at the forefront of fundamental nuclear chemistry research. Indeed, one of the earliest activation analysis papers in the U.S. was that of Seaborg and Livingood, who inadvertently activated Ga impurities in an iron target at the Berkeley cyclotron (*2*) [This was one of the first examples of nuclear chemists' awareness that "pure" compounds are not necessarily pure.] Most advances in nuclear analytical methods require a detailed knowledge of the nuclear physics of the problem, e.g., cross sections *vs.* energy, scattering theory, thermalization, as well as good knowledge of radiation-detection and data-storage and analysis methods. Although I have not personally done fundamental nuclear research for nearly twenty years, I feel that much of our success in nuclear analytical research at Maryland results from our close relationship with faculty and students who are doing fundamental research.

Most advances in detection methods appear first in nuclear research before flowing into the applications areas. In my own case, for example, I became aware of Ge(Li) detectors in 1963 and, within one year, our group at M.I.T. was using them for γ-ray spectroscopy of fission-product nuclei (*3*). We were aware of the potential value of improved techniques in nuclear analyses as a result of the radiochemical activation analysis work of John Winchester's group in nearby laboratories (*4*). The extension of this new high resolution detection method to instrumental neutron activation analysis (INAA) was fairly obvious and successful (*5*).

In summary, graduate students who wish to advance nuclear activation methods should acquire the best possible knowledge of nuclear chemistry and physics. In addition, it is valuable, perhaps essential, to have close contact with people who are making use of the methods in applications. Graduate students should also take one or two graduate level courses in analytical chemistry in order to gain an understanding of accuracy, precision and the validation of methods by the use of standards. Our group at Maryland has been most fortunate in being close to the National Bureau of Standards (NBS). Not only do we frequently have seminars given by scientists from NBS, who describe the care needed to certify the concentrations of elements in Standard Reference Materials (SRMs), but we also have had the students perform "blind, round robin" analyses of SRMs that were under development at NBS, so the true concentrations were not yet known (*6*). Of course, at Maryland as in most departments, we also expect all students to do well in "core" courses of the Department, mainly chemical thermodynamics.

III. Training for Research in Related Disciplines

Graduate students interested in using nuclear methods for research in a related discipline don't need quite the depth of knowledge of nuclear physics as those who wish to advance the methods; however, they should take as much nuclear chemistry as is available. In addition, at Maryland we periodically give an informal "short course" on the theory and practical details of nuclear analyses that covers the topic in more depth than is possible within the regular radiochemistry and nuclear chemistry courses. These courses are open to all interested graduate students, undergraduates, technicians, and research associates around the University. They typically last for about six sessions of 2 hrs each. Lectures are given by various faculty members and staff, so that no one has too great a burden. (Note that, being an informal, non-credit course, no one gets paid and it is not officially included as part of a faculty member's teaching load.) We have slowly developed the written materials for the course over the years, most of them written by us. The course starts with theory and concludes with coverage of the specific software and instruments used by our group.

One reason for our need of a short course is the fact that we have rarely been able to offer a radiochemistry laboratory course. We have little equipment that can be devoted solely to a course, so have to tie up our research equipment for extended periods. Also, the course makes heavy demands on our graduate students, because students of other areas of chemistry are not capable of serving as teaching assistants. When we have had a course (or a nuclear "module" within the context of physical chemistry laboratory), we have usually had students do a simple INAA experiment using the Triga-type reactor at Maryland. I regret that we cannot offer a laboratory course routinely. People at other institutions have argued that they don't need it because nuclear chemistry graduate students will learn it all in their research. That is usually not the case, as research usually involves in-depth use of a specific technique, not broad studies involving the range of equipment and techniques that should be included in a radiochemistry laboratory course, e.g., coprecipitation, counting statistics, use of liquid scintillation counters and β-proportional counters, etc.

One important reason for not expecting students of related research areas to take courses in nuclear physics is the fact that, being on the interface of chemistry with some other discipline(s), they need the time to acquire some knowledge of the other discipline(s) (e.g., meteorology for our atmospheric chemistry students) as well as of the area of chemistry in which they are doing research. When a field is quite young, one can function in that field with a new technique without a great deal of knowledge of the field. William Zoller and I, for example, could publish papers on concentrations of particle-borne elements in the atmosphere without much prior knowledge on our part because no one knew the "right answers" (*7*). As the field matured, it developed its own body of knowledge, which we and our students had to learn to remain competitive. When we started offering our two-semester sequence of environmental chemistry courses (covering both air and water) at Maryland in the early 1970s, it was a struggle to find enough material to make respectable courses. The field has advanced so rapidly since then that it is now difficult to squeeze in all of its important themes. Students have to work hard to acquire the knowledge needed to do vital research, whereas we older citizens of the field have more painlessly lived through its development.

My special field within atmospheric chemistry is the development of "receptor-modeling" techniques, i.e., the use of detailed composition patterns of particles (and some trace gases) as received at ambient field sites to determine the sources of those atmospheric materials and trace their movement and deposition (*8*). It is interesting that nearly all of the "first generation" researchers in this field are former nuclear chemists or physicists, the major exception being Sheldon Friedlander at UCLA, who is an aerosol physicist. The major reason for this is the fact that the development of nuclear and related methods (especially x-ray fluorescence, XRF) was necessary before one could acquire the detailed composition patterns needed to make receptor modeling feasible. The second and later generation researchers in this field know how to use INAA, XRF, etc. in research, but most don't have the backgrounds in nuclear physics and chemistry that the first generation does. It gives me much concern that the more recent students think of concentrations as values printed out by a computer on a reasonably smoothly functioning data-handling system rather than as something derived from the area under a funny shaped peak of a hand plot of the γ-ray spectrum. However, in the same vein, Manhattan Project nuclear chemists may have been concerned that nuclear chemists of my generation never constructed a Feather plot or determined a γ-ray energy from an absorption curve! Nor do I feel insufficient because I use spreadsheets to work on data, although I would have great difficulty developing the software.

Both environmental and nuclear chemistry students are unique among chemistry graduate students in their need for some exposure to statistics. In other areas of chemistry, the measurements are usually of an analog quantity rather than of a finite number of events per channel, as in nuclear counting experiments. Furthermore, unlike the case of most environmental studies, experiments are done under carefully controlled conditions that can be reproduced in time and space. For students in those areas, the error analysis methods of physical chemistry laboratory or the calculations of standard deviations as in analytical chemistry are usually sufficient for treatment of errors in their research. In contrast, nuclear chemists invariably need more knowledge of statistics for extraction of net peak areas from spectra containing small numbers of events, performing least-squares fits to determine coefficients of angular correlations, etc.

Environmental chemistry students need stronger backgrounds in statistics because of the impossibility of controlling the variables in field experiments. Careful design of sampling strategies can reduce some of the fluctuations, but never completely remove them. The only solution to the problem is the taking of rather large numbers of samples and then using powerful statistical methods, e.g., multiple linear regression or factor analysis, to extract the maximum information from the data.

Statistics is usually taught inefficiently by other departments, as they often require a 3-hr semester course to cover material that I can cover in about three weeks in our graduate-level environmental chemistry course. Furthermore, most introductory statistics courses do not include advanced topics such as factor analysis, which are needed by environmental chemists. In my view, most students do not need to know the computational details of multivariate methods such as factor analysis, as it is more important to understand how to interpret the results. The smaller amount of statistics needed by nuclear chemists could probably be taught in about two weeks within the radiochemistry or nuclear chemistry courses. Excellent software for personal computers is now available for performing simple to sophisticated treatments of data. These could be used effectively in having students gain experience in treating complex data sets.

IV. Short-Term "Retreading" of Non-Nuclear Chemists

All of us are probably guilty of seeking to fill positions in our research groups with people who already have all of the experience that the work will require. From a short-term point of view, this is the most expedient way in which to get work done efficiently. However, from the longer range point of view, we fail to take advantage of some otherwise excellent people who lack certain skills or experience. More important, the people we hire to fit exactly into certain molds get very little added breadth from the new position. This is especially unfortunate at the research associate ("post-doc") level, which should often be used to broaden the experience of prospective academicians.

The more experience I gain, the more I feel that we would serve ourselves and the field best by hiring the best qualified people even if they don't already have all of the specific skills needed for the position, e.g., a very good physical or analytical chemist for a position that requires use of nuclear methods. At the Ph.D. level, if the person's graduate school training has been done properly, the person should have mainly learned how to attack problems, not just the latest techniques and theories of their very specific area of research. If more of us would hire such people and train them in the areas that they need to know, we could overcome the growing shortage of people with nuclear skills. At Maryland, we have had good success in a number of cases in training people who have previous degrees at the B.S., M.S. or Ph.D. level, but are lacking in nuclear skills. This can be done most quickly by having them go through the short course described above while, simultaneously, being given "hands-on" experience under the guidance of a graduate student or research associate who is experienced in the use of our equipment. As this approach lacks the depth of training that our graduate students receive, we also recommend that they take or audit the radiochemistry and nuclear chemistry courses at the earliest opportunity to get the required background in the field.

V. Final Comments

Graduate training in nuclear chemistry, environmental chemistry or the other fields noted (geochemistry, cosmochemistry, etc.) has one important difference from that of the classical areas of chemistry, namely that courses in these areas are taught at so few universities that very few of our entering students have any backgrounds in these fields. Entering graduate students in physical chemistry, for example, have had a minimum of two and usually more courses in that field. In graduate school, those students probably take two or three more graduate level courses in their subdiscipline of chemistry, but at least one of them is usually a part of the core of courses taken by all students. In contrast, most students interested in the peripheral areas come to us with no prior courses and the graduate or upper division courses we require them to take are rarely part of the core curricula. Furthermore, as we are working at the interface with another discipline, students probably will not have taken courses in that area, e.g., nuclear chemistry students will probably not have previously taken nuclear physics courses or environmental chemistry students, courses in meteorology, water quality, etc. If we do not plan carefully, our students can spend more time taking courses than the typical chemistry graduate student. In addition, our graduate students may not be able to make a great deal of progress in their research until they have taken some of the graduate level courses.

A further problem for environmental chemistry students is that, by the nature of the field, they must usually collect and analyze a large number of samples in order to obtain a large enough body of data to observe statistically significant trends. Thus, the time they need to spend on research and the sizes of their theses are often much greater than those of students in central areas of chemistry.

Nuclear chemistry students suffer different, but related problems. Most "cutting edge" research now requires that the research group travel to an accelerator or other large facility to perform the experiments and bring data tapes home for subsequent analysis and interpretation of the data. Usually there is no local facility at which graduate students can afford to "screw up" their initial experiments and learn about research from the experience. Trips to facilities are normally so few and far between, that the research group has to plan very carefully to avoid mistakes, so the experiments can't be entrusted to a new graduate student. When the student's own experiment is done, he or she is often just a team member responsible for one aspect of the experiment, much as high energy physics research has been for decades. Although the student is usually responsible for interpretation of all of the data from that experiment, we must be very careful to ensure that he or she understands the total experiment. Furthermore, if an experiment fails, the student will be delayed for at least one cycle on the facility, lengthening the time in graduate school by months or a year!

The factors mentioned in this section tend to lengthen the time that students in nuclear chemistry and related disciplines require to complete their requirements for graduate degrees. I feel that Ph.D. degrees should require three to four years beyond the B.S. degree, M.S. degrees (with research theses) about two. Unfortunately, five years for a Ph.D. and three years for an M.S. are probably more typical for our group at Maryland and I suspect this is the case in many other departments offering these areas on the periphery of chemistry. We must find ways to keep the times shorter. If we develop reputations among prospective graduate students of keeping students longer than in conventional areas of chemistry, we will have an even more difficult time recruiting students for research and training in these areas.

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APPENDIX G

NUCLEAR AND RADIOCHEMISTRY AT NATIONAL LABORATORIES

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The National Laboratories, founded during and after the World War II Manhatten Project, were initially focussed on fission energy for power generation and for defense applications. Nuclear chemists and radiochemists played a central role in all aspects of the early development of nuclear power reactors and in providing diagnostic measurements of nuclear explosives. The need for trained scientists in chemistry-based nuclear disciplines was recognized at an early stage by the academic community and several universities and colleges established formal curricula in nuclear chemistry and radiochemistry to address this need.

Following a period of rapid development and expansion of nuclear-related activities in the 1950's and 1960's, public and political sentiments regarding the safety and environmental impacts of nuclear power led to a rather abrupt decline in the 1970's. Public and political sentiments regarding the development of nuclear weapons also led to a de-emphasis in nuclear weapons development during this same period. The activities of the National Laboratories slowly evolved, becoming more diversified in energy-related research that was not based on the fission process. Even the more mission-oriented laboratories, Los Alamos and Livermore, emphasized growth in laser-fusion, laser isotope separation, and magnetic fusion; programs characteristic of "big physics". The need for nuclear chemists and radiochemists did not vanish with the diversification of programs, although their activities centered more on applications rather than basic research. Diagnostics for laser imploded fusion pellets, processing of materials for isotope separation, the use of nuclear probes in materials studies, the isolation, treatment and disposal of nuclear waste, and environmental radiochemistry became new areas that attracted nuclear scientists. Although activities related to nuclear power generation continued to decline in the late 1970's, a dramatic reversal in the downward-trend of nuclear weapons development occurred after the election of a new administration. Changing National priorities increased the requirements for trained nuclear scientists, but the availability of new graduates had already diminished.

The need for trained nuclear chemists and radiochemists extends beyond the immediate high-visibility programmatic requirements and includes many areas of research for which people trained in these disciplines are required at the national laboratories. Many of these areas are listed in a very general way in Table 1. Several of the laboratories have taken steps to develop in-house training because their needs for academically trained nuclear scientists are not currently being met.

The DOE Analytical Managers Group has recognized the need for training chemists in radioanalytical skills. This group of key managers of analytical chemistry organizations throughout the DOE complex is preparing a position paper, presently in draft form, in which they reaffirm the importance of research and training in maintaining DOE's "corporate memory" in this most important technical area. The report's recommendations include:

- development of a compendium of current methodology
- modernization of radioanalytical chemistry by incorporation of advanced methodology
- investigation of new concepts for radioanalytical chemistry
- fostering radiochemistry degree programs at selected universities
- establish radioanalytical training centers (or centers of excellence)

Brief discussions of activities at Oak Ridge, Argonne, Brookhaven, Livermore, and Los Alamos National Laboratories follow. These activities have been undertaken primarily to train new employees in the skills required to carry out radiochemical tasks safely and properly. In some cases, older employees take the courses as refreshers or to learn new techniques.

OAK RIDGE NATIONAL LABORATORY

Oak Ridge National Laboratory (ORNL) has several divisions which use people trained in nuclear chemistry and radiochemistry. These include the Analytical Chemistry, Chemistry, and Chemical Technology Divisions. The Analytical Chemistry Division has both research and service functions and is the largest ORNL user of nuclear and radiochemists. All of these divisions experience difficulty meeting their staffing requirements with properly trained people to perform necessary tasks. As a result, ORNL has developed several courses for training employees in the handling and use of radioactive materials. These include:

1. A short lecture course conducted by the ORNL In-house Training organization. This course has been offered for several years.

2. A two-week summer course presented by Oak Ridge Associated Universities for the Chemical Technology Division. This course is designed to provide new employees with the minimum knowledge necessary to handle radioactivity safely and properly in a laboratory environment.

3. An in-depth Analytical Chemistry Division course for BS/MS level division members. This course, taught by a senior member of the Analytical Chemistry Division, is offered expressly because the division has been unable to hire enough properly trained college graduates, and requires a substantial commitment of time from teacher and students.

ARGONNE NATIONAL LABORATORY

Argonne National Laboratory (ANL) does not offer formal training courses in nuclear chemistry or radiochemistry although outside specialists are occasionally brought in to lecture on topics such as plutonium chemistry. The Analytical Chemistry Laboratory which is administratively within the Chemical Technology Division, has primary responsibility for analytical radiochemistry at Argonne. Other research and development activities requiring the skills of nuclear and radiochemists are also carried out in Chemical Technology and in the Chemistry Divisions. Because of the difficulty in hiring people trained in the necessary skills, the Chemical Technology Division places newly hired people to work with staff members experienced in the handling and use of radioactive materials. This form of on-the-job training has been in use for more than fifteen years.

BROOKHAVEN NATIONAL LABORATORY

Nuclear medicine and radiopharmaceuticals are the major activities at Brookhaven requiring a staff trained in nuclear and radiochemistry. The primary need is for scientists trained in both the production and the use of radioisotopes, but despite some extraordinary efforts, Brookhaven has had extreme difficulty in finding college graduates with these combined skills. Scientists trained in the area of radiopharmaceuticals are somewhat more available, but the pool of American applicants is very small. In a recent attempt to hire such individuals it became clear that their relevant expertise was primarily in radiolabeling, not in producing, purifying, and separating radioisotopes.

Because of Brookhaven's inability to find and hire properly trained scientists, they have relied heavily on their experienced staff to train newcomers. Untrained individuals are assigned to work with those experienced in the techniques of handling radioactive materials, however, Brookhaven is giving consideration to providing a formal training program.

LOS ALAMOS NATIONAL LABORATORY

Radiochemical weapons diagnostics, basic and applied nuclear physics and nuclear chemistry, radioactive isotope production and processing, nuclear medicine, actinide chemistry, radioactive waste management, atmospheric chemistry and isotope geochemistry are major activities at Los Alamos that require a trained staff in the nuclear sciences. In addition, Los Alamos has a substantial effort in plutonium processing programs that involve all aspects of plutonium chemistry --plutonium recovery from scrap, isolation and purification of plutonium and isotopic separation. The entire spectrum of activities from research on the fundamentals of process chemistry to limited production is included. Analytical radiochemistry support to the plutonium processing programs requires a significant level of trained staff.

In-house courses in nuclear and radiochemistry conducted by Los Alamos staff members, and occasionally by outside scientists, have been a part of the Los Alamos tradition for many years.

LAWRENCE LIVERMORE NATIONAL LABORATORY

Nuclear chemists and radiochemists play a central role at LLNL in providing diagnostic information on the performance of nuclear devices for use in defense and in peaceful applications. The range of activities at Livermore requiring the skills of nuclear scientists extends beyond diagnostics and includes the areas of waste isolation, nuclear properties of materials, fuel reprocessing, radionuclides in the terrestrial and marine environment, separations chemistry, nuclear instrumentation, and actinide chemistry, to name a few.

Although many of these activities reside within the Nuclear Chemistry Division. scientists with formal training in nuclear chemistry and radiochemistry, many with advanced degrees, reside in Chemistry and Materials Science, Earth Sciences, "Y" Division (Lasers), and Environmental Sciences. In-house courses have been taught periodically by the Nuclear Chemistry Division, mainly to familiarize B.S. degreed chemists with radioactivity, separation and measurement techniques, and the safe handling of radioactive materials. LLNL has an active role in the ACS sponsored summer scholarship program at San Jose State University and a small number of grants are available to these scholarship winners for continuing studies in Livermore's summer student program. Livermore has also conducted summer courses focussed on introducing nuclear and radiochemistry into the undergraduate curriculum of minority colleges and universities. These summer courses were designed to provide intensive training to physics and chemistry faculty members through a comprehensive lecture and laboratory program. The minority colleges program also includes semester courses at these academic institutions taught by LLNL staff members.

Both Los Alamos and Livermore are experiencing the loss, through retirement, of a substantial number of their "core" group of nuclear and radiochemists who have been with these laboratories since their beginnings. To some extent, the impact of declining numbers of academically trained scientists in nuclear and radiochemistry has been more severe at the two defense laboratories because their primary mission relies more heavily on these disciplines. Within the next decade, we anticipate the staffing levels of academically trained nuclear scientists will consist of the sixties and seventies generations--the period during which the problem of declining faculty, students and research funding was first addressed. Indeed, since the latter part of the 1970's Livermore and Los Alamos have had to extend their recruiting strategies to include scientists in related fields such as geochemistry and cosmochemistry to fill positions that might otherwise attract academically trained nuclear chemists and radiochemists.

The future requirements for academically trained staff at Livermore and Los Alamos include scientists having a fundamental understanding of nuclear reactions, nuclear structure, spectroscopy, and theory. Typically, academic training at the PhD level in nuclear chemistry, nuclear physics, or related disciplines is necessary to address the scope and breadth of activities in diagnostics R&D and to maintain a healthy base of fundamental research in the nuclear sciences. In terms of the expanding missions of these laboratories that include increased emphasis on actinide processing, nuclear waste, and numerous activities related to special nuclear materials, the need for academic training in radiochemistry is already critical.

In the area of national defense, the requirement for trained scientists extends beyond the National Laboratories and includes activities at production plants such as Hanford and Savannah River; process development sites like Rocky Flats; Mound Laboratory; Idaho Nuclear Engineering Laboratory, the future site for plutonium isotope separation; the Nevada Test Site nuclear waste repository. The National Laboratories and related nuclear industries will continue to provide specialized training to degreed chemists in areas that are unique to their charters and missions, but the broader skills, capabilities, and flexibility that emerges from formal academic training in nuclear and radiochemistry require years to achieve in a focussed working environment.

Our academic institutions can help alleviate the problem by including nuclear and radiochemistry in the required curriculum in chemical, physical, and life sciences. Small, central, radioisotope facilities, principally for instructional purposes could be established to familiarize students with radioactivity, the use of tracers, separations, counters, and other fundamental aspects of radioactive substances.

Table 1. ACTIVITIES AT NATIONAL LABORATORIES THAT REQUIRE TRAINING AND SKILLS IN NUCLEAR CHEMISTRY AND/OR RADIOCHEMISTRY

BASIC RESEARCH
- Chemical reaction mechanisms
- Nuclear reaction mechanisms
- Nuclear property studies
- Heavy element chemistry
- Separations chemistry
- Geochemistry
- Geochronology
- Cosmochemistry

ANALYTICAL CHEMISTRY
- Tracers in analyses
- Radiochemical analyses
- Activation analysis
- Radiochemical process control
- Instrumentation development

PROCESS APPLICATIONS R&D
- Radioactive waste treatment
- Radiotracers in process development
- In-line instrumentation

HEALTH-RELATED APPLICATIONS
- Radiotracers in bioassay
- Health physics
- Nuclear medicine

ENVIRONMENTAL APPLICATIONS
- Movement of radioactivity through the biosphere
- Mechanisms of materials transport

NUCLEAR WEAPONS APPLICATIONS
- Nuclear device diagnostics
- Heavy element chemistry

APPENDIX H

Resource Document
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Training Requirements for Chemists in Radiotracer Development for Nuclear Medicine

Introduction

Nuclear medicine is one of the most inter- and multidisciplinary of the medical subspecialties today. Although progress in the practice of nuclear medicine is driven by an integration of basic science, high technology and medical practice, it has been the advances made by chemists with specialized training in the nuclear technologies which have played a major role in shaping the state of the art as we know it today. We feel that the vitality and evolution of nuclear medicine and the development and application of the new methods and new technologies to problems in the basic and clinical research arenas will continue to be shaped, in large part, through innovation in chemistry and that the needs for chemists with advanced training will increase for the foreseeable future.

This panel was organized to address the current and anticipated future shortage of chemists with advanced training to fill positions in the nuclear medicine field. Although hard data and statistics are difficult to acquire, we will attempt to highlight the impact of chemistry on nuclear medicine and to describe the growth of the field which has led to an increasing need for chemists resulting in the current manpower shortage. We also will make recommendations for attracting Ph.D. chemists to careers in nuclear medicine research and possible mechanisms for postgraduate training. Solving this problem and establishing a long term committment and mechanism for advanced training is critically important to meet the current needs of the profession and to assure future growth and innovation.

The Impact of Chemistry

The application of nuclear chemistry to medicine has been described as one of the intellectual frontiers related to chemistry and national well-being in the 1985 Pimentel Report (Opportunities in Chemistry, National Academy Press, Washington D.C.,1985, page 263). This report also designated the "chemistry of life processes" as one of the five frontiers deserving high priority. While there are many innovations in chemistry which have advanced the practice of nuclear medicine, there are two areas which have presented a particular challenge and which exempify the key role played by chemists. These include the development of highly selective technetium-99m labeled radiopharmaceuticals and the development of short-lived radiotracers for positron emission tomography (PET).

Technetium-99m: Of the many classes of radiotracers which are currently used in the practice of clinical nuclear medicine, none has had more of a impact than technetium-99m.

Today more than 85 % of the twelve million nuclear medicine procedures performed annually involve the use of a technetium-99m labeled radiopharmaceutical. Technetium-99m is available at low cost from a generator and has nearly ideal decay properties for imaging. However, the full exploitation of technetium-99m in nuclear medicine required the development of radiotracers for imaging the brain and the heart. To this end, for the past two decades, there has been a concerted research effort by several groups directed to understanding the chemical properties of this artificial element, the structures of its compounds and the relationship of these factors to biological specificity. This fundamental approach has yielded the recent development of organ-specific new technetium-99m radiopharmaceuticals for diagnostic imaging of brain and heart.

Positron Emitter Radiotracers and PET: Over the past fifteen years, there has been an intense growth in the field of PET brought about, in major part, by the demonstration that PET and short lived positron emitting radiotracers could be used to probe biochemical transformations in the living body. Once the possiblity of obtaining metabolic information in the living human brain was demonstrated using highly selective radiotracers such as 2-deoxy-2-[^{18}F]fluoro-D-glucose (^{18}FDG), and the technology (cyclotrons, PET instrumentation, and radiotracer chemistry) became more readily available, the number of cyclotron-PET centers increased from four in 1976 to more than two dozen in 1987 (Table 1) with a projected number of 50 by 1995. Chemists have played a central role in shaping the PET field as we know it today because it is through research in chemistry that reliable methods for the production of the short-lived positron emitters such as carbon-11, fluorine-18, nitrogen-13 and oxygen-15 were developed, and new short-lived radiotracers were synthesized. It is noteworthy that while PET began in the nuclear medicine field, it has rapidly been adopted as a scientific and clinical research tool in the fields of cardiology, neurology, oncology, and psychiatry.

Development and Growth of the Field

Basic and applied research in chemistry has played a major role in developing safer, more efficacious radiopharmaceuticals for nuclear medicine. The participation of chemists in this field has increased significantly over the past two decades. The growth of the field can be attributed in large part to sustained support by the Department of Energy (DOE) and by the National Institutes of Health (NIH). New developments in radiopharmaceuticals are rapidly commercialized and radiopharmaceutical chemistry has become one of the most active sub-disciplines of nuclear medicine. Unfortunately, long term programs to address the inevitable manpower shortage resulting from this rapid growth are not in place.

Funding for the development and application of radiotracers comes from three major sources the DOE, the NIH, the Veterans Administration and the radiopharmaceutical industry (see Table 2 for funding for nuclear medicine research from the DOE (OHER), NIH and the VA). The greatest single source of continuing support originated with the Atomic Energy Commission in the form of a committment to the medical application of nuclear technology. This mission, which began nearly forty years ago, has continued under the aegis of the Energy Research and Development Agency and is currently a mission of the Department of Energy (Office of Health and Environmental Research). It is a mission characterized by the support of basic research in the development and application of new radionuclides and radiotracers and associated high technology, and state of the art instrumentation at the national laboratories and at universities. The development of technetium-99m, thallium-201 and ^{18}FDG can be sited as milestones developed wholly or in part through DOE support.

While the DOE (and formerly AEC and ERDA) has played and continues to play the major role in the long term (over four decades) support of basic research in the development of the tracers and technologies used in the current practice of nuclear medicine, there are also other important sources of support for radiotracer development and for new clinical applications of the nuclear technologies. For example, the NIH supports many investigators in the development and applications of radiopharmaceuticals. In addition, nearly a decade ago, the National Institute of Neurological, Communicative Diseases and Stroke (NINCDS) recognized the potential of PET as a scientific tool for addressing problems in the neurosciences and announced the availability of a program project grant for the development and support of a clinical and basic neuroscience research efforts which utilized PET (NIH Guide for Grants and Contracts, 7(11), August 18, 1978). Moreover, the announcement acknowledged that the potential applicability of PET was not restricted to problems in the neurosciences and encouraged collaborations in the development and use of PET facilities and services for other applications in medicine. Of the six institutions which shared in the initial $5.7 million award, all still have active PET programs. Numerous other cyclotron-PET centers have been constructed since that time supported by DOE, NIH and other sources. It is anticipated that by the year 1995 as many as 50 cyclotron-PET facilities will be operational within the United States.

Innovation in development of radiotracers and associated instrumentation has been accompanied by a rapid transfer of technology and increased commercialization and integration into the practice of nuclear medicine. At this time, several firms are committed to the development of high quality, competitively priced instrumentation for nuclear medicine. For example, in the PET field, state of the art scanners are being marketed along with radioisotope delivery systems that include a compact cyclotron and chemistry modules based on new developments in radiotracer synthesis. The industrial sector is actively addressing the issue of clinical PET and the installation of competitively priced systems in hospitals to take advantage of the new advances in diagnostic advantages of PET is underway. At the time which this report was prepared, there were 15 new Computer Technologies

Incorporated positron emission tomographs ordered and under construction with 6 in the field (K. Halliday, CTI, personal communication). Positron Corporation has sold ten tomographs within the last three years and expects to sell 12 more in 1988 and projects a worldwide market growth of 10 units per year in the research sector and 20-30 units/year in the clinical sector (N. Mullani, Positron Corporation, personal communication). Each facility receiving one of these units will require one or more chemists to develop or oversee production of the new radiopharmaceuticals.

Perhaps the growth and vitality of chemistry in nuclear medicine is best represented by the professional activities of the chemists working in the field. There is an increasing active representation of radiopharmaceutical chemists at scientific meetings and in the scientific literature. For example, in 1976, in response to a growing need for a special forum for addressing some of the unique problems in radiopharmaceutical chemistry, the First International Symposium on Radiopharmaceutical Chemistry was organized and held at Brookhaven National Laboratory and 111 papers were presented. The meeting has continued on a biannual basis and at the Sixth International Symposium held in Boston in 1986, there were 311 participants, 174 presentations and posters. There is an equally strong representation of radiopharmaceutical chemistry at the Annual Society of Nuclear Medicine meeting with a steady increase in the number of papers and sessions devoted to presentations on radiotracer development. In 1976, the Radiopharmaceutical Science Council (of the Society of Nuclear Medicine) was established. It has grown from 100 members to a current (1987) membership of 616 (Ernest Rendon, Society of Nuclear Medicine, personal communication). There are also conferences on special topics in radiopharmaceutical chemistry which are organized on an irregular basis and papers on radiopharmaceutical development and application are being presented at a growing number of meetings devoted to research in the neurosciences, in cardiology and in oncology, to name a few.

Current Manpower Shortage

The output of chemists trained in the nuclear technologies required for the nuclear medicine field has not kept up with the growth of the field. As a result, employment opportunities for chemists in clinical nuclear medicine departments and related departments and institutions currently exceed the supply of trained professionals. Many new centers (especially in the cyclotron-PET field) are unable to hire the trained chemists required to set these institutions into operation and established groups are having difficulties in adding new staff or in replacing individuals who have changed positions. This problem is already serious in the cyclotron-PET field and the predicted doubling of the number of centers by 1995 in the absence of a significant effort to recruit chemists and to provide a mechanism for advanced training would mean that most of these new centers could not be set into operation.

The shortage of chemists with training focussed on radiochemistry and synthetic techniques results both from the overall slow growth in the number of available graduates in chemistry (Table 3), the lack of active recruitment efforts on the part of the radiopharmaceutical chemistry community and the lack of programs specifically dedicated to postgraduate training of chemists in the nuclear medicine technologies. To exemplify the first part of the problem, the numbers of Ph.D. chemists produced in the specialized fields of chemistry has, for the most part, remained the same or has decreased over the past ten years. Universities are finding it difficult to fill faculty positions. It has been reported that in 1970, universities and colleges in this country graduated 2223 doctoral chemists of which 18.5 % sought academic careers. The year 1985 saw 1836 doctoral chemists graduated of which only 8 % considered academia as a career option. A survey taken in 1987, indicated that 381 academic positions were available at Ph. D. granting institutions, many of which had remained vacant for two or more years (Gassman, P. G., Will "Chemistry" Exist in the Future?, Chem. and Eng News, December 14, 1987, page 51). A negative public image of chemistry (reinforced by the recent tragedies at Bhopal and Chernobyl), the perception that chemistry is an unattractive profession and increasing scientific illiteracy and intuitive risk judgments (Slovic, P., Perception of Risk, Science, 236: 280, 1987), have exacerbated the problem resulting in a gradual decline in both the quality and quantity of students who elect chemistry as a career.

The problems being experienced in the field of chemistry in general are amplified for the nuclear medicine area. Since this research specialty is not a common interest of faculty members in major universities with graduate programs in chemistry, there is a problem in attracting Ph.D. chemists to the field during the time when they are making career choices or when they are making decisions on advanced or specialized training at the postdoctoral level.

Postgraduate training of chemists in the specialized areas of radiotracer research and development has usually taken place at the National Laboratories or at Universities having an active nuclear medicine research programs and the high technology resources. This is usually effected through a limited number of postdoctoral positions in active nuclear medicine or radiotracer research programs and is restricted by the available monies for graduate students and postdoctorals. These positions are almost solely supported by the DOE or NIH. However, the output of these training programs has not been sufficient to meet current demands and as a result, new chemists with no advanced training are frequently trained on the job in industries or at research institutions. The important point is that there is presently no formalized, long-term committment to support postdoctoral training for the chemists required to staff the existing and anticipated clinical and research facilities. The problem is compounded when the needs for specialized high technology resources (cyclotron or accelerator, special licenses, equipment, shielding, etc) and personnel qualified to carry out training programs are considered.

Training Requirements

To meet the current and anticipated needs brought about by rapid growth in the radiotracer development and PET areas of nuclear medicine, chemists with Ph.D. or equivalent training in the traditional subdisciplines of chemistry (nuclear and radiochemistry, organic chemistry, biochemistry, physical chemistry, inorganic chemistry, pharmaceutical chemistry and analytical chemistry) are required. Specialized training in the nuclear technologies related to research and development in nuclear medicine is also required, preferably at the postgraduate level. It is important to emphasize that multidisciplinary training cannot replace a rigorous education in the basic principles of chemistry followed by specialization.

While chemists in all of the subdisciplines listed above have played a role in the nuclear medicine field, there is a particular need for individuals with training in radiochemistry and synthetic (organic and inorganic) chemistry. The type of chemist required for a particular position also depends on the problems being addressed. This is not an obvious or trivial point since one frequently sees employment ads for a radiochemist when the position description is for an organic chemist. Thus while radiochemistry (and to a lesser extent nuclear chemistry) are generally required in research centering on the accelerator and reactor production and purification of the radionuclides, it is expertise in organic chemistry which is essential in the development of synthetic routes to new radiotracers. Similarly inorganic chemistry has played an essential role in the development of radiotracers labeled with technetium-99m and other inorganic radionuclides. The principles of biochemistry and physical chemistry are generally applied to the evaluation of the new radiotracers, in developing kinetic models and in developing a knowledge base on the relationship of structure to biological behavior. Pharmaceutical and analytical chemists frequently address problems in quality control and documentation for regulatory agencies although this role is frequently undertaken by individuals with other specialties. Since progress in nuclear medicine thrives on a multi- and interdisciplinary approach, chemists who work effectively in this field generally acquire some perspective on the problems of other disciplines represented.

Summary and Recommendations

There is a current shortage of chemists at the Ph.D. level who also have advanced training related to research in nuclear medicine. The shortage is especially serious with subspecialties like radiochemistry and synthetic chemistry (organic and inorganic). The shortage stems from four major factors (1) rapid growth of the field especially the PET field, (2) the decrease in the number of chemistry graduates, (3) the low visibility of career opportunities for chemists in nuclear medicine research and (4) the lack of a long term commitment and funding for programs dedicated to postdoctoral training of Ph.D. chemists to fill positions in radiotracer research and development. The following recommendations focus on addressing the manpower shortage in the nuclear medicine field. All of these recommendations will require support in terms of a long term commitment and funding to reflect the unique contributions of chemistry to the quality of life and to the delivery of health care.

Proposals to attract chemists to careers in nuclear medicine:

1. Public Relations: The contributions of nuclear medicine to health care should be publicized in the media (television and magazines) to address the problem of public awareness of the contribution of chemistry to medicine and to begin to improve the public image of chemistry. This should be undertaken by chemists and physicians in the field of nuclear medicine research with the consultation of professional science writers and media experts.

2. Contacting Chemistry Graduates: Lectures to graduate and undergraduate chemistry students on the contributions of chemistry to advances in the field of nuclear medicine should be sponsored and take place on a regular basis to contact chemists at the graduate and undergraduate level. These lectures should be given by chemists who are leaders in the field, who have active research programs and who are good speakers.

3. Presenting Radiotracer Research in the General Chemistry Literature: Chemists in the field of nuclear medicine should write review articles on research in chemistry in the nuclear medicine field for popular scientific journals read by chemists (for example Science, Accounts of Chemical Research, Chemical Reviews).

4. Symposia: Special symposia should be held at ACS meetings on research and career opportunities for chemists in the nuclear medicine field. The format should be a mixture of information on opportunites for chemists and reviews of current special topics and new developments in radiotracer research. Reviews should be sufficiently general to be interesting to chemists who have no background in the nuclear medicine field. Here it is important to communicate the vitality of the field and the role that creativity in chemistry has played in shaping the state of the art.

Proposals to address advanced training for chemists at the graduate and postgraduate level.

1. Internships and Fellowships: Internships and fellowships should be established at the graduate and postgraduate level at appropriate national laboraotries and universities which have the required high technology facilities, active nuclear medicine research programs and personnel. These programs should also have a structure and curriculum which would enable a graduate chemist to choose a program which suits a particular career goal. A training program could reflect the character and unique personnel resources and facilities of a particular institution. There should be long term support for these programs and these programs should focus on training. Proposals for training programs could be solicited and competitively reviewed by a funding agencies such as the DOE and NIH. Industrial support would also be appropriate.

2. Joint Faculty Appointments: Joint faculty appointments at nearby universities should be encouraged for research chemists in the nuclear medicine field in non-academic institutions such as the national laboratories. This is especially important in areas such as nuclear and radiochemistry which are poorly represented in academia. This would

increase the exposure of chemistry students to the research activities of chemists in the nuclear medicine field and provide expertise in teaching basic courses such as nuclear and radiochemistry at the graduate level.

These are only preliminary recommendations and it is expected that input from this workshop will lead to other proposals.

Table 1. Research and Clinical Positron Production and Imaging Centers in North America (1987) (includes completed and developing centers, updated from Wolf, A. P. and Fowler, J. S. in Positron Emission Tomography, M. Reivich and A. Alavi, editors, 1985, pages 63-80).

Baylor University, Waco, Texas
Brookhaven National Laboratory, Upton, New York
Case Western Reserve, Cleveland, Ohio
Duke University, Durham, North Carolina
Johns Hopkins University, Baltimore, Maryland
McMaster University, Hamilton, Ontario, Canada
Massachusetts General Hospital, Boston, Massachusetts
McGill University, Montreal, Quebec, Canada
M. D. Anderson Hospital, Houston, Texas
Mt. Sinai Hospital, Miami Beach, Florida
National Institutes of Health, Bethesda, Maryland
North Shore University Hospital, Manhassett, New York
Oak Ridge National Laboratory, Oak Ridge, Tennessee
Sloane Kettering Cancer Center, New York, New York
TRIUMF, Vancouver, British Columbia, Canada
University of Pennsylvania, Philadelphia, Pennsylvania
University of California, Berkeley, California
University of California, Irvine, California
University of California, Los Angeles, California
University of Chicago/Argonne National Laboratory, Chicago, Illinois
University of Minnesota, Minneapolis, Minnesota
University of Michigan, Ann Arbor, Michigan
University of Tennessee, Knoxville, Tennessee
University of Texas Health Sciences Center, Houston, Texas
University of Washington, Seattle, Washington
University of Wisconsin, Madison, Wisconsin
Washington University, St. Louis, Missouri
West Los Angeles VA Medical Center, Wadsworth Division, UCLA, Los Angeles, California

Table 2. Funding for nuclear medicine research from the Department of Energy (Office of Health and Environmental Research), the National Institutes of Health and the Veterans Administration (This data was provided by Dr. John McAfee, Upstate Medical Center, Syracuse, New York).

Agency	Total Nuclear Medicine Funds	Percent for Radiopharmaceutical R and D
DOE	$17,918,000	43.4
NIH	$45,186,000 [a]	22.2
VA	$1,360,000	na

[a] includes direct and indirect costs.

Table 3. Number of graduated doctoral chemists

Doctorate Discipline	1986[a]	1981[b]	1976[b]
Analytical	257	229	152
Inorganic	260	188	226
Nuclear	18	12	25
Organic	510	494	497
Pharmaceutical	58	52	55
Physical	293	275	355
Polymer	72	62	42
Theoretical	41	33	48
Chemistry, general	290	193	144
Chemistry, other	104	74	66
TOTAL	1903	1612	1988

[a] Summary Report-Doctoral Recipients from U.S. Universities National Academy Press, Washington D. C.

[b] Chemical and Engineering News, Sept 7, 1987, page 23.

APPENDIX I

RADIOPHARMACEUTICAL INDUSTRY

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Nuclear Medicine

Nuclear medicine may be defined as a medical diagnostic specialty which uses *in-vivo* radioactive gamma-emitting compounds, or radiopharmaceuticals, whose distribution in the body over time can be detected by external imaging with a gamma camera. Although nuclear medicine has played a major role in the diagnosis and monitoring of a broad spectrum of diseases and disorders for the past two decades, the general public is largely unaware of its scope and clinical importance. It is a very well established diagnostic imaging modality as illustrated by a number of facts:

- There are nuclear medicine departments in over 3,800 hospitals in the United States. This comprises all major teaching facilities as well as the vast majority of government-owned and community hospitals.

- One out of 10 hospitalized patients has a diagnostic nuclear medicine procedure performed.

- There are approximately 600,000 nuclear medicine procedures performed in the United States each year. This constitutes an annual market of $150 million in the U.S. alone.

The major strength of nuclear medicine is its capacity to provide unique diagnostic information. Other diagnostic imaging modalities including radiological (x-ray) procedures, magnetic resonance imaging (MRI), and ultrasound, provide anatomical or structural information; due to the use of radiopharmaceuticals, which are *in-vivo* tracers, nuclear medicine can assess organ function, such as the adequacy of the blood supply to the heart muscle, bile flow and concentration in the gallbladder, and bone metabolic activity.

Additional advantages of nuclear medicine diagnostics include their non-invasive nature, and low risk. Since radioactivity can be detected with very high sensitivity, extremely small amounts of radiolabeled drugs are required for imaging. Radiation doses are very carefully controlled in nuclear medicine and are generally comparable to those a patient may receive from medical x-ray.

An example of a rapidly growing area of nuclear medicine is the use of thallium-201 (^{201}Tl) imaging to detect coronary artery disease (CAD). Frequently, CAD is silent and patients with very significant disease, i.e., severe atherosclerosis of their coronary arteries and consequently severely compromised blood supply to their heart muscle, can appear normal at rest. In order to elicit the symptoms which will permit the problem to be diagnosed, the patient is usually first exercised on a treadmill before receiving an intravenous injection of $^{201}TlCl$ in saline solution. Within 3 to 10 minutes, the patient is placed on an imaging table and typically three views of the heart are acquired with a gamma camera. In the normal subject, the heart muscle extracts and accumulates the $^{201}Tl^+$ uniformly, and smooth even images of the walls of the heart chambers are obtained. A patient with severe coronary artery disease, however, does not show this uniform distribution as the blood flow, and radioisotope delivery, to certain regions of the heart, is compromised. This results in a heart image with "cold spots".

Radiopharmaceuticals

FDA approved, commercially available radiopharmaceuticals which are used in diagnostic nuclear medicine procedures may be simple radionuclide ions, radioactive metal ion complexes, or labeled compounds.

The most useful radionuclides for imaging are those which decay with single photon gamma emission in an energy range of 100-300 keV and a $t_{1/2}$ of several hours to days. Radiopharmaceuticals involving the relatively longer-lived nuclides are generally shipped as radioactive ready-to-use aqueous solutions (with the exception of the noble gases). Examples of these are $^{201}Tl^+$, $^{67}Ga^{3+}$, and ^{123}I-N-isopropyliodoamphetamine. Nuclides with half-lives in the range of a few hours or shorter can be delivered in the form of a radionuclide generator if a longer-lived parent isotope is available. The generator is generally a chromatography column packed with an organic or inorganic ion-exchange medium on which the parent isotope is adsorbed. As the parent decays, the daughter isotope grows in and may be eluted with a pharmaceutically suitable solvent. A generator, therefore, permits the delivery of a short-lived daughter nuclide by utilizing the longer half-life of the parent.

In current practice, technetium-99m (^{99m}Tc) is unquestionably the isotope of choice because of its excellent physical characteristics ($E\gamma = 140$ keV; $t_{1/2} = 6.0$ hrs) and its availability via a ^{99}Mo-^{99m}Tc radionuclide generator. The ^{99}Mo parent ($t_{1/2} = 66$ hrs) is adsorbed on an alumina column and is eluted once daily in the radiopharmacy with sterile physiological saline solution yielding ^{99m}Tc in the form of $^{99m}TcO_4^-$. A variety of ^{99m}Tc-radiopharmaceuticals for a number of imaging applications can be prepared by the user on the day of use by combining the $^{99m}TcO_4^-$ eluate with commercially available "kits", i.e. freeze-dried mixtures of non-radioactive compounds, which rapidly and quantitatively react to produce the ^{99m}Tc-agent.

There are no positron-emitting radiopharmaceuticals for PET (positron emission tomography) imaging which are currently commercially available or FDA approved for general medical use. Most positron isotopes of medical interest have short to ultrashort half-lives, e.g. ^{11}C, $t_{1/2}$ = 20 min.; ^{13}N, $t_{1/2}$ = 10 min.; ^{18}F, $t_{1/2}$ = 110 min., and must be produced by a cyclotron at the site of use.

In the next decade, a slow but significant growth of therapeutic applications of radiopharmaceuticals is expected. This new generation of agents will require alpha- or beta- emitting radionuclides which can produce a cytoxic effect within a radiation range of several cell diameters.

Radiopharmaceutical Industry

The radiopharmaceutical industry includes commercial manufacturers of:

- medical radioisotopes
- radionuclide generators
- labeled compounds, and
- non-radioactive "kits" for the preparation of ^{99m}Tc-labeled drugs.

There are four major radiopharmaceutical manufacturers in the US:

- E. I. DuPont de Nemours & Co., Inc.
- Mallinckrodt, Inc., a subsidiary of International Mineral and Chemical
- Medi-Physics, Inc., a subsidiary of Hoffman-LaRoche
- Squibb Diagnostics

All four offer a broad line of radiopharmaceuticals for current clinical use. With the exception of Squibb, all own and operate cyclotron facilities for the production of medical radioisotopes. Medi-Physics, Inc. also operates a nuclear reactor.

A number of smaller companies manufacture a more limited line of products:

- Benedict Nuclear produces a limited number of products based on cyclotron isotopes.
- Amersham has extensive cyclotron and kit manufacturing facilities in England, but its U.S. subsidiary is considerably more limited.

In addition, there are a number of companies involved in the development of radiolabeled antibodies as potential radiodiagnostic and radiotherapeutic agents. At this time, their activities are still primarily in R&D and clinical testing. Major players include:

- Hybritech, a subsidiary of Eli Lilly
- NeoRx
- Centocor

Several other firms manufacture devices for the delivery of radiopharmaceuticals (e.g. aerosol respirators) and commercial cyclotrons for the production of medical isotopes, particularly short-lived positron emitters. Although they are not producers of radiopharmaceuticals, the development and testing of their products may involve work with radioisotopes.

This report does not include commercial nuclear pharmacies, whose primary function is to prepare individual user-ready unit doses of radiopharmaceuticals from commercial products or hospital radiopharmacies which make, compound, and/or dispense radiopharmaceuticals. Manufacturers of *in-vitro* radiodiagnostics, including radioimmunoassays, are also excluded.

The total U.S. radiopharmaceutical industry, as defined above, employs approximately 4500 people (in 1988, Author's estimate). Although the use of radiopharmaceuticals and numbers of nuclear medicine studies may be expected to increase dramatically in the next decade, employment in the industry will not increase proportionately.

Activities and Functions

Although the facilities, capacity, and product mix vary from manufacturer to manufacturer, a number of common activities and functions involving the production and handling of radioisotopes and labeled compounds can be identified. It may be surprising to those unfamiliar with the industry that relatively few nuclear scientists with advanced training in nuclear chemistry, physics, engineering or health physics are employed. Since many functions involving the routine manufacture or testing of radiopharmaceuticals follow well-established procedures, they can be performed and supervised by individuals with more limited training. Scientists with advanced degrees are primarily employed in those functions which involve non-routine handling of radioactivity, the development of new procedures, and the instruction of new personnel.

- Isotope Production

  Manufacturers with cyclotron and reactor facilities employ a number of nuclear physicists or engineers who are responsible for target irradiation and other operations. In addition, these facilities employ specialists in automation engineering and computer science. A second major function is isotope purification including target processing, chemical separations, isotope identification and counting, chemical and radionuclidic purity determinations, and general quality control testing. These activities require one to two highly trained radiochemists per industry. In addition, all other individuals involved in this work need some training in radiochemistry.

- Research and Development

Exploratory research within the radiopharmaceutical industry involves the design, synthesis, and testing of potential new diagnostic products and requires specialists in chemistry and pharmacology who have some knowledge of radiochemical procedures and handling techniques. The design and synthesis of organic compounds generally requires individuals trained in organic or medicinal chemistry. Compound labeling may involve iodination, performed by organic chemists, or labeling with ^{99m}Technetium or other metal ions which is the province of the inorganic chemist. The testing of new radiopharmaceuticals involves animal model development, pharmacological characterization, and the development of structure-activity relationships. This work is planned and carried out by individuals trained in pharmacology.

Product development work and pilot plant operations, including formulation R&D, raw material synthesis, and process scale-up, requires specialists in organic and inorganic chemistry as well as chemical engineering. Once a prototype product has been developed, toxicologists and medical physicists need to determine its safety and dosimetry. Although all of these individuals need some familiarity with radiochemistry, most radiochemical procedures are of a routine nature.

- Radiopharmaceutical Manufacture

The three major product groups, radionuclide generators, hot products, and cold kits for the preparation of ^{99m}Tc agents, involve different facilities and procedures. Generator manufacture involves component assembly, parent isotope dispensing, sterilization, and final eluate testing. These are developed by mechanical engineers trained in automation procedures. The radioactive "hot" products may involve labeled compound synthesis such as the preparation of iodinated compounds, or simply the dispensing and sterilization of solutions of simple ions such as $^{201}Tl^{+}$ or $^{67}Ga^{3+}$. Individuals trained in chemical engineering as well as radiochemistry are needed. The manufacture of cold kits is analogous to the manufacture of non-radioactive pharmaceuticals. Operations include raw material synthesis, solution preparation, batching and dispensing, sterilization, and in many cases lyophilization. The development of procedures and monitoring of operations is generally performed by chemical engineers.

- Quality Control and Assurance

QA and QC employ chemists, microbiologists, and radiochemists, as well as individuals with advanced knowledge of regulatory requirements and good manufacturing practices (GMP). Activities include quality control method validation, process monitoring and GMP compliance, as well as product testing including radionuclide purity and concentration, sterility, pyrogenicity, etc.

- **Hot Waste Disposal**

  Most radiopharmaceuticals for in-vivo diagnostic and therapeutic use involve short-lived nuclides which can be disposed through radioactive decay. However, a number of longer-lived nuclides, by-products of cyclotron and reactor production, and research compounds for scientific studies need to be handled and disposed in appropriate ways. Waste disposal activities include radiochemical analysis, packaging and warehousing for decay, incineration, trapping of volatiles, as well as regulatory monitoring. The latter involves interactions with agencies such as the Nuclear Regulatory Commission, Environmental Protection Agency, Department of Transportation, and National Institutes of Health. These activities require individuals with training in radiochemistry, waste engineering, and regulatory affairs.

- **Radiation Protection**

  All sites and manufacturing facilities which involve the handling of radioactive materials require health physics groups who are responsible for monitoring and auditing employee exposure and contamination, environmental contamination, and plant and lab emissions. In addition, these groups are responsible for clean-up of spills and other accidents, training programs, and regulatory compliance. All companies require individuals with advanced training in health physics, radiochemistry, as well as potentially other nuclear sciences in this area.

Training Needs

An estimate of the number of employees and their training requirements within the radiopharmaceutical industry in the next decade is summarized in the attached table. Out of the 5,000 people that the total industry in the U.S. may employ, no more than 100 nuclear scientists, with a MS or PhD degree in various nuclear specialties, will be required. In addition, approximately 2200 employees with responsibility for some aspect of technical or scientific operations will require a fundamental knowledge of radiochemistry. Support personnel, including technicians performing routine functions, require some on-the-job training on an individual basis.

Radiopharmaceutical Industry

Personnel and Training Requirements

Personnel	Estimated # Of Employees 1990 - 2000	Training Requirements
o Nuclear Scientists		
- Nuclear Physics, Chemistry, Engineering	30	M.S., Ph.D. In Specialty
- Radiochemistry	50	
- Medical/Health Physics	20	
o Other Scientists, Supervisors, Managers, and Senior Technologists	2200	1-2 Semesters Radiochemistry
o Technicians, Lab Support Personnel	1300	On-the-job Training
o Non-Lab Support Personnel	1400	None
TOTAL INDUSTRY	5000	

APPENDIX J

Training Requirements, Credentialing and Standards of Practice for Pharmacists in Nuclear Medicine

Ronald J. Callahan

Introduction

The profession of pharmacy has traditionally held the responsibility for the compounding, quality control, dispensing, and rational therapeutic and diagnostic use of drugs in man and animals. During the last twenty years the profession has been undergoing a dramatic shift from a product orientation to a patient orientation resulting in the pharmacist becoming an active member of the health care team as an advisor on the rational use of drugs.

Another significant change in the profession has been the evolution of areas of specialty practice. One such area, in fact, the first recognized specialty within the profession of pharmacy, is nuclear pharmacy. The expansion of the pharmacist into the use of radioactive drugs is a natural one and was spawned by demand from the nuclear medicine community to have qualified individuals who could deal with the increasingly complex nature of radiopharmaceuticals which was occurring in the late 1960's.

Since that time nuclear pharmacy has evolved into a clearly defined specialty with several hundred members. The specialty enjoys strong support from professional organizations, has developed practice standards and has been subject to a credentialing process to ensure the competence of practitioners in the field.

As the specialty has evolved, so have the educational programs available to train individuals interested in purusing a career in nuclear pharmacy. Training programs have progressed from the primarily "on the job training" of the 1960's and early 1970's to the current availability of structured programs within colleges of pharmacy at the undergraduate, Master of Science, and Doctor of Philosophy level. In addition, residency programs are available for advanced clinical training.

Currently, nuclear pharmacists are employed in several different practice settings. The largest number of nuclear pharmacists are employed in the commercial nuclear pharmacy industry. In this industry, a centralized facility provides unit dose radiopharmaceuticals to hospitals and clinics within a geographic region. It has been estimated that 60% of radiopharmaceutical doses are now dispensed through this mechanism.

Major medical centers, and medium to large hospitals also employ nuclear pharmacists. At these institutions the pharmacist has a major role in research and teaching activities in addition to providing routine radiopharmaceutical services.

To a much lesser degree, nuclear pharmacists are employed in the radiopharmaceutical industry and government agencies. At this time, the potential contributions of nuclear pharmacists to these areas needs to be emphasized.

This paper will review the practice requirements for nuclear pharmacists as adopted by the profession in the Nuclear Pharmacy Practice Standards. In addition, the process by which specialists in this area are currently certified will be reviewed. The currently existing training programs will also be presented and correlated to the practice settings for which a graduate may be qualified. Current demand for nuclear pharmacists will be reviewed.

Creation of the Board of Pharmaceutical Specialties

In January 1973, in response to policy adopted in 1971 by the American Pharmaceutical Association House of Delegates, a Task Force on Specialties in Pharmacy was created by the APhA Board of Trustees to consider the issue of specialization in pharmacy practice and to recommend a mechanism for recognition of specialties and the certification of specialists. In pursing its assignment, the Task Force collected and considered information obtained from within the profession of pharmacy as well as from other health professions and the public in terms of the potential impact that the creation of specialties would have on developments in education and the resulting improvement in the delivery of health care. On the basis of its study, the Task Force on Specialties in Pharmacy concluded that there was, in fact, a public need to be served through the recognition of specialties in pharmacy and that there were potential areas which, in time, might be recognized as specialties. It thus recommended the establishment of an independent decision making authority. The Board of Pharmaceutical Specialties (BPS) was created on January 5, 1976 when the membership of the American Pharmaceutical Association approved the BPS Bylaws.

To insure that specialty recognition and the certification of qualified persons in an identifiable specialty area would result in real benefits to society, the Task Force also developed and recommended seven criteria for designating specialty areas in pharmacy practice. These criteria (demand, need, number of practitioners, specialized knowledge, specialized functions, education and training and transmission of knowledge) guarantee that the area of specialization is one in which there exists a significant and clear health card demand to provide the necessary public reason for certification.

Specialty Council on Nuclear Pharmacy

As part of the credentialing process, the BPS Bylaws call for the establishment of a Specialty Council for each designated specialty area to develop standards and other requirements for certification and recertification based on the seven criteria adopted by the BPS. In the instance of nuclear pharmacy , members for the Specialty Council were selected from the Section on Nuclear Pharmacy (SNP) of the APhA Academy of Pharmacy Practice. The BPS designated the SNP as the appropriate group from which the six nuclear pharmacist members would be selected since the Section represented the largest group of nuclear pharmacists (it still does) and it had been the driving force behind the petition for specialty recognition. The other three members of the Specialty Council are non-nuclear pharmacists. The composition of the Specialty Council is to assure from the beginning that input into the development of standards and other requirements for certification will truly reflect a level of competence that is beyond that of general practitioners in the field.

Standards of Practice for Nuclear Pharmacy

As is generally accepted, practice standards provide for certification by establishing a level of performance to which those who wish to be certified can be held accountable. In 1976, in anticipation of the petition to the BPS, a group of nuclear pharmacy practitioners from the SNP met to begin the process of developing standards of practice for nuclear pharmacy. With the assistance of a consultant, a task analysis was undertaken to identify the areas of responsibility for contemporary nuclear pharmacy. After 18 months of drafting, editing and validating processes, involving a large number of pharmacists actively engaged in nuclear pharmacy practice, a statement of responsibilities (standards) was at hand. The current standards of practice result from a revalidation study which was completed in 1984.

As the practice of nuclear pharmacy evolved, and more practitioners assumed broader responsibilities within the scope of nuclear pharmacy practice, it became clear that the standards of practice adopted in 1978 were in need of revalidation. The review process resulted in a new task analysis and another survey of the known population of practicing nuclear pharmacists. In 1985, an open hearing was held on the circulated draft standards. Comments were incorporated into the current document. (See Appendix I)

In drafting the original standards the Committee recognized the need to address areas of responsibility, based on the validated nuclear pharmacy task analysis, which were common to all practitioners of nuclear pharmacy in a wide variety of professional environments. The Committee recognized that standards could not encompass the entire range of activities performed by nuclear pharmacists, but rather are useful in providing guidance to nuclear pharmacists in the performance of a representative number of important functions. It is recognized, however, that as a professional practitioner, the nuclear pharmacist reserves the right to exercise professional judgment as appropriate to the provisions of quality nuclear pharmacy services.

These standards address only areas of responsibility which are unique to nuclear pharmacy, as an area of pharmacy practice, and are intended to supplement the competency based practice standards for pharmacy in general which resulted from the APhA/AACP Continuing Competence in Pharmacy Project. Moreover, it is recognized that nuclear pharmacists practice in a wide variety of settings and therefore areas of responsibility may vary significantly in individual practice. It is further recognized that individuals not under the supervision of nuclear pharmacists may perform some of the tasks indicated in these standards. It is not the intent of these standards, however, to govern the activities of these individuals.

Recognition of Nuclear Pharmacy as a Specialty

The BPS received the petition for specialty recognition from the nuclear pharmacy group in the fall of 1977. On June 19, 1978, after nine months of investigation and deliberation, the BPS recognized nuclear pharmacy as the first specialty in pharmacy practice. The submitted petition provided evidence that a demand and a need existed for a nuclear pharmacy specialty; that substantial numbers of pharmacists were practicing in the specialty; that a specialized knowledge base existed; that functions performed were clearly beyond the range of functions performed by general practitioner pharmacists; that there existed education and training programs which has as their exclusive purpose the preparation of pharmacists to practice in the specialty; and that a substantial opportunity existed for the transmission of knowledge and scientific information in the specialty.

Nuclear Pharmacy Specialty Certification Examination

Development of the Nuclear Pharmacy Specialty Certification Examination (NUSPEX) by the Specialty Council followed. The purpose of NUSPEX is to discriminate between the minimally competent specialist and nuclear pharmacist applicants who do not demonstrate such competence. To accomplish the first step in this discrimination process, qualifications to sit for the certification examination are set in advance. The pass-fail criteria for the examination are also set in advance, based on a key public purpose of specialty certification, i.e., identification of those who demonstrate the level of proficiency shown to be essential for quality patient care. There are currently 112 Board Certified Nuclear Pharmacists.

One recent development which has been affected by certification of nuclear pharmacist is the revision of Nuclear Regulatory Commission regulations governing the use of by-product material in humans. In 10 CFR Part 35 certification in nuclear pharmacy by the BPS is recognized as an acceptable credential for an individual to serve as radiation safety officer. It is anticipated that additional such recognition of certification will occur.

Curriculum Content for Nuclear Pharmacy Programs

The Curriculum Outline shown in Appendix II has been adapted from Model Guidelines for Nuclear Pharmacy Training which are being prepared by the Section on Nuclear Pharmacy of the American Pharmaceutical Association. The outline describes those areas of nuclear pharmacy education expected to be included in formal lecture and laboratory courses.

The goal of these guidelines is to provide guidance to pharmacy schools, educators and nuclear pharmacy preceptors who are engaged in education and training of nuclear pharmacists. The information provided in the guidelines lists those areas that a minimally competent nuclear pharmacist should be exposed to during his/her training program. In this way it is expected that the student will acquire a consistent level of specialized knowledge and skill needed to practice nuclear pharmacy in an independent and competent manner. It is also expected that an individual who successfully matriculates through a program meeting these guidelines will be eligible to gain authorized user status from the Nuclear Regulatory Commission or agreement state agency.

Experiential Component

The experiential component of nuclear pharmacy training is intended to provide the student with hands-on experience handling radioactive materials. This portion of training should be carried out in nuclear pharmacy under the direction of a registered pharmacist who is an authorized user of radioactive material. The student will gain experience in all aspects of providing radiopharmaceutical services to one or more institutions. This component will consist of 500 hours.

Nuclear Pharmacy Training Programs

There are 72 colleges of pharmacy in the United States. The undergraduate degree is a 5 year program encompassing the physical, biological, behavioral and pharmaceutical science as well as the humanities and liberal arts. There is a major clinical component to all pharmacy programs. Most colleges of pharmacy also offer graduate programs in various pharmaceutical sciences.

In a survey completed in January 1988 by Professor William Hladik of the University of New Mexico, all colleges of pharmacy were polled as to the existence of nuclear pharmacy training programs at their institutions. The results of this survey provide a comprehensive assesment of the availability of nuclear pharmacy training at this time. A synopsis of the survey results is presented here with permission of Professor Hladik.

The scope of programs in nuclear pharmacy ranged from a few lectures within a medicinal chemistry course to Ph.D. graduate programs. With 70 of the 72 colleges responding, 44 schools reported that they offer a complete course in nuclear pharmacy , 11 of which are required courses.

There are 11 colleges of pharmacy which offer comprehensive programs in nuclear pharmacy. These programs include undergraduate elective series at the B.S. or Pharm.D. level and graduate programs at the M.S. and Ph.D. levels. A comprehensive program is defined as one which provides a sufficient number of hours to meet NRC requirements for authorized user status.

Appendix III contains a list of the colleges of pharmacy along with the number of graduates reported for the last 5 years including the Class of 1988.

It should be emphasized that many of the graduates, especially at the B.S. level, have not pursued a career in nuclear pharmacy following graduation. Many students find nuclear pharmacy of academic interest but are lured into other careeer options in pharmacy following graduation. Steps should be taken to encourage students to maintain interest in nuclear pharmacy as a career option.

Graduates of B.S. programs with special training in nuclear pharmacy are primarily employed in commercial nuclear pharmacies and in medical centers as staff nuclear pharmacists. At the Masters and Pharm.D. level, graduates are primarily employed in medical centers as directors of nuclear pharmacy. Universities and major medical centers with active teaching and research programs are the practice settings for nuclear pharmacists at the Ph.D. level.

Current Demand for Nuclear Pharmacists

The demand for nuclear pharmacists varies considerably with the practice setting. The largest number of nuclear pharmacists are employed in the commercial nuclear pharmacy industry. It is in this area that the greatest demand currently exists. For example, the largest commercial nuclear pharmacy, Syncor International, Inc., has an annual requirement of 50 trained nuclear pharmacists . This number is needed due to turnover, promotions and expansion. The inability of colleges of pharmacy to provide an adequate number of graduates has prompted Syncor to establish its own formal training program. Even with such programs, certain geographical locations still suffer from lack of qualified nuclear pharmacists.

In the commercial nuclear pharmacy setting the demand is geatest for nuclear pharmacists trained at the B.S. level with completion of a specialized series of electives in nuclear pharmacy. Colleges of pharmacy which currently offer such electives should strive to continue and expand enrollment in these programs. Additionally, other colleges of pharmacy should explore the possibility of attracting faculty members qualified to offer these specialty courses thus adressing the current and future demand for trained nuclear pharmacists at this level.
Many fewer positions are available in academic institutions and hospitals. Traditionally, the turnover rate in these settings has been much slower with some positions at major medical centers having been occupied by the same individuals for greater than 15 years. Whereas a commercial nuclear pharmacy may employ several nuclear pharmacists, an academically based facility may employ only one or two.

Likewise, the number of new positions for nuclear pharmacists being created in hospitals and medical centers has been low. This is partially due to the impact of the commercial nuclear pharmacies and partially because some nuclear medicine departments have been slow to recognize the potential benefit a nuclear pharmacist can impart on a department.

In some areas of the country groups of small to medium sized hospitals in a region have participated in shared nuclear pharmacy services. This concept allows each hospital to benefit from the services of a nuclear pharmacist without having to support the position entirely. This concept could possibly be one which is competitive with commercial nuclear pharmacies or to provide this service in an area not currently being served by a commercial pharmacy. Expansion of this conept will increase the quality of radiopharmaceutical services and provide additional practice settings for nuclear pharmacists.

For the calendar year 1987 there were 10 classified advertisements for positions available for nuclear pharmacists. Of these only one was for a commercial nuclear pharmacy. At this time, this author is aware of two additional academic positions open.

Therefore, an informal survey has revealed that there is an estimated eight to ten academic positions which were available during 1987. Several remain unfilled as of this writing. Additionally, the largest commercial nuclear pharmacy, which holds the vast majority of the market, has an annual need of 50 trained nuclear pharmacists.

When the data in Appendix III is converted to average annual graduates one finds that there are 37 B.S./Pharm.D., 8 M.S. and 4 Ph.D. nuclear pharmacists graduating annually. This number is insufficient to meet the estimated demand which currently exists for trained nuclear pharmacists at all levels.

Nuclear pharmacy has suffered from some of the same problems as other nuclear related industries. A general anti-nuclear attitude coupled with a perceived fear of radiation has had its impact on recruitment of pharmacists into nuclear pharmacy. In addition, there is a nationwide shortage of pharmacists in all practice settings. This has resulted in very attractive salaries in areas such as retail chain pharmacies thus graduates are entering these more traditional practice settings.

Summary

Nuclear pharmacy is the first recognized specialty in pharmacy. Practitioners contribute to nuclear medicine by providing routine radiopharmaceutical services, participating in teaching programs and by serving as an important member of many research teams. The involvement of nuclear pharmacists in areas such as positron emission tomography and single photon tomography will only increse the demand for highly trained professionals in the future.

There are several training programs in colleges of pharmacy throughout the country. Model curriculum guidelines should be adopted by these colleges to ensure that all nuclear pharmacists receive training in the appropriate areas. Demand exists for individuals trained at the undergraduate and graduate levels. Undergraduate specialty elective programs should be encouraged to meet the current demands in the commercial nuclear pharmacy industry.

Formal training in radiochemistry is lacking in most nuclear pharmacy training programs. This is partly due to lack of such courses in universaity chemistry departments. A specialized program in radiochemistry available to students in nuclear pharmacy would be of great value especially at the graduate level.

A shortage of trained nuclear pharmacists currently exists. Although there are significant numbers of students completing programs in nuclear pharmacy, these numbers are inadequate to meet current demand and many do not pursue a career in the specialty following graduation. The profession should take steps to encourage students to continue in nuclear pharmacy. Management in the various practice settings should strive to make employment more desirable and competitive through review of salary and benefit programs.

It is anticipated that nuclear pharmacists will continue to make major contributions to nuclear medicine in the future. Practitioners and educators should continue to work together to ensure that an adequate number of competent pratitioners is available to meet the demand.

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Appendix I

Nuclear Pharmacy Practice Standards

FULL TEXT OF STANDARDS AVAILABLE ON REQUEST

prepared by the

Section on Nuclear Pharmacy
Academy of Pharmacy Practice
American Pharmaceutical Association

2215 Constitution Avenue, NW
Washington, DC 20037

Published 1978, Revised 1985

NUCLEAR PHARMACY PRACTICE STANDARDS

Nuclear pharmacy is a basic pharmaceutical service which has been defined as follows:

Nuclear pharmacy is a patient-oriented service that embodies the scientific knowledge and professional judgement required to improve and promote health through assurance of the safe and efficacious use of radioactive drugs for diagnosis and therapy.

A nuclear pharmacist shall possess an active pharmacist license in the state where practicing and shall have received didactic instruction or supervised professional experience in the practice of Nuclear Pharmacy. The practice of nuclear pharmacy is composed of the following general areas:

1. The procurement of radiopharmaceuticals
2. The compounding of radiopharmaceuticals
3. The performance of routine quality control procedures.
4. The dispensing of radiopharmaceuticals
5. The distribution of radiopharmaceuticals.
6. The implementation of basic radiation protection procedures and practices. General considerations; personnel monitoring; receipt of radioactive materials; storage, transfer and shielding; security; safety; equipment calibration; environmental monitoring; radioactive wastes; posting of areas; and evaluation of radiation protection.
7. Consultation and education to the nuclear medicine community, patients, pharmacists, other health professionals, and the general public regarding:
    a. The physical and chemical properties of radiopharmaceuticals
    b. Pharmacokinetics and biodistribution of radiopharmaceuticals
    c. Drug interactions and other factors which alter patterns of distribution
8. Research and development of new formulations.

Appendix II

Model Curriculum Guideline

Proposed by the Educational Affairs Committee
Section on Nuclear Pharmacy
American Pharmaceutical Association

Curriculum Outline

1.0 Radiation Physics and Instrumentation

1.01 Structure and Properties of Atoms
1.02 Radiation and Radioactive Decay
1.03 Decay Schemes of Radionuclides
1.04 Sequential Decay
1.05 Production of Radionuclides
1.06 Interaction of Radiation with Matter
1.07 Instruments for Radiation Detection

2.0 Mathematics of Radioactivity use and Measurement

2.01 Radioactivity
2.02 Radiopharmaceutical Compounding and Dispensing
2.03 Generator Operation and Use
2.04 Counting Statistics
2.05 Quality Assurance Calculations
2.06 Medical Internal Radiation Dose Calculations
2.07 Pharmacokinetic Calculations

3.0 Radiation Protection

3.01 Interaction of Radiation with Matter
3.02 Units of Radiation Measurement
3.03 Occupational and Non-occupational Exposure
3.04 Principles of Radiation Protection
3.05 Personnel Monitoring and Precautions
3.06 Area Monitoring
3.07 Radioactive Package Handling Procedures
3.08 Radioactive Waste Disposal Methods
3.09 Regulatory Considerations
3.10 Radiation Safety
3.11 Radiation Accidents

4.0 Radiation Biology

4.01 Interaction of Ionizing Radiation with Matter
4.02 Units of Energy Transfer
4.03 Biological Effects of Deposited Energy
4.04 Radiation Chemistry in Aqueous Systems
4.05 Radiation Effects on Macromolecules
4.06 Radiation Dose Response Curves
4.07 Cellular Effects of Radiation
4.08 Radiation Genetics
4.09 Radiation Effects on Tissues and Organs
4.10 Factors Affecting Radiation Injury
4.11 Radiosensitivity of Embryo and Fetus
4.12 Delayed Effects

5.0 Radiopharmaceutical Chemistry

- **5.01 Physico-chemical Properties of Radiopharmaceuticals**
- **5.02 Radiopharmaceutical Chemistry**
- **5.03 Quality Control of Radiopharmaceuticals**
- **5.04 Technetium Radiopharmaceuticals**
- **5.05 Iodine Radiopharmaceuticals**
- **5.06 Radiolabeled Blood Cells**
- **5.07 Gallium and Indium Radiopharmaceuticals**
- **5.08 Phosphorus Radiopharmaceuticals**
- **5.09 Chromium Radiopharmaceuticals**
- **5.10 Cobalt Radiopharmaceuticals**
- **5.11 Radioactive Gases**
- **5.12 Iron Radiopharmaceuticals**
- **5.13 Selenium Radiopharmaceuticals**
- **5.14 Thallium Radiopharmaceuticals**
- **5.15 Ytterbium Radiopharmaceuticals**

6.0 Clinical Applications of Radiopharmaceuticals

- **6.01 Diagnostic Imaging Procedures**
- **6.02 In vivo Function Studies**
- **6.03 In vitro Studies**
- **6.04 Therapeutic Procedures**

Appendix III

College of Pharmacy Graduates
1984 - 1988
with Nuclear Pharmacy Training

Compiled by: Professor William Hladik
University of New Mexico College of Pharmacy

Graduates with Nuclear Pharmacy Training

College	BS/Pharm.D./Residency	M.S.	Ph.D.
Temple	20		
Purdue	54	4	3
Mass. College of Pharmacy	48		
Med. Univ. So. Carolina	5		
Mercer	14		
Kentucky	15		1
U. So. California		23	5
Oklahoma		9	7
Oregon St.	6		1
Univ of Pacific		3	
New Mexico	23	3	

APPENDIX K

Radiochemiatry in the Pharmaceutical Industry

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The discovery of artificial radioactivity by Irene Curie and Frederic Joliot in 1934 has had a tremendous impact on both science and society as a whole. Yet, in the more than 50 years that have passed since this discovery, the importance of radioactivity and its application in diverse scientific areas has been widely unrecognized and unappreciated. One example is the vital role that radioactive isotopes play in medicine and the development of new drugs. It is on this latter aspect, the development of new drugs, that I wish to focus my attention.

This report will examine radiochemistry in the pharmaceutical industry in four areas. First, the current status of radiochemistry and the demand for radiochemists will be assessed. Second, the applications of isotopes in the pharmaceutical industry will be detailed. Third, the techniques which are required by the radiosynthetic chemist, the analytical radiochemist and the biologist who will ultimately use the radiolabeled compound will be examined. Last to be addressed will be radiochemical training and the question of what can be done to meet the growing radiochemistry personnel needs of the pharmaceutical industry.

The goal of the pharmaceutical industry is seemingly a simple one: to develop safe and effective drugs. The labeling of drugs with radioisotopes by synthetic organic chemists ("radiosynthetic chemists") is a key step in bringing a new drug to the marketplace. Radiolabeled drugs are vital in the determination of a drug's metabolic pathway and identification of its metabolites. Radiolabeled drugs also enable the pharmaceutical scientist to determine the optimum drug delivery system, the molecular biologist to probe drug-receptor interactions, and the pharmacologist to assess biodistribution. Radiolabeled drugs can also be used to address problems in basic chemistry, such as a reaction mechanism, and in process chemistry, where a small scale synthesis is developed into a viable commercial process. Thus, the use of isotopes interconnects several key sciences: chemistry- for synthesizing the drug in radiolabeled form, and various biological disciplines- for using the labeled compound and analyzing the data obtained. The end result of this collaboration between chemists, biophysicists, physiologists, pharmacologists and physicians is elucidation of many of the details of a drug's action.

The importance of radiochemistry is seen in some simple statistics. Over 90% of all new drugs have been synthesized in radiolabeled form, most often with tritium and carbon-14. Chemists published over 25,000 papers in the last 20 years which relied on these two isotopes. In the five year period 1982-1986 over 1250 new carbon-14 labeled compounds and nearly 850 new tritium labeled compounds were reported. The _Journal of Labeled Compounds and Radiopharmaceuticals_ was created in 1965 to serve as a vehicle for the publication of the synthesis and analysis of radiolabeled compounds. The number of papers published here has grown nearly 500% in the last 20 years; today it is the primary journal for the publication of the synthesis of radiolabeled compounds with approximately 30% of these papers being contributions from the pharmaceutical industry.

The importance of radiochemistry is also seen by the fact that a new professional society, the International Isotope Society, was formed in 1986. The mission and objective of the society is to advance knowledge of the applications of isotopically labeled compounds. The society currently has over 1100 active members.

The demand for radiosynthetic chemists is also growing. The yearly demand, as measured by advertised job openings (in Science or Chemical and Engineering News), has nearly doubled since 1984. Approximately 40% of the 14 advertised openings for radiosynthetic chemists in 1987 were at the bachelors/masters degree level. In terms of researchers who apply radiolabeled compounds to drug development, it can be conservatively estimated that there are about 40 job openings per year at the Ph.D. level (advertised in Science) for pharmaceutical scientists who have training in basic radiochemistry and radiochemical techniques; the actual number of openings may be considerably higher. Even though the yearly number of openings for radiosynthetic chemists is relatively small, this small group of radiochemists provides the key for a large number of pharmaceutical scientists to solve many of the problems faced in drug development. For example, most pharmaceutical laboratories have a radiochemistry group of less than ten chemists doing both synthesis and analysis of radiolabeled compounds. Yet, this small group of chemists produces radiolabeled compounds which are ultimately utilized by literally several hundred researchers! Unfortunately, many of these advertised job openings, especially for radiosynthetic chemists, go unfilled due to a lack of adequately trained personnel. Thus, more training of radiosynthetic chemists, radioanalytical chemists, and scientists with a background in radiochemistry is mandated.

In order to fully evaluate how to meet this clear need for radiochemists and researchers with radiochemical training, a brief overview of the applications of labeled compounds, their synthesis, and the necessary collaboration between synthetic chemist and biologist/end user is required.

Applications in the Pharmaceutical Industry

Isotopes are invaluable for research in the pharmaceutical industry for three main reasons: 1)sensitivity; conventional organic analytical methods are often unusable because of the small quantities of compound which are present, 2)discrimination; isotopic labeling of a drug allows for discrimination between compounds which are derived from the parent compound and those which are not, and 3)quantification; radiolabeled compounds allow the amounts of each compound detected to be easily quantified.

The principle isotopes that are used in pharmaceutical research are tritium, carbon-14, sulfur-35, phosphorus-32 and iodine-125. These isotopes account for greater than 95% of all the isotopes used with tritium and carbon-14 being used the most often. Of secondary importance in research are gold-195, sodium-22, calcium-45, chromium-51 and technetium-99m.

The actual choice of isotope will be depend upon its chemical and physical properties. Most of the labeling of new drugs involves direct substitution of a radioactive isotope for its stable counterpart. Thus, the chemical properties of the radiolabeled compound will be virtually identical to that of the unlabeled compound and biodistribution will not be effected. The physical properties of the isotope include half-life, specific activity and the type of radiation emitted. Here, the experimental requirements of the study to be conducted will dictate isotope selection. The actual applications are discussed below.

DRUG METABOLISM. Drug metabolism is the area in which application of radioisotopes in the pharmaceutical industry is most common. It is through the use of radioisotopes that metabolism is characterized since radioanalytical techniques allow a drug's conversion and elimination to be followed. Thus the pharmaceutical scientist can easily detect small amounts of radioactivity, which correlate with the parent drug or its metabolites, in blood, urine and feces. The amount of radioactivity may be quantified and the identity of individual metabolites determined.

Identification of metabolites is the key aspect of drug metabolism. This not only allows a metabolism path to be established, but it also may result in identification of a more potent biologically active compound or it may identify a potentially toxic metabolite. All of this information is necessary if new drugs are to be developed and approved for human use.

Typically, metabolites are identified through the use of chromatography (high pressure liquid chromatography, thin layer chromatography and gas chromatography) and mass spectrometry. Chemical structures can then be established by comparison with compounds of known structure or, if sufficient quantities can be isolated, structure may be independently established. The limited amounts of radioactive compounds normally available, however, can complicate the radiochemical analysis. Occasionaly, misleading chromatographic artifacts may be encountered as a result of oxidation, hydrolysis, exchange, or adsorption during analysis. The pharmaceutical scientist must therefore be familiar with not only these radioanalytical techniques, but also their limitations in this context.

PHARMACOKINETICS. The kinetics of drug action are also determined with radiolabeled compounds. The total activity excreted and tissue to blood levels over several days is measured. Metabolite elimination rates are also easily measured with these tracer compounds and this allows determination of the biological half-life of a drug.

DRUG BIODISTRIBUTION. Complete assessment of drug biodistribution *in vivo* is possible only through use of radiolabeled compounds. Autoradiography is one method available for precise determination of the localization of a drug. Such information allows the pharmaceutical scientist to monitor uptake of a drug in expected target tissue, to monitor potential toxicity to specific non-target organs, and to obtain inferences about the mechanism of a drug's action.

DRUG DELIVERY SYSTEMS AND BIOAVAILABILITY. Once a new drug has been identified and it has been found to be safe and effective, the question of the best way to administer the drug arises. There are many different modes of delivering a drug to the body: capsule, tablet, elixir, spray, timed-release, oral, nasal, etc. Often, selection of the optimum delivery system relies upon use of the radiolabeled drug to provide an answer. Uptake, presence in blood, excretion and the corresponding kinetics are all easily quantified by exploiting the easy detectability of radiotracers. Since these factors are dependent upon administration mode, a radiotracer study can identify the best drug delivery system for the compound in question.

MOLECULAR PHARMACOLOGY. A fundamental problem of molecular pharmacology is probing the means by which a drug may be specific in its action. Investigation of receptor systems, in particular, relies upon the use of radiolabeled drugs. Indeed, it is impossible to monitor receptor binding either directly (through measuring the actual binding of the labeled compound) or indirectly (using an unlabeled compound to displace a radiolabeled standard, i.e. competitive binding), without using radioisotopes. Here, radiochemistry has truly revolutionized pharmaceutical research. By using radiolabeled receptor ligands to probe drug-receptor interactions, the pharmaceutical researcher has been able to design drugs which maximize receptor binding and desired biological effect. The importance of this is seen in the large number of drugs that have been logically designed based on receptor studies. One clear example of this is Tagamet, an anti-ulcer drug and the number one selling prescription pharmaceutical, which operates by way of the H_2 receptor.

PROCESS CHEMISTRY. Occasionally, radiolabeled compounds have proved valuable in the development of large scale, commercial synthetic processes for new drugs. Again, the easy detectability of radioactivity is the key that allows all components of a reaction mixture to be followed. For example, a problem often encountered in scaling up a synthesis is accounting for all of the mass in a particular reaction. These mass balance problems can be solved through the use of tracer compounds; losses due to adsorption are easily detected, or compounds which may be undetectable by chromatography (with UV detection, for example) are readily detectable by monitoring radioactivity in the HPLC eluate. Efficiency of certain steps can also be monitored quantitatively through the use of tracer compounds. Extraction efficiency, for example, can be determined by simply using liquid scintillation counting on the organic and aqueous phases. Finally, radioactive compounds can also be used to examine important mechanistic questions about organic reactions.

FUTURE APPLICATIONS. The development of positron emission tomography (PET) has the potential for greatly enhancing the research capabilities of the pharmacologist. There are two distinct areas where drug development can benefit from PET. First, isotopic substitution in a new compound with an appropriate nuclide (carbon-11, nitrogen-13 or fluorine-18) would allow its biodistribution to be quantitatively and non-invasively determined. Second, labeled biological substrates could be used to monitor the effect of the drug under study on various biological parameters. Among the parameters which PET could quantitatively and non-invasively determine are drug-receptor interactions, glucose metabolism, fatty acid metabolism and oxygen consumption.

Exploitation of this new technology is just beginning in the pharmaceutical industry in this country. Some European pharmaceutical companies have not only been using PET in their investigations but have also purchased their own cyclotrons and tomographs to begin routine use of this technology. Early impact is likely to be in the area of central nervous system research where PET has already proven itself a valuable tool of nuclear medicine. Thus, the radiochemical demands made upon both the synthetic radiochemist and the pharmacologist will increase in the coming years.

Radiochemistry Techniques

The first step in applying radiochemistry in pharmaceutical research and development is the actual synthesis of a radiolabeled compound. Since the corresponding unlabeled compound will have been previously synthesized by medicinal chemists, the radiosynthetic chemist has a possible synthetic method available. However, this route will probably need modification or, in some cases, the original route will have to be abandoned in favor of a route which meets the constraints of radiochemical synthesis. These constraints arise from one or more of the following: the small scale of the labeling reaction (frequently under one millimole), the high cost of labeled starting materials (up to tens of thousands of dollars for compounds of even simple structure), the need to use simple starting materials (eg. cyanide, methyl iodide, tritium gas, etc.), the desire to introduce the radioactive label as late in the synthesis as possible (to maximize yield and minimize handling of labeled compound), and finally the desired location of the label within the molecule.

The decision as to where to place the label in a given compound is decided by the chemist in consultation with the pharmacologist or researcher requiring the labeled compound. The decision represents a balance between the synthetic constraints just mentioned, the ease of synthesis and expected synthesis time, the ultimate end use of the labeled compound, and the metabolic stability of the position to be labeled. This last factor is indeed crucial. Obviously only the labeled portion of the molecule can be followed _in vitro_ or _in vivo_. Therefore, it is important that the isotopic label position not be easily susceptible to loss through metabolic cleavage of a molecular fragment, or by chemical or biochemical reactions at the labeled site. Should this occur early in the metabolic path, much of the desired metabolism information would be lost. In some instances, a compound may have to be labeled more than once at different positions, or with different isotopes, if a complete metabolic pathway is to be discerned. Furthermore, since label location is so critical, location of the label must be known in order to avoid possible misinterpretation of biological results.

Finally, both the radiosynthetic chemist and researcher must be confident that the labeled compound is of high radiochemical purity. Often, purity of the labeled compound must be higher than that of the unlabeled compound. Since impurities themselves are subject to metabolism, both the parent impurity and its metabolites may be mistaken as deriving from the primary compound under study.

It should now be clear that application of radiolabeled compounds in pharmaceutical research is a true collaborative effort which requires a thorough understanding of radiosynthesis, radioisotope properties, specific activity, radiochemical purity, radiochemical stability/decomposition and radioanalysis on the part of _both_ the radiosynthetic chemist and the pharmacologist investigating a drug. Only through such shared expertise can logical decisions be made in the labeling of a drug and its analysis.

Ideally, the synthetic radiochemist will have a broad background in organic synthesis. The synthetic radiochemist may ultimately have the opportunity to label almost every class of organic compound. This is reflected by the syntheses recently published in the _Journal of Labeled Compounds and Radiopharmaceuticals._ Among the classes of compounds that have been synthesized are peptides, amino acids, esters, acids, benzazepines, sulfonamides, cephalosporins, quinolines and amphetamines, to name just a few.

Ironically, while a good background in radiochemical synthesis is desired, the fact is that newly hired radiochemists have little, if any, radiochemistry experience. Those that have experience have generally gained this experience in another industrial radiochemistry group. Training in universities at either an undergraduate or graduate level is almost non-existent, though there are exceptions as will be noted later.

Microsythetic experience, that is synthesis at a one millimole or less scale, is crucial for the successful radiochemist since the majority of syntheses are done on this scale. This is especially true for high specific activity tritium or iodine-125 work where micromole amounts of starting materials are the norm.

Vacuum line and specialized gas handling techniques, such as Toepler Pump use for gas transfers during catalytic tritiations, are also important for the radiosynthetic chemist.

Though it is sometimes underestimated, knowledge of safety precautions and actual experience in handling radioactivity are important. Personnel and laboratory contamination can easily occur unless carefully thought out manipulations and procedures are followed. Monitoring for radioactive contamination is a crucial aspect of safety.

Finally, and perhaps most important of all, is a thorough background in general analytical techniques as well as those specific to radioanalysis. These are the techniques that both synthetic chemist and the pharmacologist must know if radiolabeled compounds are to be successfully applied to pharmaceutical research. First among these techniques is liquid scintillation counting. Other valuable radiochemical technologies or techniques include direct probe detection (eg. proportional counters), flow detectors for monitoring radioactivity during HPLC, and TLC linear analyzers.

Radiochemistry Training

Thus far, the methods, techniques and technologies used by the practicing radiosynthetic chemist and the pharmaceutical scientist who uses these radiochemicals, has been described. This section will focus on the training which is appropriate for such researchers.

The radiosynthetic chemist must have a broad background, as we have seen, in general organic synthetic and analytical techniques and methodologies. The radiosynthetic chemist should also be familiar with microsynthetic techniques, specialized synthetic techniques (vacuum line, Toepler pump, etc.), radiolytic decomposition, and radioanalytical methods (liquid scintillation counting, HPLC and GC in line radioactivity monitoring, tritium NMR, TLC linear analyzers, and specific activity determination). The users of labeled compounds must also have detailed knowledge of these last two points: radiolytic decomposition and radioanalytical techniques.

There are only two opportunities for training; training can be learned either on-the-job (in industry or academics), or taught as part of a graduate or undergraduate chemistry program. On-the-job training has a number of obvious drawbacks. One drawback is the time that must be spent by the experienced radiochemist in teaching the new radiochemist his job. This results in lost radiosynthesis time on the part of both chemists. The major problem, however, with this type of training is that it obviously cannot provide either the pharmaceutical industry or academics with experienced radiochemists except if the radiochemist moves from the company where training was acquired to another. The most appropriate way to provide new radiochemists is for their training to be at the university level.

It has already been mentioned that there are few courses offered at either the graduate or undergraduate level which teach the radiochemistry techniques that have just been described. One notable exception is the University of Illinois at Urbana-Champaign where a radiochemistry course has long been in place (see Appendix I for the course syllabus). This course, now under the direction of Drs. John Katzenellenbogen and Lee Melhado, could serve as a model for other universities. Among the topics covered in this particular course are the characteristics of radioactivity, liquid scintillation counting, vacuum line techniques, radiation safety, radioactivity detection (including HPLC radioactivity flow detectors and TLC linear analyzers), synthesis, tritium NMR, radiochemical purity, radiolytic decomposition, isotope effects, biosynthetic applications, radiopharmaceticals and stable isotopes.

The most commonly used synthetic methods for incorporating radioactivity are rather straightforward organic reactions. Typical of these are: reduction of an olefin with tritium gas, tritium exchange with an aromatic halogen, introduction of carbon-14 via the use of carbon-14 labeled carbon dioxide in a Grignard reaction, methylation with carbon-14 methyl iodide, nucelophilic displacement by carbon-14 labeled cyanide, protein labeling with iodine-125 and an oxidant, or direct electrophilic aromatic iodination with iodine-125 labeled sodium iodide. Carrying out just a few of these experiments would allow virtually ALL of the radiochemistry techniques which have been described to be used. For example, using carbon-14 labeled barium carbonate as a source of labeled carbon dioxide and carrying out a Grignard reaction with it would use several of these techniques: vacuum line transfers, liquid scintillation counting, TLC with a linear analyzer, HPLC with radioactivity flow detection, direct probe monitoring and safe handling practices with radioactivity.

Summary

It has been my hope in this discussion to demonstrate a clear need for greater radiochemistry awareness and training. Radiochemistry is vital for the development of new pharmaceuticals where a relatively small number of radiosynthetic chemists provide labeled compounds that are used by a very large number of researchers in the areas of drug metabolism, pharmacokinetics, drug biodistribution, drug delivery systems, molecular pharmacology and process chemistry. The future demands on the radiochemist will be even greater with the advent of new technologies, such as PET, the ever greater demand for the synthesis of high specific activity tritium labeled compounds, and the increased use of isotopic tracer methods to study the molecular mechanism of drug action. Radiochemistry is a collaborative effort between these synthetic chemists and pharmaceutical scientists, BOTH of whom must be knowledgable of radiochemical labeling, radiochemical analysis, and the basic properties of radioactivity.

It is also clear that there will continue to be a strong demand for chemists and researchers in this field and that more training is not only desirable but necessary. It is certainly not an easy task, but it is one that can be successful at an undergraduate or graduate level. Perhaps this report will serve as a stimulus for modifying and expanding the curricula of our universities to include radiochemistry. While the safety aspects of handling radioactivity may inhibit the inclusion of undergraduate radioactivity experiments, the fact remains that there is no substitute for actual hands on radioactivity handling experience. The continued timely development of new pharmaceuticals depends on it.

Acknowledgements

I would like to thank Dr. Lee Melhado, of the University of Illinois at Urbana-Champaign, for her input regarding radiochemistry training. I would especially like to thank Dr. J. Richard Heys, of Smith Kline & French Laboratories, for his suggestions and assistance in preparing this manuscript.

Appendix I

"Carbon and Hydrogen Tracer methodology"
Chemistry 496 Syllabus
University of Illinois
John A. Katzenellenbogen and L. Lee Melhado

Chemistry 496 - Spring 1988
Lecture Schedule
(John A. Katzenellenbogen and L. Lee Melhado)

No.	Date	Topic	Lecturer
		I. Characteristics, Counting Safety and Manipulation of Radioactive Substances	
1	Jan 26	Characteristics of Radioactivity	K
2	28	Liquid Scintillation Counting - Principles	K
3	Feb 2	Liquid Scintillation Counting - Practice	K
4	4	Liquid Scintillation Counting - Practice	K
5	9	Liquid Scintillation Counting - Instrumentation	M
6	11	Radiation Safety	M
7	16	High Vacuum Techniques	M
8	18	Other Radiation Detection Methods	K
9	23	Other Radiation Detection Methods	K
10	25	EXAM I (lecture 1-9 and laboratory)	
		II. Synthesis and Analysis of Radiochemicals and Stable Isotope-Labeled Compounds	
11	Mar 1	Synthesis: General Issues	K
12	3	Synthesis: Carbon isotopes (C-14)	K
13	8	Synthesis: Carbon, Nitrogen, Oxygen isotopes (C-13, N-15, O-17, O-18)	K
14	10	Synthesis: Hydrogen isotopes (H-3)	K
15	15	Synthesis: Hydrogen isotopes (H-3)	K
16	17	Synthesis: Hydrogen isotopes (H-2)	K
17	22	Radiochemical Purity and Radiolysis	K
18	24	Analysis of C-14 Labeled Compounds	K
19	Apr 5	Analysis of C-14 Labeled Compounds	K
20	7	Analysis of H-3 Labeled Compounds and ^{3}H-NMR	K
21	12	Analysis of C-13 and H-2 Compounds	K
22	14	EXAM II (lectures 11-21 and laboratory)	
		III. Applications of Radioactive and Stable Isotopes	
23	19	Isotope Dilution Assays	M
24	21	Isotope Effects	K
25	26	Isotope NMR	K
26	28	Applications in Chemical Mechanisms	K
27	May 3	Applications in Biosynthesis	K
28	5	Production of Short-Lived Isotopes	K
29	10	Synthesis and Use of Radiopharmaceuticals	K
Final	16	FINAL EXAM (Monday, 1:30-4:30)	

Chemistry 496 - Spring 1988
Laboratory Schedule (Approximate)

I.	Laboratory Orientation	
	Lab Survey and Bioassays	(Feb 8)
II.	Liquid Scintillation Counting	
	1) Single Isotope Counting - SCR and ESR Methods	(Feb 15)
	2) Dual Isotope Counting	(Feb 22)
	3) Sample Preparation	(Feb 22)
III.	Vacuum Line Technology	
	1) Calibration of manifold (volume determination) $\frac{P_1V_1}{P_2} = V_2$	(Feb 29)
	2) Generation of CO_2 from $BaCO_3$ (yield and % recovery)	(Feb 29)
	3) Generation of $^{14}CO_2$ and reaction with *n*-BuMgBr to produce *n*-valeric acid-1-^{14}C	(Mar 7)
	4) Isolation of *n*-valeric acid-1-^{14}C	(Mar 14)
IV.	Isotope Dilution Assay	
	1) Addition of carrier to *n*-valeric acid-1-^{14}C and conversion to the silver salt	(Mar 14)
	2) Measurement and calculation of S.A. of silver valerate	(Mar 14)
V.	Degradation of Silver-n-Valerate-1-^{14}C	
	1) Preparation of silver salt of *n*-valeric acid-1-^{14}C	(Mar 14)
	2) Degradation of silver *n*-valerate-1-^{14}C via Hunsdiecker rxn.	(Mar 21)
VI.	Radiochromatography	
	1) Preparation of derivative of *n*-valeric acid-1-^{14}C	(Apr 4)
	2) Preparation of chromatogram	(Apr 4)
	3) Analysis of chromatogram by LSC and radioscanner	(Apr 4)
VII.	Tritium Labelling by Acid-Catalyzed Exchange	
	1) Tritiation of naphthalene (via H_2SO_4 and ^3H_2O)	(Apr 11)
	2) LSC and S.A. calculation	(Apr 18)
VIII.	Preparation of ^{3}H-Acetic Acid	
	1) Tritiation of malonic acid and cleavage to acetic acid	(Apr 11)
	2) LSC and S.A. calculation of ^{3}H-Acetic Acid	(Apr 18)
IX.	Preparation and Spectroscopic Analysis of an H-2 or C-13 Labeled Compound	
	(Using available reagents (D_2O, D_2, $NaBD_4$; $Na^{13}CN$) and general reaction guidelines, prepare a stable isotope-labeled compound and analyze its isotopic composition by NMR and MS).	(Apr 11, 18,25)
X.	Preparation of an I-125 Labeled Compound	
	(Using available reagents ($Na^{125}I$; $CH_3{}^{125}I$), prepare an I-125 labeled compound, purify by HPLC, and determine its S.A.)	(Apr 25, May 2)
XI.	Laboratory Cleanup	
	Decontamination and Waste Disposal	(May 9)

APPENDIX L

TRAINING NEEDS FOR CHEMISTS IN NUCLEAR POWER INDUSTRY

William A. Haller
Duke Power, Charlotte, North Carolina

Duke Power is a three station 7-unit nuclear utility. The stations are shown below:

Duke Power Nuclear Units

Name	Rated Megawatt	Type	Year Commissioned
Oconee 1	840	B&W	1973
Oconee 2	840	B&W	1974
Oconee 3	840	B&W	1974
McGuire 1	1145	W	1981
McGuire 2	1145	W	1984
Catawba 1	1130	W	1985
Catawba 2	1130	W	1986

The generation mix is approximately 53% nuclear, 46% fossil and 1% hydro + purchase. As you can see we rank with the largest nuclear utilities in the United States. We, comparatively speaking, are heavily staffed with professionals in the General Office and at the plants. As examples, the General Office staff in Technical Services and a plant chemistry organization are presented in Attachments 1-3.

Duke Power Company (DPC) is both similar and dissimilar to other nuclear power companies in its need for chemistry personnel. At the present time, DPC does not hire degreed chemists for technician level chemistry jobs. Degreed chemists are normally hired for staff level positions in the chemistry sections both at the plants and at the corporate office. Some of these staff positions are also filled by chemical engineers. In addition to using chemists in staff positions, DPC also uses health physics technicians and staffs in roles that, in many companies, are chemistry's domain.

Because DPC uses non-chemists as chemistry technicians, the DPC training programs for the technicians is usually much broader in scope than similar training programs at other companies. Our training programs for technicians and professionals are broad in scope. It is more specific to nuclear power plants than any training received in school (with the exception of the nuclear navy.) Figures 1 and 2 below indicate initial and ongoing training times for our chemistry/radiochemistry personnel.

Figure 1

Technician Training

A. Initial

8 weeks introductory

2 weeks station familiarization

8 weeks specific chemistry/radiochemistry

B. Ongoing

4 weeks year

Figure 2

Professional Training

A. Initial

16 weeks Orientation & System Training

B. Ongoing

3-5 weeks/year including advances technical and management training as applicable.

At the same time, the DPC training program is much more specific to nuclear power plants than any training that degreed chemists may have received in college.

Before addressing the specific training needs that are lacking in degreed chemists, it would be beneficial to point out some of the unique aspects of working in "chemistry" at a typical nuclear power plant.

1. An average of 2000 radioactive samples are analyzed per month to determine the radionuclides present. These may be broken down as follows:

   Tech Spec and Releases: 35%

   HP Job Coverage: 29%

   Chemistry & Radwaste: 23%

   Miscellaneous: 13%

2. The disintegration rate in disintegration per second (dps) varies from 0.3 dps (for environmental samples) to approximately 10^6 dps (for reactor coolant). We are also prepared to count several orders of magnitude higher in an accident situation.

3. An average of over 1000 radioactive samples are analyzed per month to determine the amount of pH, Cl^-, F^-, B, conductivity, Li^+, suspended solids, O_2, H_2, Al, SiO_2, Ca, Mg, and total gas.

4. An average of over 5000 nonradioactive samples are analyzed per month to determine the amount of pH, turbidity, BOD, conductivity, Cl^-, SiO_2, Ca, Mg, Na^+, K^+, N_2H_4, NH_3, O_2, TOC, nitrite, cromate, borax, Fe, etc.

5. An average of 3000 thermoluminescence dosimeters (TLD's) are analyzed per month to determine the amount of radiation exposure received by workers.

6. An average of 360 individuals are analyzed per month to determine the amount of internally deposited radioactive material.

7. An average of 150 environmental samples are analyzed per month to determine the amount of radioactivity present.

"Radiochemistry" at a nuclear power plant is usually a misnomer because chemical analyses are performed on samples that just happen to be radioactive. Radioactive samples have to be handled differently from non-radioactive samples simply because they are radioactive. Also most of the radioactive analysis is done instrumentally (>95%) rather than by classical radiochemistry separation and counting. Only tritium, Sr and a rare alpha count are separated and counted.

Some of the areas that we feel need to be addressed in undergraduate courses in chemistry are summarized below:

1. Students need a better understanding of what industry (the "real" world) is all about: goals, work environment, attitudes, etc. Some type of exchange program where students could get some industrial exposure would be beneficial. This program may be a "special project" arrangement with a nearby industry or it may be plant tours in addition to traditional co-op and summer programs.
2. Students need an understanding of basic engineering principles. Requiring a course similar to "Introduction to Chemical Engineering" would be beneficial. Chemists work side by side with engineers and operators to troubleshoot, startup, or improve operations of large systems and equipment. Having a general understanding of basic industrial equipment and operation, thermohydraulics, and

fluid and mass transport would make them better prepared for the plant environment. As an example, having an understanding of ion-exchange equilibrium theory in a laboratory sized column does not fully prepare an individual to refine the operations of a system in which ion-exchange vessels may be 6 to 8 feet in diameter, 20 to 30 feet high, operate at high flow and/or resins are separated and regenerated within the vessels.

3. Students need to be more familiar with the "state of the art" available analytical instrumentation (AA, IC, ICP, pH, conductivity, selective ion electrodes, etc.) used in industrial process control type applications.

4. Students need a general acquaintance with radioactivity and the biological effects of radiation and some knowledge of basic principles of health physics. They should for example be able to differentiate the health hazards of 1 millirem vs. 1 rem.

5. Students need a general acquaintance with laboratory techniques for handling/controlling radioactive samples. An overview of the types of counting equipment, theory of operation, and how to choose a particular system for specific applications should also be included in courses.

6. Students should be given a general overview of PWR and BWR systems and types and levels of radionucles encountered. They should be introduced to the levels of radiation encountered during maintenance and the restraints it imposes.

7. Students need a basic understanding of radioactive waste. They should know the regulatory and working definitions of high-level and low-level radioactive waste, how industries which use radioactive materials generate waste, and what basic treatment and disposal techniques are currently in use. Most radwaste treatment involves concentration of a trace impurity from a bulk waste stream; examples of treatment techniques are filtration, adsorption, and storage for decay of gaseous wastes, filtration, ion exchange, and evaporation for liquids, drying, encapsulation, and solidification for wet solid waste, incineration and compaction for compressible dry waste, and surface removal techniques for reusable solids such as metal and plastic surfaces. Students should know the concept of volume reduction and what volumes are generated and how this volume compares to hazardous chemical wastes and sanitary wastes.

8. Generally one or two elective courses on radiochemistry are offered in undergraduate chemistry programs. It should be beneficial if introductory material on radiochemistry is made an integral part of core physical chemistry courses. In this setup every chemistry student will get a mandatory exposure to the basic principles of radiochemistry.

9. Need to emphasize "real world" radiochemistry in the basic radiochemistry courses offered in undergraduate chemistry programs. Inclusion of reactor physics and basic principles of operation of various types of power reactors should be beneficial.

10. Courses in radiochemistry should include laboratory sessions. Laboratory sessions should provide basic understanding of radioanalytical techniques and principles of counting.

11. Needs hands-on contamination control experience. In-coming degreed personnel in general carry over their habits that are acquired in college. Usually they are pretty slovenly concerning contamination control.