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AUSTRALIAN ATOMIC ENERGY COMMISSION

RESEARCH ESTABLISHMENT

LUCAS HEIGHTS RESEARCH LABORATORIES

DATING, MASS SPECTROMETRY AND NUCLEAR SCIENCE

A PROPOSED NEW FACILITY AT LUCAS HEIGHTS

by

J.R. BIRD
P.L. AIREY
J.W. BOLDEMAN
D.D. COHEN*
P. DUERDEN

(* Australian Institute of Nuclear Science and Engineering)

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Part A

SUMMARY

1. PROPOSAL

It is proposed that the AAEC install a high-technology, multi-user facility based on an 8 MV tandem accelerator to provide new capabilities in the following fields:

(a) Radioisotope dating and ultra-sensitive trace element determination in isotope hydrology, salinity, sedimentology, erosion, actinide transport and materials studies.

(b) Physics studies for the development of methods of applying nuclear materials safeguards, the provision of neutron dosimetry standards, measurements of precision data for radiation interactions, and the development of new methods for radioisotope dating.

(c) Development of nuclear and ion beam techniques with applications in occupational health, biomedicine, materials modification, industrial problems and other fields.

(d) Special requirements for accelerator-based radiocarbon dating of geological and archaeological samples not provided by other laboratories, coordinated by the Australian National University.

These primary objectives include collaborative projects with the Bureau of Mineral Resources, Geology and Geophysics (BMR), the NSW Water Resources Commission (NSWWRC) and, under the auspices of the Australian Institute of Nuclear Science (AINSE), with Australian universities and other advanced educational institutions. Existing inter-regional programs in hydrology and neutron physics would also be served by the proposed facility making possible an expansion in the scope of joint projects with other countries in the SE Asian region.

2. PROPOSED FACILITY

To exploit advantages of new accelerator technology and to introduce new radioisotope and physics programs relevant to energy and nuclear science research and development, the proposed facility would be based on a tandem accelerator having a maximum terminal voltage of 8 MV. It would be capable of accelerating all ion masses and provide beam currents of several tens of microamps. It would incorporate the latest technology for voltage precision, freedom from contamination and computer control for optimum performance. Separate beam lines and measurement areas would be used to isolate individual applications and provide versatility in operation and scheduling. The use of these features, in a facility which is carefully optimised to meet the needs of the proposed program, would make it the only purpose-designed large tandem for dating and other applications. An existing building would be used for the project, including a heavily shielded area which would be suitable for neutron experiments which are not possible at any other facility in Australia. An extension would be added to house the accelerator and beam line areas for mass spectrometry. This extension is estimated to cost $1M and the cost of the accelerator and associated facilities is estimated to be $4.5M.

3. JUSTIFICATION

The justification for the facility derives from two main factors:

(a) The importance of the measurements which it would make possible for the advancement of knowledge, understanding and development of Australia's unique region, resources and environment; and

(b) the extent to which it would utilise existing expertise and facilities at the Lucas Heights Research Laboratories to promote current and new programs in topics vital to Australia's national interest.

An earlier generation of reactor and accelerator facilities installed at Lucas Heights has been used to build up skills and knowledge which have been applied to the study of problems in many fields. The success of this work has attracted national and international recognition and funding. The opportunity is now available to introduce a new, unique capability which would keep the Research Establishment at the forefront of research and applications in nuclear science for many years.

Proposed programs with initial priority are summarised below and discussed in more detail in Part B, together with a wider range of possible future applications.

3.1 Radioisotope Dating

The Isotope Division's Research Section has more than fifteen years of experience in applying isotope techniques to the study of groundwater hydrology, erosion and sedimentology and of subsurface transport of actinides. In recent years, this work has been principally concerned with:

- the application of new isotope techniques (^{36}Cl and ^{129}I) to the study of major groundwater resources such as the Great Artesian Basin;
- the subsurface transport of uranium and other actinides; and
- the application of environmental ^{137}Cs to the study of erosion and sediment accumulation over the past few decades.

Much of this work has been done in collaboration with such organisations as the BMR, the various state water authorities, the Commonwealth Scientific and Industrial Research Organization (CSIRO) and universities. The success of the work has led to involvement through the International Atomic Energy Agency (IAEA) and the Australian Development Assistance Bureau (ADAB) in the introduction of isotope hydrology facilities in Asian institutes. Additional funding has also been received from the US Nuclear

Regulatory Commission (USNRC) to carry out work for which Australian conditions offer important advantages.

Measurements of ^{36}Cl and ^{129}I from the Great Artesian Basin were made possible by ccllaboration with the University of Arizona and the resulting access to the 10 MV tandem at the University of Rochester, New York.

Methods for ultra-sensitive radionuclide determination have been developed overseas using tandem accelerators. Vigorous research programs have developed around the use of these accelerators because they facilitate radioisotope-dating techniques using such nuclides as ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl and ^{129}I. Sensitivities vary from a ratio of radioisotope to stable isotope abundance of the order of 10^{-13} for ^{129}I down to 3×10^{-16} for ^{14}C and ^{36}Cl. It is thus possible to carry out dating with small samples (1 mg) and short measurement times (1 hour) and carry out studies that reach back millions of years. Three examples in which these new techniques can benefit the present AAEC program are cited below.

(a) Groundwater Hydrology. In some areas of inland Australia the withdrawal of groundwater is approaching the rate of recharge. Increasingly sophisticated management aids are needed to ensure continued supply. Accelerator-based ^{36}Cl measurements, which have been effectively demonstrated in the Great Artesian Basin, can be used to calibrate models of large regional systems on which management strategies are increasingly based. The same approach can now be applied with confidence to other large basins including the Murray and the Amadeus. Profiles of ^{36}Cl in the unsaturated zone in unperturbed regions may be used to calculate the net rate of groundwater recharge which is an important parameter in any model.

(b) Salinity. Discrepancies between ^{36}Cl data and hydraulic model output may reflect unaccounted salinity terms and therefore may be used to study water quality degradation. Such degradation and the salination of soil are both important national issues. The effect of dry-land farming and irrigation on soil salinity is a man-made problem and the changes over the last few decades are of vital importance. Atmospheric nuclear testing led to a characteristic increase in ^{36}Cl intake with a maximum in the mid-1960s. By comparing perturbed and unperturbed levels of ^{36}Cl in the unsaturated zone, the effect of changing land use on chloride balance can be quantified. Improved assessments of the relative advantages of remedial measures will then be possible. It may also be possible to study in a similar fashion water quality degradation from the disposal of industrial and domestic wastes.

(c) Isotope Sedimentology. The Nuclear Geohydrology Group has extensive experience in applying ^{137}Cs measurements to the study of sediment erosion and redistribution in post-nuclear times. The same concepts could be applied to ^{14}C and ^{26}Al / ^{10}Be profiles throughout the late Quaternary. These investigations are of intrinsic scientific interest and of importance to waste disposal site evaluation.

3.2 Ultra-sensitive Mass Spectrometry

Using the same techniques as for accelerator-based dating, stable nuclides can be determined at levels down to 10^{-12} or below. Although still in the early developmental stage, this method promises to become an important new tool in science and technology. Other new techniques, such as laser ionisation methods, are being developed for trace element determination, but only in a few special cases are these likely to approach sensitivity levels possible with accelerator-based techniques.

Installation of a new facility at Lucas Heights would further promote one of the most significant roles of the Research Establishment as a centre for the application of nuclear science and technology to meet Australian needs.

(a) Actinide transport. Studies of the transport of U, Th, Pa and Ra nuclides downgradient from uranium deposits could, in principle, be extended to ^{237}Np, ^{239}Pu, ^{99}Tc and ^{129}I. Such analyses are important in geochemical studies of the long-term effectiveness of geological barriers to radionuclide transport. Application of the technique to the prediction of the long-term evironmental effects of uranium mining and milling is envisaged.

(b) Materials Development. Semiconductor materials for radiation detectors are the subject of intensive research and development at Lucas Heights; the success in testing new materials and using new methods for measuring their electrical properties is receiving considerable attention. As this work has already exploited all available methods for determining extremely low levels of impurities, it would benefit from the introduction of accelerator-based mass spectrometry.

3.3 Applied Physics

The Applied Physics Division has had 20 years of experience in accelerator operation and use in such fields as the measurement of nuclear data and the investigation of problems relating to fission and fusion energy systems. The Division also has had extensive experience in the development of nuclear techniques and their application to a wide range of problems including the automated analysis of large batches of samples for research and industrial requirements.

The Neutron Physics Group has made detailed experimental and theoretical studies of the interaction of ions, neutrons and gamma-rays with matter. This work has led to membership of the International Nuclear Data Committee over a period of many years and participation in the IAEA's Inter-Regional Project for assistance to developing countries, including those in the South and Southeast Asian regions.

As a result cf this work, Australia has had access to international banks of nuclear data and hence to full information on the properties of radiation and materials. The expertise achieved is now applied to such topics as the development of methods for safeguarding nuclear materials and requirements for fusion energy systems. A new accelerator will dramatically increase the opportunities for research and applications in these fields and other programs of current interest.

(a) Neutron Physics. Neutrons with energies up to approximately 14 MeV are involved in fission and fusion reactors, safeguards systems, dosimetry and other neutron applications. Previous work at Lucas Heights has concentrated on measurements with neutrons up to approximately 2 MeV because of the limitations imposed by the 3 MV Van de Graaff accelerator. The new facility would allow these measurements to be extended to 14 MeV and, in particular, to fill important gaps in cross section measurements between 6 and 12 MeV which are unavailable from smaller accelerators. The most serious data problems for energy systems, particularly fusion reactors, occur in this energy region. Recent improvements in the production of pulsed ion beams would be implemented on the new facility to allow precision time-of-flight measurements of neutron energies in this energy range.

Methods have been developed at Lucas Heights and elsewhere for producing accurately calibrated neutron intensities at various energies; this opens the way for reliable data measurements and accurate dosimeter calibrations which are badly needed for the measurement of neutron dose during the irradiation of biological materials and in other applications.

(b) Safeguards Research. The Australian Government has supported a program of assistance to the IAEA for research on nuclear safeguards. As part of this effort, the AAEC has been involved in research and development aimed at increasing the accuracy of existing safeguards instruments and developing new instrumentation for a wide range of safeguards requirements. A gas phase enrichment monitor has been developed for use in gas centrifuge enrichment plants. One of the present programs deals with neutron coincidence counting for the determination of plutonium in the waste from reprocessing plants. The logical extension of this program would be to include neutron "die-away" techniques. The pulsing capabilities of the tandem accelerator would be of considerable value for such a development.

(c) Fusion Research. Lucas Heights has special expertise in combining data measurements, calculations and system experiments to establish accurate methods for modelling the performance of nuclear systems. Studies have been commenced on fusion blanket systems and the new accelerator would provide an absolute neutron flux facility for measuring the precision data needed for this work. In particular, the development of an absolute neutron flux facility would be of great value for the refinement of detection systems for tritium breeding measurements.

(d) Ion Physics. Only a small fraction of nuclides has been studied with the new accelerator mass spectrometry techniques; physics research is needed to augment the information available for the establishment of the programs outlined above and to develop new methods and applications. The production, acceleration and detection of heavy ions depends on atomic and molecular processes and different methods give best results for different ranges of elements. The physics of ion stripping and charge-exchange, sputtering coefficients, electron affinities and other parameters must form a vital part of the research associated with the proposed project.

(e) Nuclear Physics The present research program of the Applied Physics Division includes some effort in nuclear physics which concentrates on the understanding of the fission process. This research would be continued using the higher performance of the proposed tandem accelerator. This type of accelerator also has a demonstrated high level of performance useful for other aspects of nuclear physics such as searches for new particles and nuclides and the measurement of their properties. Access could be attractive to some university departments for such work.

3.4 Nuclear Science and Applications

Facilities at Lucas Heights have, in the past, played a pivotal role in the use of analytical techniques such as neutron activation analysis, X-ray fluorescence and ion beam analysis. A number of research groups at Lucas Heights have been in the forefront of these developments and, by direct collaboration with other organisations and through the Australian Institute of Nuclear Science and Engineering (AINSE), have assisted in applying them to a wide range of topics. Nuclear applications using a wider range of ion beams, neutrons, gamma-rays and radioisotopes would open up new opportunities for their application to materials analysis, environmental studies, occupational health, bioscience, radioisotope research, and other aspects of the Commission's program.

In particular, the Nuclear Applications Group has developed many new applications of ion beam and neutron techniques and focused attention on their value through local and international conferences. This pioneering work has led to strong and successful interaction with research organisations and with industry. The additional capabilities provided by the new facility would allow an extension of this work to exciting new areas of science and technology.

(a) Ion Beam Analysis. Research and application of the particle induced X-ray emission (PIXE) technique by the Applied Physics Division and AINSE over the past five years, have generated a large program involving uses ranging from mining and environmental studies to biological and archaeological materials.

International trends in PIXE analysis are towards ions heavier than protons or alpha particles, and a wide range of topics in the study of X-ray production have yet to be investigated. Chemical effects, such as the bonding of target atoms, and the use of heavy ions for thick target PIXE analysis must be fully explored and quantified for trace element analysis.

Nuclear reaction and recoil elastic scattering analyses, which are being used for surface studies, would be greatly enhanced by the use of heavier and more energetic ions. For example, heavy ion bombardment of a surface enables a wide range of light elements to be forward scattered out of the surface. At the present time, only H can be profiled with the alpha particle energies available at Lucas Heights. Heavier ions and increased energies would provide multi-element profile studies of all elements up to oxygen with detection limits of approximately 10^{15} at/cm^2 in heavy materials.

Particle activation analysis has outstanding sensitivity for detecting many elements in materials that are not suitable for neutron activation analysis - being better than 0.1 μg/g in many cases. Activation occurs only at depths less than the range of the incident ions so this technique is a surface rather than a bulk technique. For example, it is very useful for the measurement of wear during machine operation.

(b) Neutron Irradiations. For the past 20 years important programs involving the neutron irradiation of living cells have been carried out on the 3 MV Van de Graaff accelerator at Lucas Heights. The aim of these experiments has been to determine cell viability and survival, to quantify chromosome aberrations, and to investigate the effects of neutrons on the living cell cycle.

There is an increasing demand for neutron irradiation studies of medical and biological samples and for radiation damage studies of this type. An 8 MV tandem accelerator would greatly expand the variety of neutron beams available for such studies and provide the necessary neutron dosimetry standard.

(c) Medical Isotope Research. Because of the range of ion types and energies available from the proposed tandem accelerator, it would be useful for the investigation of alternative production methods and uses of short-lived, neutron deficient radioisotopes such as ^{11}C, ^{13}N, ^{15}O and ^{18}F.

(d) Ion Implantation. Another topic with a vast potential is the modification of the properties of semiconductor, metal and other material surfaces. This aspect of high technology is being intensively investigated by the Royal Melbourne Institute of Technology (RMIT), the CSIRO's Division of Chemical Physics at Clayton, Victoria and Lucas Heights, and other organisations. The proposed accelerator would add to the facilities available and, in particular, make possible the implantation of selected ions to greater depths than is presently possible at these laboratories.

(e) Fusion Materials Problems. Light ions are produced by the reactions used for fusion systems; the effects of ion damage of wall materials is a potential limiting factor in system design and cost. Much overseas work is being carried out on damage rates and mechanisms, using irradiation of materials with ions of selected type and energy. New programs in such work would be possible with the proposed accelerator.

3.5 Radiocarbon Dating

The Radiocarbon Dating Research Laboratory of the Research Schools of Earth Sciences and Pacific Studies at the Australian National University (ANU) supports this proposal and would coordinate national needs for radiocarbon dating. This aspect of the program is discussed in a separate paper being prepared by the ANU.

4. RELEVANCE OF THE PROPOSED FACILITY TO THE NATIONAL INTEREST

The importance to Australia of the new facility has been emphasised by the wide variety of programs discussed in the previous section. However, several other general aspects will have significant impact in both the Australian and South-east Asian regions.

(i) Historically, Australia has imported from other countries much of the high technology required in a modern society. This has been to the disadvantage of local industries. The proposed facility would make available to Australian research and industry some of the more recent and most powerful techniques for sample analysis and materials modification.

(ii) The AAEC, through the auspices of AINSE, has had considerable experience in making advanced science and technology facilities available to educational institutions for both research and training. It could expect to achieve similar success with the proposed facility.

(iii) The procurement of the tandem accelerator could be expected to contribute to arresting the decline in knowledge and expertise in nuclear science and technology that has taken place at the AAEC in recent years owing to staff retirements and equipment obsolescence. No major facility has been installed at Lucas Heights for more than a decade.

(iv) It is well known that many important advances in science have occurred as a result of interdisciplinary research. The 8 MV tandem facility would provide new opportunities for the cooperation between scientists in many disciplines throughout Australia. It is expected that such activities would result in many advances which could benefit Australia, but which would not have arisen without the cross-fertilisation of scientific thought.

(v) Australian growth rates in science and technology are said to be well below those of its ASEAN neighbours. The new facility could help reverse this situation and serve as a focus for regional cooperation.

5. RELATION TO OTHER FACILITIES

The proposed tandem accelerator is intentionally planned to provide a performance needed for research and applications that is unavailable with other accelerators in Australia. For this reason, a maximum terminal voltage of 8 MV has been selected to take advantage of the sensitivity and versatility in dating and mass spectrometry which has been demonstrated with overseas facilities using older 6 to 14 MV machines. Tests at the University of Rochester, and elsewhere, have shown that the sensitivity for radionuclides other than ^{14}C is likely to be two to three orders of magnitude better at 8 MV than at 3 MV. An 8 MV accelerator will also make possible the range of applied physics research and applications outlined in Section 3, which cannot be carried out with other accelerators in Australia.

The ANU's 14 MV tandem accelerator is used by the Nuclear Physics Department for research into heavy ion interactions at high energy. A policy decision has been made by them, that this and other nuclear physics research is the role of the department rather than applied science.

A new type of accelerator with a maximum voltage of 2.5 MV has recently been developed specifically for radiocarbon dating. Four of these have been installed overseas for this purpose and for any other applications which prove to be successful. Another machine of this type has been installed by the CSIRO's Division of Mineral Physics at North Ryde. This machine can be expected to meet some of the initial needs for radioisotope dating and a joint program is planned for collaboration by Lucas Heights staff in such work. This should help to bridge the gap until the proposed Lucas Heights facility is operational and able to meet the expected high demand for such measurements. Limitations to the scope of such a bridging program are discussed in Part B, Section 2.4.

The 5 MV Pelletron at Melbourne University is not a tandem and cannot be used for mass spectrometry. Likewise, the 3 MV Van de Graaff accelerator at Lucas Heights is not a tandem and would only be used for a reduced program of research and development for which high currents of light ions and low energies are advantageous.

6. ORGANISATION

The accelerator would be installed and operated as an AAEC project even though it is expected that up to 40% of operating time would be occupied with dating and other requirements for outside organisations. Costs would be minimised by the use of existing buildings at Lucas Heights for part of the experimental areas. Budgeting and running costs would be handled under normal AAEC procedures.

For internal and collaborative research programs, the facility would be staffed mainly with personnel now working in the Radioisotope Research Section and Nuclear Applications and Energy Studies Section. To provide the kind of reliability required for 24 hour operation, about five additional staff, including a full time accelerator manager, would be necessary and would be provided by reallocations within current staff numbers.

The majority of external proposals for accelerator facilities and operating time would be handled through existing AINSE arrangements. It is anticipated that the ANU's Radiocarbon Dating Research Laboratory will provide support for the establishment of a dating facility and coordinate national needs for radiocarbon dating. Major independent programs would be expected to provide the staff and finances necessary for any additional aspects of their use of the experimental facilities.

A committee consisting of representatives of major user groups and convened and chaired by the AAEC's Deputy Director, Research, would meet annually to consider operating requirements and desirable changes in usage patterns.

PART B

BACKGROUND PAPER

1. INTRODUCTION

The development of atomic energy fostered many techniques which have contributed widely to progress in science and technology. Important among these have been methods for the determination of radionuclides (by counting techniques) and stable nuclides (by activation analysis, etc.), which have now become a part of the basic tools of science.

Their use in Australia was spearheaded at Lucas Heights - with the HIFAR and Moata research reactors, accelerators, and other nuclear facilities. New developments in other countries point to the need to upgrade the facilities at Lucas Heights to achieve improved performance in the detection of both radionuclides and stable nuclides.

Expertise in nuclear science has been built up at Lucas Heights over many years in the following important fields:

(a) Physics studies as a basis for the understanding and use of interactions between radiation and matter;

(b) Investigations of materials properties and the development of new materials;

(c) Investigations of the effects of materials irradiations by neutrons, gamma-rays and ions;

(d) Broad ranging contributions to reseach and industrial applications of nuclear science.

This background paper describes a tandem accelerator facility which would introduce important new capabilities in all these fields. Such a facility would, through work by Lucas Heights staff and in joint programs with other organisations throughout Australia, have an impact on Australian science and technology comparable with that of the previous generation of facilities installed in the late 1950s and early 1960s.

It may reasonably be asked: "Can such a variety of work be sustained on one facility?" The answer to this question has been demonstrated at Lucas Heights by the multidisciplinary use of HIFAR and Moata reactors. Of particular relevance to this proposal is the use of the AAEC's 3 MV Van de Graaff accelerator which, for 20 years, has had one of the highest levels of usage in the world. This included contributions to the fields listed above - from new discoveries in physics to irradiations of tomato plants and cancer cells; from the analysis of archaeological artefacts and the hair of factory workers to the development of the world's first proton microprobe and new projects in solar energy.

With this background of experience in accelerator use and the extensive record at Lucas Heights of the applications of nuclear science to the service of the Australian community, it is now proposed to move to a new generation of activities which will make major contributions to the understanding of Australia's heritage (both natural and cultural) and promote new developments in many areas of applied science and technology. Many possibilities are summarised in Table I and discussed in Part B, Section 3. Projects which would receive priority with the new accelerator are highlighted in Part A of this document.

2. DESCRIPTION OF PROPOSED FACILITY

The proposed facility would be based on a horizontal 8 MV tandem accelerator with negative ion beam injection facilities and two main experimental beam line areas. A schematic layout is shown in Figure 1(a). An existing building, which is currently being used for exploratory measurements related to neutron irradiation of materials for fusion systems, would be used as the basis for the project. Space is available for control room and ion source areas and the massively shielded experimental hall would be used for high radiation experiments including neutron irradiations. An extension to the building would provide a shielded enclosure for the accelerator and an unshielded experimental area for dating, mass spectrometry and other low radiation work. A part of the existing building would be retained for present functions (as shown in Figure 1(a)) and this would not affect the operation of the tandem accelerator. Services are already available and these would be extended to meet the requirements of the accelerator, together with some minor relocations.

The total cost of the accelerator and associated ion source and beam line equipment is estimated to be US$4.1 x 10^6 (Table II) but, where possible, components such as the main pressure tank, will be purchased in Australia. Costing is based on manufacturer's information received in August 1983. Extensions estimated to cost $A1 x 10^6 would be needed to the building, which has a current value of approximately $A6 x 10^6. The total project cost is $A5.5 x 10^6 and this would be spread over four years. Further information on the various parts of the facility is given in the following sections. However, detailed optimisation and performance requirements would be finalised at the time of ordering of equipment so that advantage can be taken of new information and ideas in this fast-moving field of accelerator applications.

2.1 Accelerator

A horizontal tandem accelerator with a maximum terminal potential of 8 MV has been selected as the most suitable. Reasons for using a horizontal accelerator include the following:

- The proximity of the ion source area to the control room is very desirable for convenient sample changing during dating and mass spectrometry work.

- Mass spectrometry with electrostatic analysers is possible without the use of a 90° magnetic analyser as is necessary at the bottom of a vertical machine.

- Space is readily available for expansion of ion source and mass spectrometry areas if required.

The need for a maximum terminal potential of 8 MV is discussed in Section 2.4.

The ultimate sensitivity and precision which can be achieved in dating and mass spectrometry are critically dependent on such factors as voltage stability, beam transmission and the absence of residual gas in the accelerator tubes.

To take advantage of recent advances in accelerator technology to obtain optimum performance in the proposed applications, the following features are required.

(i) A terminal voltage stability of 1 keV or better and sufficient charging current capacity to limit beam loading effects on terminal voltage.

(ii) A low energy tube lens or other focusing device to ensure that the beam size at the terminal is approximately one half the stripper diameter for voltages from 4 to 8 MV; high (>90%) beam transmission is required for ions of any mass.

(iii) Optimal gas, or gas plus foil stripping, together with in-terminal pumping, to minimise gas flow to the accelerator tubes.

(iv) Ultra-high vacuum accelerator tube technology to minimise the probability of beam interaction with residual gas molecules.

(v) A separately pressurised and cooled corona column system together with shorting mechanisms, if necessary, to facilitate operation of terminal voltages down to 2 MV.

(vi) Mechanical stability and alignment, and temperature control, equivalent to the provision of an optical bench from ion source (sample) through to detector.

(vii) Full computer control of all accelerator parameters to ensure optimum performance in each application.

(viii) The best possible stabilisation of all auxiliary power supplies.

Most of these features are commonly provided in new tandem accelerators for nuclear physics research. However, additional emphasis on precision, stability, beam transmission and ultra-high vacuum is required for the facility as a whole (rather than just the accelerator) to ensure optimum performance as a mass spectrometer.

2.2 Ion Source Systems

Different types of ion source are required for the neutron physics and mass spectrometry programs. A possible layout is shown in Figure 1(b), but the detailed arrangement requires further evaluation. A major emphasis will be placed on the design of the whole facility as a large-scale mass spectrometer requiring matched precision and performance for all components. In particular, the detailed design of the injection system for mass spectrometry requires beam optics calculations which include the accelerator and detector beam lines. This part of the design would be finalised at a later stage so that full advantage could be taken of new developments in technology. Some shielding would be necessary in the ion source area; this would be installed in specific areas when required, and would be designed to enable easy access for sample changing in mass spectrometry.

The ion source (A) for mass spectrometry would be of the direct sputtering type in which a Cs ion beam is focused to less than 1 mm diameter at the sample and the sputtered negative ions used for acceleration. A multiple sample holder would be required to position each sample with high precision so as to maintain the same object parameters for the beam optics of mass spectrometry. Sputtered ions would be accelerated to a relatively high energy (100 to 150 keV) to ensure minimum losses during injection into the accelerator.

In contrast to past operating practice with most tandem accelerators, a high resolution magnetic analyser (M2) would be used to give the best possible separation of ions of adjacent mass before injection. To obtain isotope intensity ratios in dating experiments, a pulsed injection system, such as that described by Wolfli et al. (1), would be needed. This appears to be preferable to the alternative approach being developed at some laboratories where adjacent mass beams are analysed, selected and perhaps attenuated, then recombined to form a composite beam for acceleration.

A separate ion source is required for the applied physics programs. A duoplasmatron (B) would be used to produce negative hydrogen ion beams and, in conjunction with a lithium charge-exchange canal, to obtain negative helium ions. It is planned to take advantage of recent developments of superconducting resonant cavities for the production of pulsed beams of the order of 100 ps duration or less. The requirements for pulsed neutron experiments would be the subject of a development program at Lucas Heights.

Not all elements give high negative ion currents with one ion source configuration. For example, BeO ions are customarily used because of the low currents of Be ions available from most sputter sources. High currents of Al have only recently been obtained by Middleton et al.(2) using a special ion source design; a change in the type of sputtering beam can suppress the production of S- ions, relative to Cl- ions. It is therefore proposed that an ion source development project be associated with the facility at Lucas Heights. This project would be planned in collaboration with the Physics Department, University of Newcastle, NSW, which is at the forefront of the study of ion interactions with surfaces.

The concept of dedication of separate ion sources to specific dating programs would also be considered once initial measurement programs were established. All ion source systems would be based on ultra-high vacuum (UHV) practice to ensure minimum beam interactions and sample contamination.

Ion microprobes have been developed which use a sputtering beam of diameter 10 μm or less, followed by mass spectrometry of the sputtered negative or positive ions. Laser excitation is also used to ionise the neutral atoms emitted during sputtering. If required, such systems could be developed for the additional injection line (C) on the switch magnet used for the duoplasmatron source.

An additional possibility is the use of the straight-through injection line (D) for an all-electrostatic system for simultaneous analysis of a band of masses (Kilius et al. (3)). This is not included in the estimates, but could be added should the need arise.

2.3 Beam Line Facilities

Two separate experimental areas are envisaged to carry out the proposed program. Ion beams for neutron experiments would be deflected to the existing shielded area shown in Figure 1(a). A switch magnet in this area would provide a number of different target stations for the programs described in Part B, Section 3.3.

A new area for dating and mass spectrometry would include magnetic and electrostatic analysers, followed by a special detector to provide particle identification techniques (Figure 1(c)). A high resolution analysing magnet (M2), having a value of ME/q^2 of approximately 450, would be used. This magnet is needed to obtain the best possible separation for all masses. One detector would be designed to give optimum performance for radiocarbon dating and will be permanently maintained for that purpose. Additional detectors for development work and for other specialised applications, as well as focusing lenses and other beam line accessories, are not shown in Figures 1(b) and 1(c). These will be included when the system design, including beam optics, is completed.

Other beam lines from a switch magnet (M3) would be used for ion physics experiments and low radiation applications work. Again, UHV equipment would be used throughout to minimise the possibility of beam interactions with residual gas atoms.

2.4 Choice of Accelerator

The program described in Part B, Section 3 is dependent on the availability of a tandem accelerator with a terminal voltage of the order of 8 MV to provide four key features.

- The capability needed to obtain optimised performance in dating using established methods for all the radioisotopes tested so far (e.g. ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl and ^{129}I).

- The versatility which is essential to permit the development of new dating and mass spectrometry methods over the periodic table.

- The production of monoenergetic neutron beams with energies up to 14 MeV for use in neutron physics studies and as a dosimetry standard.

- A range of ion types and energies for use in nuclear science and applications work not available from other accelerators in Australia.

Although some of the proposed projects would benefit from higher voltages, there are a number of specific aspects which point to 8 MV as the most appropriate choice.

2.4.1 Requirements for dating and mass spectrometry

The characteristics of accelerator facilities which are currently used for these applications are summarised in Table III. There are two main types of facility:

(a) existing tandem accelerators with maximum terminal voltages from 6 to 14 MV; and

(b) a new generation of facilities with maximum voltages from 2 to 3 MV, designed specifically for radiocarbon dating.

The latter are being used routinely for radiocarbon measurements at terminal voltages in the neighbourhood of 2 MV. The ease with which such measurements can be made depends largely on the fact that $^{14}N^-$ ions are unstable and do not interfere with ^{14}C detection, as well as the large percentage mass difference between carbon isotopes. Work on other nuclides has mostly been carried out with the first type of facility, using terminal voltages above 5 MV.

The identification of ions with particular values of mass, atomic number, charge state, energy and velocity begins with the selection of ions for injection into the accelerator followed by electron stripping at the high voltage terminal which causes the destruction of molecular ions. After final acceleration, the required ions are selected by a combination of magnetic and electrostatic analysers and a particle identification detector.

In principle, the high energy beam line analysers (magnetic and electrostatic) will only transmit ions with a specific mass (ME/q^2 and E/q). However, energy-changing or charge-changing collisions with residual gas atoms or at slit edges can result in ions of different mass having parameters that enable them to pass through analyser slits along with the selected ions. Both solid-state (Si) and gas ionisation chamber detectors can be used although the former suffer from radiation damage by heavy ions. A thin detector followed by a thick detector, or a series of thin detectors, permits the determination of the rate of energy loss, residual energy and total energy as well as the time-of-flight between detectors if required. These parameters define the atomic number and velocity of each ion so that a peak is observed for the desired ions and this needs to be well separated from peaks arising from any interfering ions. Several examples of results from the University of Rochester (4) are shown in Figure 2 to illustrate detector performance in a number of different applications.

Many factors determine the optimisation of a dating or mass spectrometry system and require separate consideration for each application. Those which are important in the choice of an accelerator include the following.

(i) Ions with the same mass but different atomic number (isobars) have different ranges and rates of energy loss. These differences can be exploited in a particle identification detector provided that sufficient energy is available for multiple measurements to be made on each ion.

(ii) Straggling, which is the energy spread arising from the statistical nature of the energy loss process, is a vital parameter in particle identification, especially for heavy ions. A final energy of at least 20, or even 30 MeV is needed, even for quite light ions, if the straggling is not to exceed the energy loss difference to be measured.

(iii) The most probable charge state produced by stripping in the accelerator terminal increases as the ion energy at the terminal is increased. This is very important when seeking to obtain sufficient energy for particle identification:

$$Ef = e\,V\,(q + 1/k) \qquad (1)$$

where k is the ratio of molecular to atomic mass (if a molecular ion is injected into the accelerator). Higher charge states are also easier to deflect in magnetic analysers.

(iv) To be able to reject ions which have undergone spurious interactions with residual gas atoms, it is desirable that M/q should not be an integer. Higher terminal voltages lead to favourable yields of 5+ or even 7+ states which increase the choice of system parameters for rejecting spurious ions. The higher ion energies also lead to much lower cross sections for scattering by apertures and other beam line components.

As the detection of each nuclide presents an individual set of problems, optimum conditions have to be separately developed for each experiment. From the cases already investigated, it is clear that for ^{36}Cl and heavier ions, the sensitivity which can be achieved increases dramatically with accelerating voltage up to at least 8 MV. Further information on factors affecting performance in dating and mass spectrometry is given in the following paragraphs.

(a) Rate of Energy Loss. The rate of energy loss by an ion peaks at an energy which increases with the atomic number of the ion. For example, Figure 3(a) shows that the energy loss by protons travelling through carbon has a maximum near 0.1 MeV. The position of the peak (MeV/amu) for ions of different Z is plotted in Figure 3(b) for He and C absorbers and compared to the energies which can be achieved with different terminal voltages.

The presentation in Figure 3(b) has been adapted from that of Henning (5) who recommends that an energy of at least twice that for maximum energy loss is required for useful dE/dx measurements. This qualitative argument illustrates the importance of a high terminal voltage for isobar separation by energy loss measurements. However, although it is clear from Figure 3(b) that a terminal voltage of 8.5 MV would be much more effective than one of 3 MV, there are other experimental factors which also favour high terminal voltages.

(b) Straggling. Measurements of energy loss, for example using a gas ionisation chamber, are subject to statistical fluctuations and the spread in results increases with the atomic number of the incident ion. This is illustrated in Figure 4(a) for ^{10}Be ions and in Figure 4(b) for ^{36}Cl ions. The estimated straggling and best detector resolution are plotted as ratios to the incident ion energy and can be compared with the difference in the rate of energy loss (dE) for isobars of mass 10 and 36 respectively.

The energy difference in the mass 10 case (Figure 4(a)) is seen to be much larger than the resolution or straggling but, in the mass 36 case (Figure 4(b)), this is only true for ion energies above 20 MeV. At higher energies, several energy loss measurements can be made; this is a useful technique for overcoming asymmetry in the straggling distribution which can further limit the possibility of separating isobar peaks.

A striking illustration of the improved performance with higher energy ions is provided by a comparison, made at the University of Rochester (6), of ^{36}Cl measurements at 3 MV and 10 MV (Figure 5). Using the same sample in both cases, the estimated sensitivity limits were 10^{-12} at 3 MV (18 MeV final energy) and 2 x 10^{-16} at 10 MV (80 MeV). The significance of these results can be appreciated when it is realised that the natural levels of ^{36}Cl vary from below 10^{-14} to above 10^{-12} so that a terminal voltage of 8 MV is needed for the proposed program of ^{36}Cl and heavier nuclide measurements at Lucas Heights.

(c) Multiple Scattering. An additional consequence of many energy loss events is multiple scattering - small changes in direction which can cause an ion to deviate gradually from the direction of an incident beam. This can modify the performance of a particle identification system in various ways, depending on the geometry and dimensions involved. The chief effect is a loss of efficiency if multiple scattering is sufficient to cause a particle to miss the final detector in an identification system. This is particularly important in time-of-flight systems which can use separate detectors spaced by many metres.

The cross section for ion scattering decreases as the ion energy increases (as $1/E^2$), so detector design is more difficult at low energies. Ion scattering at the edges of apertures and slits is also important and can cause spurious ions to take up an energy and direction which allow them to reach the detector. This process is also much reduced at higher energies.

(d) Foil Uniformity. The required thin window at the entrance to a gas ionisation detector introduces additional multiple scattering as well as an energy spread, due to thickness variations, which affect the precision of total energy measurements. The energy loss in the foil also reduces the energy available for dE and E measurements and it is this available energy which must be used in Figures 3 and 4. Again, these effects increase rapidly at low incident energies.

Thomas et al.(7) have reported difficulties in separating ^{10}Be and ^{10}B at energies below 35 MeV because of energy loss in the detector window and interference from highly stripped oxygen ions. Although these problems can probably be overcome for ^{10}Be detection, they are progressively more important for heavier nuclides and only the use of higher energies has allowed useful results to be obtained in such cases.

(e) Range. The range of an ion is also Z-dependent, decreasing as Z increases. It can be exploited to stop ions of a higher Z isobar preferentially by the use of a carefully selected window thickness for the detector. This can be done at relatively low energies for the separation of ^{10}Be and ^{10}B; in fact, low energies are advantageous in this case since they limit the occurrence of nuclear reactions induced by ^{10}B ions with hydrogen present in the absorber foil. For heavier elements, higher energies are needed, but even then the separation of isobars becomes increasingly difficult at higher masses.

(f) Charge State. Stripping probabilities control the charge state formed when a negative ion passes through a gas or foil stripper in the accelerator terminal. The same process leads to the explosion of molecular ions which is a vital feature of accelerator mass spectrometry. The increased final energy (equation (1)) is also of great importance, since it controls the ability to select a charge state to minimise interference. For example, it is much better to use $^{36}Cl^{5+}$ than $^{36}Cl^{3+}$ ions to achieve high sensitivity.

As the ion energy at the stripper is increased, higher charge states are produced (Figure 6) and, for the highest and most uniform transmission efficiency, it is desirable to select the energy at which a particular charge state is maximised.

The energy required for maximum yield of a specific charge state decreases as Z increases, provided that charge state equilibrium is reached. This is generally true for stripping in thin foils, but not in low pressure gas. A higher energy therefore, is usually required to produce the same charge state fractions with gas stripping than with foils (Figure 7). An even more striking example can be seen in Figure 8 where the yield for the Be 3+ and 4+ charge states, when using a BeO ion source and either C foil or N_2 gas stripping, are shown for varying terminal voltages. A terminal voltage greater than 6 MV is seen to be required if gas stripping is to be used, so that an adequate yield of Be ions can be obtained.

Foil stripping has the added disadvantage that variations in foil thickness cause increased energy spread and this is worsened by foil deterioration during use. If, therefore, high precision measurements are wanted, gas stripping must be used with the consequent requirement for a higher energy machine so that sufficient yield of the required charge state can be obtained.

The choice of 8 MV for the proposed Lucas Heights facility would allow the optimum use of gas stripping for ^{36}Cl and hence provide the best performance for this particularly important radionuclide. It would also provide the necessary degree of flexibility in the choice of charge state in the development of new applications - particularly for heavy nuclides.

(g) <u>Time-of-flight</u>. To reliably identify particles reaching the detector system, it is sometimes useful to use simultaneous measurements of velocity, energy loss and total energy. This can be done by measuring the time-of-flight between dE/dx and E detectors or between a special "start" detector and the dE, E detector system. For light ions, velocities are high even at relatively low energies (Table IV) and long flight paths may be needed to achieve adequate precision. The precision is further limited by the effects of multiple scattering which become very important at lower energies. For heavier ions, velocities are lower and satisfactory precision can be achieved at higher energies using a timing resolution of 100 ps or better. Since limitations in other methods of particle identification arise for heavier ions, the inclusion of time-of-flight measurements can be quite useful.

For example, the measurement of ^{129}I involves the rejection of ^{127}I; this can be aided by the use of time-of-flight measurements as shown in Figure (9). These results were obtained at the University of Rochester, using 30 MeV I ions, a time resolution of approximately 1 ns and a flight path of 2.2 m. Resolution of an order of magnitude better is possible and will be very useful in the study of heavy nuclides, which is an important aspect of the proposed program. In fact, it has been suggested that improved system performance should make it possible to achieve a sensitivity approaching 10^{-16} for ^{129}I (4).

(h) <u>Summary</u>. Most of the parameters discussed in the previous paragraphs lead to improved performance in dating and mass spectrometry at energies above 20 to 30 MeV. The use of such energies is imperative for good energy range and energy loss measurements which are the major tools for distinguishing isobars of ^{36}Cl and heavier nuclides. Time-of-flight measurements are also useful for some problems; the best precision then requires lower energies or longer flight paths or both, and possibly the use of all-electrostatic systems. Existing facilities designed for nuclear physics work have suffered from other limitations such as low energy and resolution injection and limited resolution magnetic analysers.

Since an electrostatic accelerator can be expected to give good performance at voltages down to one-half of the maximum, a horizontal 8 MV accelerator with specially designed injection and analysis equipment would meet all requirements from those of ^{14}C dating to untried concepts in heavy nuclide mass spectrometry. Some especially difficult experiments, such as those requiring high charge states or even completely stripped ions, will not be possible with such a facility, but most of these experiments require energies of hundreds or even thousands of MeV and are not a realistic prospect in the Australian context.

2.4.2 Requirements for physics and nuclear science

The size of the tandem accelerator determines the range of research and applications which can be carried out in physics and nuclear science. The importance of a maximum terminal voltage of 8 MV to the programs described in Part B, Section 3.3 and 3.4, is illustrated by the following examples.

(a) Neutron Sources. Monoenergetic neutron beams at energies between 3 and 14 MeV are needed for various studies. The proposed facility would make it possible to generate beams throughout this energy range using the reactions listed in Table V. A terminal voltage of 8 MV is required so that experiments can be carried out which bridge the gap between the neutron energies available from (d,n) and (d,t) reactions using low energy accelerators. The availability of the heavily shielded experimental area makes it possible to propose work which would not be possible at other Australian facilities.

A new method for neutron production, which would only be available with a heavy ion tandem accelerator, is the use of "inverse" reactions such as $^{1}H(^{7}Li,n)^{7}Be$ (8). In this method, a ^{7}Li beam is accelerated to seven times the proton energy normally used and neutrons are produced from a hydrogen target. The forward momentum of the ^{7}Li ions changes the observed neutron angular distribution and this can be exploited to obtain favourable conditions for precision data measurements and irradiations. Other inverse reactions also hold promise for use in a similar fashion. Terminal voltages above 4 MV are needed for this type of work.

(b) Ion Interactions. Atomic interactions by heavy ions are an expanding field of research with implications for:

- the development of new applications of dating and mass spectrometry;
- applications of ion beam analysis methods which are not available with lower energy accelerators; and

- improvements in data and theory needed for such applications.

Accelerator requirements for the first topic necessarily follow those discussed in Section 2.4.1. The availability of terminal voltages up to 8 MV would allow a number of additional applications. Recoil profiling using a beam of 30 to 40 MeV ^{35}Cl ions has recently been demonstrated as a valuable tool for simultaneous depth profiling of all light nuclides up to oxygen. For example, H and B profiles in Si can be measured in this way (9).

Other methods for determining hydrogen depth profiles use ^{7}Li, ^{15}N or ^{19}F ion beams and terminal voltages above 4 MeV allow a choice of reactions and depth ranges. In a third application of growing importance, thin layer activation (to a depth of the order of 100 μm) can be used in wear and corrosion studies - a field which has become a major activity with the Harwell tandem accelerator (10).

X-ray emission from heavy-ion irradiation is also a field of new interest and potential application. However, present ionisation theories are based solely upon direct ionisation and are adequate only for Zion/Ztarget < 0.3. Other processes including, for example, ion-electron capture and pseudo-molecule formation (ion-atom) are important for Zi/Zt > 0.3. A full range of incident ion types is needed to study these processes and, additionally, an incident energy of 1 to 4 MeV/amu is needed. A terminal voltage of at least 6 MV is therefore required.

An important component of the proposed PIXE research and applications development program using highly energetic heavy ions, would be the the study of the production of inner shell ionisation in the presence of multiple outer shell vacancies. This study of multiple vacancies in the L and M shells, which are more closely related to the outer shell bonding electrons, will provide information on the effect of chemical environment. A target with Z in the range 60 to 90 would be advantageous and the choice of 8 MV for the proposed facility would allow the maximum flexibility for the research program as it would then provide the required heavy ions with energies covering the range of interest.

A recent development in the use of energy dispersive PIXE for ions other than protons is the field of collision-induced intrashell transitions. Here the reorganisation of vacancies created by an ion during the collision time of the ion is studied, and has been shown to be very significant for L and M shell transitions. Theories are being develcped to handle this and experiments in the range from 0.1 to 10 MeV/amu are needed. Once again 8 MV terminal voltage would be well suited for research in this area providing a wide range of heavy ions with energies covering the range of interest.

2.5 Relation to Other Facilities and Techniques

2.5.1 Other facilities

The relation between the proposed facility and other accelerators installed in Australia has been summarised in Part A, Section 5. In addition to providing performance and applications which are complementary to those of other accelerators, the Lucas Heights facility would ensure that the significance of the expertise and postgraduate training at nuclear physics departments at the Australian National University and Melbourne University are extended through the existence of an applied science program developed to meet national needs.

In the three to five years which it would take for the proposed facility to become fully operational, some of the proposed programs can be initiated through collaboration in the use of the HIAF accelerator at the CSIRO Mineral Research Laboratories. The factors discussed in Part B, Section 2.4 indicate that the scope of an interim program will necessarily be much more limited than that discussed in Part B, Section 3.

Much of the development of dating and mass spectrometry has been carried out using old tandem accelerators at nuclear physics laboratories (see Table III). Although some of these are being further adapted for this work the majority will not be used in applied science now that the demonstration experiments have largely been done. With its use of the most modern accelerator technology and a design optimised for dating and mass spectrometry, the Lucas Heights facility would have unique characteristics and performance. It would also draw upon and add to the specialist expertise at Lucas Heights in ion physics, materials science, environmental science and other fields. The proposal, therefore, represents a major advance in the role of Lucas Heights in both national and international science and technology.

2.5.2 Other techniques

As discussed in Part A, Section 3.1, accelerator dating methods offer the advantage of handling milligram samples at 1 to 10 samples per hour throughput and can be used for radioisotopes not previously suitable for decay counting. In addition, it can be shown that cost estimates are also favourable. Table VI gives a comparison of costs for decay counting and accelerator measurements for ^{36}Cl, which initially will be one of the principal applications of the proposed facility. In spite of the high capital cost of the accelerator, the cost per sample for the two techniques are seen to be comparable. There is no competitive technique available which can offer sensitivities for the determination of the ratio of radioactive to stable isotope abundances below 10^{-15} g/g.

Many new methods are being developed for sample analysis at very low levels of trace elements. For example, activation analysis, low energy secondary ion mass spectrometery (SIMS) and Rutherford backscattering can achieve sensitivities of the order of 10^{-9} to 10^{-10} g/g in specific cases. Of special interest for comparison with accelerator mass spectrometry are the so-called "atom-counting" methods based on laser interactions. In the case of noble gases, resonance ionisation by a tuned laser beam releases photoelectrons which can be counted individually. An enquiry into recent work of this kind shows that it does not offer a method for determination of very low isotope ratios since there is insufficient wavelength shift between isotopes of one element when compared with line broadening.

An extension of resonance ionisation spectroscopy uses a laser to selectively ionise neutral sputtered atoms with the promise of a better sensitivity than with normal SIMS. This approach can also be adopted in the ion source for accelerator mass spectrometry so that the performance achieved (currently down to 10^{-12} g/g) will be further improved and will remain better than for the equivalent low energy methods.

The ion microprobe, which is a SIMS system with a sputtering beam of 10 μm or less diameter, provides a very sensitive method for studying element distributions across geological and other specimens. This approach can also be adopted by the provision of an appropriate ion source for accelerator mass spectrometry. A microprobe ion source and all-electrostatic injection and analysis beam lines are being developed at the University of Toronto for ultrasensitive mass spectrometry (3). This topic is discussed further in Part B, Section 3.2.

3. PROPOSED PROGRAMS AND POTENTIAL APPLICATIONS

3.1 Radioisotope Dating

Among the many scientific revolutions which have taken place in recent years, the growth of understanding of global changes in the earth, the oceans and the atmosphere has stimulated a reappraisal of the role of man's activities. The establishment of a balance between resource exploitation and doomsday predictions of climatic change, environmental pollution, genetic change, etc. depends on an accurate reading of the record of the past and of early indications of significant changes.

Australia is unique in its geology, geography, ecology, climate, resources, prehistory and current circumstances. Scientists in this country are in a position not only to assess these topics at a local level but can also provide an important component of information for assessment of global processes. The proximity of Australia to Antarctica, with its even more unusual role in such investigations, is also significant.

The concept of ultra-sensitive nuclide determination using a high energy accelerator was used before World War 2 in a search for naturally occurring ^{3}He. However, this work was discontinued until 1977 when a number of papers were published giving initial results from the use of cyclotrons and tandem accelerators in the search for super-heavy nuclides and quarks and for ^{14}C dating. Results on the first two topics were negative but the observation of ^{14}C at a level of 1 part in 3×10^{15} led to many proposals for determining other radionuclides with longer half-lives.

The really exciting development in accelerator dating is the proved potential for determination of radionuclides with half-lives too long for standard counting techniques. Table VII lists some of the published performance figures.

The use of these nuclides dramatically expands the scope of absolute dating in problems involving time-scales that reach back from the recent past to the order of a million years. This increased scope bridges the gap between radiocarbon dating and other techniques such as fission track dating and isotope ratio analysis which are useful chiefly for time-scales from millions to billions of years.

As potentially significant is the dramatic increase in sample throughput made possible with accelerator techniques. For instance, in the case of ^{36}Cl, the measurement time decreases from two weeks using radioactive counting to less than one hour with the accelerator. Assuming that 2000 hours of accelerator running time is dedicated to dating applications, a typical program of measurements, such as that in Table VIII, would be possible.

Accelerator methods are revolutionising the field of isotope geoscience because not only can a time span of thousands to millions of years be studied, but also measurements can be made on milligram samples to levels of 10^{-12} and below. For the first time, geochemists are able to study the chlorine cycle with a well-established dating technique and with an authority which is only possible when a large number of samples can be measured. It will also be possible to use other radioisotopes which have hitherto been unavailable; examples include ^{41}Ca, ^{129}I and ^{237}Np.

In proposing a program of applications, the following criteria have been used:

(i) Projects must be of a major, on-going nature, supporting investigations of recognised national importance;

(ii) In view of the investment in the accelerator, projects must involve measurement capabilities presently unavailable in Australia.

For instance, no reference has been made to uranium series dating applications which can be pursued adequately using alpha-particle counting techniques.

3.1.1 Groundwater hydrology

(a) Nature of the Problem. Groundwater is an essential national resource. In 1974, it was estimated that, excluding flowing wells from the Great Artesian Basin, 2.6 x 10^9 tonnes of water was abstracted from 348,000 bores. The future of much of the Australian interior is critically dependent on assured supplies of potable groundwater. On the average, the groundwater demand is only about 3.7% of the recharge rate. However, in certain regions, the situation is very different. In the Murray-Darling drainage division, for instance, the ratio of groundwater abstraction to recharge is about 44%; in the South Australian Gulf division it is about 79% (11).

As the usage ratio increases, more and more sophisticated aids to groundwater management will be required if the continued supply is to be assured. The use of mathematical models to develop management strategies is increasing. Environmental isotope techniques can play an important role in the development, calibration and verification of hydraulic models on which management models are based.

When evaluating a resource, questions of groundwater quality are as important as those of sustainable yield. An understanding of the reasons for variations in water quality can contribute to the good husbandry of the resource as well as to the development of strategies for future exploration. Measurements of ^{36}Cl on a tandem accelerator can enhance this knowledge.

(b) Environmental Isotopes and Hydraulic Models. ^{36}Cl is a cosmogenic isotope which enters groundwater systems dissolved in recharge water. Because of its long half-life (301,000 y) it can be used to date water up to 2 x 10^6 years and to study the dynamics of large hydraulic basins. The validity of the method has been demonstrated in the Great Australian Basin (12) where a detailed comparison has been made of the ^{36}Cl ages and those calculated from the BMR's mathematical model of the Basin (Figure 10). The comparison of the isotope and hydraulic ages has led to a refinement in the parameter (hydraulic conductivity/porosity) which hitherto could only be estimated to within an order of magnitude. This refinement should increase the predictive value of the model.

Having been verified in a well-understood system, the ^{36}Cl technique can be applied with more confidence to other large groundwater systems such as the Murray and Amadeus Basins. The more sparse the availability of good quality hydraulic data, the greater is the significance of isotope techniques for understanding the groundwater dynamics on which mathematical models are based. They are therefore likely to be of particular value in arid and semi-arid zones.

The Great Artesian Basin project was undertaken in collaboration with the BMR and the University of Arizona. Measurements were made on the tandem accelerator at the University of Rochester. This facility is operating at saturation and further access cannot be guaranteed.

(c) <u>Investigation of Groundwater Quality</u>. The level of dissolved solids in groundwater is normally higher than in recharge water because of:

- evapotranspiration, and
- sub-surface solution, particularly of evaporites.

The proposed technique depends on the ^{36}Cl level being a monitor of that component of the chloride which has resided within 1 metre of the surface for a significant period within the last million years. Processes leading to salinity increases have different effects on the total chloride concentration, the ^{36}Cl concentration and the $^{36}Cl/Cl$ ratio; these are shown in Table IX.

These investigations need not be restricted to groundwater. The ^{36}Cl could be used, for instance, to quantify the components of the salinity loading of the Murray river.

(d) <u>Sustainable Yield of Groundwater</u>. The assessment of sustainable yield of a groundwater resource requires knowledge of the ratio of the average net recharge rate to the rate of abstraction. For long-term prediction, recharge rate calculations should be averaged over the longest period possible. Using ^{36}Cl, the mean value over the past few decades may be obtained. The principle is as follows.

Since 1955, the major source of ^{36}Cl has been atmospheric nuclear testing. The input from these tests reached a maximum in the mid 1960s and subsequently decreased following the implementation of the atmospheric nuclear test ban treaty. As a consequence, a well-defined isotope pulse may be identified in the unsaturated zone (Figure 11), which migrates down through the profile with the infiltrating water (13). The rate of migration is a measure of the recharge rate averaged over the past 30 years. Recharge measurements could be requested by engineers assessing groundwater potential in arid and semi-arid zones.

3.1.2 Salinity

(a) Nature of the Problem. The Australian Water Resources Commission (AWRC) Working Group on Water Research Policy has identified several gaps in current research effort including salinity and the use of aquifers for waste disposal (14). It has pointed out that increased salinity in runoff from areas where dryland farming is practised, is becoming a major threat to Australian water resources. The replacement of deep-rooted trees with shallow-rooted ones leads to a reduction in transpired water. Consequently, water tables rise and soluble salts are relocated near the surface, leading to considerable soil damage. The area of dryland salting is estimated to be twice that affected by irrigation-induced salinity and is likely to double within the next twenty years (15).

The nature of water logging and salinity problems associated with irrigation have long been recognised, but have become more pronounced in recent years. The problem is so great in the Murray Valley that it has been estimated that $75 x 10^6 will be required over the next five years for the most urgent remedial measures (16).

(b) Investigation of Soil Salinity. Salinity of agricultural land is a man-made problem. Isotopic techniques must therefore be sensitive to changes that have occurred not over geological time but during the past few decades. Studies of the ^{36}Cl "test" pulse is therefore appropriate.

As indicated above, the effect of weapons testing is reflected in a ^{36}Cl profile in the unsaturated region of an undisturbed soil with a maximum corresponding to the mid 1960s. In many cases, changes in land use leads to a drastic alteration in the chloride balance, and therefore in the ^{36}Cl profile. If perturbed and unperturbed profiles are observed within a given region, a means is available for quantitatively describing the redistribution of chlorides. This should lead to a much more precise definition of the problem and a much better assessment of the various remedial measures.

3.1.3 Erosion and sedimentation

The Hydrology Group is actively engaged in the application of environmental isotope techniques, including ^{137}Cs and ^{210}Pb to investigations of sedimentation and erosion. Studies are therefore restricted to processes which have occurred over the past few decades, a period of great significance in the development of Australian agricultural, pastoral and mining industries. These techniques are used by such organisations as the CSIRO and a number of universities. An accelerator mass spectrometry facility will enable an extension of these methods to a one million year time-scale.

Systematic measurements of ^{26}Al / ^{10}Be ratios in exposed rocks and accumulated alluvium will allow the rates of erosion and sediment accumulation to be assessed throughout the late Quaternary, resulting in a quantitative picture of the evolution of Australian landscape. This is of interest from the scientific viewpoint and is also of importance in the location of waste disposal sites.

3.1.4 Oceanography

This section deals with the application of a tandem accelerator to questions associated with the dumping of radioactive wastes. Being an island continent with important interests in the South Pacific, Australia will inevitably be involved in the continuing debate despite the fact that such dumping is contrary to government policy. Australia's interest should be supported by an appropriate program of scientific research. The following are possible applications of accelerator measurements.

(i) Sediment Accumulation. $^{10}Be/^{26}Al$ ratio could be used to estimate the rate of sediment build-up over the past 3 million years. These data will supplement those obtained over much shorter time scales using ^{14}C, $^{235}U/^{231}Pa$ and $^{234}U/^{230}Th$ dating techniques.

(ii) Convective Transport. By systematically studying the levels of cosmogenic isotopes and the $^{129}I/^{238}U$ ratios, information may be obtained on the large-scale convective transport of marine sediments.

(iii) Solute Transport. By studying the $^{36}Cl/^{238}U(+^{232}Th)$ ratio through a marine sediment profile, information may be obtained on the solute flux. In general, the higher the flux, the lower is the ratio.

Although relevant to questions of the dumping of waste on or below the surface of the oceanic sediments, items (ii) and (iii) have yet to be demonstrated.

3.1.5 Glaciology

Deep ice cores provide a record of atmospheric deposition over several hundred thousand years. Over geological time they have provided answers to such factors as volcanic activity, micro-meteorite input and indicators of palaeoclimatic change such as variation in CO_2 content; for more recent times they provide information on man's impact on the environment.

Technically, there are serious problems because of the need to date the cores with very small samples of ^{10}Be, ^{14}C, ^{36}Cl and other cosmogenic isotopes, as well as measuring small quantities of other elements included within the ice. The dating of complete ice cores will shed light on the dynamics of the accumulation of the polar ice sheets. The cyclical variation in the extent of the arctic and antarctic ice sheets is correlated with palaeoclimatic changes.

3.1.6 Mineral exploration

(a) Uranium and Associated Elements. The isotope (^{129}I) has 2 principal modes of generation - the spallation of xenon in the upper atmosphere and uranium fission. Within a uranium deposit the fission yield is likely to dominate, hence the level of the isotope in groundwater should indicate whether there has been a significant up gradient accumulation of uranium. Indirectly, it will indicate the presence of elements correlated with the uranium. In the Northern Territory, a study of the mobilisation and transport of ^{129}I is under way in the vicinity of deposits in the East Alligator River region.

(b) Hydrocarbons. When developing exploration strategies for extending existing oil fields, it is important to know the relationship between hydrocarbon accumulation, the associated brines and the source rocks. A number of geological (palaeontological), chemical and isotopic techniques have been developed to address this problem.

A potentially powerful technique involves the use of ^{129}I. Because of the long half-life of this isotope (1.7×10^{7} y), it should be possible to date the iodide residues in the source rocks, and the iodide in the oilfield brines throughout the Tertiary, provided that there are no interferences from sub-surface fission. In the presence of uranium it would be necessary to distinguish the supported and unsupported ^{129}I; it is not yet known whether this is possible.

3.1.7 Scope for further research

There is immense scope for further research in the field of radioisotope dating. Two examples are cited.

(a) Calcium - 41. The cosmogenic isotope ^{41}Ca (half-life 13,000 y) is potentially useful in extending the dating of shells, bones and teeth beyond the ^{14}C limit. A serious problem in interpretation arises because the isotope is generated by the activation of ^{40}Ca by cosmic-ray neutrons. When formed on the Earth's surface and released by erosion, the input function depends on the relative contribution of ^{41}Ca from various sources. Correlation with ^{14}C and uranium series dates could provide information on:

- the calcium cycle, in the case of alluvial samples; and
- sources of calcium, in the case of hydrological samples.

(b) Silicon - 32. It may be possible to use ^{32}Si to study erosion rates over the past few hundred years. One approach was outlined in Part B, Section 3.1.4, using cosmogenic isotopes to study the evolution of landscapes over the past three million years. In practice, the measurement of erosion over the past 200-300 years would be of greater importance. The possibility of using ^{32}Si (half-life 110 years) could be explored. The problem is that the levels of ^{32}Si are expected to be approximately 1×10^{-16}, which is too low for existing measurement sensitivities. It has been suggested that the sample might be enriched before measurement. Another possibility is to measure the level of the grand-daughter ^{32}S. If the average residence time is 100 years, about 10^6 sulphur atoms per gram of silicon will accumulate. A non-^{32}S carrier would certainly be needed.

3.2 Ultra-sensitive Mass Spectrometry

Stable isotopes and radionuclides can be determined by accelerator techniques but there have been few published examples. Platinum and iridium have been determined in geological samples at levels of 1 part in 10^{12} during investigations of a possible cataclysmic event associated with the extinction of the dinosaurs (see Figure 2). Research projects at Oxford and Toronto Universities are aimed at such ultra-trace element determination, particularly for heavy nuclides. Toronto also plans to use special ion source equipment to achieve microprobe analysis of specific regions (beam spot sizes of 10 μm or possibly less eventually).

The achievement of ultra-trace sensitivity will require optimisation of parameters to specific groups of nuclides and will involve a considerable research and development program to determine the full potential of accelerator mass spectrometry applications. There are numerous areas in which such techniques would contribute to existing projects at Lucas Heights; these include hydrology, sedimentology, improved materials for radiation detectors and such topics as the distribution of key nuclides in the neighbourhood of mines or waste repositories.

Accelerator mass spectrometry would also be useful for assaying trace elements in small samples. It should be possible to assay actinides in atmospheric samples and hence obtain information on the nature and yield of atmospheric nuclear tests. More generally, it should be possible to assay small samples for most nuclides of geochemical significance. The range of such applications is limited only by the imagination.

3.2.1 Actinide transport

(a) Uranium Mining and Milling; Ore Genesis Studies. The AAEC undertakes a number of environmental programs:

- to monitor the migration of uranium series nuclides, heavy metals and other products mobilised by the mining and milling operation;
- to study the effect of these products on the natural ecosystems; and
- to predict the ultimate fate of these products following cessation of operations and rehabilitation of the area.

Long-term prediction is only possible if a sound knowledge of the transport mechanism is available. Recent work has shown that uranium, thorium, radium and other heavy metals are not uniformly distributed through ore samples. For instance, in the weathered region of the Ranger and Jabiluka ore deposits, uranium and thorium are mainly deposited within the iron minerals. On the other hand, radium is usually associated with the clay/quartz fraction (17). An understanding of the distribution of heavy metals between mineral components is essential for the prediction of long-term transport and assessment of accumulation mechanisms (ore genesis).

Work at the AAEC combines chemical separation and radiometric assay techniques. The capabilities of the tandem accelerator to measure ultra-low levels of a wide range of elements would greatly enhance this work. Enormous advances would be made if it were possible to use microprobe techniques to study the distribution of uranium series nuclides and heavy metals through the mineral components of untreated ore. Further comments on the potential of microprobe techniques are presented in Part B, Section 3.2.3.

(b) Siting of High-level Radioactive Waste Repositories. The analysis of nuclides that have been dispersed in small quantities throughout the biosphere since the advent of nuclear testing, or which enter the environment from natural ore deposits, can provide useful data on which to base radioactive waste disposal methods. However, because the levels are so low, radioactive counting techniques are quite impracticable. The tandem accelerator could alleviate this problem.

3.2.2 Materials development

Trace element determination in semiconductor materials for the production of radiation detectors has been undertaken with all available methods, including sensitive techniques such as the spark source spectrometer. Methods with greater sensitivity would allow radiation detector technology to be developed even further.

3.2.3 Ion microprobe

An ion microprobe consists of a sputter ion source attached to a conventional mass spectrometer. The sputtering beam (e.g. Cs) is focused to a diameter of the order of 10 um or less and the sample mount is moveable in two dimensions so that the yield of secondary ion species can be plotted as a function of position on the surface of the sample. There are many uses of an ion microprobe, with the study of geological specimens on a micrometre scale being of special interest. Potential applications to Lucas Heights programs include:

- the prediction of the transfer of actinides and heavy metals (Section 2.7.1);
- the study of ore genesis; and
- the development of exploration strategies.

There is great promise for the use of an accelerator-based ion microprobe although difficulties, such as the variation in sputter yield by up to a factor of five due to "matrix" effects, must be overcome as in low energy SIMS. A microprobe ion source could be added to the Lucas Heights facility should this be required.

3.3 Applied Physics

Physics research at the AAEC has concentrated in two broad areas. Initially, the principal interest was in the generation of data required for energy systems such as fusion and fission, and an understanding of the relevant interactions, so that those data which were impossible to measure, could be accurately calculated. Areas of interest included neutron interactions within the energy range of existing facilities, with an emphasis on neutron fission data and the systematics of the neutron capture process. These studies led to international recognition and membership of the International Nuclear Data Committee. This membership has been valuable to Australia, since it has allowed access to regularly updated nuclear data sets. Out of the data studies there also arose an invitation to participate in the Inter-regional Project (INT-018), organised by the IAEA, to assist the technological advancement of developing nations. In this context, the specific interaction by Australia has been with countries in the South East Asian region. Other collaborative projects are listed in Table X.

The second principal interest has been the exploitation of ion beam techniques and nuclear analysis methods in a wide variety of applications. This research effort grew out of the nuclear data studies and the availability of general purpose facilities. However, as the program increased in size, with concomitant success, a number of new techniques were developed. This pioneering work, which has become the focus of Australian conferences on nuclear techniques of analysis, is being extended by the use of new accelerators at the Royal Melbourne Institute of Technology and the University of Melbourne; the CSIRO's Division of Mineral Physics is now entering the field.

The success of the physics programs rested on the suitability of the major research facilities within Applied Physics Division, namely, the 3 MV Van de Graaff accelerator and the reactor Moata. Unfortunately, these facilities are unsuitable for the resolution of important new problems. For example, neutron data requirements for fusion energy systems occur at neutron energies which cannot be produced with this accelerator. Furthermore, within the nuclear applications area the limitation imposed by the restricted ion beam energies and the ion beam varieties has become an increasing problem. In fact, for one exciting new area of application - accelerator mass spectrometry - it has no capability at all. Thus, to maintain a proper research effort in physics-related problems which can exploit recent developments for the enhancement of Australian technology, a higher energy accelerator is required. The availability of this facility would allow the 3 MV Van de Graaff to be devoted to straightforward measurements and irradiations which would require much reduced technical effort for maintenance and development.

3.3.1 Neutron physics

The new tandem accelerator would be particularly suitable for the study of a wide range of neutron physics problems. By using

3.3.2 Safeguards research

In attempting to understand the physics of fission reactors there are a number of problems related to methods of applying international safeguards. This is particularly significant in this country, owing to Australia's commitment to the Nuclear Non Proliferation Treaty. Furthermore, Australia has made a significant financial investment in the creation of a national nuclear competence in this field. The retention of this competence is important to the pursuit of an appropriate uranium policy.

In the application of safeguards to strategic nuclear material, the principal method for determining the plutonium content of waste from reprocessing plants is neutron coincidence counting. There is a major program at the AAEC to improve methods based on this principle. However, the technique can be applied only to material containing plutonium-240 as this is the origin of the coincident neutrons. A more general method of applying safeguards, which is less specific than neutron coincidence counting, is the neutron 'die-away' technique. This technique requires a pulsed source of neutrons so that delayed neutron emission can be measured and related to the known decay times for different fissile isotopes. The new tandem accelerator would be an ideal machine on which to develop the technique.

3.3.3 Fusion research

An advanced understanding of neutron physics is as important in fusion systems as it is in fission reactors. In the fusion reaction ($^{2}D(t,n)^{4}He$) approximately 80% of the energy is carried off by the emitted neutron. The interaction of these neutrons with the first wall materials contributes some of the radiation damage. The interaction of these neutrons with a breeding material such as ^{7}Li replenishes the tritium fuel; the method of extraction of the kinetic energy from these neutrons determines the efficiency of the reaction as a power source. The new research program would therefore include the following studies.

(a) First Wall Damage Studies. Differential cross section measurements of the (n,p), (n,α) and (n,n') reactions for structural materials are required in the energy range 7 to 14 MeV. The cross sections for these reactions are largest in this energy range and it is serious, therefore, that the data are unsatisfactory in this region.

(b) Tritium Breeding. The AAEC's Nuclear Technology Division has a research program on the study of fusion blankets and, specifically, of tritium breeding in the blankets. It is fundamental to the commercial success of a fusion reactor to breed tritium fuel. The relevant nuclear data are particularly poor. Specific requirements include:

- measurements of neutron multiplication cross sections, i.e. $(n,2n)$ in the energy region from 7 to 14 MeV; and
- measurements of the principal tritium production cross section - $^{7}Li\,(n,n',\alpha,t)$.

3.3.4 Nuclear physics

Accelerators similar to the proposed tandem have been installed, primarily for nuclear physics studies, at the Hahn-Meitner Institut in Berlin and at the University of Sao Paulo. The Hahn-Meitner Institut machine will concentrate on heavy ion interactions. The program for the 8 UD at the University of Sao Paulo includes a large component of low energy nuclear structure studies in addition to the study of heavy ion interactions. Equivalent machines having the same or higher terminal voltages, installed at other institutions, devote the principal component of their running hours to basic nuclear studies. It can be seen, therefore, that the proposed 8 MV tandem accelerator would have considerable capability as a basic nuclear research facility. Apart from the limited program on the study of the fission mechanism (Part B, Section 3.1), the proposed nuclear physics program is envisaged initially to be quite minor. However, the capability of the accelerator would be made available to interested university departments.

There are many interesting problems of fundamental importance which could be considered. The proof of the existence of super heavy elements, quarks, proton decay, etc. has been the subject of considerable scientific effort for almost a decade. The accelerator mass spectrometry capability of the new tandem accelerator offers the opportunity for searches of this kind, the measurement of half-life of rare nuclides and other applications.

3.3.5 Ion physics

The production of heavy ion beams depends on atomic and molecular processes and different methods give the best results for different ranges of elements. The production of positive, neutral and negative ions are all applied in ion source designs. The ions have different coefficients for electron stripping and charge-exchange which are exploited to obtain high final ion energies and to achieve high background rejection in accelerator dating and mass spectrometry. Molecular ions are a major feature of normal mass spectrometry but they 'explode' when several electrons are removed. This is also an important feature in background rejection. The physics of atomic and molecular processes, and ion beam transport and detection, will be a vital part of the research associated with the proposed project.

3.4 Nuclear Science and Applications

3.4.1 Ion beam analysis

Ion beam analysis methods are particularly advantageous for the study of surface layers on glass, semiconductors, metals, solar absorbers and other materials. The non-destructive depth profiling of many light nuclides is widely exploited as also are rapid and sensitive methods for automated analysis of most materials. Such accelerator-based methods are usually complementary in the capabilities that they offer to those which use reactor facilities. The scope of this work can best be illustrated by the number of recent projects carried out by the Nuclear Applications Group at Lucas Heights in collaboration with other organisations (Table XI).

The higher energy beams and greater range of ion types available from the tandem accelerator would extend the range of applications of these methods. This includes:

- non-destructive profiling of hydrogen, helium, carbon, nitrogen and oxygen (at present only H can be profiled with limited resolution and range);
- the simultaneous absolute determination of many elements by ion induced gamma-ray emission, which is a versatile method for non-destructive analysis at ppm levels and below;
- the provision of a wider range of beams for optimising the PIXE method as an analytical tool; and
- the extension of PIXE research to heavy ion induced X-rays and to the study of the effect of chemical bonding on satellite X-ray emission.

(a) PIXE. The PIXE research program, carried out jointly by the Applied Physics Division and AINSE has, over the last five years, generated a large program of applications of the technique for elemental analysis of a wide range of interests ranging from mining and environmental studies to the analyses of biological and archaeological materials.

International trends in particle induced X-ray emission are towards ions heavier than protons or alpha particles, and a wide range of the features of X-ray production have yet to be investigated. Highly energetic heavy ions are capable of producing multiple inner-shell ionisation and the resulting spectrum of X-rays from a particular target atom is composed of a complex series of satellite lines. Figure 12 shows an example of high resolution spectra obtained with protons, alpha particles and oxygen ions incident on a solid Ti target (20). The degree of ionisation increases very rapidly with the projectile Z and the amount of multiple ionisation decreases slowly as the Z of the target increases.

Chemical effects cause the redistribution of intensity from one satellite group to another; these changes can be correlated with bulk chemical properties (valence-electron densities, effective charges, covalencies, etc.). It appears, therefore, that the study of heavy ion induced satellite X-ray spectra would make a powerful contribution to the understanding of chemical bonding in complex chemical compounds. Figure 13 shows an example of these satellite lines for sulphur K alpha X-ray spectra produced by 36 MeV Ar ion interactions with 12 sulphur compounds (21).

A study of the effect of chemical form on L shell X-ray satellite peaks of molybdenum compounds and alloys has shown a correlation with the valence electron density. This suggests that heavy-ion-induced L X-ray studies can probe the chemical nature of alloys and compounds of a large region of the periodic table (e.g. transition metals). There is a possibility of obtaining new chemical information on, for example, implanted materials in metal alloys but considerable experimental and theoretical work must be done to understand both the parametric and the fine structure of satellite lines.

Some experimental measurements of cross sections have been reported which agree with theory as long as the major discrepancies are attributed to multiple ionisations which can profoundly change the X-ray emission probabilities. It is quite evident that many more X-ray production measurements are needed with sufficiently heavy and energetic ions to enable a systematic comparison with multiple ionisation theories. Such a study would complement and extend the extensive L-shell cross section measurement and theoretical evaluation of light ion interactions (proton and alpha particles with energies in the range 0.15 to 3 MeV/amu) which have been carried out at Lucas Heights.

Applications of the analyses of Cl and S in polluted atmospheres have used Ar ions of 2 to 6 MeV incident energy. These have sensitivities that are better than for 2 MeV proton measurements but this will change markedly for targets in the mid-range of the periodic table, where the inner shell vacancy production peaks when the projectile energy is a few MeV/amu. With Ar ions and energies of the order of 100 MeV, the X-ray output for these targets will be much larger than it is for protons or other light ions at any energy.

Energy dispersive PIXE analysis for ions other than protons has recently been shown to be strongly dependent on collision induced intrashell transitions, particularly for L and M shells. Modern Si(Li) detectors can resolve these for target atoms with $Z > 60$ and ion effects on vacancy distributions in target atoms have been observed for the impact of C, N and O on Au. More dramatic effects are expected for heavier ions. Theories are being developed to handle this and experiments in the 0.1 to 10 MeV/amu range are needed to verify the theoretical approach. The 8 MV tandem accelerator will be ideally suited to such research as it can provide a wide range of heavy ions with energies covering the range of interest.

No work has been done on low Z trace elements in a high Z matrix target using heavy ions (even ions as light as $Z=3$); this area of research could have significance for trace element analysis in materials development. Heavy ion thick target PIXE has yet to be explored and quantified for trace element analysis. Surface roughness and structure is probably one problem that will require much work.

Even neutrons, although uncharged, can cause ionisation and hence X-ray emission when there is a sufficiently direct collision with the nucleus of a sample atom. The resulting recoil of the nucleus may give rise to ionisation. Studies of this process will help to verify the theoretical methods used for calculating ion induced X-ray yields, which also involve recoil effects.

(b) Nuclear Reactions and Recoil Elastic Scattering. The wider range of ion types and greater energies will greatly enhance the AAEC's surface studies program. For example, Li, N or F ions can be used to initiate nuclear reactions to profile hydrogen with greater sensitivity and to greater depths than can be done with the 3 MV accelerator. Table XII lists a number of methods that are suitable for the resonance scanning of hydrogen depth profiles and includes the depth ranges, sensitivities and resolutions.

Heavy ion bombardment of a surface also enables all light elements to be forward scattered out of the surface. At the present time only H can be profiled with the alpha particle energies available from the Van de Graaff accelerator, and depth profiles are limited to approximately 0.8 μm. With heavier ions and increased energies, multielement profile studies will be possible. As an example of the potential of this technique, profiles of C and O in Ti have been obtained with detection limits of approximately 10^{15} atoms/cm^2 using time-of-flight analysis of the recoil particles produced with incident 20 MeV Ar ions.

Some work has already been done to extend the possibilities for surface analysis where multielement depth analysis by Rutherford Backscattering and the detection of projectiles and recoils have been carried out with a time-of-flight technique. In this work, 90 MeV ^{40}Ar and 199 MeV ^{86}Kr ions have been used, the Ar ions providing depth profiles to 20 μm.

It is quite clear that the provision of the proposed accelerator with the range of highly energetic ions available would enable the AAEC's surface analysis programs to be greatly extended and would have wide application in the study of prepared surfaces and in general materials analysis.

(c) Particle Activation Analysis. Particle activation analysis has outstanding sensitivity for detecting many light elements ($Z < 30$), and in many cases is better than 0.1 $\mu g/g$. Activation occurs only at depths less than the range of the incident ions so it is a surface rather than a bulk analysis technique. The choice of incident ion and energy affects both the sensitivity and selectivity of particle analysis (both trace and major components being activated). The complexity of the options appears to have delayed the understanding and application of the technique for surface analysis. Table XIII lists a variety of incident ions and their energies and shows the range of minimum detection limits.

An important application of particle activation is for wear studies. The thin surface layer which is activated by an ion beam produces activated wear products which can be readily observed even though the total activity in the sample is minute. This method can be used in measurements on engines and machines that are in operation.

3.4.2 Neutron irradiations

The irradiation of biological materials has already been mentioned in Part B, Section 3.3.1, in the context of providing an absolute neutron flux standard. Neutron radiobiology offers the opportunity for research into the oxygen enhancement effect, variation of radiosensitivity with cell cycle, age and type, repair of sub-lethal and potentially lethal damage, and dose rate effects. Further, a limited research program on aspects of fast neutron therapy would be possible with the tandem accelerator. University research in this field will be continued under existing arrangements with AINSE.

A 30 mA beam of 16 MeV deuterons on a Be target will deliver a dose of 30 cGy (rad per minute) to a target at 1 m. This dose rate is comparable to that of many cyclotron facilities for fast neutron therapy of cancer, although the energy is at the lower range. The tandem accelerator could readily play an important research role in support of clinical trials with a medical cyclotron.

The provision of an absolute neutron source would eliminate problems relating to neutron dose determination for radiobiological experiments. Monoenergetic neutron beams can also be used to study radiation damage in metals and other materials, although this can often be speeded up by direct ion irradiation, as discussed in Part B, Section 3.4.5.

3.4.3 Medical isotope research

Short-lived isotopes, such as carbon-11, nitrogen-13 and oxygen-15, have been produced by the 3 MV Van de Graaff accelerator and used for tracer experiments in the biochemistry of nitrogen uptake by plants. Other isotopes, such as fluorine-18, have also been used in activation studies of oxygen diffusion. However, the activities available from the 3 MV accelerator are inadequate for a full range of radioisotope applications. The tandem accelerator would produce adequate quantities of these isotopes for a biomedical research program.

Appropriate tumour/organ affined compounds could be labelled with short-lived radioisotopes and used in conjunction with positron emission tomography (PET) to obtain detailed information on the location and metabolism of the target tumour/organ. Although PET imaging holds promise for clinical applications, its major advantage lies in its potential for researching in vivo biochemical interactions, materials studies, etc. As its contribution to PET research, the AAEC could synthesise specific labelled compounds which define the metabolic processes in the brain, heart and other organs, and in tumours. In-house accessibility for labelling these compounds with short-lived positron emitting isotopes would permit tests in animals with relatively simple gamma-ray detectors.

Positron emission tomography also offers the possibility of grading cancers and monitoring their response to different therapeutic modalities. This will be a most important development, for it could lead to a greatly improved understanding of the short-term efficacy of different therapies, resulting in much more specific prognoses for different cancers and grades of tumours. Such research would therefore provide a much sounder basis for the introduction of fast neutron therapy in Australia.

3.4.4 Ion implantation

Ion implantation is a standard method for producing semiconducting materials, from microchips to solar cells. It also is a vigorous field of development for modifying the surface properties of metals and for other materials modification. Implantation is usually carried out at very low energies for which the ion penetration is, at most, a few atom layers. The proposed heavy-ion tandem will enable implantation to depths of the order of 1 to 10 micrometres. This capability will supplement the work of lower energy facilities, particularly in the development of novel alloys and other materials modification work, and in research into radiation detector materials.

After the transfer of AAEC ion implantation work to the CSIRO's Division of Chemical Physics, an Ion Implantation Research Group was established to promote interaction between the CSIRO, AAEC and the Microelectronics Centre at RMIT. Meetings are held periodically at which staff from these three centres and other organisations share information and progress reports. The facilities, including the 3 MV Van de Graaff accelerator at Lucas Heights, are also shared. It is envisaged that a new facility will further contribute to this high-technology field.

3.4.5 Fusion materials problems

A major structural component of a fusion reactor is the first wall, which must be able to withstand radiation damage levels of the order of hundreds of displacements per atom (dpa). The main irradiation effects are void swelling, formation of dislocation loop structures and radiation-induced segregation, leading to helium grain boundary embrittlement and phase instability; these factors influence the engineering properties of the material. Studies of these effects are the basis for major international research programs.

The two materials proposed for structural components in a fusion reactor are steels and the more recently developed high strength titanium alloys. These materials must be able to sustain radiation damage levels of hundreds of dpa and helium gas levels of thousands of atomic parts per million at temperatures up to 1000 K. This level of damage cannot be achieved in a nuclear reactor.

Studies of irradiation damage have been made on these materials both in Australia and overseas, but only to a level of two to three dpa. The materials have suffered from radiation-induced defects such as embrittlement and void formation, but the results of higher fluence damage remain speculative. More highly irradiated titanium, supplied by Oak Ridge National Laboratory, revealed a different form of radiation damage, but was still only at the order of five dpa. This required approximately three years of ccllaborative effort.

The main problems of using nuclear reactors to induce damage are the extremely long periods of irradiation, possibly several years, the long delay times before the irradiated material can be safely handled, and the increase in high activity waste. The materials testing reactor HIFAR cannct be used for significant research on these problems, although it can be used to carry out the initial studies. In comparison, a high energy ion beam facility gives damage rates of several dpa per minute in the zone of maximum energy deposition. Experiments can be planned and executed in days instead of years and comprehensive damage studies can be performed.

Materials researchers have considerable use for an ion beam facility to study steels and titanium alloys without the associated problems of radioactivity and waste disposal. Use also would be made of the depth profiling methods discussed in Part B, Section 3.4.1. The facility would, therefore, enable the AAEC to contribute further to the knowledge and understanding of the behaviour of first wall materials in a fusion reactor environment.

3.5 Radiocarbon Dating

Successful ^{14}C dating has been demonstrated on tandem accelerators with terminal voltages as low as 1.2 MV. However, all developmental work to demonstrate high sensitivity has been done at higher energies. Because of technical limitations, the new 3 MV tandem accelerators are being used at 2.5 MV or below and the full capability of these machines has yet to be established. The maximum efficiency for production of 3+ ions lies at energies between 2.5 and 3 MeV and good sensitivity can be achieved in this region. Background levels observed so far have correspcnded to limiting ages in the range from 40,000 tc 70,000 years BP. Despite these performance figures and the small sample capability, there has been some equivocation in the radiocarbon dating community about the economic justification of tandem accelerators.

Low-level counting techniques have improved in recent years to achieve a limiting age in the region of 50,000 BP and it is felt that it is possible to push this back even further. However, it takes many weeks, or even months to count one sample whereas the same results can be achieved on an accelerator in a few hours. This is because an accelerator mass spectrometer measures the total ^{14}C content of a sample rather than the small fraction that decays during a laboratory experiment. It has been proposed to push the accelerator limit back towards 100,000 BP, but the realistic limit may well be fixed by problems of sample contamination rather than measurement sensitivity.

Gas counting techniques have also been developed which can use as little as 10 mg of carbon; on the other hand, accelerator dating requires 1 mg or less. This is an attractive feature in special cases but the quantity of available material is not always a limiting factor and problems of representative sampling become severe for very small samples.

The main role of accelerators in ^{14}C dating appear to be:
(i) to provide a greater throughput - a very important aspect in view of the vital importance of time-scale in current archaeology and related studies; and
(ii) to tackle specific problems involving very small quantities of material, or ages at the limit of counting techniques.
Both aspects are of interest in Australia where archaeological material dating to 35,000 BP has already been found. The need for large sample throughput was emphasised at the First Australian Conference on Archaeometry in 1982.

3.5.1 ANU interest

Six laboratories in Australia have radiocarbon counting facilities; of these, only the laboratories at ANU and Sydney University offer significant dating services although a commercial dating service has recently been initiated. The ANU laboratory is the focal point for dating work for the Research Schools of Earth Sciences and Pacific Studies as well as other applications to archaeology, geology, oceanology, climatology, Antarctic studies, etc. The laboratory has prepared proposals for the installation of a dating accelerator at ANU and participated in the development of sample preparation techniques for ^{14}C dating. This ANU technique has proved to be superior to other methods in work carried out at the Zurich and Toronto accelerators.

The possibility of installing an accelerator at ANU has been dropped in favour of the proposal that this be done at Lucas Heights, with support by the ANU in return for favourable access. Costs and the need to establish and sustain a strong physics team have been the main factors in this change. It is a policy decision that the ANU's Department of Nuclear Physics will not carry out extensive dating work.

The Australian National University would like to date at least 1000 samples per year, and perhaps several times this number if a rapid automated system is established. Sample preparation is likely to set the limit, although the effective throughput for an accelerator system has yet to be established. Most of the samples would be younger than 10,000 years BP, so actual measuring times should be less than an hour - depending on the precision required.

Scientists from the ANU's Radiocarbon Research Laboratory have actively promoted the introduction of accelerator mass spectrometry (AMS) facilities into Australia. They have prepared a comprehensive case including an anticipated demand for ^{14}C dating of very small (1 - 10 mg) or alternatively very old (50,000 y) samples.

The ANU proposes to use 20% or more of the time of an AMS facility and will provide the necessary staff and financial resources for that part of the work.

4. IMPLEMENTATION OF THE PROPOSED PROGRAM

4.1 Organisation

The proposed program envisages both research and service projects and a notional breakdown of operating time is shown in Table XIV. A total operating time of the order of 5000 hours per year has been shown to be feasible with the 3 MV Van de Graaff accelerator at Lucas Heights. A similar performance is planned for the new facility, through an emphasis on efficient maintenance. Operation during long series of measurements should be possible with the supervision of experimental staff rather than shift operators.

Staffing requirements for maintenance and operation of the AAEC program and collaborative projects will chiefly be met from the Commission's existing staff in the Radioisotope Research Section and Nuclear Applications and Energy Studies Section. However, to provide the effort needed during the initial stages of the project and the efficiency required to maintain high productivity, three additional staff would be needed for accelerator work, including a full-time project manager.

It is planned that the Radioisotope Research Section will establish an associated sample preparation laboratory for key cosmogenic isotopes such as ^{36}Cl. This aspect is as important as accelerator performance if a high sample throughput is to be achieved, and two additional support staff would be required. It is anticipated that the Australian National University will similarly operate a radiocarbon sample preparation laboratory and provide the effort and materials for a coordinated program of dating measurements.

Recent collaborative work by the Radioisotope Research Section, is summarised in Table XV; the comparable situation five years ago has also been reported (22). This experience will ensure that the full potential of the proposed dating and mass spectrometry program can be implemented in the national interest. Because of the number of other agencies having specific briefs in the applied fields, the emphasis of AAEC work will be to develop the specialist knowledge and expertise needed to make the new techniques available wherever they are required.

It is current practice for AINSE to provide staff, materials and equipment and to arrange for the additional use of AAEC facilities. The new facility would accommodate this procedure in a straightforward fashion - with a significant transfer of operation from the older facilities to the tandem accelerator. Other proposers of independent use of the facility would be expected to provide their own materials and effort.

Project management would also follow practices established over many years to promote the efficient use of Lucas Heights facilities - largely through AINSE, but also through direct arrangements. This involves regular consultation with current and prospective users and includes such activities as workshops and national meetings to promote interaction and focus attention on methods and achievements.

Within the context of service measurements, experience is also available within the Nuclear Applications and Energy Studies Section which has provided analytical services to the uranium industry, with up to 13,000 samples per year being processed through the uranium assay rig on Moata reactor. This service is costed and charged on a per sample basis. Batches of thousands of samples have also been studied using the 3 MV Van de Graaff accelerator in a number of collaborative projects (Table XVI).

4.2 National Projects

4.2.1 AINSE.

The AAEC has a long tradition of making its facilities available to the scientific community through AINSE. It is envisaged that the Institute will play an important role in:

- coordinating access of user organisations to the AMS facilities; and
- representing the views of off-site users on committees determining accelerator priorities.

4.2.2 BMR.

In the fields of hydrology and sedimentology, the AAEC and BMR roles are largely complementary. There has been fruitful collaboration in studies of the Great Artesian Basin and joint studies of the Murray and Amadeus Basins are foreshadowed. Extension of this collaboration to investigations of sedimentology and evolutionary geomorphology is appropriate - particularly in view of the new research role being undertaken at BMR. The principal role of the AAEC in such work would be in measurements of isotopic data on samples collected by BMR and joint involvement in interpretation.

4.2.3 Antarctic Division.

Accelerator mass spectrometry techniques are ideally suited to the assay of low levels of cosmogenic isotopes incorporated in ice cores. Discussions have been held on this topic but the extent to which such work is needed has yet to be established.

4.3 Regional Collaboration

For a number of years, the AAEC has been involved with the IAEA in a program aimed at introducing isotope hydrology capabilities into a number of countries in the South East and East Asian regions. Environmental tritium enrichment facilities have been installed in The Republic of Korea, Indonesia and Malaysia. Equipment has been committed to Sri Lanka and Thailand. The new capabilities are being used to complement the hydrological programs.

As with Australia, problems of water quality degradation are as important in other countries as those of sustainable yield. In the drier parts of the region particularly, tragic losses of agricultural potential are being sustained as a result of salination induced by a number of factors, including irrigation.

The use of ^{36}Cl to quantify aspects of chloride balance is of great potential importance. Australia could contribute to the understanding and hence alleviation of this serious problem by providing access to the new facility. Benefits would be obtained without the necessity of committing substantial amounts of foreign capital. This would be of particular benefit to the poorer countries, where the problems are the most desperate.

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TABLE I

PROPOSED PROGRAMS AND POTENTIAL APPLICATIONS

RADIOISOTOPE DATING

Field : Groundwater Hydrology (3.1.1)

Application	Advancement of Science	National Interest
Groundwater Dating (chlorine-36, Status 1)	. understanding of the groundwater dynamics of large basins, inc. Amadeus Basin, Canning Basin, Murray Basin . understanding of origins of environmental ^{36}Cl	. calibration of regional groundwater models on which water management models are based

Field : Salinity (3.1.2)

Evolution of Groundwater Salinity (chlorine-36, Status 2)	. understanding of sub-surface migration of chloride - connate water - sub-surface evaporites, etc.	. assessment of the causes of variation of quality; separation of man-made and natural effects . assist in the prediction of the deterioration of water quality and of the impact of engineering works on water quality
Dynamics of Chloride Cycle (chlorine-36, Status 2)	. understanding the contribution of - marine accession - local recycling - surface rock erosion to, e.g. Central Aust. salt	. assessment of the long term viability of agricultural and pastoral industries in arid and semi-arid regions

Field : Erosion and Sedimentation (3.1.3)

Erosion Rates (beryllium-10, aluminium-26, Status 2)	. long term rates of erosion are important in assessing models for the evolution of Australian landscape	. assessment of sites for the shallow burial of low level waste
Sediment Accumulation (continental) (beryllium-10, aluminium-26, Status 2)	. evolution of landscapes particularly in arid and semi-arid areas	. base line data for assessment of documented land use change on the stability of catchments
Sediment Accumulation (marine) (beryllium-10, aluminium-26, Status 1)	. rate of sediment build-up on the continental shelf	

TABLE I (Continued)

Field : Oceanography (3.1.4)

Residence Time of Chloride in Marine Sediments (chlorine-36 Status 2)	. understanding of transport processes on the oceanic floor	. assessment of the consequences of leakage of rad. waste from shallow burial in marine sediments

Field : Glaciology (3.1.5)

Glaciology (chlorine-36, Status 1)	. study the dynamics of the evolution of the Antarctic ice cap . study aspects of global atmospheric dynamics	. contribution to Australian Antarctic research

Field : Mineral Exploration (3.1.6)

Mineral Exploration (iodine-129, uranium, Status 1; hydrocarbons, Status 3)	. migration of I^- . dating of oil field brines through the Tertiary	. remote technique for the exploration of uranium (^{129}I is a fission product) . to contribute, together with other techniques, to the development of strategies for hydrocarbon exploration

ULTRA-SENSITIVE MASS SPECTROMETRY

Field : Actinide Transport (3.2.1)

Environmental Survey (neptunium-237, Status 3)	. kinetics of the transport of ^{237}Np under natural conditions	. ^{237}Np is the most critical nuclide in the assessment of repository location; a base line study of its distribution through Australian ecosystems is important
Role of Sediments in neptunium Transport (neptunium-237, Status 3)	. investigation of sediment/soil induced migration of ^{237}Np by comparison with well-known ^{137}Cs behaviour	. ^{237}Np is the most critical nuclide in the assessment of repository location; a base line study of its distribution through Australian ecosystems is important
Assay of Actinides in the Atmosphere (actinides, Status 3)	. investigation of global atmospheric migration processes	. nuclear safeguards - assessment of the nature and yield of atmospheric nuclear explosions

TABLE I (Continued)

APPLIED PHYSICS

Program Area	Advancement of Science	National Interest
Neutron Physics (3.3.1)	•Understanding of neutron interactions; determination of neutron data; development of fusion and fission energy systems.	•Provision of neutron standards; dosimetry. •Access to current international data files; scientific aid to South East Asia.
Safeguards (3.3.2)	•Development of Nuclear Techniques	•Australian assistance to IAEA; Non-Proliferation and National Uranium Policy.
Fusion (3.3.3)	•Provision of relevant data for first wall damage studies and tritium breeding	•Long term energy option
Nuclear Physics (3.3.4)	•Understanding of fission mechanism. •Fundamental physics.	•Establishment of a first class research environment.
Ion Physics (3.3.5)	•Advancement of atomic physics. •New methods for dating and mass spectrometry.	•Assistance to the application of ion physics to national interest problems

NUCLEAR SCIENCE AND APPLICATIONS

Field: Ion Beam Analysis (3.4.1)

Program Area	Advancement of Science	National Interest
Nuclear Reactions and Recoil Elastic Scattering	•Depth profiling for increased number of elements and greater depth range. •Hydrogen profiling using ^{7}Li, ^{15}N and ^{19}F ions to depths of 8 μm. •Multielement profiles using time of flight analysis of recoils, forward scattered by heavy ions	•Materials development; industrial problems; archaeometry.
Heavy Ion Induced X-ray Emission	•Extension of PIXE to heavy ions. •Experimental and theoretical study of multiple inner shell ionisation. •Understanding of fine structure of satellite lines and the effect of chemical bonding.	•Occupational health; environmental, industrial problems. Implanted materials analysis.

TABLE I (Continued)

NUCLEAR SCIENCE AND APPLICATIONS

Field: Ion Beam Analysis (3.4.1)

Particle Activation Analysis	•Investigation of reactions induced by heavy ions. •Optimisation of ion/energy for sensitivity and selectivity for trace and/or major element analysis.	•Trace element analysis; materials; industrial problems; archaeology.
Field: Irradiations		
Neutron Irradiations (3.4.2)	•Understanding of physical properties of materials. •Understanding of effects of radiation on biological cells	•Contributes to advanced technology. •Contributes to nuclear medicine.
Medical Isotopes (3.4.3)	•Availability for tracer studies using short-lived isotopes.	•Contributes to nuclear medicine.
Ion Implantation (3.4.4)	•Development of new materials and materials properties.	•Contributes to micro-electronics; solar energy; industry, etc.
Ion Irradiations (3.4.5)	•Radiation damage mechanism in first wall materials of fusion systems.	•Long-term energy option.

Notes:

*Numbers in parenthesis refer to the sub-sections in the text.

†The status of the applications is described as follows:

Status 1 - application demonstrated.

Status 2 - measurement demonstrated, but not the application.

Status 3 - measurement yet to be demonstrated.

TABLE II

COST BREAKDOWN

	$US	$A
Accelerator	2.81M	
Additional components (SF$_6$ system, 2nd stripper, Corona tube, lens, computer control)	0.45M	
Ion source system (Duoplasmatron, switch magnet, sputter source, high resolution magnet, accessories)	0.39M	
Analysis system (90° magnet, high resolution magnet, switch magnets, ES analyser, detector, accessories)	0.43M	
Sub-total	4.08M	4.48M
Building extension		1.00
TOTAL		5.48

TABLE III

ACCELERATORS USED IN DATING AND MASS SPECTROMETRY

Accelerator (Max. voltage)	Laboratory	Dating	Mass Spectrometry
14UD Pelletron (14 MV)	Rehovoth	^{14}C	
MP Tandem (12 MV)	Uni. Rochester	^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{32}Si, ^{129}I	Pt, Ir
	Yale Uni.	^{10}Be, ^{26}Al	Be, Si, Nb, Sb, Te
	Orsay	^{36}Cl, ^{41}Ca	
MP Tandem + Linac	Munich	^{36}Cl, ^{41}Ca	
	AECL	^{14}C	
FN Tandem (8/9 MV)	ANL	^{14}C, ^{26}Al, ^{32}Si, ^{36}Cl, ^{41}Ca	
	Uni. Pennsylvania	^{10}Be, ^{26}Al	
	Rutgers Uni.	^{10}Be	
	Uni. Washington	^{10}Be, ^{14}C	
	McMaster Uni.	^{10}Be, ^{14}C	
	Saclay	^{14}C	
EN Tandem (6/7 MV)	Harwell	^{14}C	
	Uni. Oxford	^{129}I	
	Uni. Utrecht	^{14}C	
	ETH Zurich	^{10}Be, ^{14}C, ^{36}Cl	
	DSIR, Wellington	-	
Pelletron (3/4 MV)	Cal. Inst. Tech.	-	
Tandetron (2/2.5 MV)	Uni. Oxford	^{14}C	
	Uni. Arizona	^{14}C	B, P
	Uni. Toronto	^{14}C	Heavy
	Gif-sur-Yvette	^{14}C	
	Nagoya	^{14}C	
	CSIRO, North Ryde	-	
Cyclotron (30 MeV)	Orsay, Grenoble	^{10}Be	

TABLE IV

ION TIME OF FLIGHT

E (MeV)	^{9}Be ns m^{-1}	^{10}Be ns m^{-1}	^{36}Cl ns m^{-1}	^{37}Cl ns m^{-1}	^{129}I ns m^{-1}
3.0	125	132	250	254	474
5.0	97	102	194	197	367
7.5	79	83	158	160	300
8.5	74	78	149	151	281
10.0	69	72	137	139	260
15.0	56	59	112	113	212
20.0	48	51	97	98	184

TABLE V

NEUTRON SOURCE REACTIONS

Reaction	Incidental Particles		Monoenergetic Neutron Energy Range (MeV)
	Type	Energy (MeV)	
3 MeV Accelerator			
$T(p,n)^{3}He$	Protons	1.80-3.00	1.00-2.20
$D(d,n)^{3}He$	Deuterons	1.00-3.00	4.00-6.00
$Ti(d,n)^{4}He$	Deuterons	1.00-3.00	13.0 -17.0
$^{7}Li(p,n)^{7}Be$	Protons	1.88-3.00	0.03-1.30
8 MV Tandem			
$T(p,n)^{3}He$	Protons	3.00-16.0	2.20-15.0
$D(d,n)^{3}He$	Deuterons	3.00-4.00	3.00-7.00
$H(^{7}Li,n)^{7}Be$	Lithium-7	13.10-16.51	1.40-3.80

TABLE VI

MEASUREMENT OF CHLORINE-36 - A COMPARISON BETWEEN ACCELERATOR AND RADIOACTIVE COUNTING TECHNIQUES

	Measurement Technique		Comments
	Accelerator	Counting (1)	
Sample Size	10-100 mg	2-5 g Cl	
Measurement Time	1 hr	2 weeks	
Detection Limit	$^{36}Cl/Cl$ 10^{-15}	10^{-13}	Environmental samples in range 10^{-15}-10^{-12}
Capital Cost	$5.5 M	$30,000	Include buildings
Amortisation over 5 y	$220 per sample	$240 per sample	Accelerator : assume 5000 h/year. Counting : assume 50 weeks
Sample Preparation, Loading, Machine Operation	$40	$80	Accelerator : 2 h/ sample Counting : 4 h/ sample, inc. overheads
TOTAL COST	$260	$320	

(1) The comparison is based on scintillation counting techniques using standard commercial equipment.

(2) Additional costs associated with the running of standards and background samples are the same for both techniques.

TABLE VII

ULTRA-SENSITIVE MASS SPECTROMETRY - SOME PUBLISHED PERFORMANCE FIGURES

Nuclide	Half-life (y)	Abundance	Sensitivity Achieved
^{10}Be	1.6×10^{6}	10^{-9}	10^{-14}
^{14}C	5730	1.2×10^{-12}	3×10^{-16}
^{26}Al	7×10^{5}	1.7×10^{-12}	10^{-14}
^{36}Cl	3×10^{5}	2.2×10^{-11}	3×10^{-16}
^{41}Ca	7.7×10^{4}		10^{-14}
^{129}I	1.7×10^{7}	10^{-16}	3×10^{-13}
^{195}Pt	-	0.338	10^{-12}

TABLE VIII

ESTIMATED INITIAL SAMPLE THROUGHPUT

Isotope	Number of Samples[1] (approximately)	Machine Time (h)
^{14}C	1250	1250[2]
^{36}Cl	250	250
^{10}Be	40	100
^{26}Al	30	50
^{129}I	30	50
Others	?	300[3]
SUM	1600+	2000

Notes

(1) Number of samples excluding standards and check samples.

(2) A minimum of 20 per cent running time (est. 1000 h) for carbon-14 is guaranteed.

(3) This time will be allocated to the actinides, calcium-41, and other pilot studies.

TABLE IX

THE EFFECT OF PROCESSES ON GROUNDWATER SALINITY AND CHLORINE-36 LEVELS

Process	Chloride Concentration	Chlorine-36 Concentration	$^{36}Cl/Cl$
Surface evaporation	increase	increase	no change
Evapotranspiration	increase	increase	no change
Sub-surface solution (uptake of evaporites)	increase	no change	decrease
Groundwater mixing[1]	either	either	either
Mixing with connate water	increase	decrease	decrease

(1) A well defined mathematical relationship exists between the three parameters.

TABLE X

COLLABORATIVE PROJECTS
NUCLEAR PHYSICS GROUP

Topic	Institution
Measurement and analysis of ^{232}Th fission cross sections	Lawrence Livermore National Laboratory
Measurement and analysis of kinetic energy data	Centre d'Etudes de Bruyerès-le-Châtel
Measurement of $\bar{\nu}$ (E_n) for ^{232}Th	Centre d'Etudes de Bruyerès-le-Châtel
Fission neutron spectra	Los Alamos National Laboratory
Fission product yields for thermal and epithermal fission of ^{233}U, ^{235}U and ^{239}Pu	West Australian Institute of Technology
In-line gas phase monitor	Department of Foreign Affairs
Neutron coincidence counting	Department of Foreigh Affairs
14 MeV neutron data	IAEA
Neutron capture cross section of ^{27}Al	CBNM Laboratory, Geel
Nuclear synthesis	West Australian Institute of Technology
Neutron capture Gamma-ray spectra	University of Wollongong

TABLE XI

RECENT COLLABORATIVE PROJECTS

NUCLEAR APPLICATIONS GROUP

Trace elements in oil shales	CSIRO
Distribution of K, Th and U in rocks of the Sydney Basin	Wollongong Univ.
Measurement of actinide particle size distributions using fission tracks	Maralinga survey
F and other trace elements in Australian coal	Darling Downs CAE
Deposition measurement on soils of freshwater catchments	ANU
U concentration in submarine phosphorites	New Zealand DSIR
Radioactive disequilibrium in low-level U and Th determinations	Adelaide University
Build-up of U in phosphate fertilised soils	New Zealand DSIR
Determination of ^{18}O in water as a monitor of annual fluid balance	Western Australia University
Occupational health of mine workers (Ranger): U in hair, urine, etc.	ANU
Metabolic pathways in mammalian systems	ANU
Neutron radiography of roots growing in soils	La Trobe University Tasmania Unversity
Human genetic disorders involving sensitivity to ionising radiation	Queensland University
Trace elements in healthy and diseased teeth	Flinders University
Trace element analysis of human hair and blood serum	NSW Dept. of Industrial Relations
Generation centre study in Si devices	W.A. University

TABLE XI (Continued)

Neutron radiography study of detonators	Dept. of Supply
Corrosion study in aircraft components	ARL
Materials analysis by RBS and channelling (semiconductor devices)	RMIT
Surface tomography	NSWIT
Hydrogen profiles in prepared surfaces	Sydney University
Oxygen depth profiles	NSWIT
Pottery studies: Motupore, New Guinea	ANU
Elemental analysis of pottery from Buka	Sydney University
Provenance studies on S.W. Pacific obsidian	ANU Otago University
Elemental analysis of Aboriginal ochre	Queensland University
Hydration studies on obsidian	ANU
Admiralty Islands pottery components	ANU
Provenance studies	Museum of Applied Science, Philadelphia

TABLE XII

TYPICAL PARAMETERS OF ION BEAM PROFILING REACTIONS

Reaction	E_r (MeV)	σ_o (mb)	Γ (keV)	E_a (MeV)	I_a (nA)	τ (mins)	E_b, E_γ (MeV)	Surface Resolution (nm)	Maximum Depth (μm)	Sensitivity μg/g
HYDROGEN										
($^7Li,\alpha\gamma$)	3.075,7.21		80	3-4.4	450	100	14.7,17.6	70	6	$\lesssim$10
($^{15}N,\alpha\gamma$)	6.385	200	6		2-20	120	4.43	2-6	4	$\lesssim$10
($^{19}F,\alpha\gamma$)	6.42	100	45				6.1,6.9,7.1		1.2	
	16.44,17.56	500	90	16-22	30	40-180	6.1,6.9,7.1	20	2(υ)	$\lesssim$5
($^{11}B,\alpha$)	1.793		66	1.6-2.2	20-60	45	3	60	4	$\lesssim$5
α Recoil				2.4,2.6	20	5		70	0.7	$\lesssim$50
^{12}C Recoil				12				30	1.5	
^{35}Cl Recoil				35				50		$\lesssim$5

TABLE XIII

POSSIBILITIES AND PERFORMANCE OF CHARGED PARTICLE ACTIVATION ANALYSIS

Means of Activation	Determinable Elements	Achievable detection limits* (ng g^{-1})
	B,N	0.1 - 1.0
	C[1],O[2],Ca,Ti,Cr,Ni,Cu,Ga,Ge, Zn,Se,Br,Rb,Y,Zr,Mo	1 - 10
p^b	Li,S,V,Fe	10 - 100
	Ru,Pd,Ag,Cd,Sn,Sb,Te,I	20 - 200
	In,W,Re,Ir,Pt,Au,Hg,Tℓ,Pb	50 - 100,000
d^b	N,B	0.5 - 5
d^c	Li	20 - 50
	O	0.1 - 5
	Na,Mg,Al,Si	10 - 20
t^d	S,Cl,V,Mn	100 - 300
	Ti,Cr,Ni	1,000 - 3,000
	C,O,Al,Ti,V,Mn,Ni,Zn,Nb	1 - 50
$^{3}He^e$	Mo	50 - 100
	Mg,Cr,Fe,Zr,Ag	100 - 500
α^f	Be	5 - 50
$^{7}Li^g$	H	100 - 500
$^{10}B^g$	H	100 - 500
$^{11}B^g$	D	100 - 500

a In the absence of interferences, for irradiation periods of up to 1 h.
b E : 10 MeV; 1: 1μA
c E : 25-30 MeV
d E : 3.5 MeV; I: 1μA
e E : 14 MeV; I: 2μA
f E : 30-40 MeV
g E : 40-80 MeV

1 Via carbon-11
2 Via nitrogen-13

TABLE XIV

NOTIONAL DIVISION OF OPERATING TIME (%)

Project	AAEC	Other Organisations	
		Collaborative	Independent
Radioisotope Dating	10%	5%	20% ANU + 5% Other
Mass Spectrometry	5%	5%	5%
Applied Physics	20%	5%	5%
Nuclear Science	5%	5%	5%
	40%	20%	40%

TABLE XV

AAEC NUCLEAR GEOHYDROLOGY GROUP - CURRENT COLLABORATIVE PROGRAMS

Project	Collaborating Organisations	Comments
Isotope hydrology of the Great Artesian Basin	BMR University of Arizona ANU CSIRO Institute of Fossil Fuel Macquarie University	Project incorporated within the US/Australia Science and Technology program.
Murray Basin hydrogeological study	BMR Water Resources Commission NSW State Rivers and Water Supply Commission, Vic.	AAEC is contributing to the joint Commonwealth/State hydrogeological study coordinated by the BMR.
IAEA-Regional Co-operative Agreement project, Isotope Hydrology and Sedimentology	IAEA and Atomic Energy Agencies in Korea, Indonesia, Malaysia, Thailand, Sri Lanka, Philippines	Introduction of isotope hydrology programs in the Asian region; together with associated project work.
Radionuclide migration in the vicinity of uranium ore bodies : analogue of radioactive waste repositories	University of Sydney University of Wollongong University of Arizona CSIRO Division of Mineral Physics Water Division, Dept. of Transport & Works, NT	Project is funded with a major grant from the US Nuclear Regulatory Commission; support received from Ranger Uranium Mines Ltd, Pancontinental Mining, Queensland Mines Ltd, Denison Aust. Ltd.
Water balance studies using artificial tritium	CSIRO Division of Plant Industry	
Erosion and sediment redistribution in Maluna Catchment - (Hunter Valley) - a ^{137}Cs application	Dept. of Geography, Newcastle University Soil Conservation Service, NSW	

TABLE XV (Continued)

Project	Collaborating Organisations	Comments
Application of ^{137}Cs to the study of sediment accumulation in lakes and reservoirs	NSW Water Resources Commission CSIRO Division of Plant Industry ANU	
Sediment redistribution in catchments	Exeter University, UK Newcastle University	

TABLE XVI

MAJOR ANALYTICAL PROGRAMS

Technique		User	No. of Samples (max/y)
Delayed Neutron	Uranium Ore Analysis	WMC URANERG Geopeko AAEC Ex.	35 000 (13 000)
	Uranium Analysis	CSIRO AMDEL	4 200
	Collaborative Projects	AAEC, universities, etc.	16 000
Neutron Radiography	Aircraft components	QANTAS	100
	Corrosion Study	ARL	50
	Plant Growth	Universities, etc.	100
	Other collaboration		
PIXE-PIGME	Hair Analysis	NSW Health Commission	2 000 (1 000)
	Archaeological Artefacts	Queensland, Adelaide, Sydney, Otago and AN Universities	10 000 3 000)
	Other collaboration	Universities, etc.	4 000

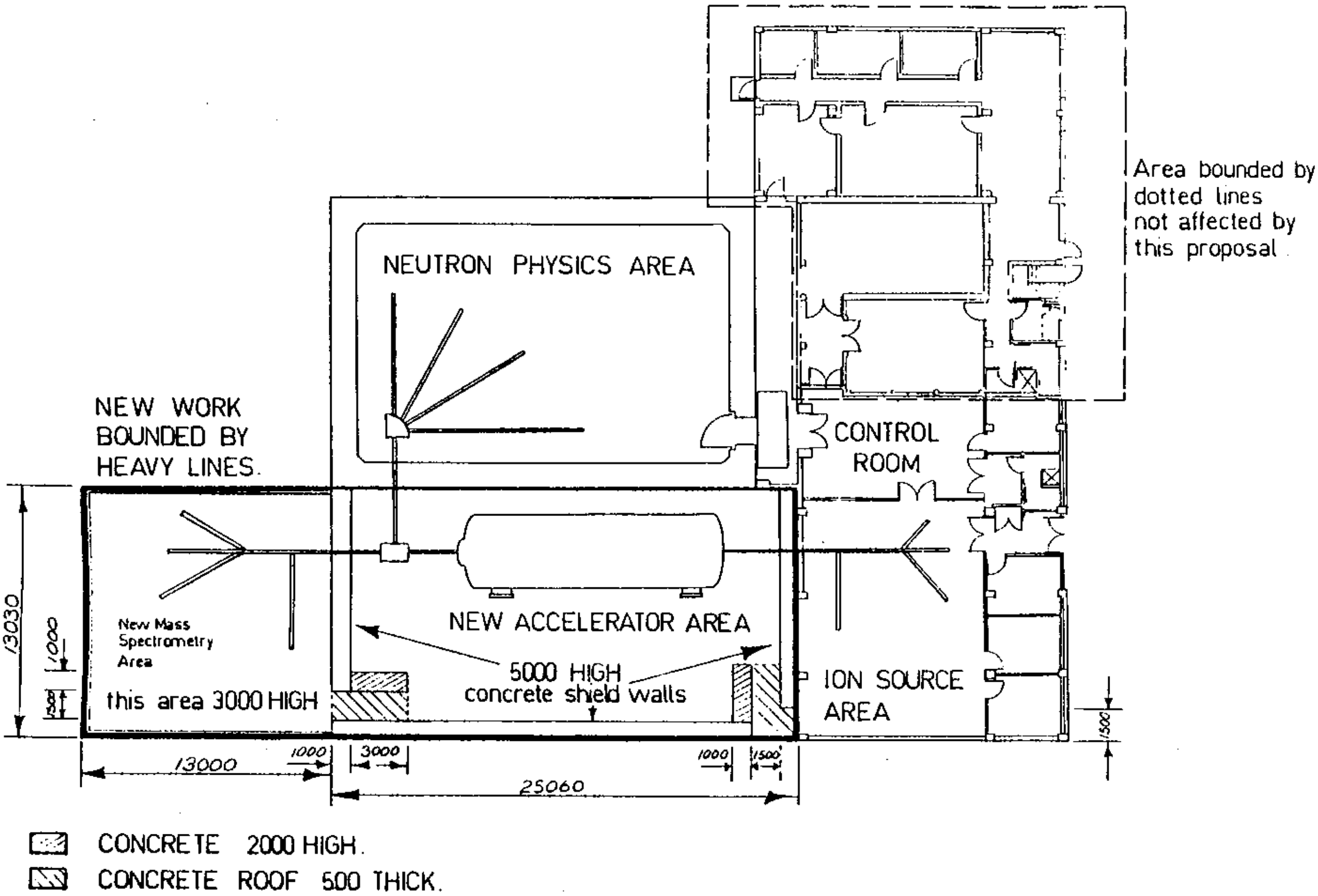


FIGURE 1a Schematic layout of accelerator and building.

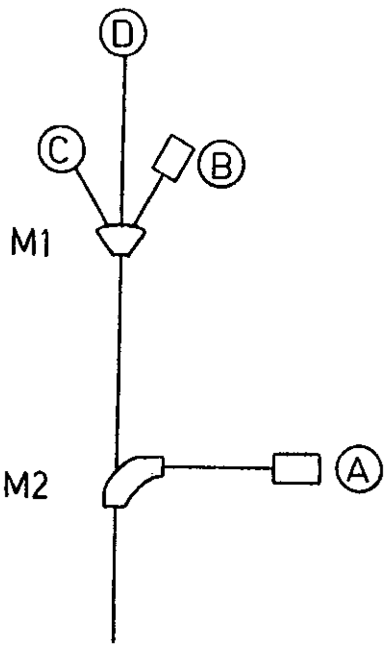


FIGURE 1b Possible layout of ion source area.

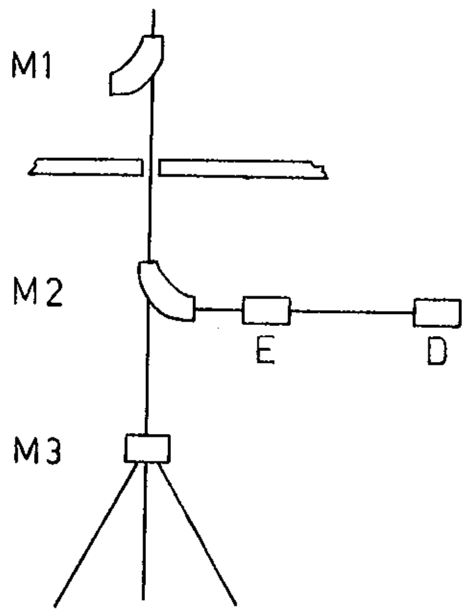
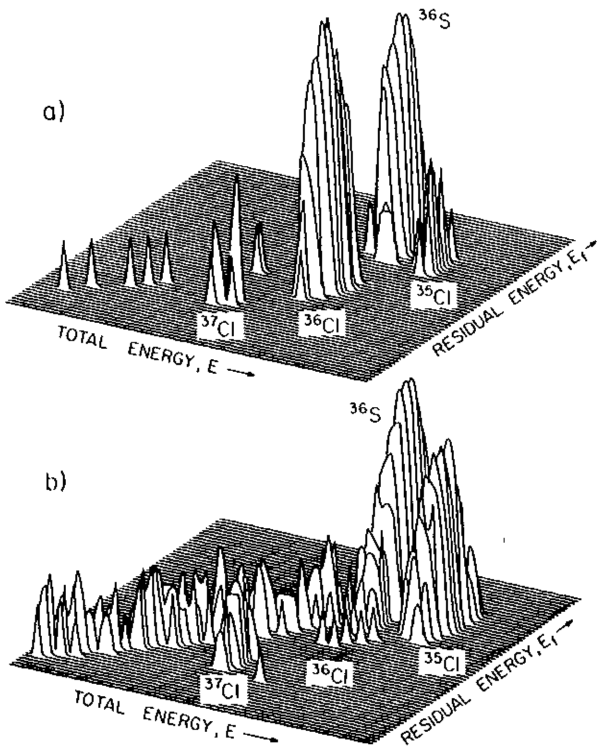
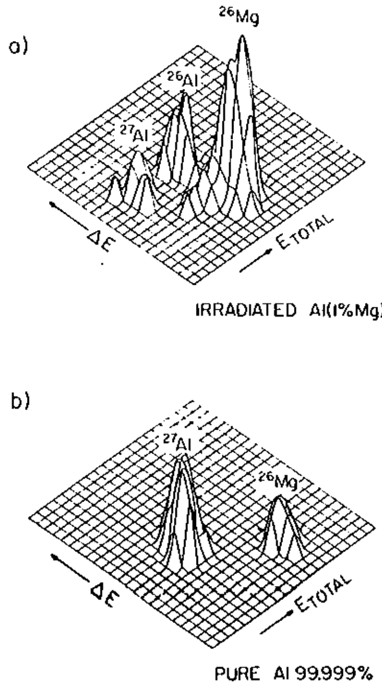


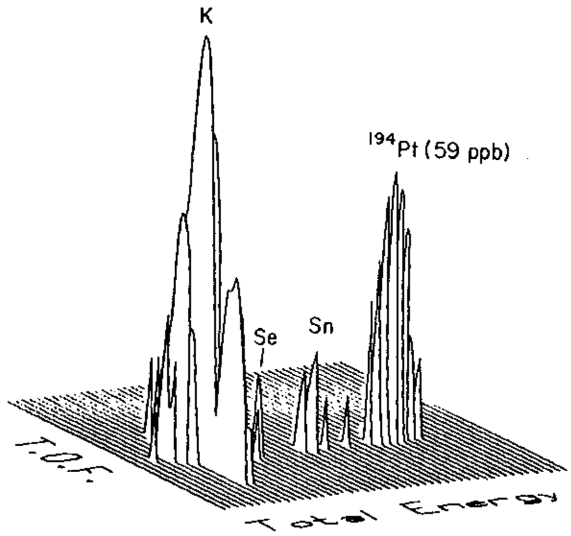
FIGURE 1c Schematic layout of dating and mass spectrometry area.



A two parameter logarithmic plot of the counts in the final heavy ion detector for runs on (a) a water sample from Lake Ontario and (b) zone refined reagent grade AgCl.



A two-parameter logarithmic plot of the counts in the final heavy ion detector for runs on (a) an Al–Mg (1%) sample that had been irradiated by gamma rays and 40 MeV electrons and (b) on a pure (99.999%) aluminum sample.



A three dimensional representation of the logarithm of counts vs total ion energy and time of flight is given for a sulphide powder sample containing 59 ppb platinum.

FIGURE 2 Results from experiments at the University of Rochester, illustrating particle identification techniques. Figures 2a and 2c from Ref. 4b, Figure 2b from Ref. 4a.

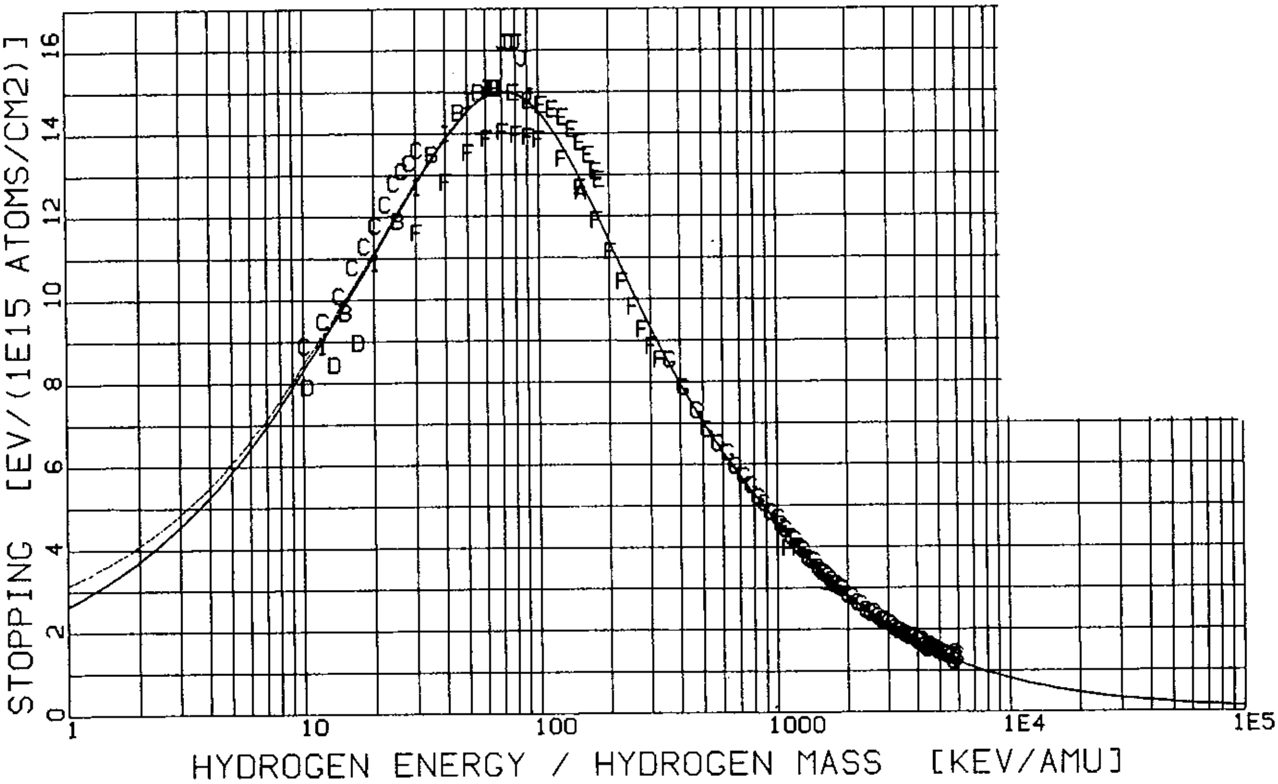


FIGURE 3a Energy loss by protons travelling through carbon.

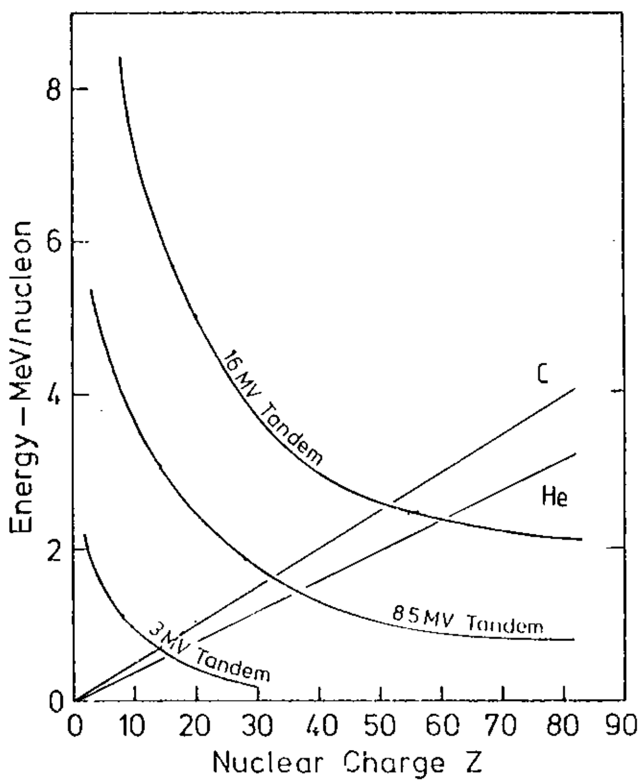


FIGURE 3b Maximum energy loss for ions of different Z travelling in He and C, compared to energies achievable with different terminal voltages.

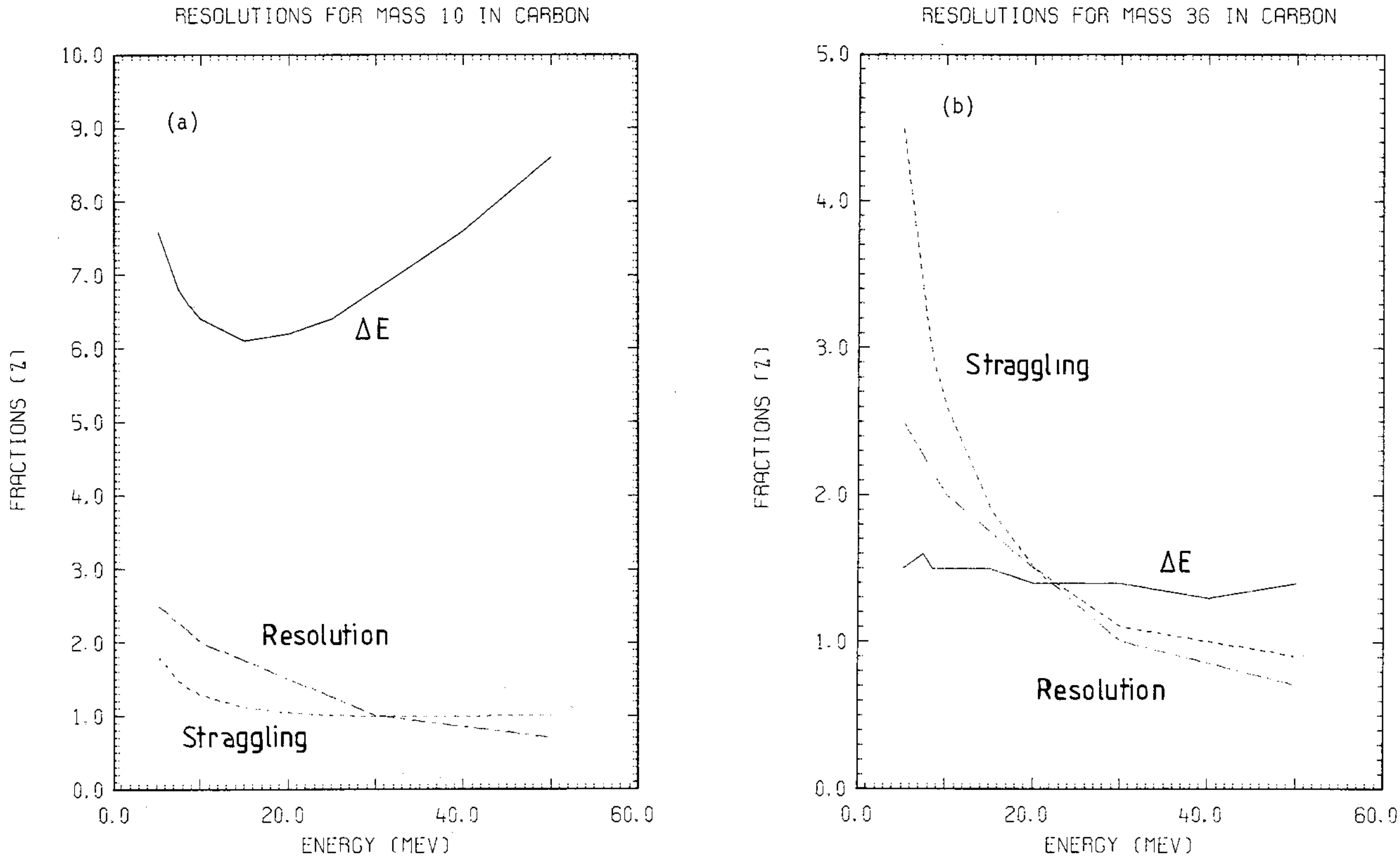


FIGURE 4 The ratio to the initial ion energy of the difference in energy loss, the FWHM energy straggling and the best ionization chamber resolution for :

(a) ${}^{10}_{4}Be$ and ${}^{10}_{5}B$ ions, (b) ${}^{36}_{16}S$ and ${}^{36}_{17}Cl$ ions.

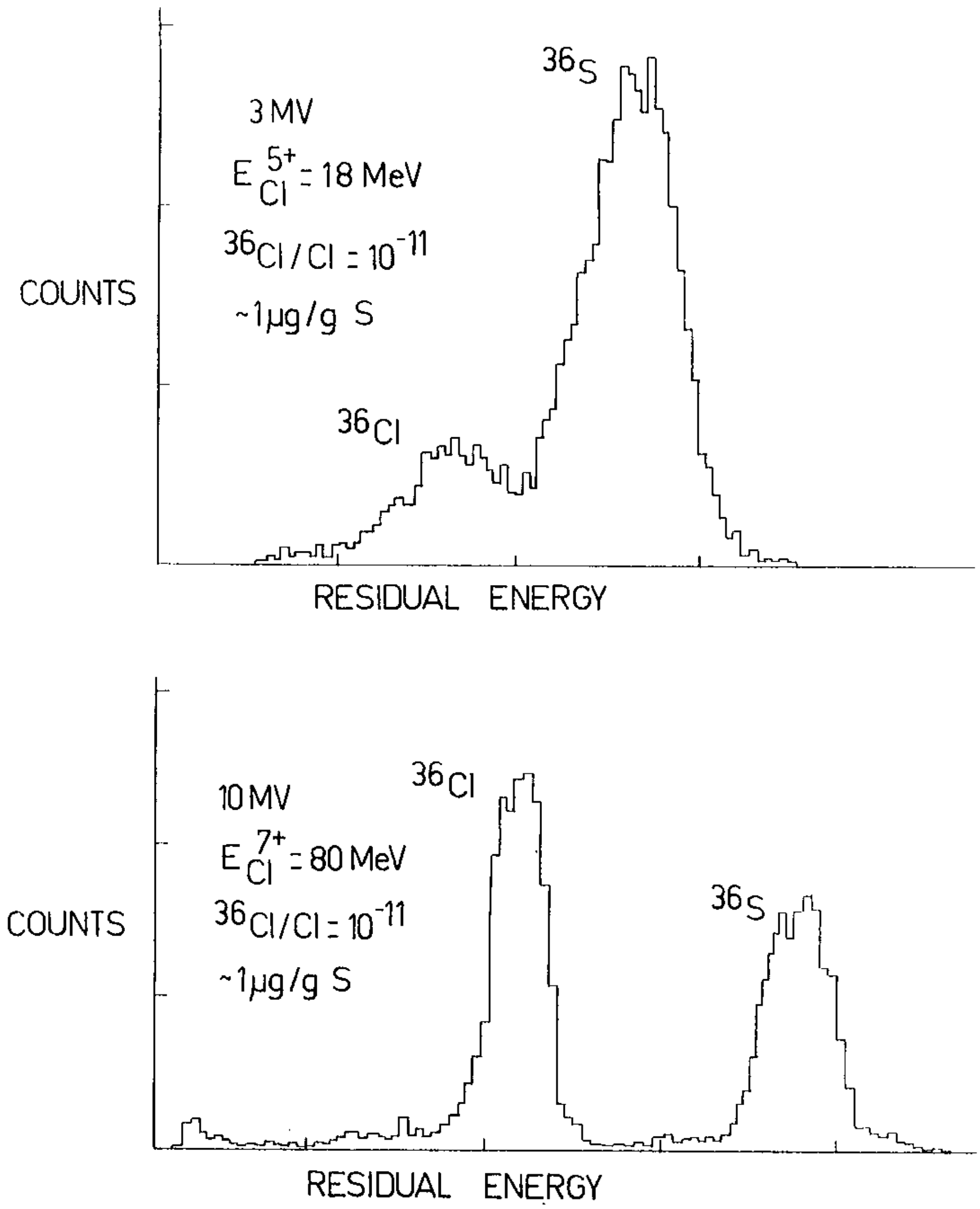


FIGURE 5. Measurements of ^{36}Cl, in the same sample, carried out at the University of Rochester (6) using 3 MV terminal voltage, charge state 5+, ion energy 18 MeV (top) and 10 MV terminal voltage, charge state 7+, ion energy 80 MeV (bottom). The estimated sensitivities were 10^{-12} and 2×10^{-16} respectively

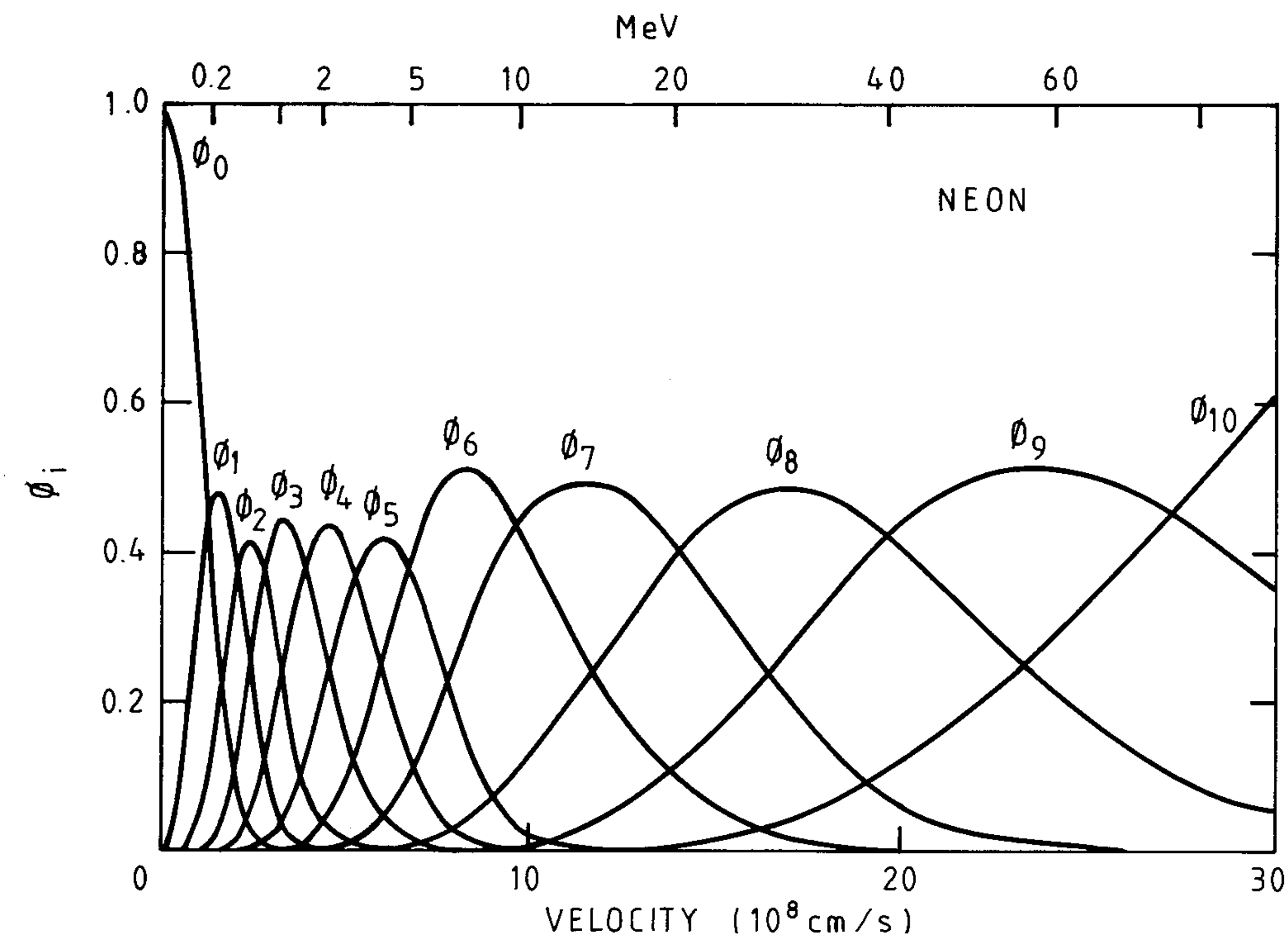


FIGURE 6 Equilibrium charge states

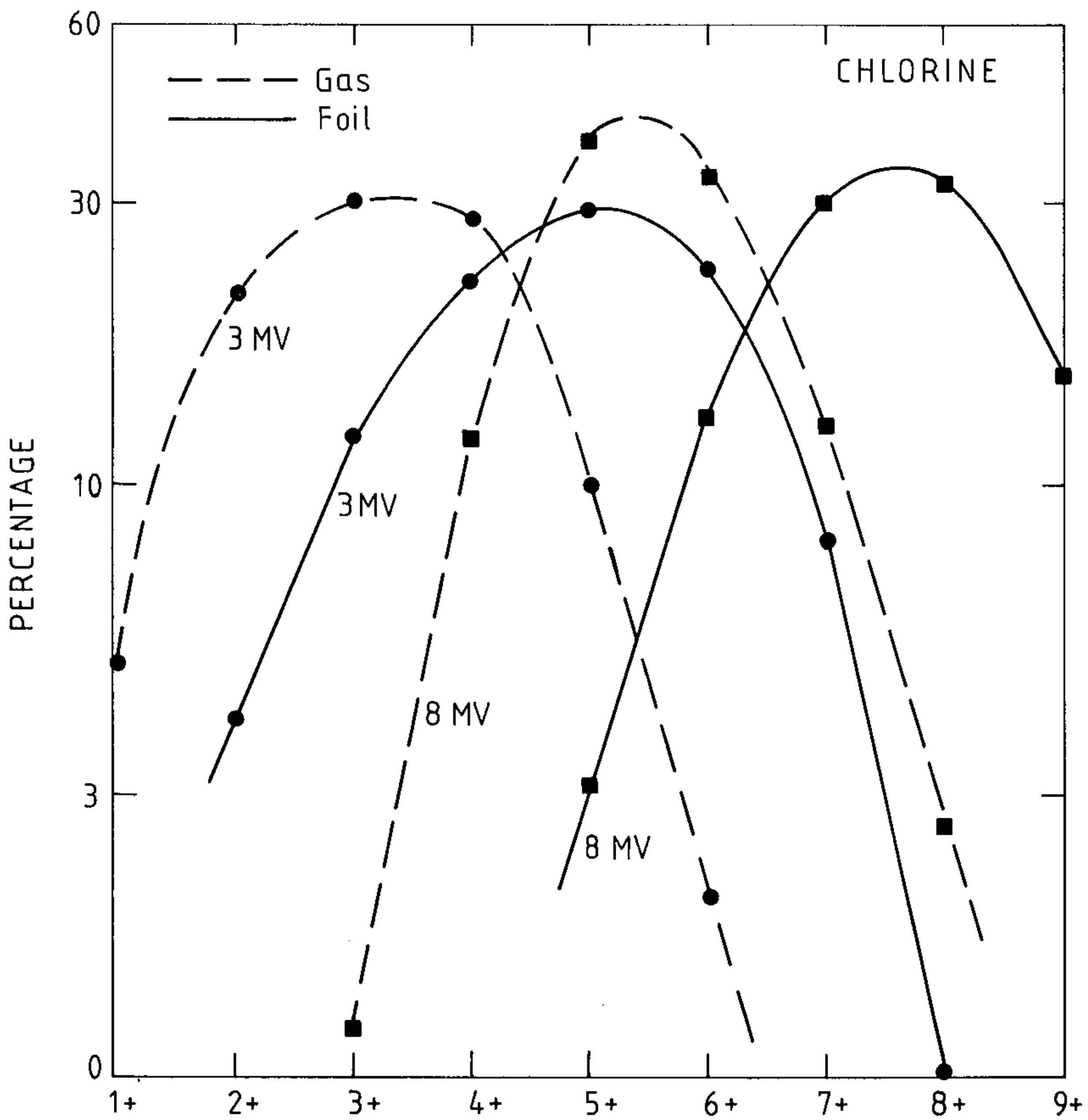


FIGURE 7 ^{36}Cl charge state fractions versus terminal voltage for C foil and N_2 gas stripping

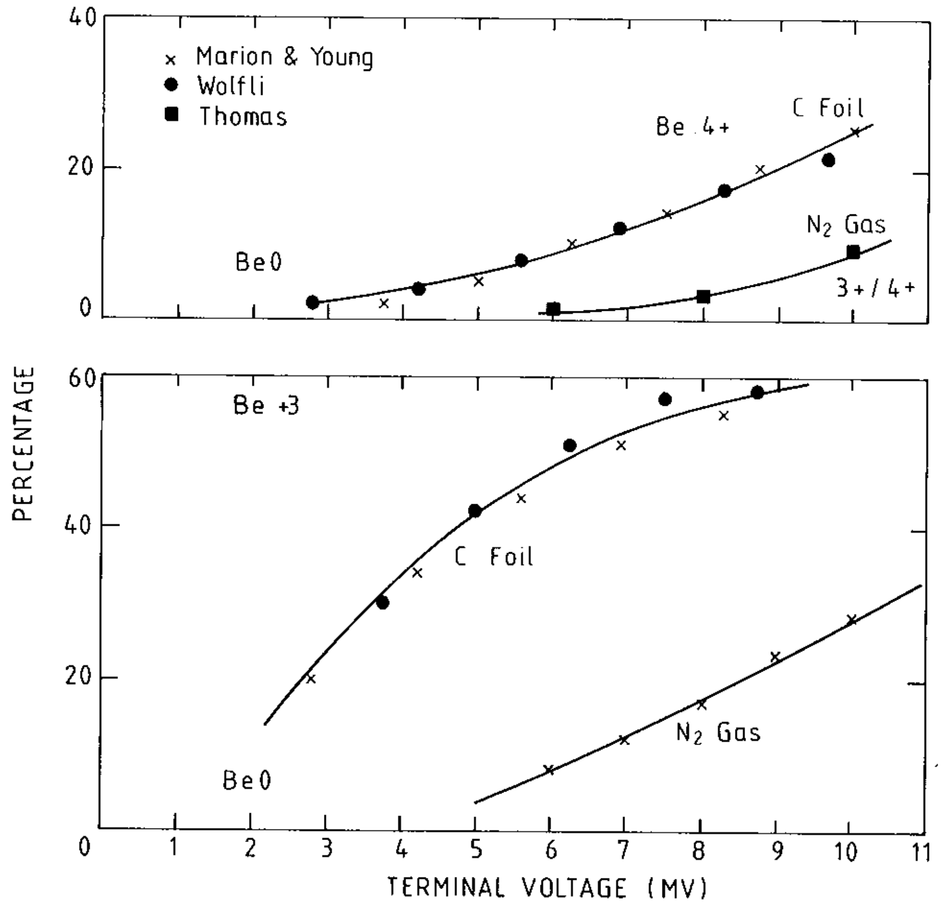


FIGURE 8 Variation in charge state fraction with energy for Be +3 and Be +4 ions obtained using a BeO-ion source and either N_2 gas or C foil stripping

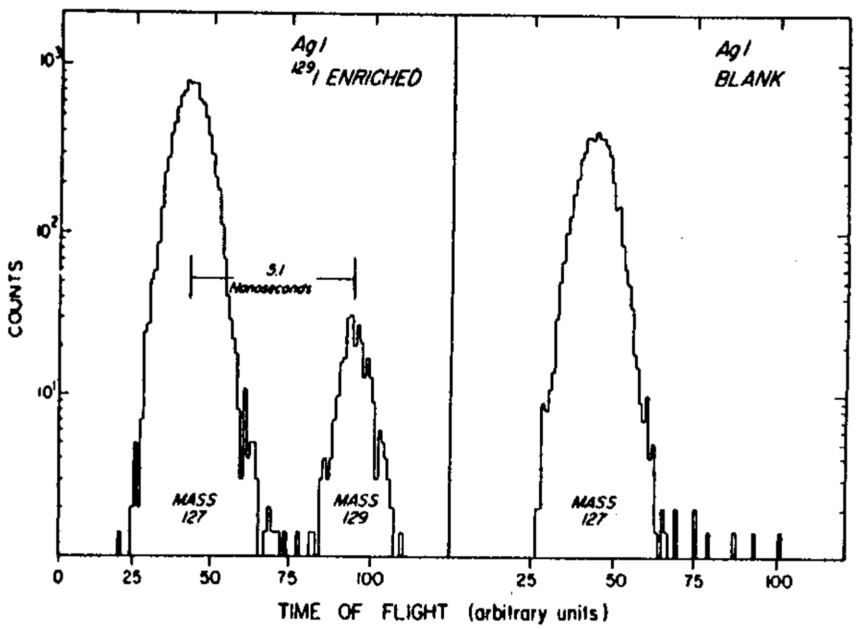


FIGURE 9 Time-of-flight spectra after electrostatic analysis for AgI enriched to $^{129}I/^{127}I \sim 10^{-11}$ and for AgI without ^{129}I. The ^{127}I and ^{129}I peaks are separated by 5 ns.(9)

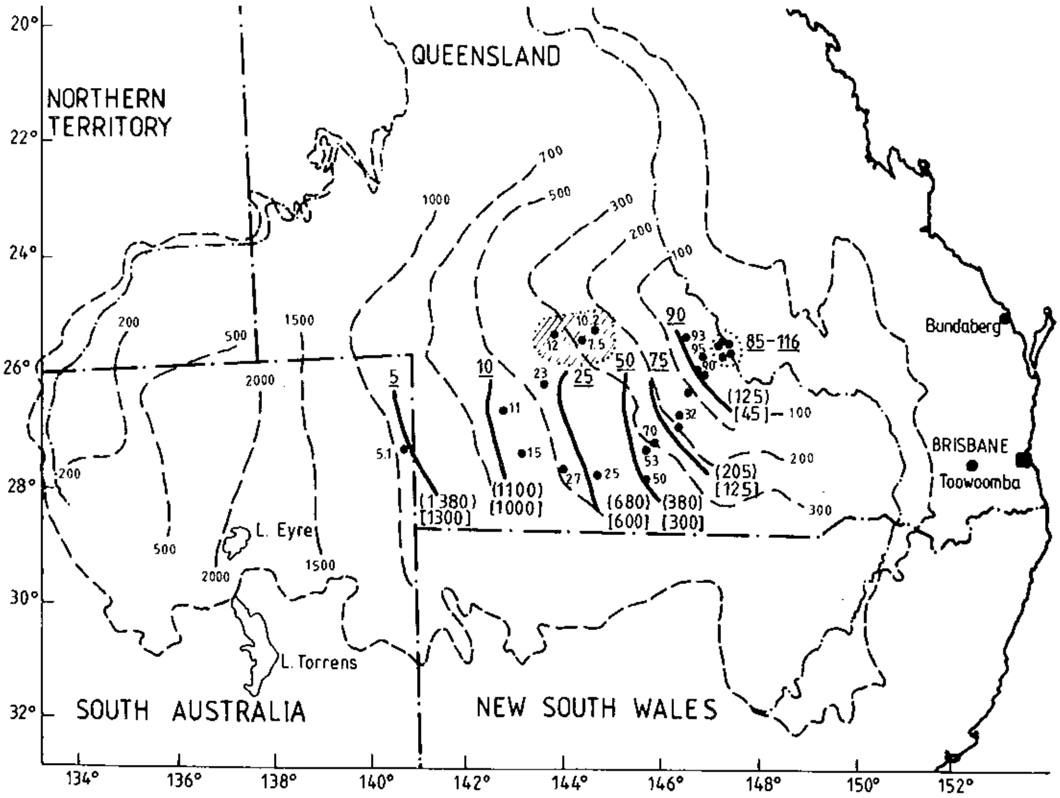


FIGURE 10 Superposition of the ^{36}Cl (——) and hydraulic age (—·—) contours. The 10^{15} $^{36}Cl/Cl$ ratios are shown. Input values of 150 and 100 have been used to calculate ^{36}Cl isotope ages in round and square brackets respectively. An anomalous region has been distinguished by shading

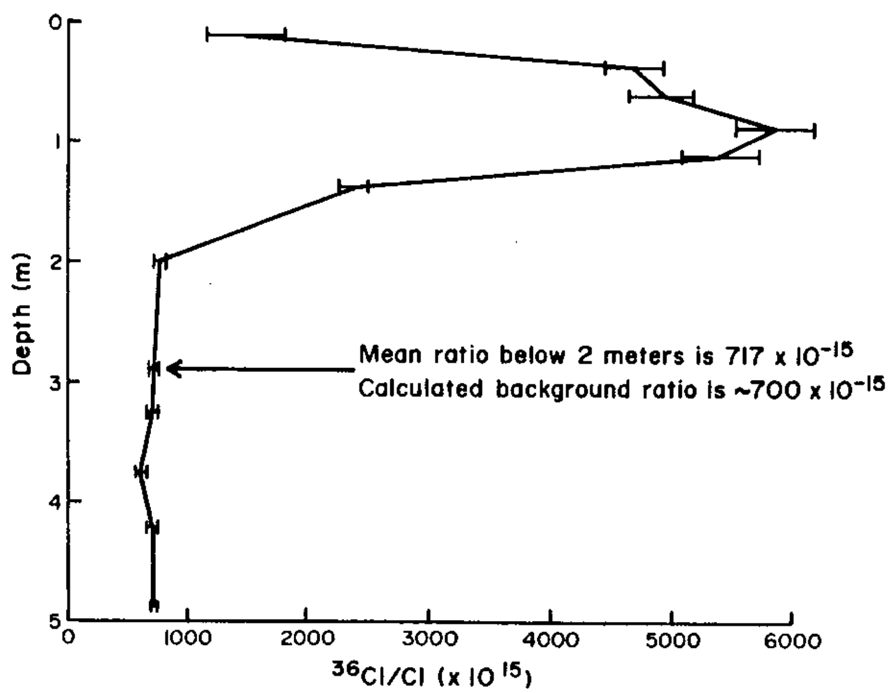


FIGURE 11 The $^{36}Cl/Cl$ ratio of soil-water solutions in the vadose zone from a vertical borehole near Socorro, New Mexico

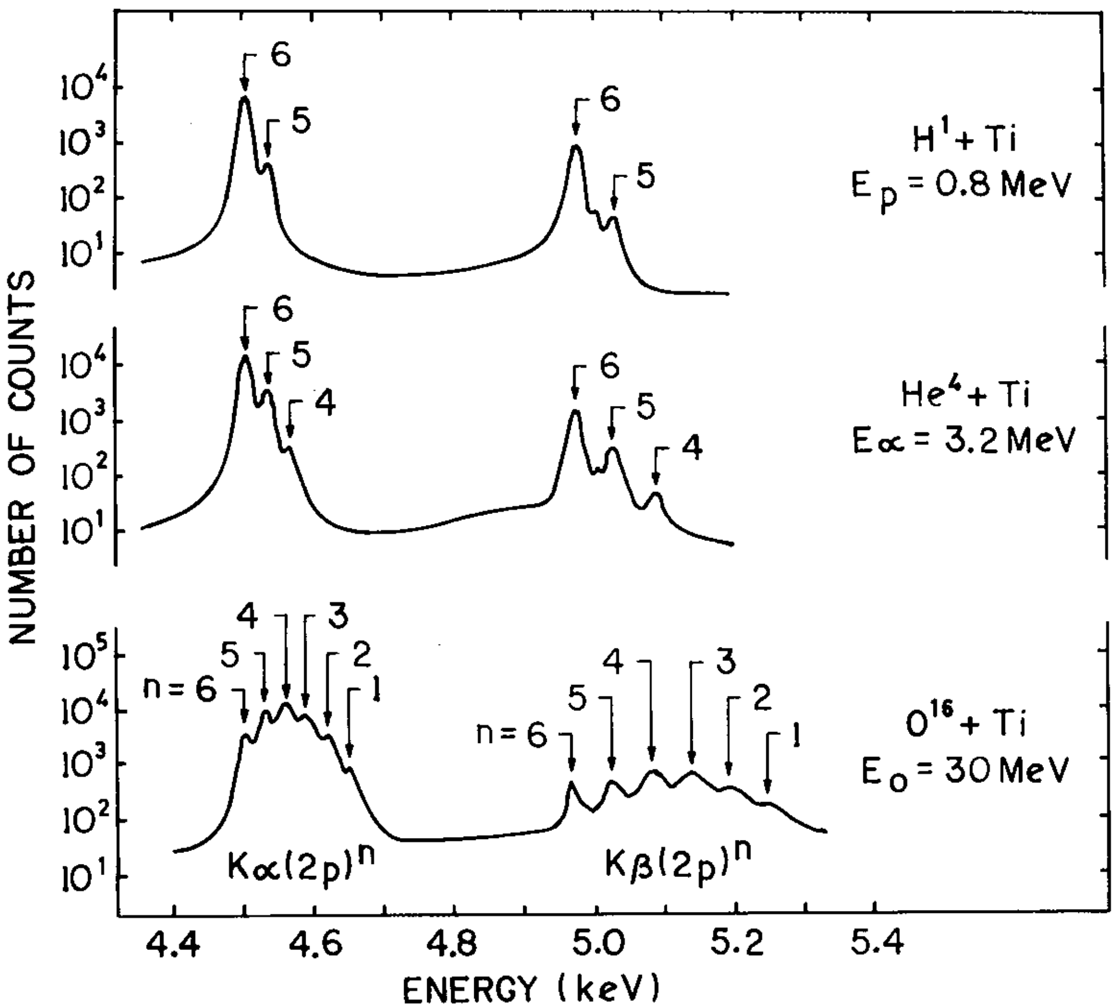


FIGURE 12 The K X-ray spectra of ^{1}H, ^{4}He and ^{16}O on Ti, demonstrating the variations in multiple ionisation with increasing projectile Z

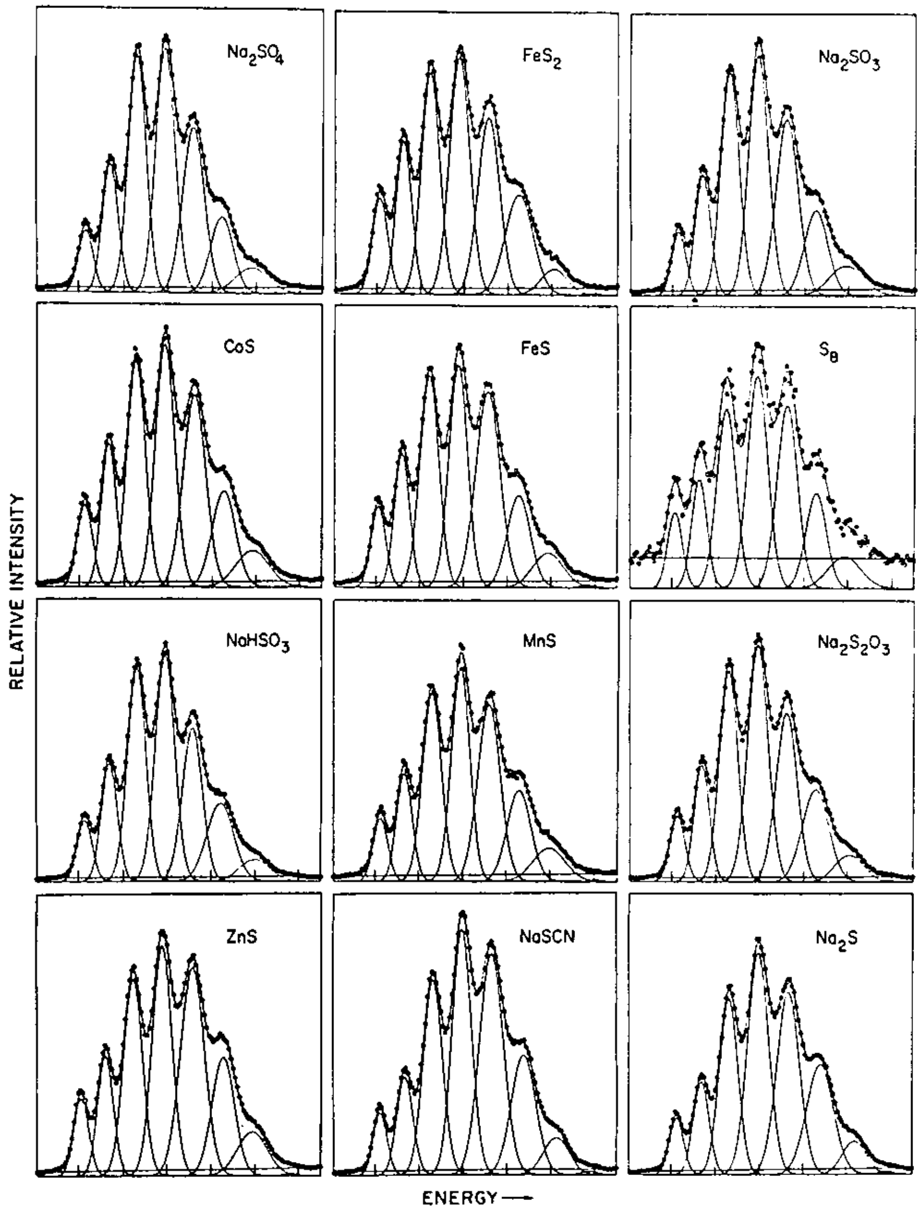


FIGURE 13 Sulphur Kα satellite spectra and fits for 12 compounds excited by 0.9 MeV/amu Ar ions. The centre of the abscissae are at 2.37 keV and each frame represents ∿ 200 eV