Alternatives to a 20 MW Nuclear Reactor for Australia

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Gregory Morris and Robert J Budnitz
Future Resources Associates, Inc.

For Sutherland Shire Council

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Future Resources Associates, Inc.
2039 Shattuck Ave., Suite 402
Berkeley, CA 94704 USA
(510) 644-2700

Introduction

ANSTO, the Australian Nuclear Science and Technology Organisation, has owned and operated the 10 MW HIFAR nuclear reactor for more than 30 years in the Lucas Heights region outside of Sydney. This reactor, which is used for a variety of purposes, is nearing the end of its useful operating life, and will be retired from service unless a substantial investment is made in the next few years to upgrade it to meet modern safety standards. ANSTO has been promoting the concept of building a new 20 MW reactor at the same location, which would be used for essentially the same purposes as the present reactor.

Local opposition to the commissioning of a new nuclear reactor in Australia has led to a national policy debate over its merits. One of the important services that is provided by the HIFAR is the production of radioisotopes for a variety of important applications in Australia. Radioisotopes are taking on increasing importance in medical practice and other areas, and their future availability is one of the important issues that must be addressed in the debate.

Some of the radioisotopes that are currently made in HIFAR could be made using particle accelerators in Australia. Accelerators are smaller and cheaper than nuclear reactors, and produce significantly less radioactive waste. The remainder of the reactor-produced isotopes would have to be imported into the country from foreign sources, most likely North America and Europe. Australia already participates in the international isotope market, importing a variety of radioisotopes into the country. Radioisotopes are hazardous materials, and require special shipping and handling considerations. This becomes a particular problem for radioisotopes that have short half-lives. Nevertheless, importation of radioisotopes and more extensive use of accelerators for isotope production represent a viable alternative to the building of a new reactor in Australia.

Most of the increased radioisotope importation that would be associated with a decision not to go forward with a new nuclear reactor could be mitigated if Australia

decided to get involved with the development of an accelerator approach to the production of Technetium-99m (Tc-99m). Tc-99m accounts for almost ninety percent of the amount of radioisotopes used today in nuclear medicine. All Tc-99m today is produced in nuclear reactors. Two different approaches to its production using accelerators have been extensively developed in the U.S. Australia might consider making a national commitment to the finalization of the development and commercialization of one of these technologies, which would probably require a one-to-two year effort involving several person-years of work. The payoff would be that Australia would not only minimize the amount of increased importation of radioisotopes in the absence of a reactor, it would develop and possess valuable expertise in a nearly radioactive waste-free route to the production of the world's medically most important radioisotope.

Table 1 shows a matrix of the attributes of the three basic alternatives available to Australia with respect to the procurement of radioisotopes:

- build a new reactor
- no reactor, but develop an accelerator method for the production of Tc-99m
- no reactor, no accelerator production of Tc-99m

The entries in the table are discussed in detail in the text that follows.

Production of Radioisotopes

A wide variety of radioactive isotopes are used for medical, industrial, research, and commercial applications. Radioisotopes are classified as hazardous materials that require specialized storage and handling techniques. Radioisotopes are manufactured using highly specialized equipment at a limited number of locations in the world. Many radioisotopes have short half-lives, which means that they must be manufactured continuously, and used as quickly as possible after they have been prepared.

Some radioisotopes can be produced by any one of several different nuclear reaction pathways, but the number of options is limited due to physical properties of the production process. Radioisotopes are produced by irradiating target materials with nuclear particles. The target atoms either transmute directly into the desired isotope, or a parent radioisotope is produced that decays and subsequently generates the desired product. The latter is the case, for example, in the production of the important medical imaging isotope Technetium-99m. In current practice reactors are used to produce Molybdenum-99, which is the parent of Tc-99m. The Mo-99 is packed into generators that are shipped to users of Tc-99m. Technetium is eluted from the generators as needed for use.

Two different technologies are used to provide the source of radiation for radioisotope production: nuclear reactors, which produce a flux of neutrons, and particle accelerators, which produce a flux of charged particles, usually protons, but sometimes electrons or other particles. For the most part these technologies are complementary, allowing the broadest range of nuclear reactions to be carried out. Most radioisotopes in current and expected use can be manufactured either only in a

reactor, or only in an accelerator. Some radioisotopes can be produced in either a reactor or an accelerator.

Nuclear production reactors used for radioisotope production are major pieces of capital equipment, often costing in the hundreds of millions of dollars. Most of the reactors used in the world for the production of radioisotopes are government owned, and were built for multi-use purposes. These reactors typically are not optimized for the production of radioisotopes, and radioisotope production has to compete with a variety of other applications for reactor time.

Particle accelerators used for radioisotope production tend to be much smaller and cheaper than nuclear reactors, typically costing in the tens of millions of dollars, and sometimes less. Several private international pharmaceutical manufacturers own their own accelerators, which are dedicated to the production of radioisotopes. Accelerators tend to produce significantly less radioactive waste than reactors, although they are not waste-free.

Value of domestic source of supply vs. imports

Should Australia decide to forego the building of a new nuclear reactor, a few of the radioisotopes that would have been produced by the reactor could be produced using existing or new accelerators in Australia. The rest of the radioisotopes that would have been produced by the reactor will need to be imported, mostly from North American or European suppliers. Most observers consider the international radioisotope supply network to be secure and possessed of sufficient production capacity that importation does not represent a substantial risk to Australia's access to supplies of radioisotopes, at least for the foreseeable future.

Importation does, however, entail certain constraints that need to be taken into account in making national policy decisions. Importation adds one-to-three days to the time between the production of a radioisotope product, and the point at which a user in Australia has access to the material, as compared to a domestic source for the same material. For isotopes with short half-lives, a good deal of the product can be lost in shipment. Shipping delays can compound the problem. Isotopes with half-lives of a few hours or less simply cannot be imported into Australia. On the other hand, Australia has a long history of successfully importing radioisotopes from international suppliers, including Tc-99m, the most important medical radioisotope. Moreover, HIFAR operations include periodic long-term outages for maintenance, and these extended outages have been managed without supply disruptions to the country's use of radioisotopes.

The Market for Radioisotopes in Australia

A great variety of radioisotopes are currently used in Australia, for a variety of different applications. In many cases radioisotopes make processes and products possible that cannot be provided in the absence of a radioisotope material. Many of

the great advances that have been made in medicine over the past couple of decades, for example, are in the area of, or dependent on, nuclear medicine. These trends are likely to continue.

Technetium-99m has become the most important radioisotope in the world, due to its special value in medical imaging. Technetium is used in 80 – 90 percent of all nuclear medical procedures. Tc-99m is currently produced in nuclear reactors. Most of the world's supply comes from a single supplier, MDS Nordion of Canada, which has recently commissioned two new "MAPLE" reactors that will be used to produce the bulk of their Technetium generators. Australia currently produces the majority of its Technetium requirements domestically using the HIFAR reactor, and imports the remainder of its needs from foreign sources. Many other radioisotopes are imported into the country as well.

Applications for Radioisotopes in Australia

Radioisotopes are used for medical, industrial, research and commercial applications. Several isotopes have already assumed important roles in the Australian economy. For example, thallium-201 is used for medical cardiac imaging, calcium-44 is used in bone growth studies, iridium-192 is used for nondestructive testing of construction and other materials, and americium-241 is used in smoke detectors. In addition, rapid advances in nuclear medicine and other fields are focusing attention on a number of isotopes that have not previously been considered commercially important.

Table 2 illustrates the breadth of applications used for radioisotopes (IOM 1995). Radioisotopes are used in everyday products, in routine industrial practice, and in medical applications for both diagnostic and therapeutic purposes. Nuclear medicine continues to grow in its importance to modern medical technology.

Radioisotopes are used in medicine for both diagnostic and therapeutic applications. Radioisotopes are particularly useful for imaging applications, and are crucial for such non-invasive imaging techniques as positron emission tomography (PET). Isotopes used for imaging, such as Tc-99m, are administered as radiopharmaceuticals, which are biologically active molecules labeled with a radioactive isotope that target particular organs or parts of the body. Radioisotopes are also being used increasingly for therapeutic applications, mainly cancer treatment. Isotopes are directed to or inserted in the diseased tissue, where they deliver a gauged and localized radiation dose to the cancerous growth. Radioisotopes used for therapeutic purposes are administered as radiopharmaceuticals, or in sealed packages that are surgically inserted.

More than 10 million diagnostic procedures and nearly 100 million laboratory tests are performed annually in the United States using radioisotopes (IAEA 1990). In addition, radioisotopes are used therapeutically for more than 200,000 patients each year. Table 3 shows some of the radioisotopes that are in common use for medical applications.

Tc-99m, the most important radioisotope for medical use

Technetium-99m is the workhorse of the nuclear medical imaging world. The physical properties of Tc-99m allow it to be combined with a wide variety of substrates. In this way it can be delivered to very specific target tissues and organs. Tc-99m produces high-energy gamma rays, which makes detection easy, and its short half-life of 6 hours minimizes the radiation dose delivered to the patient. Nuclear medical imaging is unique in its ability to analyze organ structure and functioning. It allows the gathering of diagnostic information that would otherwise require surgery, or not be available at all. It also promotes early detection and treatment of cancers and other problems.

Tc-99m has been used widely since the late 1960s, and its use continues to grow. Tc-99m is the decay daughter product of Mo-99, an isotope with a half-life of 66 hours that is produced in nuclear reactors as a fission product of the neutron bombardment of a uranium target material. This is the source of all of the Tc-99m used in the world today. After irradiation, Mo-99 is recovered from the target, and packed into a production device from which technetium can be eluted in quite pure form as needed for preparing radiopharmaceuticals for nuclear medical procedures. ARI produces Tc-99m generators in Australia from Mo-99 produced in the HIFAR reactor. Domestic production accounts for approximately 80 percent of the current use of Tc-99m in Australia. The remainder of the supply is imported from North America or Europe.

Domestic supply and importation for the Australian radioisotope market

Australia produces a wide variety of radioisotopes for its domestic market, but it is not completely self-sufficient. Domestic radioisotopes are produced mainly by Australian Radioisotopes (ARI), a government-owned private enterprise that manufactures and distributes radioisotope products for the domestic and export markets. ARI is organized within the framework of the Australian Nuclear Science and Technology Organisation (ANSTO). ARI produces radioisotopes in the HIFAR nuclear reactor, and in several particle accelerators located in Australia. The HIFAR reactor is aging and scheduled for retirement within the next decade. In addition, some radioisotopes are produced in non-ARI accelerators in Australia.

Several international pharmaceutical companies, including Nycomed Amersham, Tyco-Mallinckrodt, and Syncor, market radioisotope products in Australia that are imported into the country. Most of the imported radioisotopes are produced in North America and Europe. In addition, Isoflex USA, a company that is an international marketer of stable isotopes from Russian supplies, is moving into the radioisotope business, and has expressed an interest in selling Russian-sourced radioisotopes in Australia. Due to their classification as special materials, radioisotope imports into Australia require special handling and shipping considerations. Generally, access to dependable supplies is not a major consideration.

Shipping and handling considerations are particularly important for radioisotopes that have short half-lives. These materials decay quickly, so it is important to use them as rapidly as possible after their manufacture. Due to Australia's remote location, shipments from North America or Europe take a significant amount of time. Most radioisotope imports are transshipped, meaning that they come on at least two different flights from the source country. Transshipping, and the special handling requirements and paperwork associated with the importation of hazardous materials, mean that importation typically delays the delivery of radioisotopes by 1 – 3 days as compared with the supply of material from domestic production sources. For an isotope with a half-life of 66 hours, such as Mo-99, the parent molecule for Tc-99m, this means that a generator that is imported to Australia will provide 25 – 50 percent less technetium than an identical generator manufactured in Australia. For isotopes with half-lives of a day or less, importation becomes almost unfeasible.

As a general rule, the proton-rich radioisotopes that are produced in accelerators have relatively short half-lives, while the neutron-rich radioisotopes that are produced by reactors have relatively longer half-lives. As a result, most of the radioisotope products that can only be made in a reactor can be supplied by foreign sources should Australia not build a new nuclear reactor. There are, however, important exceptions. Moreover, the presence of a domestic source of these materials does confer important market and supply-security benefits for the country.

Production of Radioisotopes

By their nature radioisotopes are unstable materials that must be manufactured in order to be available for the various applications they serve. Radioisotopes are created via nuclear processes in which atomic nuclei targets are irradiated, resulting in a nuclear transformation reaction. The two most common types of transformations that are used for radioisotope production are initiated by neutron and proton bombardment. Neutron fluxes are usually provided by nuclear reactors, while proton fluxes are produced in particle accelerators.

Production Options for Radioisotopes

Radioisotopes can be produced in either nuclear reactors, or in particle accelerators. Nuclear reactors are used to perform transformations involving neutron reactions, while accelerators are used for proton or electron promoted transformations. Of the broad range of radioisotopes used in nuclear medicine and other applications, some of the radioisotopes can only be produced in particle accelerators, some can only be produced in nuclear reactors, and some can be produced in either an accelerator or a reactor. Table 4a shows a list of radioisotopes that are only made in accelerators, Table 4b shows a list of radioisotopes that are only made in reactors, and Table 4c shows a list of radioisotopes that can be made using either technology (Schenter, R., 2001).

It is interesting to note that Tc-99m, which is used for as much as 90 percent of all nuclear medical procedures, is listed as a reactor-only isotope. All of the Tc-99m used medically in the world today is produced in reactors. Due to the overriding

importance of this isotope, a great deal of research has been done on developing alternative sources of supply. Two different approaches using particle accelerators (discussed below) have been identified that show promise of leading to a commercial alternative to reactor production of Mo-99. Once one of these methods has been fully proven, Tc-99m can be switched from Table 4b to Table 4c.

Use of accelerators to produce radioisotopes

The use of particle accelerators to produce artificial radioisotopes dates back to the beginnings of the accelerator era under Lawrence in Berkeley in the early 1930s. The use of proton accelerators in particular provides a rich potential, and hundreds of isotopes of various types are at least technically feasible. Other beam types, such as deuteron or alpha beams, can also be used and indeed have been. Also, producing neutrons from a proton accelerator through spallation processes allows the production of different isotopes (see the next section.) Finally, a high-energy electron beam can produce still other isotopes through gamma-n and gamma-p reactions.

Many important isotopes are produced in commercial quantities today using particle accelerators. For some of these isotopes there is no other feasible way to make them, meaning that accelerators occupy a vital niche in the overall isotope-production scheme. For those isotopes whose half-lives are so short that they cannot feasibly be imported, the only approach is a production facility located in Australia. For the others, with long enough half-lives, importation is fully feasible, and indeed is the accepted approach today in Australia for many products.

Unfortunately, and crucially, there is a list of radioisotopes (Table 4b) that simply cannot be made by accelerator techniques. Physics limitations govern many of these. In some cases the nuclear reactions simply do not exist, or the physical cross-sections are too small to be of commercial interest. In other cases, the production of the desired isotope is practical but its production is accompanied by other isotopes of the same element, which would require difficult separation processes to make enough material, or pure enough material, for practical use.

Spallation accelerators as a neutron source

In recent years the technology of spallation-source neutron production has received increasing attention around the world. A few such facilities have existed for some time and all of the basic problems with their operation have been overcome, at least insofar as the accelerator-technology aspects are concerned. The basic idea is to use a proton accelerator to bombard a heavy-element target, producing several neutrons for each proton in the incident beam. These so-called spallation neutrons can then be collimated into a beam useful for scientific studies, or otherwise used to initiate nuclear reactions. A host of potential nuclear reactions is feasible, depending on whether one desires fast neutrons emerging directly from the target, or thermal neutrons produced by slowing down the emerging fast-neutron flux in a thermalizing element such as water.

The number of feasible neutron reactions for producing radioisotopes is large, and using the fluxes available from such a facility the potential exists for producing all sorts of isotopes for medical or other applications.

One might envision two different approaches to the development of such facilities in Australia. In the first, a spallation facility would be built and used as a multiple-function facility, for use in basic and applied scientific studies as well as for routine isotope production. In the second, the spallation facility would be dedicated entirely (or mostly) to isotope production. The former might make sense for Australia, but would require a national decision to build the facility for the broader applications to which it is suited. Such a facility would be expensive and could be justified only through its broad range of applications.

Whether the latter approach (building a dedicated spallation facility in Australia dedicated to isotope production) makes sense is difficult to assess. We know of no studies that have explored how such a facility might work in terms of size, cost, throughputs, other applications, and potential technical problems.

Production of Mo-99 (Tc-99m parent) in accelerators

Although essentially all of the Tc-99m used in nuclear medicine today is produced in nuclear reactors by the fission process, it is technically feasible to produce it using an accelerator to effect the desired nuclear transformation. Two such schemes have been reported in the literature; however, neither of them has been developed to the point where a full-scale production facility exists. These accelerator schemes both share an advantage in that far less nuclear waste is produced than in the existing reactor-fission scheme. The entire Australian market for Tc-99m could be served by one or two accelerators of either variety. The two accelerator schemes are technically quite different and hence are discussed separately in the following sections.

In the first approach, which has never been executed but whose individual elements have been studied extensively, an electron accelerator in the 40 MeV range would be used to produce a gamma-ray beam through bremsstrahlung in a high-Z target. The gamma rays would strike a molybdenum target that has been highly enriched in the isotope Mo-100 (which occurs naturally in molybdenum only at the 13% level.) The gamma rays convert the Mo-100 to Mo-99 (the radioactive parent of Tc-99m) directly by knocking a neutron out of the target, in a so-called gamma-n reaction. The Mo-99 decays to Tc-99m with a 66-hour half-life, and the Tc-99m must then be extracted from the molybdenum target. The scheme investigated at the Idaho National Engineering and Environmental Laboratory (INEL) would perform the extraction using a thermal-separation method (Bennett, R., et. al., 1999, Christian, et. al., 2000).

A project carried out several years ago at INEL explored the technical potential for this approach in great detail, including identifying the key technical difficulties. There are a number of complexities in this approach, but through some very detailed experimental work supported by analysis, many of them have been overcome. In particular, the approach seems capable of being tailored nicely to the actual scheduling needs of hospitals and other medical facilities for Tc-99m. Also, the electron accelerator needed for this scheme is well within existing technology today, and the size and cost of the proposed facility are modest enough (a few million US

dollars for the facility, about 1 million US dollars annual operating cost) that distributing two or three of these accelerators around Australia would be feasible from both a logistical and engineering perspective, and could perhaps meet Australia's needs for Tc-99m very nicely.

The Idaho group developed the process quite far, to the point that only a few technical problems remain unsolved. Several impressive technical advances were made, so that the scheme as proposed optimizes the beam energy and production efficiency, makes an end-product with acceptably small impurities so as to meet the medical requirements, and produces the short-half-life Tc-99m in a form not very different from that now available using the reactor-production scheme. Perhaps the most vexing problem that remains to be solved is to demonstrate a reliable thermal-extraction process for removing the desired Tc-99m from the molybdenum target. Although promising technical advances have been made, this aspect definitely requires more experimental development. Otherwise, the next logical step would be a full-scale demonstration of the approach by actually building and operating such an accelerator.

The Idaho group reported (Bennett, private communication, 2001) that interest was expressed by commercial enterprises, to the extent that quite serious explorations of the technical details were pursued by at least one firm, but in the end no commercial development of the process has occurred.

The proposed scheme has several advantages. One major advantage is that by design the approach is aimed at producing Tc-99m in several small accelerator facilities (that could be distributed regionally) rather than in one larger national facility. The projected cost per unit Tc-99m dose also seems to be in a reasonable range, although this cannot be known in detail until the additional technical work is completed that provides the full scientific and engineering basis for the scheme.

Our evaluation is that a few technical person-years of effort would be required to establish a firm enough technical foundation to allow this approach to be pursued to maturity. Although the scheme shows great promise, and has important advantages, there is no guarantee at this stage that all of the technical issues can be resolved. On balance, even if adequate resources were devoted to the development of this scheme, its full-scale technical feasibility would probably require a few calendar years of work. Then a full-scale facility would need to be designed, built, and operated before this scheme could be pronounced as established. This is an area in which Australia could make a major contribution.

Direct production of Tc-99m in accelerators

In this approach a proton accelerator would be used to produce Tc-99m directly from a target material. The process involves bombarding a target of highly-enriched Mo-100, which undergoes a so-called (p,2n) reaction in which two neutrons are knocked out of the target nucleus. This method is explored in a paper that describes experimental investigations using a cyclotron that accelerates protons in the 12-to-22-MeV range (Lagunas-Solar, M., and Zeng, N., 1997).

The yield of Tc-99m from the reaction is acceptably high, and the purity of the end-product meets or exceeds medical criteria. The method has the potential to produce rather large quantities of Tc-99m using one-hour bombardment times, which is crucial since the 6-hour half-life of the Tc-99m means that the turn-around times in the accelerator must be very short indeed.

The direct-production approach for technetium eliminates the need for the second step (elution of Tc-99m from Mo-99) that is a central feature of the standard reactor-production method. However, the key liability is that Tc-99m has a short 6-hour half-life, which requires that the production accelerator facility be relatively close to the medical end-use points.

A facility along the lines of the one explored in the cited paper would likely produce enough Tc-99m for all of Australia's needs. However, having only one such facility in Australia could be a problem given the 6-hour half-life of the isotope and the transportation logistics (Perth is about one half-life away by air from the eastern cities.)

Modern proton accelerators with large beam currents are now available for this application, and the remaining elements of the proposed scheme seem feasible in principle; indeed, many of them have been demonstrated already or are not likely to be problematical. One key issue is that the practicality of the approach depends on achieving high specific activities of Tc-99m in the target, since many of the important medical applications require such. This has not yet been demonstrated fully although it seems feasible in principle.

Several technical and engineering issues remain to be addressed, and to do so would probably require several person-years of scientific and engineering effort. The cost of the end product also needs to be understood better, as do the logistical issues involved in taking the Tc-99m as produced and transforming it for medical use. Only then would it be feasible to build a production facility, assuming that each unknown issue can be worked-out favorably.

Sources of import supply for reactor-derived material

ANSTO currently operates a nuclear reactor (HIFAR), and a particle accelerator (NMC). Both of these units are used for the production of radioisotopes, as well as for a number of other purposes. ANSTO-produced radioisotopes are used to supply the domestic market for these materials, as well as for export sales. The domestic market for radioisotope products cannot be fully supplied from ANSTO’s current production capabilities. Approximately twenty percent of the country’s Tc-99m use is supplied by import sources, and various other isotopes are also imported into Australia.

The proposed new Australian reactor has a power rating that is twice as large as the existing HIFAR reactor. The increased size and capabilities designed into the new reactor are not being sought because of a deficiency with respect to domestic radioisotope production capabilities in Australia. In fact, the decision to import a portion of the country’s radioisotope supply has to do with competing uses for the reactor, and with post-reactor processing requirements for various products. It is

likely that even with a new 20 MW reactor Australia will import some radioisotopes, and will export some radioisotopes. Thus, the additional cost of the larger reactor design has to be judged on issues other than adequacy for radioisotope supply.

The major alternative to the building of a new nuclear reactor in Australia for the supply of reactor-produced radioisotopes is importation of these materials from international sources, most of which currently are in North America and Europe. Since most of the important radioisotopes that are produced in reactors have reasonably long half-lives, timing is not a major hurdle in obtaining import supplies. Technetium-99m generators, which have half-lives of 66 hours (Mo-99), lose 25 – 50 percent of their cumulative production capacity compared with domestically-produced sources, but technetium generators are currently successfully imported into Australia, and import supplies could be expanded if the country did not have a production reactor. In this case, Australia might decide to support some of the research that is still needed in order to bring one of the accelerator methods of Tc-99m production into commercial development. Having a domestic source of Tc-99m would minimize the overall quantity of radioisotopes that would have to be imported to Australia if a replacement reactor were not built.

Environmental and Economic Implications

Nuclear reactors and particle accelerators both produce radioactive waste, but the amount of waste generated by an accelerator is much less than that associated with a reactor. Both technologies require very expensive equipment. Reactors generally are much larger projects than accelerators. Neither of the two types of systems employ a large number of staff, but the jobs required by both include a high percentage of positions requiring advanced technical skills.

Environmental consequences of reactor vs. accelerator operation

Except for the generation of radioactive wastes, neither the reactor option nor the accelerator option is associated with important environmental consequences. The routine emissions of airborne or waterborne pollutants are minor for both options, as are the other routine and expected consequences (land use, occupational safety and health, risks associated with transportation, etc.) Safety concerns are always important for any reactor. Although the small size of the proposed new Australian replacement reactor for HIFAR means that the safety concerns are less than for a large electric-power reactor with a power level a hundred-fold greater, a there is still an open question as to whether the design will be adequate to protect against radioactive releases that might harm offsite populations and the environment. The reactor's design requires careful analysis to assure that it embodies all of the latest technical advances in reactor safety, and until the design is finalized such a safety analysis cannot be performed with the requisite detail. The comparable risks from accelerator operation are unimportant.

Radioactive wastes are, however, clearly different: Whereas an accelerator produces only minor amounts of such wastes from the activation of its materials, any nuclear reactor produces fission products proportional to the integrated power produced, and these include the full spectrum of long-lived fission products that must be isolated from the environment for very long times, some measured in millennia. This issue is well known and well understood. Since the new Australian reactor is being designed for twice the power level of the existing HIFAR, it will therefore produce annually about twice as much in the way of fission-product high-level radioactive waste.

It is important to note that most or all of the countries that supply highly enriched fuel for reactors like the one under consideration in Australia also remove spent fuel from the country as one of the conditions of sale. This is done for reasons of global security. The spent fuel from the HIFAR reactor, for example, is ultimately destined for return to Europe (originally the U.K., more recently France), although the timeliness of the cycle puts its effectiveness into question. What the ultimate fate of the waste from the spent fuel will be is also in doubt, due to uncertainties about the fate of the material after it is returned to its point of origin. The plan for the spent fuel from HIFAR, for example, is that it will be reprocessed in the Europe, with radioactive waste returned to Australia for ultimate disposal. Uncertainties about the future of reprocessing, as well as global political uncertainties, put the ultimate fate of spent fuel from reactor operations in Australia in some degree of doubt, regardless of the contractual arrangements made for the procurement of fuel for the new Australian reactor.

The other environmental consequences seem minor. Neither the reactor option nor the accelerator option would have much impact on global warming, although each would consume electricity in the course of operations, and electricity involves greenhouse-gas emissions with global-warming implications (the accelerator would consume more such electricity, but the absolute amount is not large for either option). And either would be a “good neighbor” environmentally in terms of routine impacts, which would likely be dominated by the normal human activities associated with running any high-tech facility, such as traffic and its associated impacts from the staff commuting to work, trash from their normal day-to-day activities, etc.

Investment, job creation, multiplier effects

Nuclear reactors and particle accelerators are both highly capital-intensive equipment. Reactors tend to be much larger than accelerators, with accelerators typically costing in the millions to tens of millions of dollars, and reactors in the hundreds of millions. The new reactor proposed by ANSTO is estimated to cost approximately $300 million (Aus.), and would take about four years to build. Accelerators, being smaller projects than reactors, and producing much less nuclear waste, can be designed, licensed, and built more quickly.

Employment is created during both project construction, and project operations. The amount of construction employment that is associated with these types of projects is probably in the range of 100 – 500 on-site workers during the construction period. Once the facilities are commissioned, the amount of employment associated with their operations is modest, probably in the range of 50 – 100 workers for each facility. Many of the jobs are high-level technical jobs. In addition, the operation of these

types of facilities provides educational and job-upgrading opportunities for students and others in Australia.

The investment capital necessary to build a new nuclear reactor in Australia is substantial. Due to the capital-intensive nature of the equipment required, and the fact that a foreign vendor will be used, the public-sector investment in a new reactor will have a low economic multiplier effect compared to other possible uses of the capital. A network of particle accelerators in Australia would probably have a slightly higher multiplier effect, because most of the equipment could be produced domestically. In addition, a network of accelerators would, in the aggregate, cost significantly less than a single nuclear reactor.

The alternative to a new reactor for the supply of many important radioisotopes in Australia is importation. This is true in the short term for Tc-99m, the most widely used radioisotope in medicine, although in the longer term Australia could play a key role in the development of an accelerator method for technetium production, which would provide the world with an alternative that produces far less radioactive waste than the conventional reactor-production method.

A key consideration in comparing isotope importation with domestic production in a new reactor is the price of the radioisotopes for the user. Price, however, is a very elusive quantity in the radioisotope world, due in large part to the fact that virtually all nuclear reactors in the world used for radioisotope production are either government owned or substantially subsidized by the public sector. While many radioisotope production operations, including those using the HIFAR reactor in Australia, are charged “at-cost” for use of space and neutron flux in the reactor, determining the true cost of this service is impossible. Various studies available on radioisotope production costs for HIFAR vs. the cost of imported isotopes show everything from domestic production at half the price of imports, to imports being able to undercut domestic sources. The truth is that a variety of purely subjective criteria are tied to the pricing of both domestic and imported radioisotopes, and various suppliers may manipulate these prices for their own reasons. As long as the international supply of radioisotopes remains in relatively plentiful supply, as it currently is, there is no way to determine a price advantage or disadvantage for radioisotopes produced from a new reactor in Australia.

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Table 1

Attributes for Alternative Scenarios for Radioisotope Procurement in Australia

	Reactor	Accelerators for Tc99m
Capital Cost	hundreds of millions	tens of millions
Radioactive Waste	significant amount	small amount
Radioisotope Supply	70 - 85% domestic	65 - 80% domestic
Employment	50-100 permanent	50-100 permanent
Tech Jobs	many	many
Research, Training	excellent	excellent
Intellectual Property	good	excellent

Table 2

Applications for Radioisotopes

Field	Major Applications
Food and agriculture animals	**o improve nutritional status and health of plants and**
	o maximize optimal crop production o reduce food-borne diseases and increase food preservation
Biochemistry, biology, animals	**o improve nutritional status and health of plants and**
Biotechnology, chemistry, Physics, physiology	**o maximize optimal crop production**
Cosmology	o exploration and understanding of the universe
Earth sciences: geochemistry, geology, geophysics, hydrology, and marine sciences	o exploration and preservation of natural resources o study of water resources and maintaining a safe and abundant water supply
Ecological and environmental Research	o environmental chemistry and measurements o environmental pollution studies: occurrence, cause, and remedy
Health care	o diagnostic nuclear medicine such as cardiological diagnosis o PET research and applications o radionuclide treatment of disease such as cancer o radiopharmaceuticals o drug research (uptake, binding, metabolism, clearance)
Industrial manufacturing and research production	o materials sciences o radioisotope thickness gauges for steel plate or paper o computer chip production
Nutrition	o disease prevention and health promotion research (cancer, heart disease, obesity, osteoporosis, etc.) o energy metabolism in humans and animals o tracer techniques to determine nutrition requirements
Toxicology	o risk assessment o soil and water exposure studies

Source: *IAEA, 1990*

Table 3

Radioisotopes Used for Medical Applications

Carbon-11, Fluorine-18, Nitrogen-13, Oxygen-15: Used in PET imaging.

Chromium-51: Labeling red blood cells.

Cobalt-60: External beam radiotherapy.

Gallium-67: Detection and localization of tumors and lesions.

Iodine-125: Used in laboratory analyses such as radioimmuno assays.

Iodine-131: Detection and therapy of cancer, especially of the thyroid.

Indium-111: Used for brain studies.

Iridium-192: Tumor treatment.

Iron-59: Used in studies of iron metabolism in the spleen.

Potassium-42: Used for coronary blood flow studies.

Samarium-153: Used in treatment of bone cancer.

Sodium-24: Used for studies of electrolytes within the body.

Technetium-99m: The most commonly used isotope, technetium is used for medical imaging applications in all parts of the body.

Thallium-201: Diagnosis of artery and heart disease.

Xenon-133: Used for pulmonary ventilation studies.

Ytterbium-169: Used for cerebrospinal fluid studies in the brain.

Yttrium-90: Used for cancer therapy and arthritis treatment.

A variety of other radioisotopes are also either in use or under study for use in medical applications.

Table 4a, Accelerator Produced Radioisotopes

1. As72
2. As73
3. At211 – Alpha emitter – RIT (Brain Cancer treatment)
4. Ba128
5. Be7
6. Bi205
7. Bi206
8. Bi207
9. Br75
10. Br76
11. C11 – Very short lived PET
12. Co55
13. Co56
14. Cu61
15. F18 – Very short lived PET
16. Fe52
17. Ga67
18. Ga68
19. Gd146
20. Gd148
21. Ge68
22. Hf172
23. Hg195m
24. I123
25. I124
26. In111 – Diagnostics
27. Kr81m
28. Lu172
29. Lu173
30. Mg28
31. Mn52
32. N13 – PET
33. O15 – PET
34. Pb203
35. Pm145
36. Rb81
37. Rb82
38. Ru97
39. Se72
40. Sr82
41. Ta178
42. Te118
43. Ti44
44. Tl201- Blood flow studies
45. V48
46. W178
47. Y86
48. Y87
49. Zn62
50. Zr88

Table 4b, Reactor Produced Radioisotopes

1. Ac227 – Parent of Ra223 – RIT
2. Ag111
3. Au198
4. Au199
5. Br82
6. C14
7. Ce141
8. Cf252 – Brain cancer treatment
9. Co60 – “Gamma knife” Cancer treatment
10. Cs137 - FP
11. Dy165 – Arthritis treatment (2 hr.)
12. Er169
13. Fm255
14. Ga67 – SPECT
15. Gd153 – SPECT calibration – Osteoporosis detection
16. H3
17. Ho166 – Multiple Myeloma treatment – 1.1 day half-life
18. I129
19. I131 – Cell directed therapy (“Smart Bullets”) – “RIT” – several forms of cancer
20. Ir192
21. Lu177 –RIT
22. Mo99 – Diagnostic – 40,000 procedures a day in US – comes from Canada, etc. -(Parent for Tc99m)
23. Os191 – Sent to Children’s Hospital, Boston from FFTF 1992
24. Os194 – RIT
25. P32 –Heart disease treatment
26. P33 – Requires high energy neutrons
27. Pd109
28. Pt195m
29. Re186
30. Re188 – From W188 generator – for RIT cancer, heart disease treatment
31. Re188 – From Re187 – for RIT cancer, heart disease treatment
32. Rh105
33. Ru105
34. S35
35. Sb119
36. Sc47 – RIT
37. Se75 – Sent to NIH for research from FFTF
38. Sm153 – Bone Cancer Pain Relief – Has FDA approval – “QUADRAMET”
39. Sn113
40. Sr85
41. Sr89 – Bone Cancer Pain Relief – Has FDA approval – “METASTRON”
42. Sr89 – from Y89 – “Carrier free Sr89” – bone pain relief – requires high energy neutrons
43. Te123m
44. Th228 – Alpha emitter grand parent of Bi212 (AML, RIT, et al)
45. Th229 – Alpha emitter grand parent of Bi213 (AML, RIT, et al)
46. Ti44
47. Tm170
48. Xe133
49. Y90 - FP
50. Y90 – From Y89 – Liver cancer treatment – “microseeds”
51. Y91 – RIT
52. Yb169

Table 4c, Accelerator or Reactor Produced Radioisotopes

1. Ag105
2. Ag108m
3. Ag109m
4. Al26
5. As74
6. Br77
7. Br80m
8. Cd109
9. Ce139
10. Cr51
11. Co57
12. Cu62
13. Cu64 – RIT
14. Cu67 – RIT – Accelerators can't keep up with demand (see Denardo's comments)
15. F18
16. Fe55
17. Fe59
18. Hg197
19. Ho163
20. I125 – Brachytherapy ("seeds") – Prostate, Breast, et al treatments
21. Na22
22. Pd103 – Brachytherapy ("seeds") – Prostate, Breast, et al treatments
23. Pm149
24. Rb83
25. Rb86
26. Rh105
27. Ru103
28. Sc44
29. Sc46
30. Sc47
31. Si32
32. Sm145
33. Sn117m
34. Ta179
35. Tc95m
36. Tc96
37. Xe122
38. Xe127 – Diagnostics – "Xe-127 production continues to be a problem for the combined capabilities of BNL and LANL…"
39. Y88
40. Zn65
41. Zr89

Curriculum Vitae,

Robert J Budnitz and Gregory Morris

Future Resources Associates, Inc.
2039 Shattuck Avenue, Suite 402, Berkeley, California 94704
(510) 644-2700 FAX (510) 644-1117
e-mail: <budnitz@pacbell.net>

ROBERT J. BUDNITZ

Occupation:	Physicist in Energy/Environmental Research and Nuclear Safety
Birth:	October 12, 1940 in Pittsfield, Massachusetts
Family:	Married in 1961 to Barbara Paresky Budnitz, Licensed Clinical Social Worker. Three children: Paul (born 1967), Benjamin (born 1970), Elizabeth (born 1976)

Education

High School:	Pittsfield High School, Pittsfield, Massachusetts (1957)
Universities:	Yale University, New Haven, Connecticut B.A. Physics (1961)
	Harvard University, Cambridge, Massachusetts M.A. Physics (1962) Ph.D. Physics (1968)

Present Professional Position

Principal Post: President, Future Resources Associates, Inc. (since 1981)

Past Professional Positions

Teknekron, Inc.
Berkeley, California

1980 - 1981 Vice President, and Director of the Energy and Environmental Technologies Division

U.S. Nuclear Regulatory Commission
Washington, D.C.

1979 - 1980 Director, Office of Nuclear Regulatory Research

1978 - 1979 Deputy Director, Office of Nuclear Regulatory Research

Past Professional Positions (continued)

Lawrence Berkeley Laboratory
University of California
Berkeley, California

1978 - 1980	Leave of Absence Status
1975 - 1978	Associate Director of LBL, and Head, Energy & Environment Division
1974 - 1975	Program Leader, LBL Environmental Research Program
1971 - 1974	Physicist, LBL Environmental Research Program
1967 - 1971	Post-Doctoral Physicist, LBL High-Energy Physics Program

Honors and Awards

American Nuclear Society (elected Fellow, 1998)
Society for Risk Analysis (elected Fellow, 1996)
American Physical Society (elected Fellow, 1988)
American Nuclear Society, Reactor Safety Division, Best Paper Award (1988)
National Science Foundation Graduate Fellowship in Physics (1961 - 1963)
Phi Beta Kappa, Yale University (1961)
Sigma Xi, Yale University (1961)
Student Marshall, Yale Baccalaureate Procession (1961)
Varsity Letter, Track Team, Yale University (1961):
track team won national indoor championship, Intercollegiate
Amateur Athletic Association of America

Other Professional Activities (Current)

Member, National Research Council/National Academy of Sciences, Board on Radioactive Waste Management (1998 - present)

Member, Secretary of Energy's Panel on Emerging Technological Alternatives to Incineration, under the DOE Secretary of Energy Advisory Board (2000 - present)

Member, Regulatory Working Group under the US-Russian Joint Steering Committee on Scientific and Technical Cooperation in the Management of Plutonium (2000 - present)

Member, National Research Council/National Academy of Sciences,, Committee on Alternatives for the Control of Solid Materials from NRC-Licensed Facilities (2000 - present)

Member, Expert Panel on the Role and Direction of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission (2000 - present)

Chairman, Writing Group on the External-Hazards-PRA-Methodology Standard, Risk Informed Standards Consensus Committee, American Nuclear Society (1998 - present)

Chairman, Writing Group on the Low-Power-and-Shutdown-PRA-Methodology Standard, Risk Informed Standards Consensus Committee, American Nuclear Society (1998 - present)

Member, Program Committee, American Nuclear Society's Nuclear Installations Safety Division (1999 - present)

Member, Risk Informed Standards Consensus Committee, American Nuclear Society (1998 - present)

Member, Quantitative Risk Assessment Expert Panel for Anniston, Umatilla, and Pine Bluff, U.S. Army Program Manager for Chemical Demilitarization (1999 - present)

Member, Editorial Board, Journal of Reliability Engineering and System Safety (1999 - present)

Member, Project Team on Risk Management for Nuclear Facility Applications, Board on Nuclear Codes and Standards, American Society of Mechanical Engineers (1998 - present)

Member, Committee on Nuclear Risk Management, Board on Nuclear Codes and Standards, American Society of Mechanical Engineers (1998 - present)

U.S. Representative, Nuclear Safety Advisory Committee of Lithuania, reporting to the Prime Minister of Lithuania (1997 - present)

Member, Scientific and Technical Advisory Committee to the University of Chicago, overseeing Argonne National Laboratory (1997 - present)

U.S. Representative, President of Armenia's Nuclear Energy Safety Council (1996 - present)

Member, Board of Directors, California Radioactive Materials Management Forum (1988 - present)

Member, Independent Review Committee for the Research Reactors Division, Oak Ridge National Laboratory (1987 - present)

Other Professional Activities (Past)

Member, Performance Assessment Peer Review Panel, DOE Yucca Mountain Project Office (1997 - 1999)

Rapporteur, Group of Senior Experts to Review the Russian Nuclear Power Plant Safety Research Strategic Plan, OECD Nuclear Energy Agency, (1998 - 1999)

Member, Executive Committee, Nuclear Installations Safety Division, American Nuclear Society (1996 - 1999) [Chairman (elected), 1997-98]

Member, Senior Technical Review Panel, Continued Storage Analysis Project, Yucca Mountain Project (1998 - 1999)

Member, Special Committee on Social Issues and Human Values [formerly Special Committee on Socio-Technological Issues], American Nuclear Society (1988 - 1998)

Member, Organizing Committee, OECD Nuclear Energy Agency Tokyo Workshop on Seismic Risk, OECD Nuclear Energy Agency (1999)

U.S. Representative, Ignalina Safety Panel to Advise the European Bank for Reconstruction and Development on the Ignalina (Lithuania) Nuclear-Power-Plant Safety Analysis Report (1994 - 1998)

Chairman, Technical Review Team for DOE Natural Phenomena Hazards Existing Facilities Project, U.S. Department of Energy (1992 - 1998)

Consultant, to Division of Nuclear Safety, International Atomic Energy Agency, Vienna, on subject of Seismic and Fire PRA (1992 - 1997)

Chairman, National Research Council/National Academy of Sciences, Committee on Remediation of Buried and Tank Wastes, under Board on Radioactive Waste Management (1992 - 1996)

Member, Government of Austria, International Expert Team to Review Mochovce Nuclear Power Plant Safety (1998)

Member, Board of Directors, Pacific Environment and Resources Center [formerly Golden Gate Energy Center], Ft. Cronkhite, California (1985 - 1998)

Member, Visiting Committee for the Department of Advanced Technology, Brookhaven National Laboratory (1996 - 1997)

Member, U.S. Environmental Protection Agency, National Advisory Council on Environmental Policy and Technology, Advisory Committee on WIPP, the Waste Isolation Pilot Plant (1993 - 1998)

Chairman (1991 and 1995) and Member (1988 - 1997), University of Chicago Review Committee for the Engineering Development Division [formerly Engineering Physics Division], Argonne National Laboratory (1988 - 1997)

U.S. Representative, Safety Review Group for the Nuclear Safety Account for Upgrading Soviet-Designed Reactors, European Bank for Reconstruction and Development (1993 - 1997)

Chairman, Oversight Panel, Yucca Mountain Seismic Hazards Evaluation, U.S. Department of Energy (1995 - 1996)

Member, Expert Panel on Risk Assessment, U.S. Army Chemical Demilitarization and Remediation Activity, Edgewood Arsenal, Maryland (1994 - 1997)

Member, Performance Assessment Peer Review Panel, DOE Waste Isolation Pilot Plant, Sandia National Laboratories (1987 - 1996)

Member, Expert Panel on Aircraft Crash Risk Analysis Methodology, U.S. Department of Energy (1994 - 1996)

Chairman, Senior Seismic Advisory Panel for the Savannah River Site, Westinghouse Savannah River Company (1994 - 1995)

Chairman, Senior Seismic Hazard Analysis Committee, co-sponsored by U.S. Department of Energy, U.S. Nuclear Regulatory Commission, and Electric Power Research Institute (1993 - 1996)

Member, National Research Council/National Academy of Sciences, Panel on Options for Disposition of Weapons-Related Plutonium, under Committee on International Security and Arms Control (1992 - 1995)

Member, National Research Council/National Academy of Sciences, Committee on Technical Bases for Yucca Mountain Standards (1993 - 1995)

Member, Review Team for the U.S. Department of Energy's Natural-Phenomena-Hazards-Mitigation Order and Standards (1994 - 1995)

Chairman, Peer Review Panel for the Rocky Flats Site Seismic Hazard Assessment (1994)

Member, Advisory Group on Treatment of Hazards in Probabilistic Safety Assessment, International Atomic Energy Agency, Vienna (1986 - 1992)

U.S. Coordinator, Case Studies Preparation Task for "Manual for Probabilistic Safety Assessment and Its Application in Safety Decisions", International Atomic Energy Agency, Vienna (1984 - 1992)

Member, Board of Directors, Energy and Technology Management Corporation (a spin-off of Science Applications International Corporation) (1992 - 1993)

Chairman, Seismic Consolidated Peer Review Group, Savannah River Site, U.S. Department of Energy (1990)

Chairman, Senior External Events Review Group, Office of New Production Reactor, U.S. Department of Energy (1989 - 1992)

Member, High-Level Review Committee, Savannah River Site Probabilistic Risk Assessment, U.S. Department of Energy (1989 - 1990)

Member, Peer Review Group for the Hope Creek Risk Assessment, Public Service Electric and Gas Company (1989 - 1990)

Member, Severe Accident Advisory Committee, Savannah River Laboratory (1988 - 1992)

Principal Speaker, Commonwealth Club of California, Weekly Nationally Broadcast Address (1989)

Chairman, External Review Board for ATR (Advanced Test Reactor) Safety Analysis Program, Idaho National Engineering Laboratory/EG&G-Idaho (1989)

Member, N Reactor PRA Independent Review Board, Westinghouse Hanford Company (1988 - 1990)

Member, Executive Committee, Northern California Section, American Nuclear Society (1988 - 1989)

Member, Review Group on Nuclear Reactor Research Integration, Idaho National Engineering Laboratory/EG&G-Idaho (1987 - 1989)

Chairman, Advanced Reactor Peer Review Group, U.S. Nuclear Regulatory Commission (1987 - 1988)

Member, Advisory Panel on Seismic Component Fragilities, Brookhaven National Laboratory (1986 - 1990)

Chairman, Expert Panel on Seismic Design Margins, U.S. Nuclear Regulatory Commission (1984 - 1987)

Chairman, Peer Review Expert Panel on Plant Aging, Battelle Pacific Northwest Laboratory for U.S. Nuclear Regulatory Commission (1987)

Member, New Production Reactor Panel of the DOE Energy Research Advisory Board, U.S. Department of Energy (1988)

Member, Expert Panel on Front-End Issues, NUREG-1150 Analysis Team, Sandia National Laboratories for U.S. Nuclear Regulatory Commission (1987 - 1988)

Member, U.S. Army Chemical Munitions Disposal Risk Assessment Review Panel, GA Technologies, Inc. (1987)

Member, Panel on Energetic Events, Review Group on Uncertainties in Source Term Estimates from Severe Accidents in Nuclear Power Plants, U.S. Nuclear Regulatory Commission (1987)

Chairman, Panel to Review EPRI's Seismic Margin Methodology, U.S. Nuclear Regulatory Commission (1987)

Chairman, Peer Review Group, Maine Yankee Seismic Margin Study, U.S. Nuclear Regulatory Commission (1986 - 1987)

Chairman, Seabrook Emergency Planning Zone Study Peer Review Group, New Hampshire Yankee Division, Public Service Company of New Hampshire (1985 - 86)

Member, Chernobyl Advisory Panel, Electric Power Research Institute (1986 - 1987)

Member, Improved Confinement Review Panel, Savannah River Laboratory, E.I. DuPont de Nemours, Inc. (1986 - 1987)

Member, Board of Directors, Northern California Chapter, Society of Risk Analysis (1986 - 1987)

Member, Senior Committee on Environmental, Safety, and Economic Aspects of Fusion Energy, U.S. Department of Energy (1985 - 1987)

Liaison from Energy Engineering Board to Committee on Nuclear Safety Research, National Research Council/National Academy of Sciences (1985 - 1986)

Member, Exploratory Committee on the Future of Nuclear Power Generation, National Research Council/National Academy of Sciences (1984)

Organizer, First Seminar on Excellence in Energy Management, Association of Professional Energy Managers, San Francisco (1984)

Consultant on Comparative Risks in the Nuclear Fuel Cycle, to the Nuclear Energy Agency of the Organization for Economic Cooperation and Development, Paris (1984)

Member, Independent Review Panel for Environmental Assessments, Roy F. Weston Inc., for the Office of Civilian Radioactive Waste Management, U.S. Department of Energy (1984)

Member, National Research Council/National Academy of Sciences, Energy Engineering Board (1983 - 1986)

Chairman, Peer Review Group, DOE Office of Crystalline Repository Development, Battelle Project Management Division (1983 - 1986)

Consultant, Study Group on Radionuclide Releases from Severe Nuclear Power Plant Accidents, American Physical Society (1983 - 1985)

Member, U.S. Environmental Protection Agency Science Advisory Board, Subcommittee on High-Level Radioactive Waste Disposal (1983 - 1984)

Member and OECD/NEA Liaison Representative, Programme Group, Second Specialist Meeting on Probabilistic Methods in Seismic Risk Assessment for Nuclear Power Plants, OECD Nuclear Energy Agency, at Lawrence Livermore National Laboratory (1983)

Member, Three Mile Island Mass Balance Project Review Committee, NUS Corporation, for U.S. Department of Energy (1982 - 1983)

Invited Participant, Workshop on Technological and Regulatory Changes in Nuclear Power, U.S. Congress Office of Technology Assessment (1982)

Member, Advisory Committee to Review the Agency's Nuclear Safety Activities, International Atomic Energy Agency, Vienna (1982)

Member, Peer Review Committee to Review the International Atomic Energy Agency's Transportation Dose Model INTERTRAN, sponsored by U.S. Department of Energy (1981 - 1982)

Technical Coordinator, Special Inquiry Group into the Three Mile Island Accident (the "Rogovin Inquiry"), U.S. Nuclear Regulatory Commission (1979 - 1980)

U.S. Representative, Committee on the Safety of Nuclear Installations, Nuclear Energy Agency of the Organization for Economic Cooperation and Development, Paris (1979 - 1980)

Member, Panel on Public Affairs, American Physical Society (1978 - 1981)

Speaker, ENERGY-2020 Lecture Series, sponsored by National Science Foundation (1978)

Member, Editorial Advisory Group, "Electric Power Systems Research", journal published by Elsevier (1977 - 1985)

Member, Risk Assessment Review Group (the "Lewis Committee"), U.S. Nuclear Regulatory Commission (1977 - 1979)

Editor-in-Chief, "CRC Forums on Energy", CRC Press, West Palm Beach, Florida (1976 - 1980)

Member, National Research Council/National Academy of Sciences, Panel on Sources and Control Techniques, Environmental Research Assessment Committee (1975 - 1977)

Co-organizer (with T.H. Pigford), University of California Extension Courses on "Environmental Impacts of Electricity Generation", week-long course given in 1974, 1975, 1976, 1977

Member, Reactor Hazards Committee, Berkeley Research Reactor, University of California, Berkeley (1974 - 1978)

Member, Subpanel on Energy, U.S. Atomic Energy Commission High Energy Physics Advisory Panel (1974)

Member, Reactor Safety Study Group, American Physical Society (1974 - 1975)

Publications

"Unsuccessful Search for an Excited Electron", R.J. Budnitz, J.R. Dunning, M. Goitein, N.F. Ramsey, J.K. Walker, and Richard Wilson, Physical Review 141, 1313 (1966)

"Measurements of Elastic Electron-Proton Scattering at High Momentum Transfers by a Coincidence Technique", M. Goitein, R.J. Budnitz, L. Carroll, J. Chen, J.R. Dunning, K. Hanson, D. Imrie, C. Mistretta, J.K. Walker, Richard Wilson, G.F. Dell, M. Fotino, J.M. Patterson, and H. Winick, Physical Review Letters 18, 1016 (1967)

"Quasi-Elastic Electron-Deuteron Scattering at Forward Angles", R.J. Budnitz, J. Appel, L. Carroll, J. Chen, J.R. Dunning, M. Goitein, K. Hanson, D. Imrie, C. Mistretta, J.K. Walker, and Richard Wilson, Physical Review Letters 19, 809 (1967)

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"Search for the Electroproduction of the N'(1470) Resonance from Deuterium", J. Alberi, J. Appel, R.J. Budnitz, J. Chen, J.R. Dunning, M. Goitein, K. Hanson, D. Imrie, C. Mistretta, and Richard Wilson, Physical Review 176, 1631 (1968)

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"CP-Violating Charge Asymmetry in the Decay K_L^o --> pi + mu + neutrino", R.L. McCarthy, J.H. Brewer, R.J. Budnitz, A.C. Entis, R.M. Graven, D.H. Miller, and W.N. Ross, Physics Letters 42B, 291 (1972)

"Charge Asymmetry in the Decay K_L^o --> pi + mu + neutrino", R.L. McCarthy, J.H. Brewer, R.J. Budnitz, A.C. Entis, R.M. Graven, D.H. Miller, and W.N. Ross, Physical Review D 7, 687 (1973)

"Radon-222 and Its Daughters - A Review of Instrumentation for Occupational and Environmental Monitoring", R.J. Budnitz, Health Physics 26, 145 (1974)

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"Plutonium: A Review of Measurement Techniques for Environmental Monitoring", R.J. Budnitz, IEEE Transactions on Nuclear Science, NS-21(1), 430 (1974)

"Krypton-85: A Review of Instrumentation for Environmental Monitoring", R.J. Budnitz, in Noble Gases, R.E. Stanley and A.A. Moghissi (editors), U.S. Environmental Protection Agency, Las Vegas, Nevada (1975)

"Instrumentation for Environmental Monitoring in Biological Systems", N.A. Amer, R.M. Graven, R.J. Budnitz, and D.A. Mack, IEEE Transactions on Nuclear Science, NS-22(1), 633 (1975)

Report to the American Physical Society by the Study Group on Light-Water Reactor Safety, H.W. Lewis, R.J. Budnitz, A.W. Castleman, D.E. Dorfan, F.C. Finlayson, R.L. Garwin, L.C. Hebel, S.M. Keeny, R.A. Muller, T.B. Taylor, G.F. Smoot, and F. von Hippel, Reviews of Modern Physics 47, Supplement No. 1 (1975)

"Review of the American Physical Society Light Water Reactor Safety Study", R.J. Budnitz, IEEE Transactions on Nuclear Science NS-23(1), 25 (1976)

"Social and Environmental Costs of Energy Systems", R.J. Budnitz and J.P. Holdren, in Annual Review of Energy, J.M. Hollander (editor), Vol. 1, 553 (1976)

"Sources of Residuals and Techniques for Their Control: Research and Development Needs", Panel on Sources and Control Techniques, Environmental Research Assessment Committee (R. J. Budnitz, member), National Research Council/National Academy of Sciences (1977)

"U.S. Electricity Through the Year 2000: Coal or Nuclear?", R. J. Budnitz, L. D. Hamilton, J. P. Holdren, and J.D. Morgan, CRC Forum on Energy, CRC Press (1977)

"U.S. Energy Through the Year 2000: How Much Will Be Required?", K.C. Hoffman, R.J. Budnitz, J.H. Gibbons, P.F. Swenson, and D. Wood, CRC Forum on Energy, CRC Press (1977)

"Risk Assessment Review Group Report to the U.S. Nuclear Regulatory Commission," H.W. Lewis, R.J. Budnitz, H.J.C. Kouts, W.B. Loewenstein, W.D. Rowe, F. von Hippel, and F. Zachariasen, Report NUREG/CR-0400, U.S. Nuclear Regulatory Commission (1978)

"Human Disease from Radon Exposures: The Impact of Energy Conservation in Residential Buildings", R.J. Budnitz, J.V. Berk, C.D. Hollowell, W.W. Nazaroff, A.V. Nero, and A.H. Rosenfeld, Energy and Buildings 2, 209 (1979)

"Highlights of the NRC Licensing Process and the NRC R&D Program for Deep Geological Storage Facilities", R.J. Budnitz, IEEE Transactions on Nuclear Science, NS-27(4), 1268 (1980)

Three Mile Island: A Report to the NRC and to the Public, U.S. Nuclear Regulatory Commission Special Inquiry Group, in four volumes: Mitchell Rogovin, Director (R.J. Budnitz, Technical Coordinator), U.S. Nuclear Regulatory Commission (1980)

"How Reactor Safety is Assured in the United States", article in Energy for the Year 2000, Richard Wilson (editor), Plenum Press, New York (1981)

"The Role of Risk Assessment in Reactor Safety", article in Energy for the Year 2000, Richard Wilson (editor), Plenum Press, New York (1981)

"The Response of the Nuclear Regulatory Commission to the Accident at Three Mile Island", article in The Three Mile Island Accident: Lessons and Implications, T.H. Moss and D.L. Sills (editors), Annals of the New York Academy of Sciences, Vol. 365 (1981)

"Review and Critique of Previous Probabilistic Accident Assessments for the Shoreham Nuclear Power Station", R.J. Budnitz, P.R. Davis, S. Fabic, and H.E. Lambert, Future Resources Associates, Inc., Report prepared for Suffolk County (New York) Radiological Emergency Response Plan Steering Committee (1982)

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RESUME

Occupation: Management Consultant in energy analysis, policy development, planning and project development.

Born: November 18, 1952 in Rochester, New York.

Family: Married in 1977 to Ruth Morris. Three children.

EDUCATION AND PROFESSIONAL EMPLOYMENT

B.A., Natural Science, University of Pennsylvania, 1974.
M.Sc., Biochemistry, University of Toronto, Canada, 1977.
Ph.D., Energy and Resources, University of California, Berkeley, 1982.

1982-Present: Management Consultant; Principal with Future Resources Associates, Inc., Director of the Green Power Institute, and member of the affiliated faculty, University of California, Berkeley, Energy and Resources Group.

Research and Analysis, Public Policy Development

Regulatory Analysis and Participation

Writer and Editor for: *Renewables Working Group Report to the California Public Utilities Commission*, 1996, expert on policies for renewable generating sources and environmental protection within the context of the restructuring of the electric utility industry. Consulting to electric utility companies and the renewable energy industries in policy analysis and preparation of testimony in a variety of regulatory and legislative forums. Write column for the monthly newsletter of the National BioEnergy Industries Association.

Public Interest Research on Behalf of Renewables

Founder and director of the Green Power Institute, a program of the Pacific Institute for Studies in Development, Environment, and Security. The Green Power Institute is a non-profit organization devoted to monitoring and analyzing the development and evolution of renewable energy generation within the context of deregulated electricity markets in the U.S. and abroad.

Environmental and Risk Analysis

Participant in a variety of studies of the environmental and economic impacts of energy systems and their components. Expertise includes conventionally regulated pollutants, and unregulated emissions like greenhouse gases. Authored ground-braking report on the climate change implications of

renewable energy systems. Expert in probabilistic risk assessment methods for safety analysis, and managerial decision making.

1159 Glendora Ave. **(510) 644-2700**
Oakland, CA 94602 **(510) 530-6570**

University Level Instruction

Visiting Lecturer at the Energy and Resources Group, University of California, Berkeley, 1995. Taught course on renewable energy engineering, including considerations of technology development, commercialization, and project development. As member of the affiliated faculty, have advised a variety of graduate students on projects and theses.

Commercial Energy Project Development

Energy Project Development, Financing, Due Diligence Analysis

Consultant to developers and investors in independent power and cogeneration projects, providing expertise in the areas of project concept and design optimization, project financial analysis and procurement of funding, contract negotiations, regulatory affairs, and project implementation. Experience with projects in the size range of 5 - 150 MW using the following technologies: biomass, fluidized bed combustion, gas turbines including combined cycles and STIGs, wind, PV, and solar-thermal electric. Experience with off-grid rural electrification projects in the size range of 20 - 500 kW using PV home systems, and renewable community energy systems (biomass, PV and wind / diesel hybrids). Develop sophisticated computer models for the financial analysis and planning of energy-development projects.

Biomass Energy Development

Specialty in the analysis and development of biomass as an energy resource, including conducting biomass fuel-supply surveys for biomass-fired power facilities in all areas of the U.S. and internationally; biomass fuel-supply contract negotiations and fuel procurement planning; assistance in procuring funding for biomass projects; and other project-development activities. Analysis of biomass industry issues and preparation of testimony for regulatory and legislative initiatives.

Energy Planning for Developing Countries

Planning studies and policy analysis of energy development opportunities in a variety of developing countries. Led fuel studies and provided development support for biomass power generation projects in Honduras, Costa Rica, Indonesia, Belarus, Ukraine, and Malawi. Experience with energy projects in Brazil, Colombia, Peru, Micronesia, Pakistan, India, and the Czech Republic.

Research and Development, Technology Transfer

Development and application of an analytical framework for the integrated analysis of commercialization prospects for a variety of new energy technologies. Commercialization studies performed for the following technologies: biomass fuel plantations, biomass gasification, alcohol production from biomass resources, solar and wind energy systems, aerogel superinsulating materials, and electric vehicles.

AFFILIATIONS AND AWARDS

Member, American Chemical Society (1975-)
Member, American Association for the Advancement of Science (1977-)
Member, National BioEnergy Industries Association (1993-)
Graduate Cum Laude with Distinction in Natural Science (1974)