Atomic Energy of Canada Limited

THE INTENSE NEUTRON GENERATOR

DL-72

by

W. B. Lewis

Presentation to the University Deans of
Engineering and Applied Science,
Ottawa, October 25, 1966

Chalk River, Ontario
October 1966

AECL-2818

AECL-2818

Le générateur de flux intenses de neutrons

par W. B. Lewis

Mémoire présenté à la réunion des Doyens des Facultés de Génie et de Science appliquée tenue à Ottawa le 25 octobre 1966.

Résumé - Ce mémoire passe en revue les avantages pouvant résulter, dans les contextes scientifiques et économiques, de la production, en quantités grammes, de flux intenses de neutrons par des moyens électriques et sans uranium 235. La production de radioéléments, par ce moyen, promet d'être rentable. Le Générateur de flux intenses de neutrons, dont la puissance sera de 65 mégawatts et qui servira à de multiples fins, fera appel à une grande variété de techniques comme le transport de la chaleur par métal liquéfié, la courbure et la focalisation des faisceaux par aimants supraconducteurs, l'emploi de supraconducteurs pour obtenir des systèmes HF à grande puissance et à faible perte, la production d'une énergie HF au moyen de dispositifs efficaces, le recours à des nouveautés loin d'être éprouvées dans la pratique, en physique des plasmas, pour engendrer et pour accélérer des ions d'hydrogène à haute intensité, la production de courant continu par une machine à haute tension de plusieurs mégawatts qui pourrait avoir diverses applications. Les travaux effectués desservent surtout la science des matériaux par les interactions neutron-phonon et autres interactions quantiques ainsi que par les diffractions neutroniques qu'ils impliquent. La physique nucléaire est desservie par la production de mesons μ , π et K. La production des radioéléments intéresse de nombreux domaines en science appliquée.

Chalk River, Ontario
Octobre 1966

ATOMIC ENERGY OF CANADA LIMITED

THE INTENSE NEUTRON GENERATOR

by W.B. Lewis

Presentation to the University Deans of
Engineering and Applied Science,
Ottawa, October 25, 1966

DL-72

Chalk River, Ontario
October 1966

AECL-2818

DL-72

THE INTENSE NEUTRON GENERATOR

by

W.B. Lewis

Presentation to the University Deans of Engineering
and Applied Science,
Ottawa, October 25, 1966

ABSTRACT

The presentation discusses both the economic and research contexts that would be served by producing neutrons in gram quantities at high intensities by electrical means without uranium-235. The revenue from producing radioisotopes is attractive. The array of techniques introduced by the multipurpose 65 megawatt Intense Neutron Generator project includes liquid metal cooling, superconducting magnets for beam bending and focussing, superconductors for low-loss high-power radiofrequency systems, efficient devices for producing radiofrequency power, plasma physics developments for producing and accelerating hydrogen ions at high intensity that are still far out from established practice, a multimegawatt high voltage D.C. generating machine that could have several applications. The research fields served relate principally to materials science through neutron-phonon and other quantum interactions as well as through neutron diffraction. Nuclear physics is served through μ-, π- and K-meson production. Isotope production enters many fields of applied research.

Chalk River, Ontario
October 1966

AECL-2818

THE INTENSE NEUTRON GENERATOR

Presentation to the University Deans of
Engineering and Applied Science,
Ottawa, October 25, 1966

by W.B. Lewis

Some of you know AECL very well, many have visited Chalk River and one or two are already quite closely connected with the ING study. Others, however, are still strangers, although we have been mostly "unclassified" for more than 10 years and AECL is now involved in engineering projects totalling over $500M, a large fraction of which represents effort and innovation in Canadian Industry as you can see from the advertisements in "Canadian Nuclear Technology". Moreover, we are quite well known outside Canada, particularly for having selected and developed the heavy water moderated neutron economical power reactors that we believe should remain viable and competitive for longer than any other "proven type" of power reactor. To remain competitive in such a big league we need to keep on our toes and it seems time also to broaden our base slightly. I am not expecting to see competition develop soon from thermonuclear fusion but that field might take a turn such that we would wish to have a broader base. Looking to our future - Canada's future - in this way we found ourselves three years ago with an idea that seemed to open the way to a most attractive array of techniques. That is the multipurpose project we label ING. It reminds me of some 35 years ago when I was playing bridge, which I had played little then as now. I was playing for a team in a friendly match and was dealt something like 4 Kings, 3 Aces and most of the other cards in one suit. I knew it was a wonderful hand but also that something great was expected of me. ING reminds me of this; the more expert you are the greater the opportunity seems, but we in Canada are hesitating because some who don't know the game or the cards are wondering why the excitement. Obviously in the short time I have I cannot explain the whole game and all its fine points, but I will do my best. Just as an indication of its being appreciated by experts elsewhere let me say that in June 1965, at an international meeting in Rome, Oak Ridge National Laboratory of the USA switched their meson factory proposal to adopt our neutron generator. This year at international meetings at Dubna, USSR, and Santa Fe the

Canadian ING project has been recognized as the leading prospect for an intense source of neutrons for most of the purposes of such a source.

I must limit this introduction and general philosophy as there is so much to say about the study itself. It is, however, necessary that we establish its context. I would draw your attention to the four pages 157-160 in the 1964 First Annual Review of the Economic Council of Canada on research and development and quote the following:

> "Over the past decade there has been a noteworthy increase in R & D activity in Canadian industry.... the federal government has sought to stimulate further this rate of activity by means of special programmes....In addition, a number of provincial governments have established research councils and have instituted new measures....While these events have been taking place in Canada, there has been a striking increase in the emphasis placed on R & D by most of the advanced industrial nations of the world....Nearly all of the principal industrial countries have in recent years stepped up sharply their total investment of resources in R & D to annual rates of increase in the order of 10 to 15 per cent a year. Total annual expenditures on R & D are now running in the neighbourhood of 3 per cent of Gross National Product in the United States, between 1 and 3 per cent in several European countries and in Japan.... The Director General of the Organization for Economic Co-operation and Development has said: 'Indeed, if the OECD member countries are to achieve the collective growth target of 50 per cent in real Gross National Product during the decade 1961-1970...they will have to call upon every resource which science and technology can provide.' If Canada is to realize the high rate of growth needed for a very rapidly expanding labour force and is to achieve the betterment in productivity required for continued improvement in standards of living while remaining competitive in the world, we have all the more reason to call upon the resources of science and technology....Over the past several decades the fastest

growing secondary industries in all the main industrial countries have been the science-based industries. Also, the products of these science-based industries have been the fastest growing element in world trade. In order to achieve our economic objectives it will be necessary for Canada to participate adequately in these developments and to find a basis for effective and profitable specialization through her own efforts and skills.... The most urgent need for further rapid development pertains to the universities and to private industry. In...the universities the principal obstacle has been the woeful lack of resources which need to be increased substantially. In the case of private industry the main difficulties are likely to lie in the scarcity of professional and highly skilled manpower, and in the adequacy and operation of the available incentives."

In 1962 I wrote a review of the situation in which I pointed out that although science and technology provides the means for increased productivity, experience has shown that since the war progress in the United States, where it has been most notable, has stemmed not so much from their prior possession of the technology as from a succession of incentives, first the Russian bomb, then the Korean war and the H-bomb, then the tremendous spur from Sputnik that reached right down into education and is also credited with bringing about the age of the electronic computer. It seems that we also will need these incentives, in fact it could be said that the government needs only motives to put into effect the recommendations of the Economic Council. Over the years there is no shortage of money but we may be short of motive in directions to lead to economic well-being. I am not suggesting that the ING project would solve most of our problem but neither would it take up a large fraction of our effort. I hope to show those who are not already convinced that it does provide a motive and that it will lead to an economic return.

AECL has always taken the line that revenue from our activities is desirable and important. More than half the construction cost of the NRU reactor has been recovered from export revenue. It is today operating at 100 MW whereas 60 MW is all that is required to provide the research facilities. By running at the higher power we are able to produce more Co-60 and recover more than the cost of the extra power. I foresee a very similar situation in the operation of the ING. The reference design would promise 1.2 g of neutrons per day, most of them at very high intensity. The OECD has made a forecast of future prices of radioisotopes for 1975 and shows many of them at prices more than ten times those of Co-60 when evaluated in terms of neutron cost. As I mentioned at the Canadian Nuclear Association meeting last May, if ING only produced Co-60 the revenue might be three million dollars a year, perhaps just sufficient to pay the power bill. If we realized a price ten times this, it would be thirty million dollars a year which would more than repay the total operating cost. We live, however, in a competitive world and it is unlikely that others would sit by and let us produce all the isotopes commanding a high price. On the other hand, the high intensity of neutrons would give ING a special advantage in producing isotopes for which the inventory costs are high or capture of several neutrons in a given nucleus is required, and there seems to be no reason why we should not be first in that field.

Turning now to research, there is an important difference between research at a government establishment and that in universities, namely that we have to be efficient when assessed solely on the basis of research progress. Although Chalk River has supplied seventeen professors to the universities in Ontario and recently six to British Columbia, not including three to the military colleges, this output of some of our best scientists is not credited to our account in assessing efficiency. Soon after I came to Chalk River 20 years ago it was necessary to make some changes, two of which relate to what I have to tell. I went to the NRC chief of administration and said that for the budget I had the number of scientists was too large and the number of technicians too small. Although it was believed to be novel, the change was made. The second problem concerned electronics equipment. Its demands for maintenance were preventing forward progress so we reviewed what we had and declared some types of instrument as not worth maintenance and that was that. We went ahead to establish electronic equipment of higher performance and good reliability and have never looked back. I think we can claim to have become efficient and I would invite comparison with similar laboratories, say Oak Ridge or any other in the U.S. In all such <u>efficient</u> laboratories the optimum expenditure per professional has risen from about \$10,000 to \$50,000/year. Chalk River now has nearly 200 research scientists and a research budget of about $10M/year. In another 10 years I expect the optimum efficiency ratio to double the budget for the same number of scientists. Other efficient laboratories by their larger size and number will determine the ratio. If Canada is to be in the front rank we must follow suit or do even better, i.e. pay less to the scientist for a given research output. To quote a former member of our Board, AECL is not a charitable institution for mediocre scientists and engineers.

We do not pursue efficiency for the sake of the principle but to yield the highest economic return for our expenditure. We are putting the ING project forward in this context.

ING happens to concern principally materials research* but it involves radio and electrical engineering, plasma physics, meson production, nuclear physics and isotope production, as well as other aspects. The objective is not inbred nuclear science but to keep Canadian industry advanced in the so-called atomic age, which will still be there despite the space age when ING comes into production.

One last word on the money question. In round numbers I expect the construction cost to be $20M/year for 7 years, followed by a gross operating cost of $15M/year, offset by revenue

---

* There are some misunderstandings current concerning materials research because the science of materials is so complex. Any given solid may have to be considered from the point of view of its constituent atoms or molecular groups, its phonons and other characteristic vibrations, its crystalline texture, its crystal structure, its electronic and magnetic characteristics, the effects of minor constituents or impurities; and now radiation effects add another dimension. By the effects of radiations that displace atoms, forms are produced that cannot be made in any other way. Correspondingly, materials scientists range from theoretical physicists (for example, Professor Volkoff, a university member of the ING Study Advisory Committee), solid state physicists (e.g. Professor Brockhouse, also a member), metal physicists, physical metallurgists, ceramicists, extractive and chemical metallurgists, to engineering metallurgists, the modern successors of the blacksmith, silversmith and goldsmith. Some of these scientists follow such a narrow discipline that they communicate only with difficulty with others in the general field of materials science and their stature and contribution is sometimes overlooked.

of \$5M/year, making \$10M/year net, but if, as hoped, the project opens up new vistas and the country has more research scientists to apply, then of course the annual research and further development expenditure the project could support would be higher and might be \$20M/year in 9 or 10 years' time. Expanding at 12% per year leads in 9 years to a multiplication by 2.8 so any research effort today amounting to \$7M/year and expanding at that rate would amount to \$20M/year in 9 years. In any case the ING project would not in 9 years' time be equal to the present size of Chalk River, unless circumstances change and Canada wishes to make it larger.

For the immediate future, as soon as we get a little more money for the study we would hope to expand some of the contracts we now have with industry and with universities and to introduce some new ones. We know there are many people interested but we are facing a lean budget for 1967-8.

I hope you have been able to read the slender briefs I sent you last month, so that I may touch on the highlights without being unintelligible. Nuclear science suggests there are three types of reaction for producing neutrons in large amount: fission, fusion and spallation. The ING adopts spallation. A beam of 65 mA of 1000 MeV protons (i.e. 65 MW continuous) plunges into a flowing liquid metal target of lead-bismuth eutectic. The target is surrounded by heavy water to slow down the neutrons and make them available at thermal energies and high intensity to a number of beams for experimental uses. Most of the neutrons are eventually captured to make radioisotopes for sale.

Beams of intense neutrons from the NRU reactor have put us in a strong position at Chalk River. Recently we have lost this supremacy of equipment to Brookhaven where there is an HFBR (High Flux Beam Reactor) with four or five times the intensity. ING would take us a factor of 10 or more above the HFBR. The intense neutron beams from NRU still attract the top scientists, for example in Physical Review Letters for October 3 two scientists from the University of Edinburgh (Scotland) and two of our own staff who all worked this summer with neutron beams from NRU announce the discovery of important semiconducting ferroelectrics. These binary crystalline compounds of tin telluride, Sn-Te, and germanium telluride, Ge-Te, showed a strange transition at low temperature, found on the basis of previous work to lead to semiconducting ferroelectrics. We can now predict that at liquid helium temperatures Ge-Te, if sufficiently pure, would be a piezo-electric transducer with a signal to noise ratio some orders of magnitude higher than customary materials such as barium titanate. Exploitation of this is more likely to leap ahead in the U.S. than in Canada because they have a broader base of technology. In other words, this latest advance is a bit too rich for Canada. The reason why those who work in this field of lattice vibrations would like an ING is to refine their techniques where they are working with small effects.

Another example is to note (see AECL-2600) that many transitions in the solid state are dependent on many parameters. To plot the relations between frequency and wavelength for all characteristic directions and related to temperature and magnetic field might take years for one transition using the NRU reactor, whereas the ING with 50 times the intensity might enable the job to be done in a month or less.

Certainly those who work in this field of the inelastic scattering of neutrons have no doubts how they would benefit from neutrons at higher intensity.

New techniques are also possible. Very cold neutrons, i.e. slow neutrons have such a long wavelength that they can be guided by total internal reflection along a curved pipe through thick shielding to a place where the neutron background intensity is very low. By interacting with a moving target the effective wavelength could be adjusted to study by diffraction delicate and complex structures such as protein molecules and even genetic chromosomes, with hydrogen atoms replaced by deuterium to simplify the scattering pattern. Such is the type of extension from present techniques that bigger and better neutron beams would make possible. Such neutron diffraction techniques already complement X-ray techniques. Dalhousie University now uses the NRU reactor for such studies on relatively simple molecules and crystals.

In our study for the ING we have done experiments with the Cosmotron (closing down in December) at Brookhaven and with the proton synchrotron at Birmingham, England to determine the yield of neutrons, and we have done experiments in the ZEEP tank at Chalk River on the assembly of beam tubes in heavy water to determine the neutron flux. The results confirmed our earlier estimates but we now feel sure.

There is much less certainty that we have reached the optimum design of accelerator but the linear accelerator or LINAC, based on the Los Alamos LINAC, that is now our reference design promises to be adequate. Any improvement would be an added benefit.

At the outset of our study we rejected the LINAC because the radiofrequency copper losses would have been higher than the total beam power. The Los Alamos design of the last two years represents a major advance that effectively cuts the losses in half. Moreover, by making a longer accelerator, 4,000 ft., the losses are still further reduced, and although the losses are still higher than for the Separated Orbit Cyclotron design that was our first reference, the LINAC offers very great advantages in development and maintenance. The LINAC is composed of sections that have almost identical functional specifications and if a major advance such as the development of a superconducting section comes about it would be possible to replace individual sections. The superconducting LINAC may not be so far away. There is a project on it already at Stanford. The LINAC also has the advantage of a straight-line path that should make alignment easier than on the curved path in the SOC. A considerable saving in cost arises from eliminating the large magnets of high precision. The LINAC still needs many quadrupole focussing magnets and some beam bending magnets offering scope for the development of these in superconducting form. The advance introduced by Los Alamos may be characterized as supplying the radiofrequency in parallel to a series of pill-boxes instead of transmitting the radiofrequency power along with the beam up axial channels. It is possible that this parallel construction can be taken further and the optimum radiofrequency may change if low loss materials such as magnetic ferrites or titania dielectric are introduced. To supply RF power to the LINAC the most efficient RF generator in prospect appears to be the Amplitron. This is similar to a cavity magnetron designed for an amplifying role. It uses a platinum secondary emitting cathode that promises an extremely long life. Empirical design of the internals is required to achieve maximum efficiency and it is hoped that this will raise the efficiency from about 75% to 90% or more, even at 800 MHz. In our study we have been trying to interest Canadian industry in the development of all major components. We have adopted the policy that the only development we will pay for must be done in Canada or by Canadians on temporary attachment elsewhere. So far we have not succeeded in the case of the Amplitron but the manufacturers, Raytheon, indicate that they would be willing to receive Canadians into their development team. Later they might equip a subsidiary in Canada for the production of the tubes required by the ING. The Los Alamos group has switched over to the Amplitron as its preferred RF drive this year and we may claim that our study played some part in this change. We enjoy close cooperation with both the Oak Ridge and Los Alamos groups. The Los Alamos project involves a pulsed beam, the peak amplitude of which is equivalent to that we propose, but the duty cycle will be only a few percent.

The reference design for our ion source and beam injector or pre-accelerator also follow the same pattern as adopted by Los Alamos. Personally I am hopeful that a much improved design will result from our further work. The present design begins with a 750 kV Cockcroft-Walton D.C. generator carrying the ion source in air at high potential. Some recent developments at Yale University that we have followed up at Chalk River suggest it may be practicable to produce the required current in negative hydrogen ions, in which case the ion source would be close to ground potential and would feed into a D.C. tandem accelerator with 10 or 20 MV on the terminal. At the terminal the electrons would be stripped off and the ions would proceed as protons, receiving a further acceleration. If it is possible to use the higher voltage the injection might then proceed directly into the pill-box type LINAC. If not, a LINAC section of the Alvarez type operating at a sub-multiple of the LINAC frequency would be interposed as in the Los Alamos design.

There is, however, quite a far-out project that may make these ideas of the pre-accelerator and possibly even the LINAC as well come to seem out of date. A very considerable advance has been made in producing beams of electrons of 2-1/2 MV, 17,000 amperes in 20 nanosecond pulses. These beams have been self-focussing to current densities of 5000 A/cm^2. In plasma physics there is a well-known phenomenon of ion drag associated with any <u>bunch</u> of electrons or plasma. Protons are attracted to the centre of an electron bunch and taken along with it. The whole accelerator might be reduced to an accelerator for 100 A of electrons to 2 MV accompanied by 100 mA of protons. Protons would have the required 1000 MeV energy when travelling at the same velocity as electrons of only 600 keV. In order to keep the electron bunches together, however, they would be spiralling around the path taken by the bunch and therefore have individually higher energies. It is in principle possible to separate the protons and electrons and recover much of the residual energy from the electrons to feed back into the radiofrequency bunching system. These ideas are certainly far out from established practice but preliminary estimates suggest that such developments of proton accelerators could perhaps reduce the cost of devices like ING or make higher power accelerators possible. Alternatively, if these far-out ideas do not prosper it is still possible they may indicate means of obtaining much finer beams for acceleration in conventional LINAC's.

I have not yet explained why one might be interested in higher power proton accelerators or cheaper accelerators comparable to ING. Basically the reason is the production of neutrons at acceptable cost. The scheme has the advantage of being independent of the existence of the fissile U-235 isotope and would enable the production of plutonium or U-233 to proceed from the more abundant U-238 and Th-232. In this connection Alvin Weinberg has called the Canadian ING proposal an "electrical breeder". The idea is not new. It was developed in secrecy in several places as soon as the spallation reaction was discovered. We did work on it in Canada in 1952. The project has, however, been shelved because the cost was not competitive with neutrons from the abundant supplies of uranium available. It does, however, have special reasons for consideration even if the neutrons are more expensive than those from natural uranium, but there I am getting too far into the future and I should come back to the 20 MV D.C. accelerator that I mentioned for the pre-injector. No such device yet exists but it is not far beyond one design target being aimed at by High Voltage Engineering Corporation. The tandem accelerator at Chalk River made by that Corporation reached 15 MV on the terminal during its commissioning tests and extrapolation to 20 MV appears straightforward. On the other hand, the current is measured in microamperes, being limited by the belt type generator. Means are being studied for generating higher power by a long insulated shaft driving a series of generators. We are in the process of negotiating a contract with the University of Toronto Electrical Engineering Department to cooperate with HVEC in the development of such machines.

This leads me to point out that the very rapid expansion of universities throughout the world is providing a considerable market for advanced machines of such a type. Toronto itself would like one. Moreover, in the whole field of electric power generation which is expanding so rapidly it is possible to introduce a new type of generator in some location where it could be economic and from there to expand by improvement to more general use. It is possible that the type of generator just mentioned might be adapted to generate hundreds of megawatts at 1 MV D.C. to save transmission costs. On the other hand, for research applications there is still an unexplored region where putting two uranium nuclei together might result in nuclei with special properties. This is an objective for the HVEC development.

I should now discuss the production of mesons by the ING. These may be taken from relatively thin targets that the protons pass through before plunging into the neutron target. π-mesons and K-mesons are useful tools as yet relatively unexploited for the study of nuclei and nuclear matter. The K-mesons require rather higher energy for abundant production and that makes us keep open the question of extending the accelerator to higher energies.

I should mention that all these nuclear reactions are not produced without leading to extremely high levels of radiation and radioactivation of all materials exposed to the high energy particles. In some ways the problems of shielding and access posed appear even greater than for operating a high power reactor such as NRU. However, the experience at Chalk River and in other establishments that have operated such high power reactors leads us to believe that although difficult, the problems will be surmountable. It is, nevertheless, generally considered that the ING would have to be sited in an isolated area of no less than 3000 acres to avoid complex problems of radiation shielding to protect the public during special operations. Technically there appears to be no problem of locating ING within the existing Chalk River exclusion area. It would also be cheaper there. The only arguments against this location concern organization, cultural facilities and communications. It is proposed that the organization for ING should be based on the experience of university cooperation at laboratories such as Brookhaven, the Rutherford High Energy Laboratory, CERN and others, none of which are very close to a university campus. Concerning cultural facilities and communications, we might look forward to considerable improvement at Deep River if in fact the ING is established at Chalk River. In conclusion I would like to quote again from J.B. Adams on the CERN project that you will find in one of my briefs.

> "It is from the universities that well trained research physicists come to use the facilities of CERN and it is back to universities or to national laboratories that they should go after working in the CERN laboratory. At the very beginning of the CERN idea, there were those people in university laboratories who saw CERN as a threat to their own existence. CERN they

> thought would become the darling of the governments of Europe, something to lavish funds upon; in short, the affluent international laboratory, and as CERN absorbed the moneys of Europe the laboratories of the Member States would wither away from neglect. In fact just the opposite happened; CERN acted like a catalyst to release more resources for the national laboratories, not so much for those in universities, but for new regional laboratories set up in the different countries and used by the local universities."

Then he illustrates by the Rutherford High Energy Laboratory I mentioned. I believe such institutes are an essential feature to keep science in Canada, both in and outside the universities, competitive in appeal for the best scientists. ING stands up well on this point.

Additional copies of this document
may be obtained from
Scientific Document Distribution Office
Atomic Energy of Canada Limited
Chalk River, Ontario, Canada

Price - 50¢ per copy

4083-66