Studsvik Report

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# THE ACCELERATOR BREEDER

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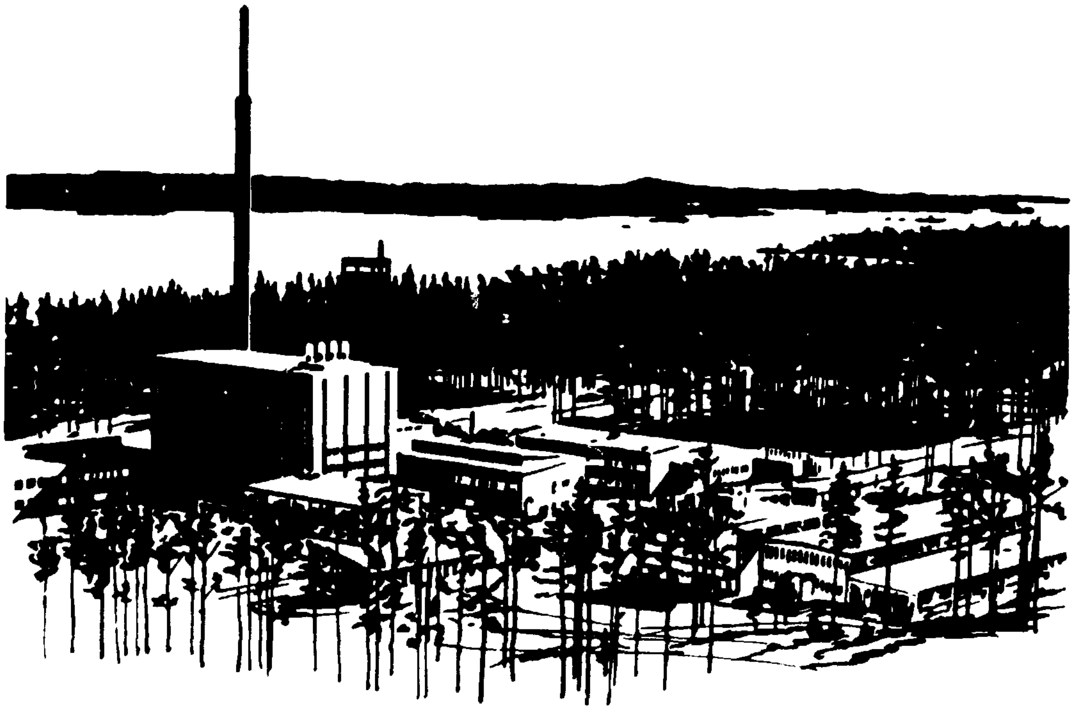

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# THE ACCELERATOR BREEDER

## ABSTRACT

Interactions of high-energy particles with atomic nuclei, in particular heavy ones, leads to a strong emission of neutrons. Preferably these high-energy particles are protons or deuterons obtained from a linear accelerator. The neutrons emitted are utilized in the conversion of U238 to Pu239 or of Th232 to U233. The above is the basis of the accelerator breeder, a concept studied abroad in many variants. No such breeder has, however, so far been built, but there exists vast practical experience on the neutron production and on the linear accelerator. Some of the variants mentioned are described in the report, after a presentation of general characteristics for the particle-nucleus interaction and for the linear accelerator.

## HUVUDINNEHÅLL

Växelverkan av högenergetiska partiklar med atomkärnor, särskilt tunga sådana, leder till en kraftig emission av neutroner. Dessa högenergetiska partiklar är företrädesvis protoner eller deutroner erhållna från en linjär accelerator. De emitterade neutronerna utnyttjas för konversion av U238 till Pu239 eller av Th232 till U233. Det ovanstående utgör grunden för acceleratorbridern, en anordning som utomlands studerats i många varianter. Ingen sådan brider har emellertid ännu blivit byggd, men en omfattande praktisk erfarenhet finns både för neutronemissionen och för den linjära acceleratorn.
Några av de nämnda varianterna beskrivs i rapporten, efter en presentation av allmänna karakteristika för partikel-kärnväxelverkan och för den linjära acceleratorn.

Approved by

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# 1 INTRODUCTION

Efficient utilization of Earth's uranium and thorium resources in energy production requires a conversion of the fertile nuclides U238 and Th232 into the fissile ones, Pu239 and U233, respectively. So far, nuclear reactors are, directly or indirectly, mainly based on U235, occurring in 0.7 % in natural uranium. Some of the neutrons emitted on the fission of this nuclide lead to the formation of Pu239 or U233 (though the latter alternative has not been very much applied yet). Fissions of these nuclides in turn give new neutrons with further production of fissile material, and so on. With a wise fuel strategy, i.e. with a global system containing breeder reactors, one can burn about 70 percent of the uranium and thorium mined.

The production of neutrons needed for conversion can, at least in principle, be done with two alternative methods, none of which depends on U235. One of these methods is based on fusion reactors, the other on particle accelerators. In both cases the neutrons released act upon a subcritical fission reactor. The systems thus created are called fusion-fission hybrid and accelerator breeder, respectively.

The accelerator breeder, which is the topic of this report, is based on the strong production of neutrons from targets bombarded with high-energy particles from an accelerator. A description is first given of this particle-nucleus interaction, usually called the spallation reaction. The linear accelerator (the linac), very likely the best choice, is then described.

Finally some suggested systems are presented. The report is mainly based on papers and books from abroad, in particular from the United States and Canada. So far we have not carried out any technical studies of our own at Studsvik on this breeder type.

## 2 THE SPALLATION EVAPORATION REACTION

### 2.1 Discovery and General Principles

The strong emission of neutrons from targets bombarded with particles of high energy, i.e. hundreds of MeV, was demonstrated in the late forties. Two very early experiments on the subject are those of Goeckerman and Perlman (1) and of O'Connor and Seaborg (2), both from University of California, Berkeley. The first paper even gives a quantitative result,stating that about 12 neutrons are boiled off from the compound nucleus - for each 200-MeV deuteron hitting the bismuth target. The second paper dealing with 380-MeV alfa-particles and a uranium target, on the other hand, does not state anything definite concerning the emission of boil-off neutrons.

Before proceeding to more recent measurements on neutron emission - with special emphasis on protons and heavy-atom targets - let us first briefly discuss the elements of charged high-energy particle interaction with matter.

Protons and other heavy charged particles mainly interact with matter through two processes. The first one consists of the ordinary ionization of the atoms, meaning for the present purpose an unwanted energy loss of the particle. The second process is a nuclear interaction, for high particle energy leading to neutron emission. For protons and deuterons of energy around 100 MeV, the energy loss through ionization dominates. Towards higher energies there is a gradual change, and around 1000 MeV the energy loss though collisions in the nuclei is instead the dominating process.

The nuclear interaction of the high-energy particle consists of a so-called spallation cascade followed by other nuclear phenomena. The whole process is sometimes called a spallation-evaporation reaction. "Spall" as a noun means according to the Webster Dictionary "a small fragment or chip". Information on such processes can be found in several reports, e.g. in Rudstam (3). Vasil'kov et al (4), and Grand et al (5).

The high-energy particle collides with an individual nucleon in a target starting the cascade. This is a very complex chain of events involving the emission of various particles, among them neutrons. Some of these emitted particles may trigger intranuclear cascades in other nuclei. If the incident energy is large enough mesons will also appear in the process. The cascade comes gradually to an end leaving the residual nucleus in a strongly excited compound state, i.e. a state with the excitation energy distributed among the nucleons. The nucleus gets rid of this energy by emitting neutrons and other particles and also gamma rays in the so-called evaporation process, possibly intermingled with fission (note in this context the term boil-off cited above from Ref 1 and the term Fission in the title of Ref 2). Neutrons can thus be emitted both in the spallation cascade and in the evaporation phase. In heavy nuclides, like U238, there is an important increase of the neutron intensity due to fissions by high-energy nucleons, by evaporation neutrons, and by fission neutrons. Some increase of the intensity will also occur because of (n,xn) reactions.

## 2.2 Neutron Emission Values for Various Targets

Several measurements have been made of the neutron emission in spallation-evaporation reactions. Figure 1 thus shows results obtained at the Brookhaven Cosmotron by a Chalk River/Oak Ridge team in 1965.

As the number of neutrons emitted is crucial for the accelerator breeder let us look at this parameter a little more. The measurements primarily give the number of neutrons captured in a big $H_2O$ tank surrounding the target. In older presentations, maybe for the one in Figure 1, one usually added the number of thermal neutrons captured in the target to get the total number of neutrons emitted. This capture, important for instance in uranium, is hard to estimate. Figure 2 gives results for the capture in the $H_2O$ alone from the experiments at the Brookhaven Cosmotron for the U case (compare Figure 1). Note that the ordinate is given as "Thermal neutron capture in the $H_2O$" which is, however, probably close to "Total neutron capture in the $H_2O$".

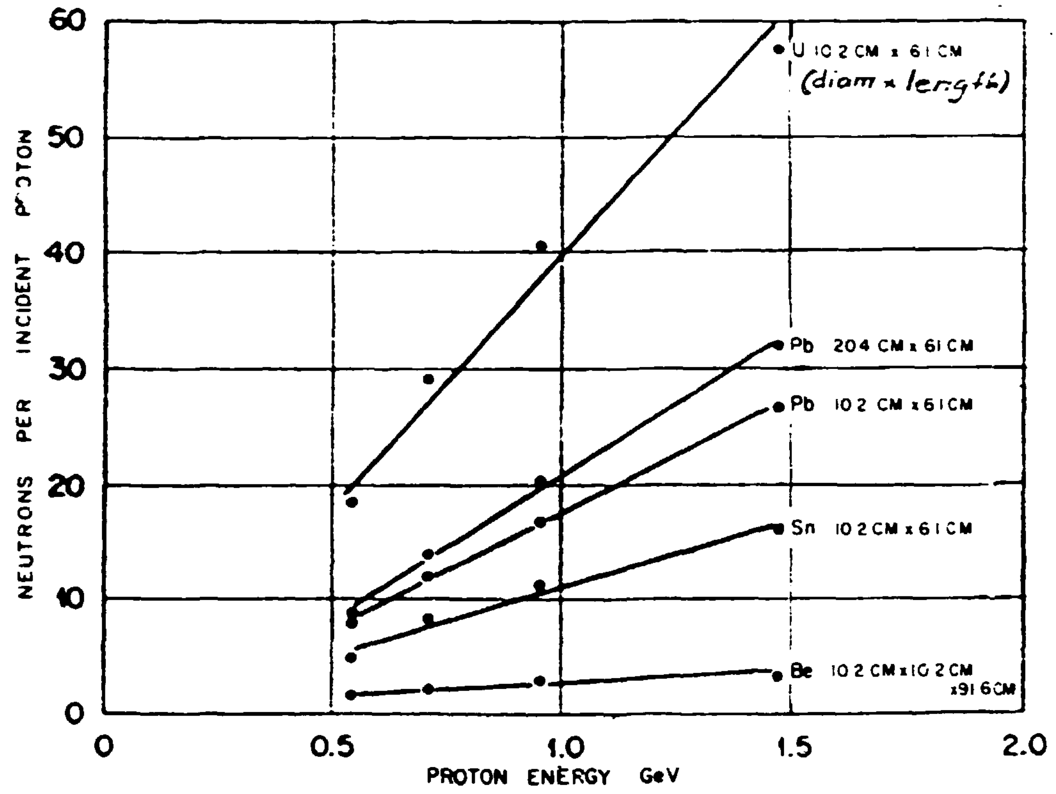

Fig 1 Neutron emission from various targets measured by a CR/ORNL group in 1965. The U target contained 0.22 w% U235 (Figure from Ref 6)

Whatever the reason, the results in Figure 2 are about 25 percent below the corresponding results in Figure 1. Figure 2 also indicates that the neutron emission can be calculated with a reasonably good accuracy. Monte Carlo methods were used. The parameter $B_0$ is associated with the level density.

Some further results on the neutron emission from a target bombarded with high-energy protons are given in Table 1.

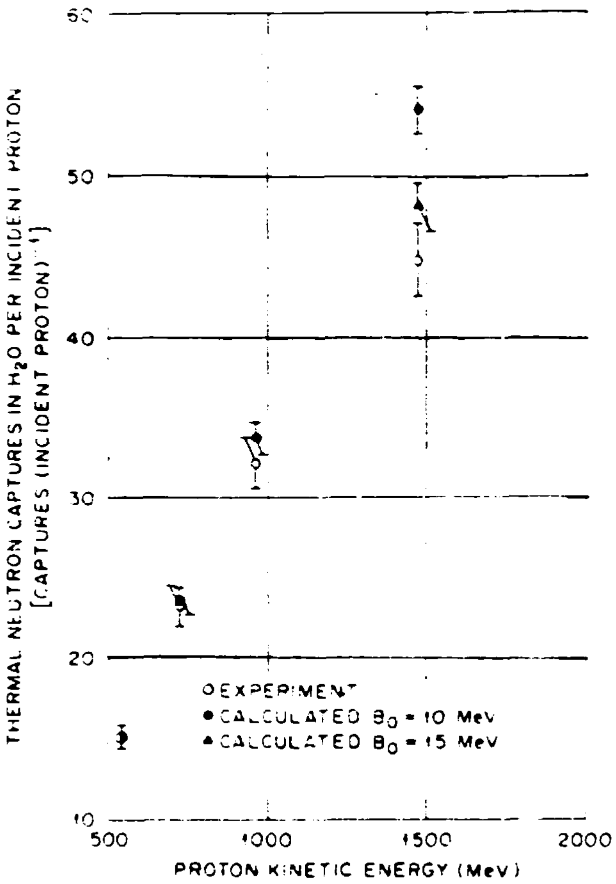

Fig 2 Neutron capture in $H_2O$ for the uranium target in Figure 1 (Figure from Ref 7)

Table 1

Measured number of neutron capture events in $H_2O$ per incident proton

| | Target | | | Proton | Number | |
|---|---|---|---|---|---|---|
| Material | U235 w% | Diam cm | Length cm | energy MeV | of capture events | Ref |
| U | 0.26 | 3.3 | 30.48 | 480 | 9.6±0.7 | Fraser et al (8)[a] |
| | | 8.6 | | | 14.1±0.9 | |
| | | 19.8 | | | 17.1±1.0 | |
| Th | - | 4.2 | | | 8.1±0.6 | |
| | | 18.3 | | | 9.6±0.7 | |
| Pb | | 10.2 | | | 8.3±0.5 | |
| U | 0.20 | 10.0 | 40.65 | 800 | 25.3 | Russel et al (9)[b] |
| | 0.25 | 20.1 | | | 28.8 | |
| Th | - | 18.3 | | | 17.1 | |
| Pb | | 9.9 | | | 13.0 | |
| Pb | - | 15 | 55 | 660 | 12.8±1.3 | Vasil'kov et al (4)[c] |

a) Measurement at the TRIUMF cyclotron, Vancouver

b) Preliminary results from LAMPF, the Clinton P Anderson Meson Physics Facility, Los Alamos

c) Measurement at the synchrocyclotron, Dubna.

On comparing various results in Table 1, Figure 1, and Figure 2 one need not worry about the target length as long as it is that long. If we look upon the (useless) ionization processes only, a proton of energy E(MeV), gradually losing energy, would be stopped in a material of density $\rho\,(g/cm^3)$ after a travel of $L=0.46 \cdot E/\rho$ (cm) - as given in Ref 10. For the materials of main interest in the rest of this paper, i.e. U, Th, and Pb, the length of the target in the experiments is larger than L throughout. It can be noted, however, that L is quite long in some of the cases, i.e. 61 cm for lead at 1.5 GeV proton energy. It should be noted also that the proton beam is attenuated by the nuclear processes - that lead to the neutron production. The neutron emission as a function of distance from the entrance surface will decrease because of that attenuation as well as because of the proton energy degradation. Using a non-uniform density in the target one can stretch out the axial neutron production distribution. Many possibilities are of course open in that context.

As shown both in Figure 1 and in Table 1 the neutron emission increases with the diameter of the target. It also seems that a diameter of about 20 cm could be large enough from the neutron production viewpoint - for U, Th and Pb. At 1000 MeV(=1 GeV) proton energy which is a reasonable choice we would then, on the basis of Figure 2 and Table 1, estimate the neutron capture values given in Table 2.

Table 2

Number of neutrons captured in $H_2O$ surrounding long cylindrical targets of 20 cm diameter bombarded with an axial 1-GeV proton beam. The uranium contains 0.25 w% U235

| Target | Neutron capture events per proton |
|---|---|
| U | 34 |
| Th | 22 |
| Pb | 19 |

The values in the table were obtained without any large uncertainties due to discrepancies between the various experiments. One can also observe that the value for lead is very close to the values in Figure 1 not used in the estimate.

The value, 34, for uranium is definitely lower than the value based on Figure 1, estimated to be about 45. Whether the difference depends on neutron capture in the uranium or on some other effect is not clear. The value, 22, for thorium is much lower than the value for uranium because of a smaller fission contribution in thorium. It should also be noted that the concept of a cylindrical uranium or thorium target in a way loses its meaning in accelerator breeder designs because the proton beam would preferably be swept across the whole subcritical reactor. For materials like lead, on the other hand, the heat removal is easier and a well-defined cylindrical target would be used. Examples on both variants will be given in Section 4.

An alterative to protons would be deuterons, whereas particles with larger Z values are unfavourable because of the ionization losses. Deuterons with the energy 1 Gev would give about 30 percent more neutrons than would protons of the same energy, see Ref 11. However, the use of deuterons lead to some special problems and protons are preferred in most cases.

Let us conclude this section with Figure 3 showing calculated and measured neutron spectra for a uranium target bombarded with 750-MeV protons. From the spallation cascade there might be neutrons up to the full proton energy. The largest neutron energy measured in this particular case is about 400 MeV. The evaporation neutrons have an average energy of the order of 4 MeV. The corresponding value for the fission neutrons is about 2 MeV.

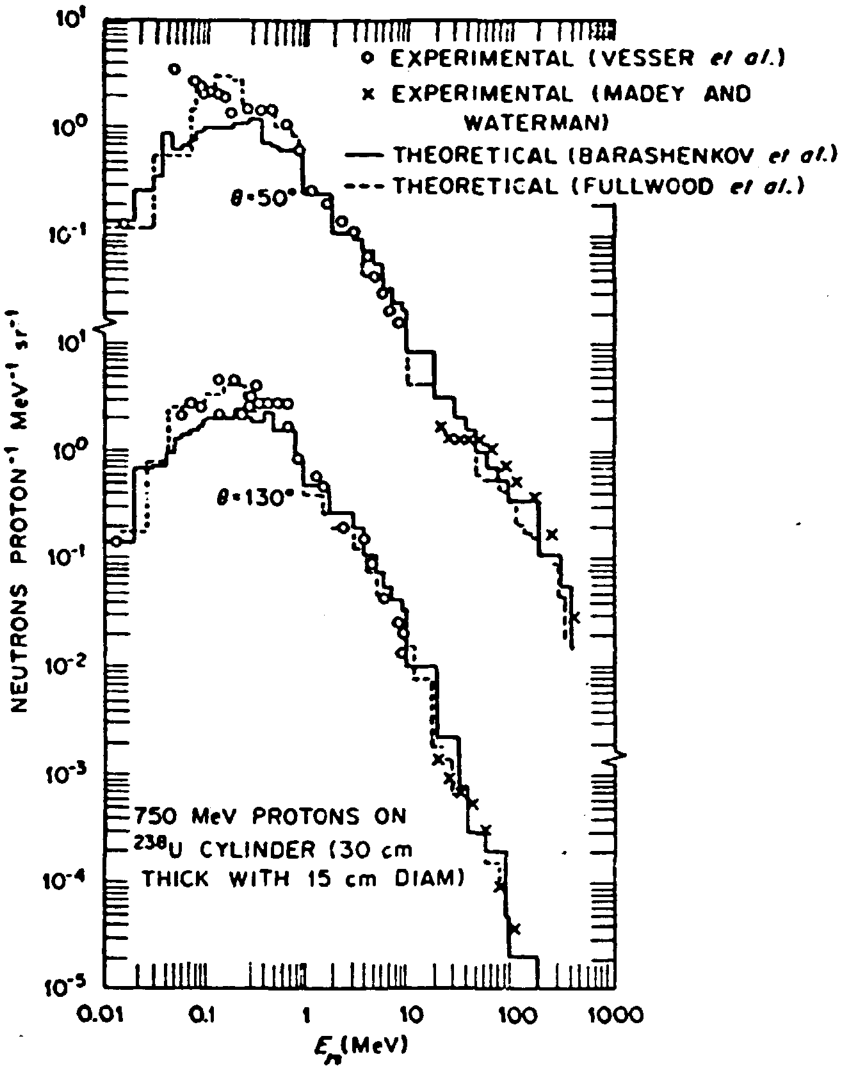

Fig 3 Neutron Spectra (Figure from Ref 12)

## 3 THE LINEAR ACCELERATOR

### 3.1 Introductory Remarks

The primary purpose of the accelerator breeder is the production of fissile material by neutron absorption in U238 or Th232. To get a quantitative grip on this procedure let us make a simplified estimate. We assume that S neutrons are produced per incident charged particle, that the particle current is I mA, that the breeder operates t hours per year, that the atomic weight of the created fissile atom is A, and that all S neutrons and no others are absorbed in the fertile material. The quantity Q kg of fissile material produced per year is then obtained as follows:

$$Q = \frac{I\cdot 10^{-3}\cdot t\cdot 3600\cdot S\cdot A}{\underbrace{1.602\cdot 10^{-19}}_{\text{unit charge(As)}}\cdot \underbrace{0.6023\cdot 10^{24}}_{\substack{\text{Avogadros number}\\ \text{(atoms per A grams)}}}\cdot 1000} = 3.73\cdot 10^{-8}\cdot I\cdot t\cdot S\cdot A$$

For a lead target bombarded by protons of energy 1 GeV, a reasonable value, we have S=19, as shown in Table 2. If the fertile material is U238, i.e. A=239, and if t=6570, i.e. 75 % load factor we get

$$Q = 3.73\cdot 10^{-8}\cdot 6570\cdot 19\cdot 239\cdot I = 1.11\cdot I \text{ kg}$$

What is then a meaningful Q value? To estimate that, we note that a normal-lattice 1000-MWe LWR at 75 % load factor in Pu fuel operation of equilibrium character will require about 360 kg of fissile Pu per year. That would correspond to a proton current of more than 300 mA according to the formula. Now, an accelerator breeder, to be at all economic, must be able to sustain more than one normal-lattice LWR. That would be possible even for a current limited to 300 mA. Thus, if the protons act upon uranium instead of lead, the neutron source would be about doubled. Furthermore, the subcritical lattice surrounding the lead target or constituting the uranium target will give so-called subcritical multiplication leading to a neutron source $S/(1-k_{eff})$

rather than just S. By and large a proton current of 300 mA seems to be high enough. It should be noted also that this current combined with a proton energy of 1 GeV means a beam power of 300 MW, i.e. like the electric power of first generation LWRs.

High-energy protons or deuterons can be produced either in a cyclic machine, like a synchrotron, or in a linear accelerator, commonly called a linac. Both these types can give particles with energies of the order of 1 GeV as we have just seen in the preceding section in connection with the neutron intensity measurements. With cyclic accelerators one can go far above this energy, the largest present machines giving energies of several hundreds of GeV. Linacs giving high-energy particles will be quite long. Thus the 0.8 GeV proton accelerator LAMPF mentioned in the preceding section is about 1 km in length.

In some cyclic accelerators, such as the synchrotron, one cannot produce particle currents as large as hundreds of milliamperes. On the other hand, the low current is counteracted by the large particle energy attainable, greatly increasing the neutron production in a target. A study (13) from Fermilab, Batavia, Illinois says that 1000-GeV protons, planned to become available at the synchrotron, would each produce 60 000 neutrons in a uranium block, The proton intensity would be $10^{12}$ per second and thus $6 \cdot 10^{16}$ neutrons would be produced per second

The corresponding value in our case would be

$$\frac{I\cdot 10^{-3}\cdot S}{1.602\cdot 10^{-19}} = 6.2\cdot 10^{15}\cdot I\cdot S \text{ neutrons per second.}$$

With I=300 and S=40 this expression gives $7.4\cdot 10^{19}$ n/s, i.e. about 1000 times the Fermilab result. Would fissile fuel production at such a big accelerator as the Fermi really be worthwhile with that low neutron production?

Profound studies on the use of a cyclic accelerator for neutron production were done in the Canadian ING (Intense Neutron Generator) project (14). In this project, terminated in 1968, one first favoured a special type of cyclotron, the SOC (Separated Orbit Cyclotron) machine, to produce a 1-GeV proton beam having an average current of 65 mA. Gradually, however, partly based on experience from LAMP at Los Alamos, the Canadians became more interested in the use of a linac. Nowadays, both in Canada and elsewhere, this accelerator type is the only one seriously discussed for intense neutron sources for research purposes or for accelerator breeders. A description of the linac, including its development, now follows.

## 3.2 Early Linear Accelerators

The development of linear acceleators began back in the twenties. There are from these early days especially three scientific articles often cited in monographs and other publications on this development. These articles are G Ising (15) from 1924, R Wideröe (16) from 1928 and Sloan and Lawrence (17) from 1931.

As indicated by the name, particles travel along a straight line in a linear accelerator. Any accelerator of that type is, however, not called a linear accelerator. It is also required that the acceleration be caused by a radiofrequency field, step by step increasing the particle energy. This possibility of acceleration was probably observed early, maybe even by Maxwell himself when developing his electromagnetic theory. The first generally known work on such acceleration was made by Gustaf Ising, a Swedish physicist. The principle is shown in Figure 4 copied from Ising's original article (15). A spark discharge at F

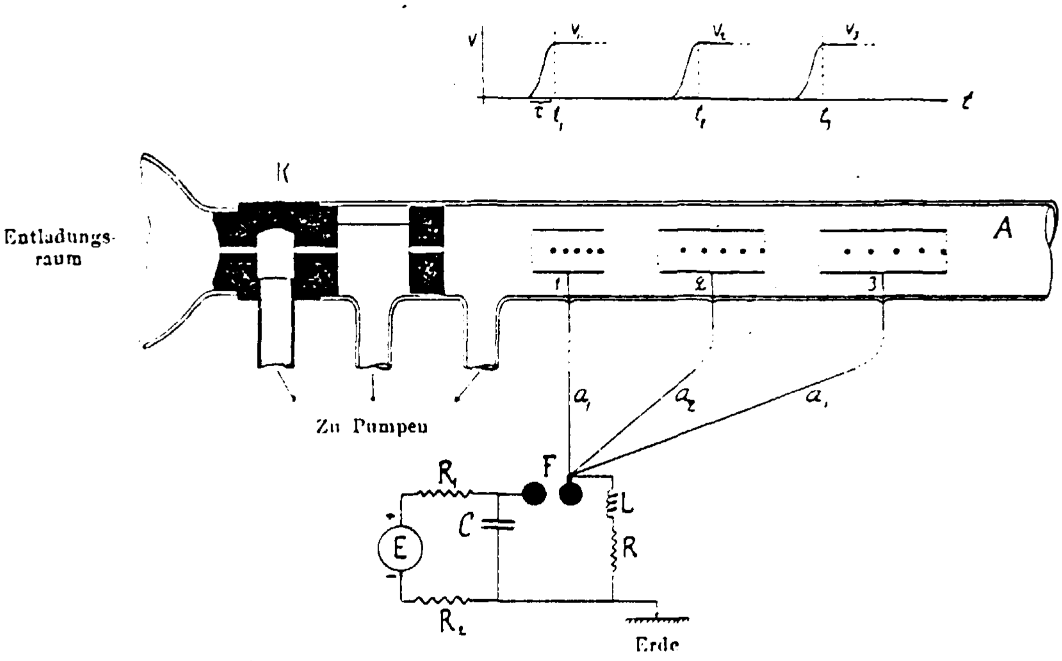

Fig 4 Ising's linear accelerator (15)

leads to electrical wavefronts in the delay lines $a_1$, $a_2$, and $a_3$. Some of the positive ions originating from the discharge tube at K will be accelerated in the gaps between drift tubes 1 and 2 and between 2 and 3. This can be arranged by a suitable choice of the delay lines and the length of tubes and gaps. No acceleration occurs within the drift tubes because of zero electric field. The potential on the drift tubes is zero (Erde) before the spark discharge - as can be seen in the Figure. Whether Ising made such an accelerator work is not clear. Whatever the case his suggestion demonstrates the basic principle of particles arriving at the right time for successive acceleration.

Rolf Wideröe, in his famous article (16), which was his thesis at the Technical University of Aachen, suggested the accelerator shown in Figure 5.

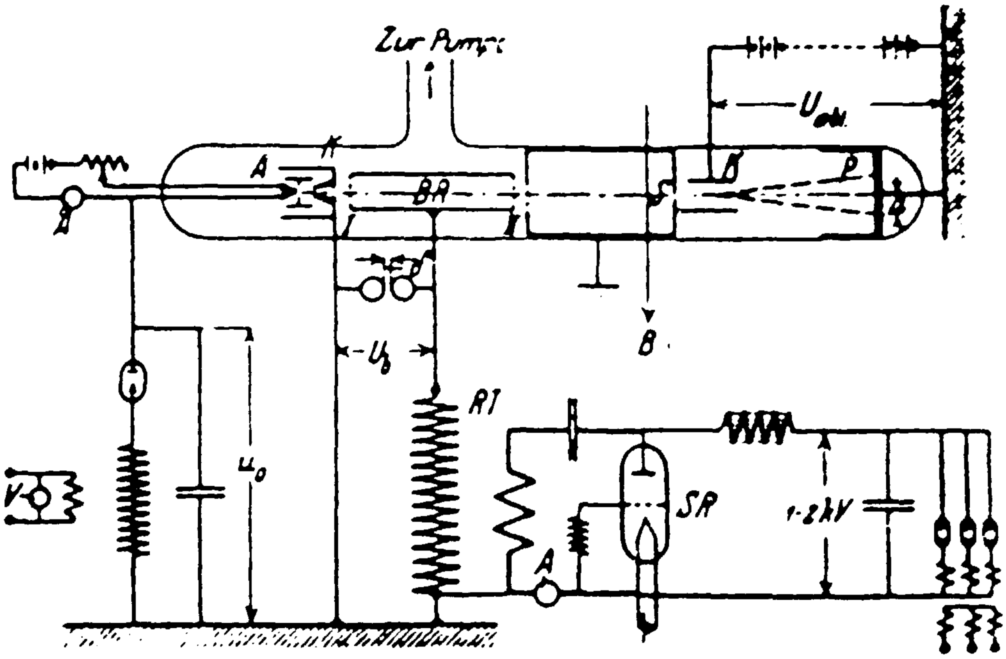

Fig 5 Wideröe's linear accelerator (16)

Wideröe's and Ising's accelerator concepts are basically similar and Wideröe was aware of Ising's work and refers to it in his article. However, Wideröe applies the acccelerating voltage in a different and more workable fashion, without reliance upon delay lines. In the design shown in Figure 5 the first and third drift tubes are grounded, whereas the second one is connected to a high-frequency source of about 1 MHz and 20 kV. Ions would aquire 20 keV in kinetic energy at the first gap and then travel at constant speed through the second tube. The parameters would be so arranged that the potential on this second tube would change sign during this transit time and the ions would acquire another 20 keV in the second gap. Wideröe's accelerator worked.

On reading a translation of Wideröe's paper, E O Lawrence got the basic idea for the cyclotron. The paper was also of fundamental importance when he together with D H Sloan built the linear accelerator shown in Figure 6.

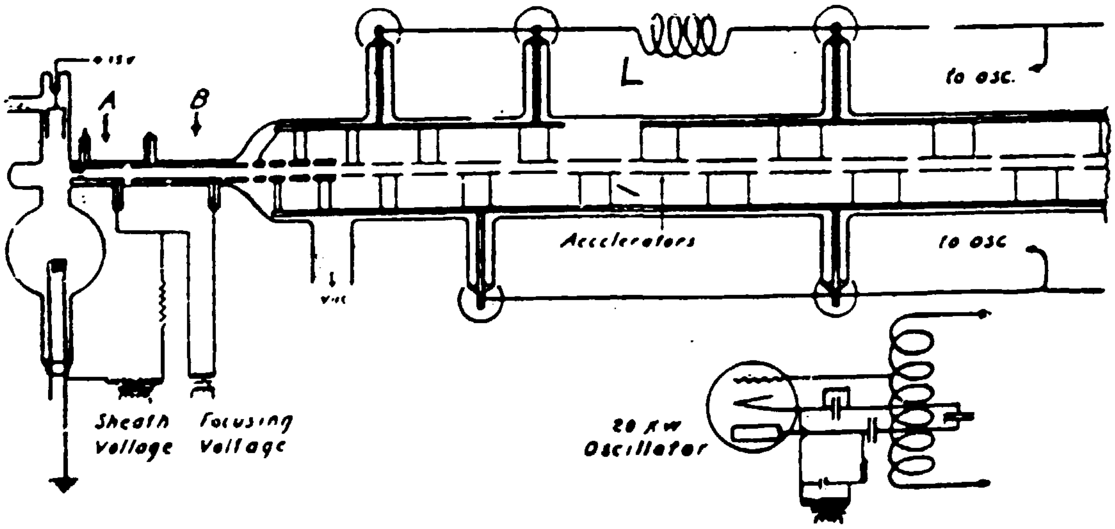

Fig 6 Sloan's and Lawrence's linear accelerator (17)

With this machine, having altogether 30 drift tubes, they managed to accelerate mercury ions to an energy of 1.26 MeV.

Most of these early attempts dealt with heavy ions. The acceleration of particles like protons, greatly important for instance in nuclear physics studies, would require a much higher frequency - or a much longer accelerator - for a given final energy. Great changes in this area took place with the extensive development of radiofrequency sources in the radar activities conducted during World War II.

## 3.3 High-Power Radiofrequency Sources

Most of the relatively early linacs for protons built after the war got their radiofrequency power from triodes. The development of such triodes and other radiofrequency sources as well, is a very important spin-off from the radar efforts during the war. The first proton linac, i.e. the 32-GeV machine built by Alvarez and his team (18) at Berkeley, even made direct use of existing surplus triodes.

Later on, other radiofrequency sources were developed. The most important one so far for linacs is the klystron. The principle for this radiofrequency source was devised as early as the thirties. The tube was used during the war, but only as a low-power source, e.g. for signal purposes. Later on it was developed into a high-power source of great importance for linear accelerators.

The first operating klystron was described in 1939 by Varian and Varian (19). The device is based on resonant cavities, i.e. resonant in the electromagnetic sense, studied by W W Hansen who worked for some time with the Varian brothers. The principle is illustrated in Figure 7, which shows an early-type klystron.

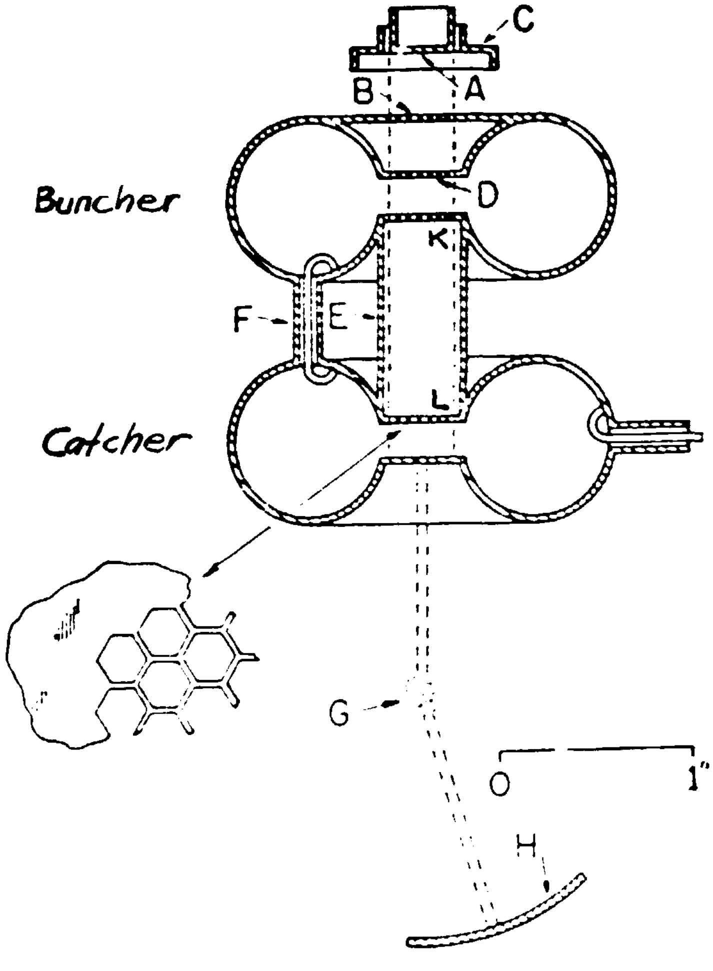

Fig 7 Main parts of an early klystron oscillator. Items G and H are used for indication (not essential). From the original article of Russel and Sigurd Varian (19)

These are two resonators, called the buncher and the catcher. Electrons are emitted at A and accelerated in an electrostatic field along AB. Then these electrons travel through a field-free space before entering the buncher at D. The buncher, coupled via a feed-back loop F to the catcher, has a weak radiofrequency field that slightly modulates the velocity of the electrons.

The following quotation from the article explains the bunching occurring in the field-free space between K and L:

"Beyond the third grid, K, the changes of speed have important effects. These are understood best by first considering an electron which passes the center of the high frequency field just as that field is changing from opposing to helping electrons. At the third grid, this electron has practically the same speed as at the second; but another electron which passed the center of the field a few electrical degrees earlier has had its speed reduced; and a third one, passing a few degrees later, is going faster. If there is plenty of field-free space beyond the third grid, these differences in speed cause the electrons ahead and behind the one of unchanged speed to draw nearer to it. Another electron of unchanged speed, a half-cycle earlier or later, has its neighbors draw away from it. Consequently at a suitable distance from the third grid the stream contains bunches of electrons denser than the stream at the third grid and separated by regions less dense."

The bunches then enter the catcher, which oscillates in the right phase to slow down the electrons, whose energy is picked up by the field in the catcher. The klystron thus converts DC power to radiofrequency power. The efficiency in that process could be more than 50 %.

The extraction of power from the klystron in Figure 7 is done by means of the coupling loop to the right on the catcher.

Several different types of high-power klystrons have been developed. One example, shown in Figure 8, is a test klystron for the German SNQ

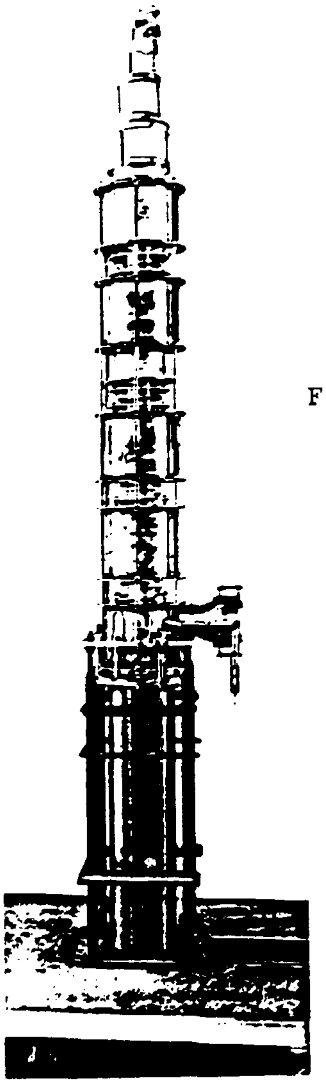

Fig 8 A test klystron for SNQ, from (20)

project (now terminated). The average radio-frequency power would be somewhat above 1 MW at a few hundred megacycles per second (MHz). Tests have indicated an efficiency as high as 70 %. According to another figure in the German article (20) the height of the klystron would be a few meters.

In the remaining part of this report we will occasionally return to klystrons and their application as power supplies for linear accelerators.

## 3.4 Modern Linacs

### 3.4.1 General Presentation

This paragraph (3.4) almost entirely deals with proton linacs. Electron linacs, mainly operating in the traveling-wave option, seldom used for protons, will not be treated at all. Let us first look at an existing machine, the LAMPF at Los Alamos, shown in Figure 9.

In the drift-tube structure, often called the Alvarez structure, the protons in LAMPF are accelerated to 100 MeV. The subsequent acceleration to 800 MeV takes place in the side-coupled cavity structure. The current is of the order of 1 mA. An Alvarez structure followed by some kind of coupled-cavity structure is used in many proton linacs.

Another linac, powerful enough to be used in an accelerator breeder, is shown in Figure 10, taken from a Canadian study. This figure also includes the breeder and its associated parts.

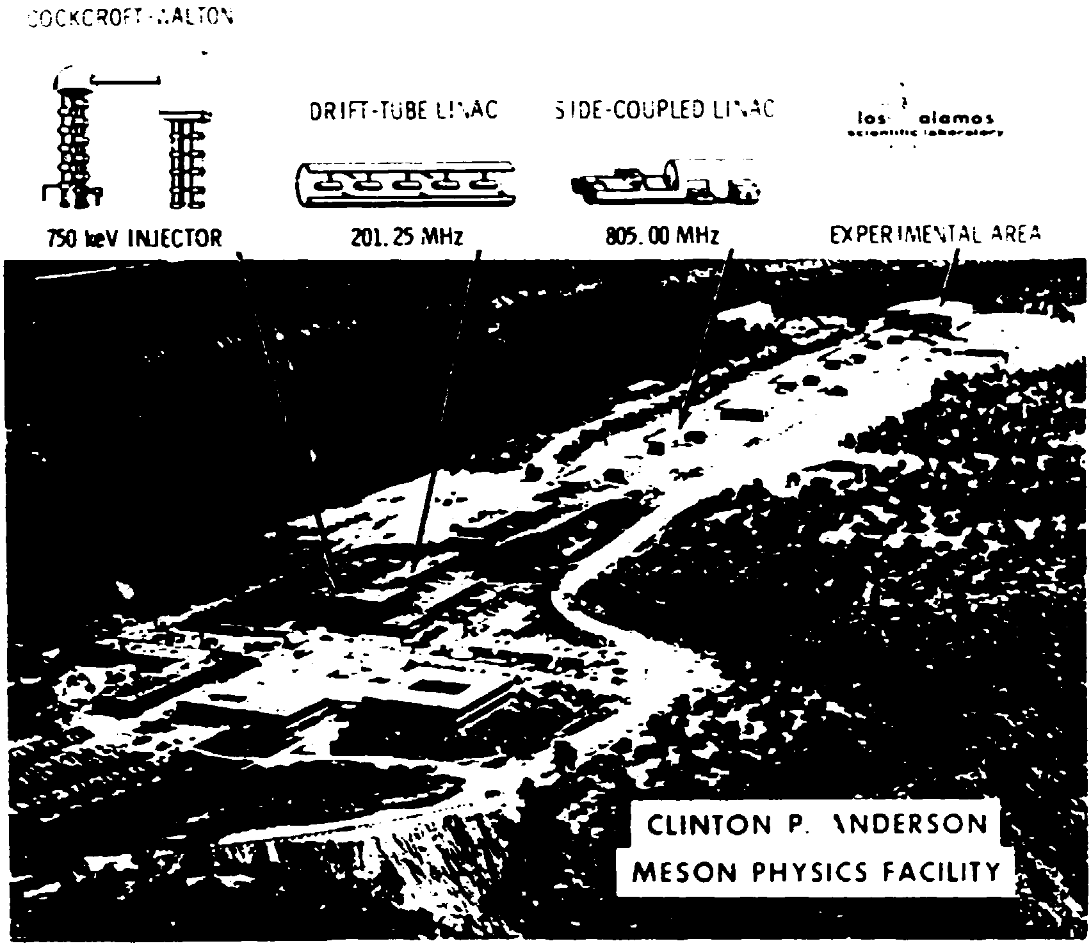

Fig 9 An aerial photo of LAMPF. The distance from the front of the office building to the far end of the experimental area is 1.1 km (Figure from Ref 21)

In Figure 10 a buncher is indicated before the drift-tube structure. This buncher, based on velocity modulation, as has been described for klystrons in Paragraph 3.3, leads to a more efficient acceleration procedure as more protons will appear in the right phase for acceleration, than if there were no buncher.

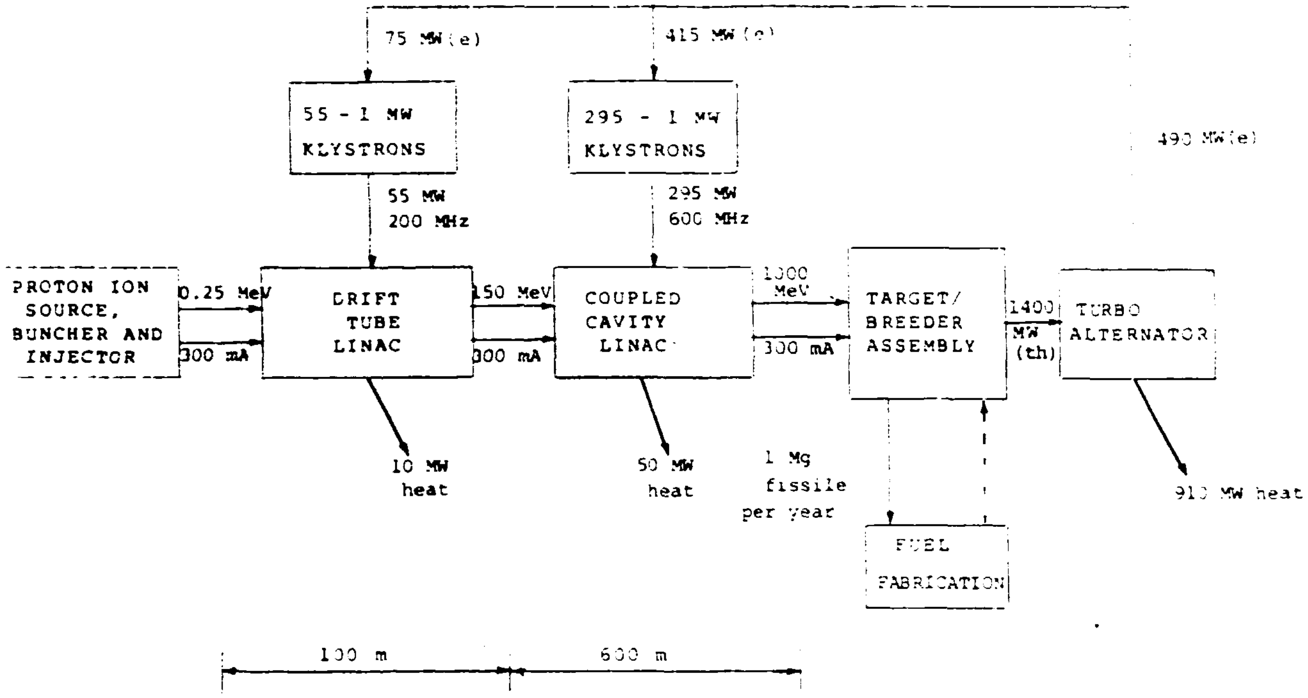

Fig 10 A linac for an accelerator breeder (Figure from Ref 22)

The current required, 300 mA, is far above the LAMPF value. However, some people claim, that if high peak currents during short intervals could be obtained, then there are good prospects also for high continuous-wave (cw) currents - as required in an accelerator breeder. For instance, the linac injector to the Fermi synchrotron gives a peak current of 300 mA - and a proton energy of 200 MeV.

Before proceeding with the linac description we would like to give some information on parameters used to characterize fast-moving particles. The general expression for the kinetic energy, $E_{kin}$, is

$$E_{kin} = \frac{m_o c^2}{\sqrt{1 - \frac{v^2}{c^2}}} - m_o c^2$$

$m_o$ is the rest mass. v/c is often written as $\beta$.

$m_o c^2$ is the rest mass energy, which for protons is 938 MeV.

Thus $E_{kin} = 938 \left(\frac{1}{\sqrt{1 - \beta^2}} - 1\right)$

Some numerical values are given below

| $E_{kin}$,MeV | 2 | 150 | 1000 | 2000 |
|---|---|---|---|---|
| $\beta$ | 0.065 | 0.507 | 0.875 | 0.948 |

Protons in the GeV range are strongly relativistic as $\beta$ is rather close to unity.

Turning to the description of the linac structures we can mention that there is a vast amount of literature on these matters, in the form of reports as well as books. One book, that has been of great value to this report is "Linear Accelerators" (23).

### 3.4.2 The Alvarez Structure

The first accelerator built by Alvarez and his team, i.e. the 32-MeV machine at Berkeley (18), has already been mentioned - in Paragraph 3.3. A section of a typical Alvarez structure is shown in Figure 11. In contrast to the earlier accelerators, shown in Paragraph 3.2, the voltage is not applied directly to the drift tubes. Instead the radiofrequency power, obtained for instance from klystrons, is introduced by one or more loops (one is shown in the figure) exciting the tank, which is tuned in resonance with the radiofrequency.

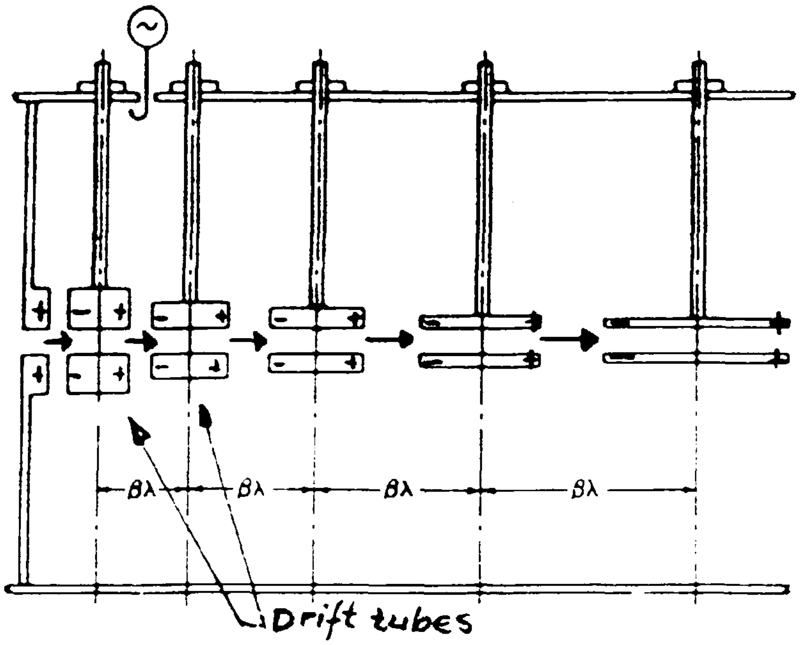

Fig. 11 The layout of an Alvarez structure

The structure is excited in the standing-wave option. There will be an axial electric field, having the same phase throughout the tank, accelerating the proton bunches in the gaps. When the field in these gaps is in the wrong direction the protons are inside the tubes where the electric field is zero.

In Figure 11 protons go from left to right. The arrows indicate the direction of the electric field when acceleration occurs. The corresponding charge distribution on the drift tubes is also indiacted. There is no net charge on these tubes.

Special measures are needed to attain phase stability and transverse (radial) stability. Phase stability is obtained if the acceleration takes place when the electric field increases. Unfortunately one will simultaneously get radial instability. This can be counteracted by quadrupole magnets located in the drift tubes as shown in Figure 12. These radial focusing requirements are strongest in the first part of a linac.

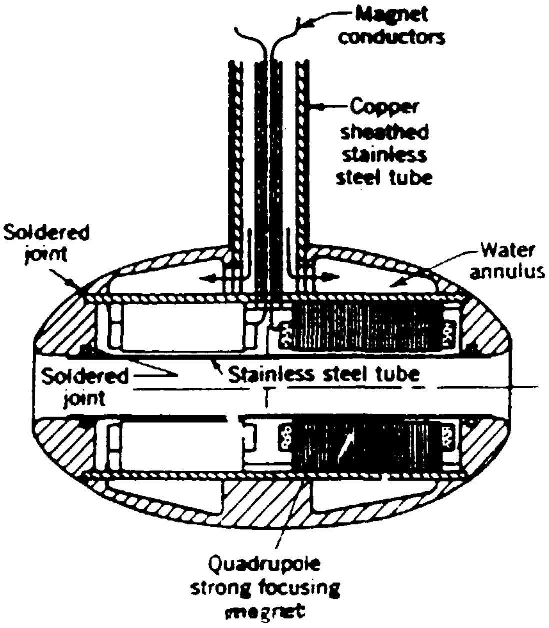

Fig 12 A drift tube with magnets for radial focusing

The radiofrequency for an Alvarez structure is usually 100 to 200 MHz. It is limited upwards because the radial variation of the axial electric field must not be too large.

When $\beta$ is about 0.5 (E=150 MeV) the drift tubes are quite long. This again means a lowered shunt impedance and thus an increased power loss in the cavity system. Therefore the Alvarez structure has to be replaced by another structure at about this energy, 150 MeV.

### 3.4.3 The Coupled-Cavity Structure

Like an Alvarez tank a so-called coupled-cavity structure is excited by one or a few loops from a radiofrequency source. Usually the frequency chosen is higher than for the Alvarez structure. The ratio of the two frequencies must be an integer, e.g. 4.

The structure can be excited in different modes, each with a certain phase difference between successive cavities. The phase shift obtained depends on the frequency. A suitable choice is $\pi/2$ having a good stability somewhat reducing the severe tolerance requirements generally encountered in linacs. A drawback of the $\pi/2$ structure is that every second cavity will not be excited. However, one can get rid of this drawback by moving the unexcited cavities thus obtaining the so-called side-coupled $\pi/2$ structure. This was suggested by Knapp in 1964 (24).

A side-coupled $\pi/2$ structure with a disk and washer cavity system is shown in Figure 13 taken from the SNQ studies. The disk and washer type of design was first developed in the Soviet Union (25).

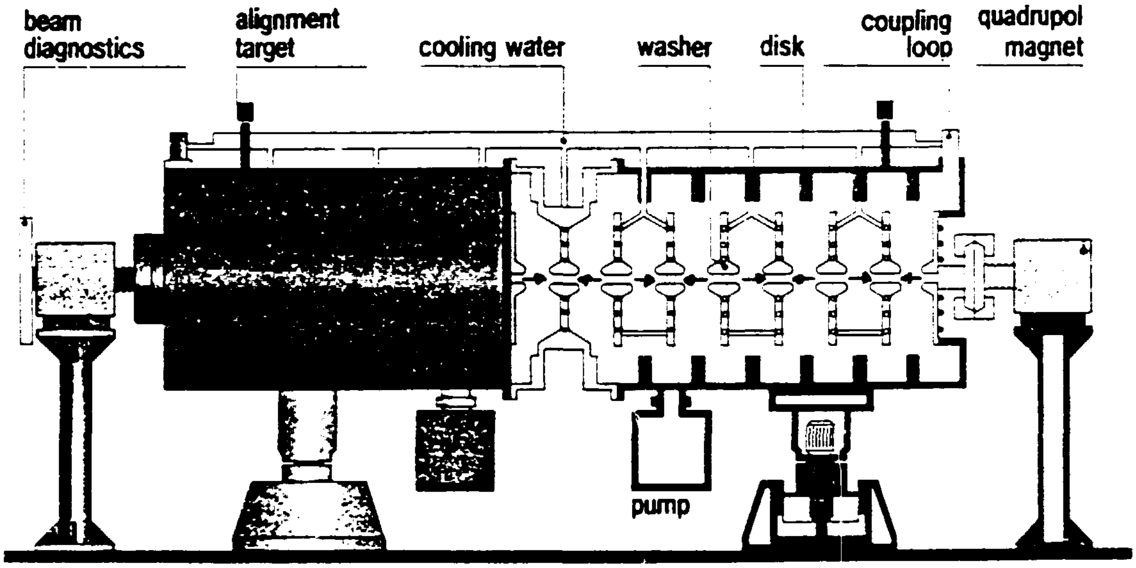

Fig 13 A twin-tank of the Disk-and-Washer accelerator. Accelerating cells are formed by pairs of washers, whereas the ringshaped slit between disks and washers provides a high flow of energy. The axial electric field at a certain moment is indicated (Figure from Ref 20)

To remind ourselves of typical data for a linear accelerator to be used in fissile fuel production we can go back to Figure 10. Quite big machines with a few hundred klystrons (or other devices) and with a proton beam power of the order of 300 MW are needed. Such linacs do not exist yet but, as has been mentioned, experts in the field consider these machines, and even still larger ones, possible.

# 4 ACCELERATOR BREEDER VARIANTS

## 4.1 The Origin

According to Ref 26 the real originator of fissile fuel production by means of charged particles was W B Lewis. Already in 1944, Lewis, later on head of Chalk River, described such a method in a classified paper. It is not clear what type of neutron-producing reaction Lewis had in mind. Maybe something was known about spallation reactions even at that time although the first open papers appeared a few years later.

At Chalk River Lewis further studied the accelerator method for fissile fuel production, publishing in 1952 an open paper (27) on the subject, now with the aim of producing fuel for civilian reactors. Interest in neutron production by charged particles has been continued at Chalk River - through the ING project (14) in the sixties and through subsequent accelerator breeder studies, e.g. (22).

In the United States a big accelerator project for fissile fuel production for military purposes was under development in the years around 1950. A brief description of this project, called MTA, will now be given.

## 4.2 The MTA Project

MTA, the Materials Testing Accelerator Project, was carried out at Livermore under the leadership of E O Lawrence. A description of the project is given in Ref 28.

At the end of the forties very little was known about domestic resources of mineable uranium ore in the United States. However, there were large amounts of depleted uranium and if a method could be found for efficient conversion of this uranium into plutonium the country could become independent of uranium from abroad. This is the background for the MTA project.

A proposed MTA production plant would include a linac, accelerating deuterons to 500 MeV in an Alvarez-type machine operating at 50 MHz. The beam current chosen was 320 mA. The deuterons would impinge on a primary target of beryllium surrounded by a secondary target of depleted uranium. The plutonium production rate would be 564 kg per year. The data for this machine are similar to those for accelerator breeders studied today, 35 years after the MTA project.

One serious drawback at the time of the project was the lack of high-power, continuous-wave sources for frequencies larger than 12 MHz. Because of this low frequency the Alvarez test section built turned out to be very large, with a diameter of 18 m. The machine, completed in January 1952 and operating until December 1953, finally gave a cw (= continuous-wave) current of 50 mA and a deuteron energy of 12 MeV. The current is, after all, fairly high and gives some support to the expectations in present-day accelerator breeder studies having cw currents of a few hundred milliamperes.

The MTA project certainly had some technical success. However, even more successful was the uranium ore exploration in the early fifties. The deposits found in the United States were large enough to permit the use of low-converting production reactors to meet the military plutonium needs. This method was much cheaper and so the MTA project was terminated around 1954.

## 4.3 Modern Accelerator-Breeder Proposals

### 4.3.1 General Comments

Most, if not all accelerator breeders include a subcritical reactor, either surrounding a target, e.g. a lead cylinder, or itself constituting the target. In the latter case the particle beam is swept across the entrance surface of the reactor. In some cases there must be a window (wall) between the high-vacuum linac and the subcritical lattice. In others, e.g. in cases with molten lead, the window can be omitted.

Data and the general layout for a representative accelerator breeder are given in Figure 10, which is taken from a Canadian report (22). This particular case is designed to be self-sufficient in energy. The fissile fuel production is 1000 kg per year, i.e. about 5 times the value for a 1000-MWe Na breeder.

Four accelerator breeder variants will be presented below. Results are quoted from the reactor physics calculations but the methods used are not discussed.

### 4.3.2 A Helium Cooled Concept

The layout of a helium cooled concept studied at Oak Ridge (29) is shown in Figure 14. The horizontal proton beam (1 GeV, 300 mA) from the linac is deflected 90 degrees and then swept across the bottom surface of the subcritical reactor. These operations are executed by electromagnets not shown. Neither shown in Figure 14 is the window needed between the high-pressure helium (∿ 90 bar) and the high-vacuum accelerator. A possible window suggested in a Brookhaven paper (10) is shown in Figure 15.

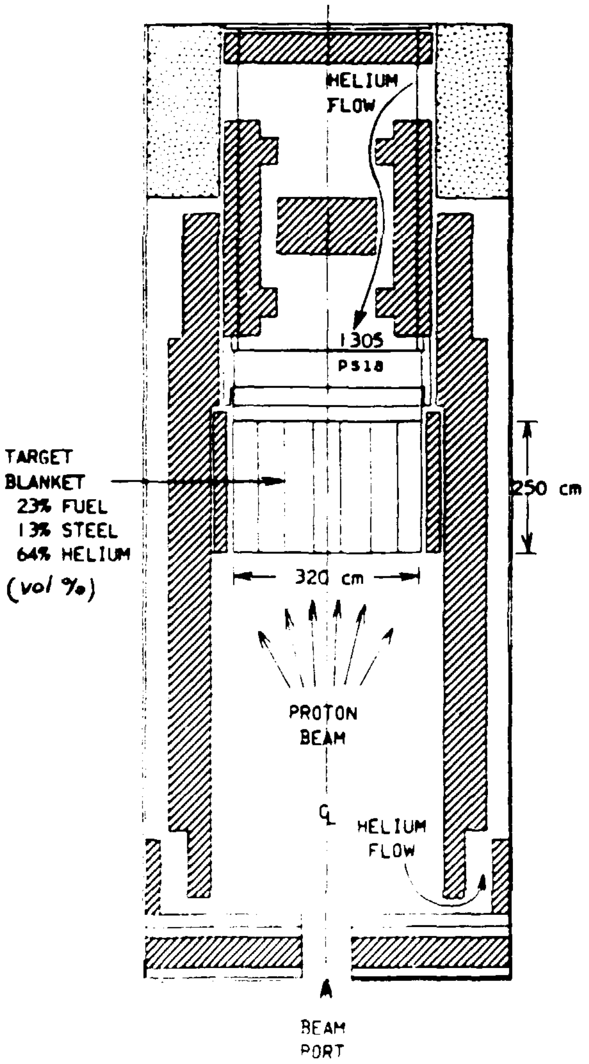

Fig 14 A helium cooled concept (Figure from Ref 29)

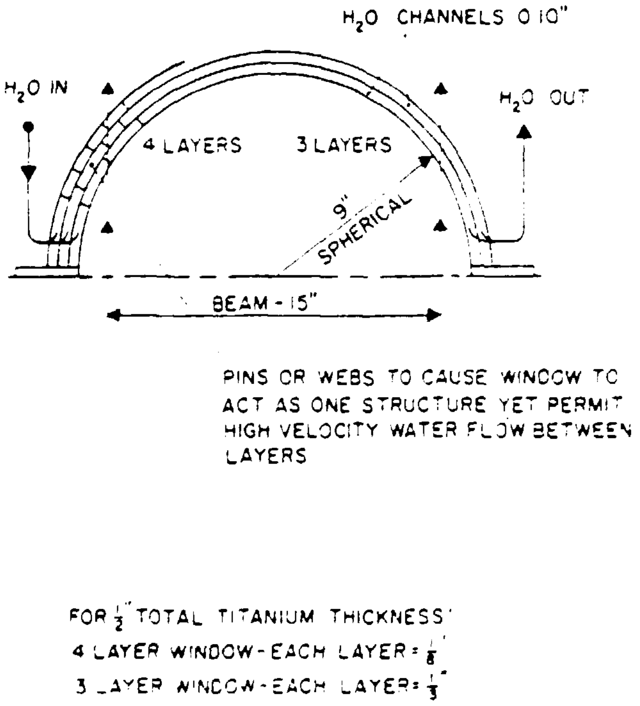

Fig 15 A high-pressure window (Figure from Ref 10)

The window may present a problem. Perhaps it may have to be replaced frequently. The Brookhaven paper considers a design with more than one window to make replacement possible at operating helium pressure and accelerator vacuum.

As shown in Figure 14 a fast reactor core is used. Consequently there is no graphite present. The fuel would consist of $UO_2$ or of $ThO_2$, on average containing about 1 % Pu239 or 1 % U233, respectively. Some additional data for the design are presented in Table 3.

Table 3
Data for the helium cooled concept shown in Figure 14

| Fertile nuclide | U238 | Th232 |
|---|---|---|
| Thermal power, MWth | 1500 | 800 |
| Net production of fissile fuel, kg/day | 4.0 | 2.8 |

The power values in the table refer to the average enrichment, 1 %. Both the power and the fuel production are lower in the Th case than in the U/Pu case. This mainly results from the comparatively low fission in Th232 as compared to U238.

The net production per year for a load factor of 0.75 will be 1100 kg for Pu239 and 770 kg for U233. These values are about five times the corresponding values for a normal gas-cooled fast breeder. The power for the U/Pu case, 1500 MWth, will give about enough electric energy to drive the linac. This accelerator breeder is thus self-sufficient in energy. The Th case, on the other hand, would need some additional power from the grid.

### 4.3.3 A Sodium Cooled Concept

Another variant studied at Oak Ridge (29) is the sodium cooled concept shown in Figure 16.

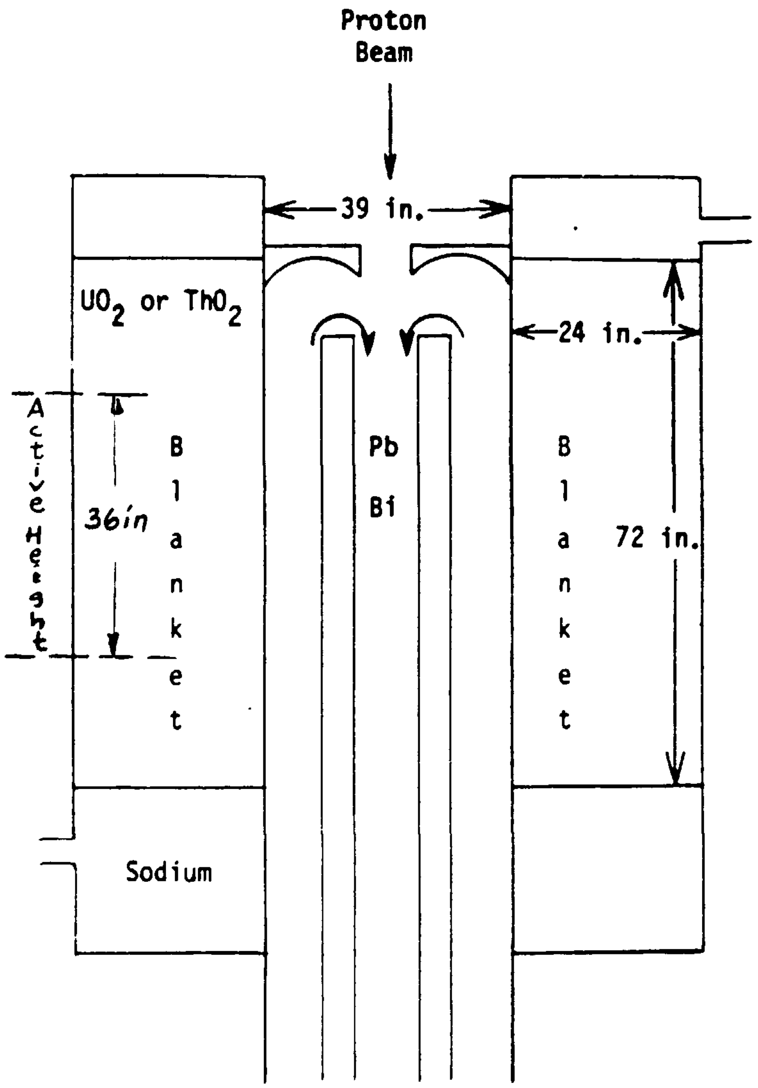

Fig 16 A sodium cooled concept
(Figure from Ref 29)

The proton beam, 1 GeV/300 mA, impinges on a eutectic Pb/Bi target. Such a material holds 44 wt% Pb and 56 wt% Bi and melts at 125 °C. No window (wall) is needed. The Pb/Bi surface is thus in direct contact with the accelerator vacuum. The target requires a central pipe and there also has to be a wall between the target and the blanket. This pipe and this wall will be exposed to a very strong radiation. Thus the neutron flux might be as large as $5\text{x}10^{16}$ per $\text{cm}^2$ and second, perhaps requring frequent replacement of these parts.

The blanket, consisting of $UO_2$ and $ThO_2$ rods in sodium, will have a pronounced radial variation of the neutron flux. This is the case, more or less, for any rod lattice surrounding a central target. The fissile fuel production will also have a strong radial variation. In addition the total amount of fissile material present will grow rapidly.To flatten the power distribution somewhat and to keep the power reasonably constant one must reshuffle and replace fuel frequently. In an example for a blanket containing 216 subassemblies, each with 91 rods, one would replace 18 every 17 full-power days by subassemblies of depleted $UO_2$ or $ThO_2$.

In a case based on $UO_2$ one would obtain a net production of 690 kg Pu239 per year for a load factor of 0.75. The corresponding value for a normal sodium-cooled fast breeder is about 180 kg. The thermal power, in target + blanket, would be 830 MW giving about 290 MW electric power. This is not enough to drive the linac which would require up to twice the beam power, i.e. $2 \cdot 1 \cdot 300 = 600$ MWe.

### 4.3.4 A Molten Salt Concept

A very special example on an accelerator breeder examined at Oak Ridge (29) is presented in Figure 17. The main ingredients of this concept are a liquid lead target and a molten salt blanket. The liquid lead is pumped around in its special loop and falls in the shape of a cylinder into the salt, thereby creating the rotation indicated in the figure. The salt is located in a large container and is in direct contact with the lead. The composition of the

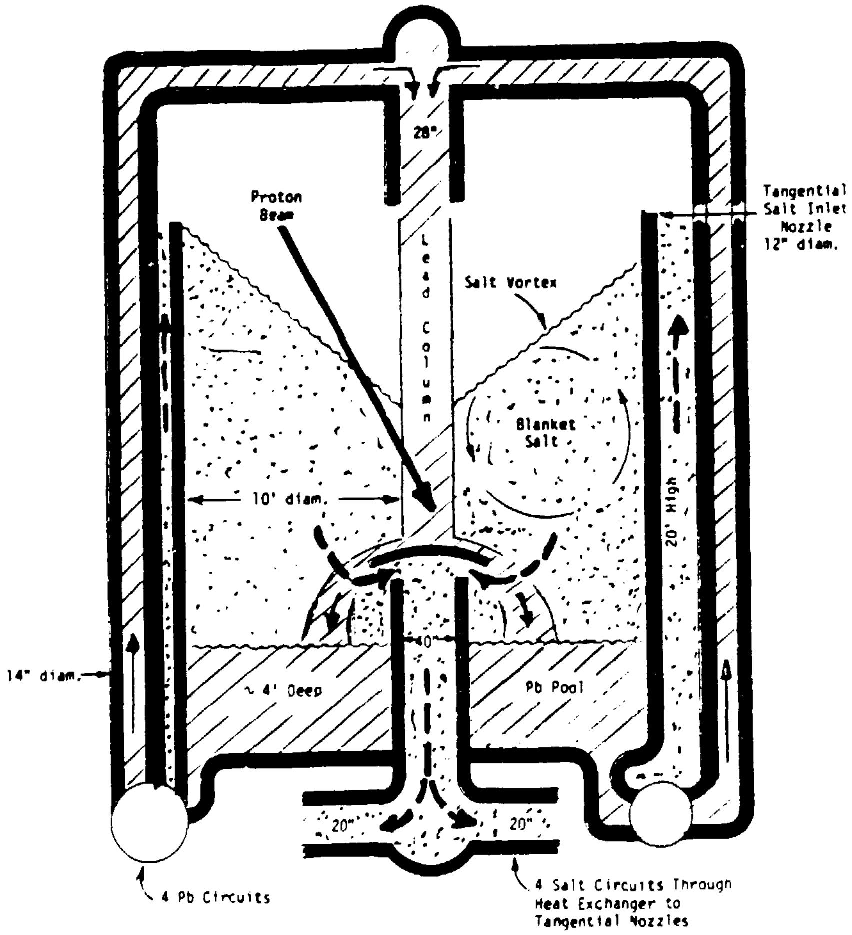

Fig 17 A molten salt concept
(Figure from Ref 29)

salt (in mole percent) is 27 % $ThF_4$, 71 % LiF, and 2 % $BeF_2$. The salt is pumped through four heat exchangers and enters the container tangentially creating a rotational motion (not shown in the figure). This rotation leads to the vortex allowing the proton beam to reach the centre of the reactor.

The concept has several advantages. There is no wall (possibly with the exception of the plate under the lead cylinder) that may be quickly damaged by the radiation. Neither is there any wall in the proton beam. Furthermore the strong radial dependence of neutron flux and power are of little significance because of the turbulent motion in the salt. Finally the circulating fuel could be reprocessed on line - with extraction of Pa233 for decay into U233, avoiding the creation of Pa234. If advantageous, some of the U233 could then be returned to the reactor.

The design is based to some extent on practical experience of molten salt operation acquired at Oak Ridge during the MSBR (Molten Salt Breeder Reactor) project. It is known that the lead and the salt will not intermix very much and also that their vapour pressures are low enough with regard to the accelerator.

The proton beam will heat up the lead. However, this heat is effectively removed by the circulating salt and no heat exchangers are needed in the lead loop. The lead flow rate is 0.8 $m^3$/sec and the salt flow rate 2.7 $m^3$/sec. The inlet and outlet temperatures for the salt are 600 $^oC$ and 760 $^oC$, respectively.

Preliminary calculations for a 1 Gev, 300 mA proton beam and a load factor of 0.75 indicate a U233 production of only 330 kg per year. More detailed calculations would, however, lead to a somewhat larger value. Possibly one could simplify the design by omitting the lead target and letting the protons act upon the salt. Calculations indicate that this might be acceptable.

Whether this concept, with or without lead, would be a reasonable one is not clear. We can, however, mention in this context, that the Molten Salt Breeder Reactor, though attractive in many respects, has so far not developed into a competitive reactor.

### 4.3.5 The APEX Nuclear Fuel Cycle

Several nuclear fuel cycles involving the accelerator-based production of fissile fuel have been studied at Brookhaven National Laboratory. One example is the Linear Accelerator Fuel Regenerator (LAFR). In this concept spent LWR fuel assemblies would be irradiated by neutrons created by means of an accelerator. In this way the fissile content could be raised to a level sufficient for another LWR fuel cycle. The procedure could possibly be repeated a few times, depending among other things upon the integrity of the canning. In this paragraph we will, however, concentrate on another BNL concept, the so-called APEX nuclear fuel cycle. The presentation will be based mainly on a description in Ref 30 (whether the word APEX has any particular significance, such as an abbreviation of something, is not clear from the reference).

The main idea of the APEX nuclear fuel cycle is to use an accelerator breeder to supply a certain number of reactors (LWRs) with makeup fissile fuel. In addition no long-lived radioactive materials are allowed to leave the circulation.

A block diagram of the APEX cycle is shown in Figure 18.

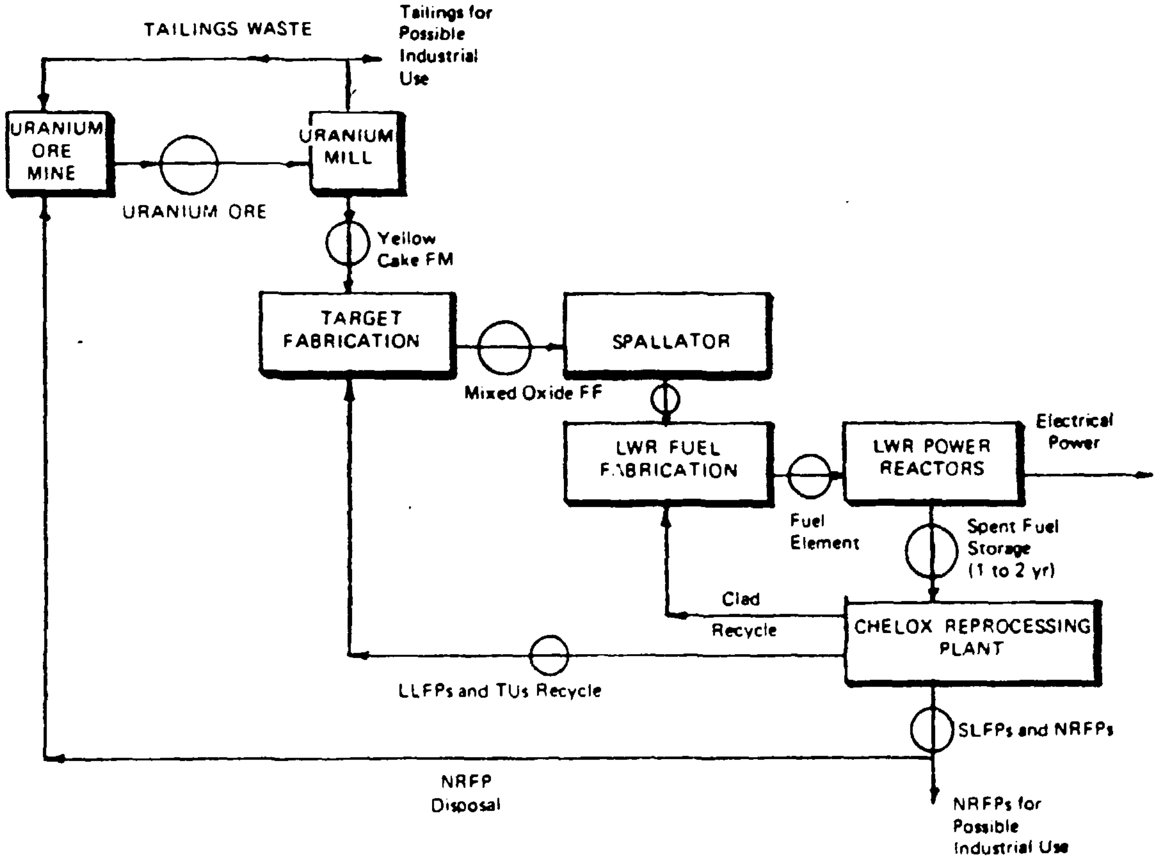

Fig 18 The APEX nuclear fuel cycle shown for U/Pu operation. Th/U233 operation would also be possible.
SLFPs = Short-Lived Fission Products, half-life < 2 years
LLFPs = Long-Lived Fission Products, in particular Cs and Sr
NRFPs = Non-Radioactive Fission Products, e.g. lanthanides
TUs = Transuranics (Pu, Am, Cm, Np)
(Figure from Ref 30)

Spent fuel from light water reactors is reprocessed and partitioned. A special method called the chelox process is used in this context. The oxide fuel is treated with an organic liquid, β-diketonate, a so-called chelating agent, that will leach out and capture the fission products and some of the TUs. The bulk of the oxide material is not dissolved. The partitioning, in which the NRFPs and the SLFPs, are separated from the rest, is based on a distillation procedure possible because of the very different vapour pressures for the various chelates formed in the chelating process. Only the harmless SLFPs and NRFPs are taken away from the fuel cycle and therefore, there are no large external waste problems. The LLFPs, the TUs, and the uranium (the latter not indicated in the diagram) remain within the cycle.

It should be noted that the chelox process has so far not been tested for this particular application. It might fail, for instance because of radiation damage to the chelating agent. However, if so, one could go back to the common Purex process. Chelox reprocessing is not an absolute requirement for the APEX scheme.

The LLFPs, the TUs, and the uranium are used for fabrication of target rods for the accelerator breeder, i.e. the spallator in Figure 18. An external uranium feed for this fabrication is also indicated. One could possibly use a feed of depleted uranium - for which large amounts are available.

After the spallator, soon to be described in more detail, fuel elements for the LWRs will be fabricated. Maybe one can use pellets or even whole rods taken directly from the spallator. However, if the fuel from the spallator has a strongly nonuniform content of fissile material, one might have to refabricate pellets for the fuel assemblies to be put into the LWRs. The LLFPs (Cs137, Sr90) will not be affected very much by the irradiation in the reactors - because of small neutron absorption cross sections. As a consequence they could as well be kept in a storage for decay without interfering with the fuel cycle. Retaining the TUs in the cycle is, on the other hand, very important.

The linear accelerator chosen for the spallator is shown in Figure 19. The machine is composed of elements discussed earlier in this report. The length is about 1500 m. It can be noted that the proton beam power is enormous, 600 MW (2 Gev, 300 mA), i.e. twice our previous reference

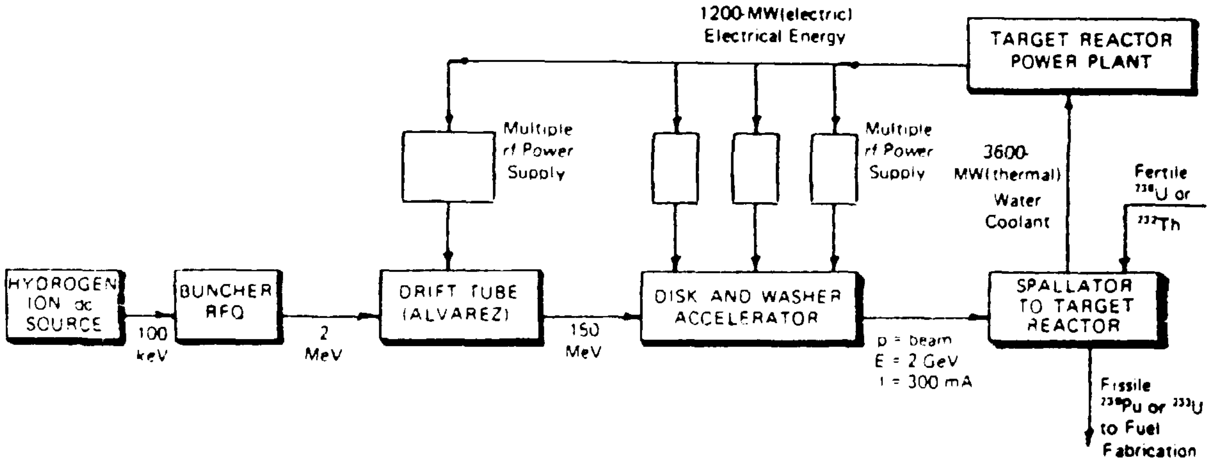

Fig 19 A linac for the APEX spallator
(Figure from Ref 30)

value. The experts at Brookhaven think that such a powerful linac is both technically and economically within reach .

The target, i.e. the subcritical reactor, is shown in Figure 20. It is built up of a large number of pressure tubes, each containing a water-cooled rod bundle, replaceable during operation - as in a Candu reactor. The tube region is vacuum pumped and is sealed off from the high-vacuum accelerator by plates. The proton beam is swept magnetically across the curved surface of the tube region. The inner bundles have a water to fuel volume ratio of 0.5, i.e. about the same as in tight-lattice PWRs, presently being studied in several countries. Some of the outer bundles have a volume ratio of about 2, as in a normal-lattice PWR. Altogether the parameters are chosen so that the accelerator breeder is just self-sufficient in energy. Some parameter values are given in Table 4.

The plutonium production is really very large in this machine. The value 3300 kg Pu239 per year is sufficient to drive nine 1000-MWe LWRs and is eighteen times the net production in a 1000-MWe Liquid Metal Fast Breeder Reactor (LMFBR). It should be remembered, of course, that many obstacles may arise when it comes down to the practical design - and the costs may go up. However, the great potential for fissile fuel production is beyond doubt.

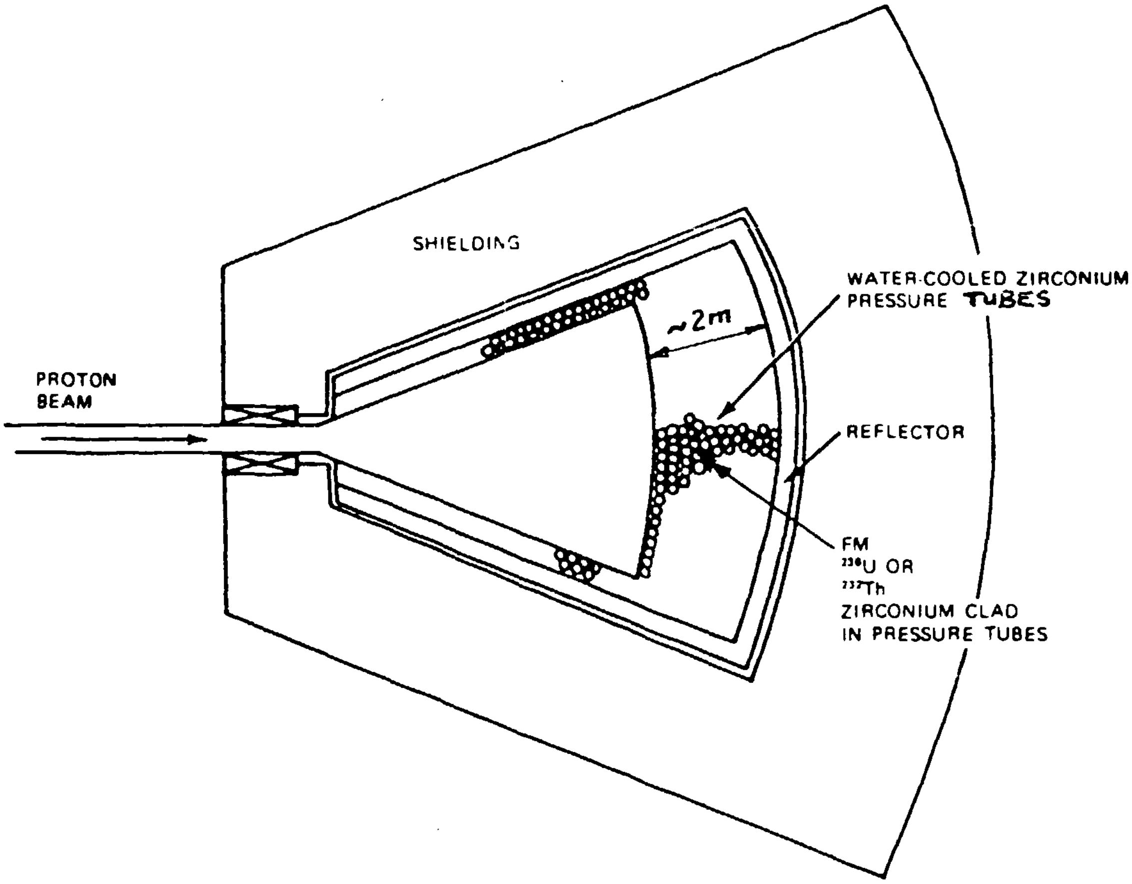

Fig 20 The subcritical reactor (target) for the APEX fuel cycle
(Figure from Ref 30)

Table 4

Parameters for the APEX nuclear fuel cycle.
Investment values in 1980 dollars

| | |
|---|---|
| Proton energy | 2 GeV |
| Net fissile atom yield for $UO_2$ (Zr clad-$H_2O$ cooled) | 94 fissile atoms/ GeV-proton |
| Current cw (continuous wave) | 300 mA |
| Beam power | 600 MW |
| Accelerator efficiency | 50 % |
| Power to accelerator | 1200 MW (electric) |
| Power generated in target | 3600 MW (thermal)<br>(self-sufficient) |
| Plant factor | 75 % |
| Pu239 FF production rate (net) | 3300 kg/yr |
| FF needed for one 1000-MWe LWR 75 % load factor and 0.6 C.R. | 360 kg/yr |
| Number of 1000-MWe LWRs supported | Nine |
| Linear accelerator capital investment | 600 M$ |
| Subcritical reactor capital investment | 1200 M$ |

## 5 SUMMARIZING AND CONCLUDING REMARKS

High-energy particles, like protons accelerated to energies of the order of 1000 MeV, impinging on a target will lead to spallation-evaporation reactions with a large emission of neutrons. These neutrons can be absorbed in U238 or Th232 in a subcritical reactor surrounding the target leading to the production of the fissile nuclides Pu239 and U233, respectively. Alternatively one can sweep the proton beam across the subcritical reactor leaving out the central target. The combination of the accelerator, preferably a proton linear accelerator, and the subcritical reactor is usually called the accelerator breeder.

The technical foundations for the accelerator breeder are reasonably well established. Thus, the neutron production in the spallation-evaporation reactions is well known from experiments and there are also good calculational methods in this field. Furthermore, it is unlikely that the subcritical reactor would show up any unsolvable problems. In many respects, this reactor can be based on proven design and one could even avoid the use of fast reactors. Ordinary LWR technology would do. The weakest constituent is probably the linear accelerator because of the severe requirements being typically a proton energy of 1000 MeV and a continuous-wave current of 300 mA, meaning an enourmous beam power, 300 MW. However, experts believe that such a value, and even larger ones, can be reached.

An accelerator breeder differs from a normal power reactor in several ways. It can start with depleted uranium or thorium. No fissile material is needed. Furthermore, the reactor is subcritical and would not need any control rods or safety rods. Its power for a certain composition would be proportional to the beam power (roughly). If the beam is turned off, there would be some residual power - as in a normal reactor on shut-down.

An accelerator breeder can be made self-sufficient in energy. The thermal power in the subcritical reactor would then give an electric energy large enough to drive the linear accelerator, i.e. to drive the radiofrequency amplifiers powering the linac cavities.

The fissile fuel production in an accelerator breeder can be very large. Thus, for a 1000-MeV proton current of 300 mA one can get a net production of 1500 kg Pu239 per year. This is about what eight 1000-MWe sodium breeders would give and enough to drive four 1000-MWe LWRs.

The capital investment for an accelerator breeder capable of producing makeup fuel for nine 1000-MWe LWRs has been estimated in a study done around 1980. According to this study the linear accelerator, 1500 m long, would require an investment of 600 M$ and the subcritical reactor twice that amount.

So far no accelerator breeder has been built. However, this alternative might have great potential as one such breeder could supply makeup fuel for several ordinary LWRs or other converters. A fission reactor strategy based on such accelerator breeders and LWR converters could be imagined and seems to be possible from the technological viewpoint.

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