The accelerator requirements for an economic spallation breeder system are reviewed. An intermediate energy, high current proton linear accelerator is the preferred choice. Present designs of drift tube and coupled cavity structures can be adapted to 100% duty factor operation. From recent work on meson factory and synchrotron injector linacs it appears likely that beam spill can be reduced to acceptable levels. For economy the emphasis is on the efficient production of radiofrequency power, most of which must be delivered to the accelerated beam. Some trends in current development are outlined.

Introduction

A rare isotope of uranium is the only naturally occurring fissile material. The supply of fissile material can be multiplied several hundred times if the much more abundant fertile isotopes of uranium and thorium were converted to fissile isotopes.

The idea of using high power accelerators for "breeding" fissile material is not new. In 1948, Goeckerman and Perlman observed that the fission of bismuth by bombardment with 190 MeV deuterons was preceded by the evaporation of 12 neutrons. O'Connor and Seaborg, later the same year observed a similar phenomenon with uranium bombarded by 380 MeV alpha particles. The copious accelerator-based neutron production from the spallation reaction began to be exploited soon afterwards in the MTA program at Livermore with the objective of producing 239Pu and 233U in commercially useful quantities. The project was stopped in 1952 not because it was unpromising but by the discovery of high-grade uranium ores in Colorado. About the same time W.B. Lewis, at the Chalk River Nuclear Laboratories in Canada, independently recognized the significance of the large neutron yield from heavy elements excited to high energies in the breeding of fissile material, especially from 232Th. This led to a Canadian experimental study of neutron yields from a variety of targets using cosmic ray protons. Later the Intense Neutron Generator Study at Brookhaven estimated that beam spill can be reduced to acceptable levels. For economy the emphasis is on the efficient production of radiofrequency power, most of which must be delivered to the accelerated beam. Some trends in current development are outlined.

Since the early 1950's accelerator physics and technology have made great advances and we have seen in recent months a renewed interest in accelerator-based spallation breeding as an alternative source of fissile material for nuclear power reactors. The U.S. Energy Research and Development Administration recently sponsored an Information Meeting on Accelerator Breeding at Brookhaven. Estimates given at that meeting are that 100 mrem/h (1 mG/h) of neutron captures per incident particle is achievable in the spallation reaction, which is about twice the level that can be achieved in a reactor. However, the reactor requires much less infrastructure, and the accelerator-based system is more expensive.

Table 1

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy</th>
<th>Current</th>
<th>Availability</th>
<th>Radiation Field from Induced Activation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>1 - 2 GeV</td>
<td>&gt; 100 mA</td>
<td>~ 90%</td>
<td>≤ 100 mrem/h (1 mG/h)</td>
</tr>
</tbody>
</table>

Fig. 1 The calculated relative neutron capture rate in the 238U component of a large block (> 1 m³) of natural uranium bombarded by deuterons (d) and protons (p) normalized to unity for 1 GeV protons. The neutron (n) and triton (t) curves are derived from the deuteron and proton curves.

Neglecting the binding energy of the deuteron, a deuteron beam can be considered as a neutron and proton beams each of half the deuteron energy. The neutron and triton curves are derived from the calculations of Barashenkov et al. for deuterons and protons.
In the low energy portion of the accelerator, the activation of the structure and surrounding components by spilt beam is much more severe with deuterons and tritons than with protons. Furthermore, the space-charge limit is about four times higher for protons than for deuterons of the same energy. Because the marginal gain to be had from deuteron or triton beams is offset by the increased structure activation, and because of the higher space-charge limit for protons, protons of between 1 and 2 GeV seem to be the preferred projectile for the spallation breeder.

Parametric studies have shown that spallation breeding costs fall toward an asymptote for large installations in which the fissile production rate exceeds 3 kg/day. Calculations, supported by experiments, predict that an average proton beam current of 300 mA at 1 GeV directed at a large natural uranium target will produce 239 Pu at the required rate. The efficient production of a 300 MW proton beam will favor operation of the accelerator at 100% duty factor.

Pulsed acceleration schemes such as the linear induction accelerator, synchrotrons and some varieties of collective-effect accelerators are unlikely to succeed unless they can produce high peak currents at high repetition rates. A sector-focused cyclotron with continuous injection from a 50 MeV proton linac has been proposed by the Dubna group; in a recent monograph, Banchev et al. proposed a large separated-magnet 8-sector cyclotron to produce a circulating beam of 100 mA at 900 MeV. Expansion of the orbit separation to 2 cm would facilitate a high extraction efficiency. The result of beam spill concentrated in the extraction channel of a cyclotron would lead to higher radiation levels than an equivalent spill rate distributed along a linac. Thus it may be difficult to limit radiation fields close to a cyclotron to a level allowing occasional access for maintenance without elaborate, portable shielding. Other potential problems that need investigation are the effect on the beam behaviour of the heavy beam loading in the resonant accelerating cavities and the high concentration of rf power in such a device.

The linear accelerator is the most promising device at present. The superconducting variant with its very small structure power dissipation offers no advantage when the beam power is 300 MW. We are left, then, with the modern room-temperature, high-shunt impedance linear accelerator as the preferred design for the spallation breeder. As I will show, in the economics of fissile material production, there is a requirement for efficient production of radiofrequency power, by far the largest cost component of the spallation breeder accelerator.

**Current Status**

The pioneering work on the development of intermediate-energy linear accelerators for meson factories was done at the Los Alamos Scientific Laboratory and, for synchrotron injector linacs, at Brookhaven and CERN. The injector linacs deliver peak currents in excess of 300 mA during pulses of a few microseconds but at a low repetition rate. It has been found that with careful alignment and with extensive use of beam loss monitors along the structure the beam spill after the first few drift tubes can be kept down to about 1 part in $10^4$ of the accelerated beam. If this level can be maintained in the low-energy drift-tube section with 100% duty factor operation and reduced to 1 part in $10^2$ in the higher energy coupled-cavity section it should be possible to limit the radiation fields near the structure a few hours after a shutdown to less than 100 mrem/h (1 mG/h). This is a radiation field low enough to allow "hands-on" maintenance. Experience at Los Alamos has shown that proper alignment of the linac is crucial in reducing activation by spilt beam.

If any component that effects the transport of the beam failed, a fast-about-system would be needed to limit the amount of spilt energy to the order of magnitude of the stored beam energy. In a 300 mA beam in flight through a 1 GeV superconducting linear accelerator, the stored energy is about 1 kJ. The localized spill of this much energy, roughly equivalent to the allowable distributed beam spill during one second, would be tolerable.

For a given accelerating gradient, the power dissipation density in the structure is increased by a large factor for 100% duty factor operation. Two experiments at the Chalk River Nuclear Laboratories have shown that a drift-tube structure operating at 268 MHz, and a side-coupled structure at 805 MHz, can be operated at 100% duty factor with no difficulty. Sufficient improvement has been made in the heat-transfer system to permit operation at 20 times the structure power density of the LAMPF structure operated at 6% duty factor. The usual cold-cavity structure has been upgraded to 50% beam loading with electrons. The rf accelerating field was controlled to within 0.2% in amplitude and 1° in phase. A small but finite beam-induced phase tilt along the structure was observed. At the required beam loading of 9UX, the phase tilt would have to be taken into account in the design of long structures. Experiments are continuing on the behaviour of structures under the beam loading required by a spallation breeder.

Work has also been underway for several years at Chalk River on the development of dc ion sources and accelerating columns. One column is designed for low emittance using a gradient of 3.1 Mw/m with the source at 750 kV. It has operated at up to 45 mA dc with spark free periods of greater than one half hour. Photo-electron emission from insulator and electrode surfaces appears to be the most likely cause of beam-induced breakdown. At Oak Ridge, operation of the BEC-2 injector column has been more successful, a current of 100 mA has been maintained at 600 keV for several days without a breakdown but of unknown emittance.

The steady state structure power dissipation in a 1 GeV linac patterned after LAMPF is about 30 MW, much smaller than the 300 MW required for accelerating the beam. Current estimates of rf power generating equipment range from $0.35/w$ to $0.70/w$ when many units are bought. The capital investment in rf equipment would be from $115 M to $230 M. A current estimate of the linac cost, adjusted by a factor of two for inflation from a 1967 estimate for the ING accelerator, is $40 M. The target thermal power, probably in excess of 1000 MW, would be converted to electric power to supply most or all of the spallation breeder demands. At $800/Mw this would amount to about $350 M with an ac to rf conversion efficiency of 75%. Thus there is a premium on the efficiency of the production of rf power and on the efficiency of the target in the production of fissile material. The efficiency of each step in the power cycle — ac to dc, dc to rf and rf to beam must be maximized. The ING study showed that ac-to-dc conversion is optimized in a module size of 18 MW. This result is probably still valid today. At the present time, klystron power amplifiers are the
most suitable efficient converters of dc power to rf power; efficiencies of 74% have been achieved in a 100% duty factor, 50 kW klystrons at 2940 MHz. For the PEP storage ring, 353 MHz, 500 kW klystrons are being developed with an efficiency of at least 70%. There is no reason to believe that extension of the same design principles would not yield efficiencies above 80%.

Currently, a klystron in the 0.5 to 1 MW range is probably an economic size. For low beam-loading applications such a large-size klystron can serve several long modules representing a linac segment with a large energy gain. The consequence of a failure of a power unit would be severe. Voelker has proposed the use of an rf manifold to parallel the outputs of several power amplifiers and to distribute the combined power to several structure modules or tanks. This concept is receiving attention in the PIGMI program at Los Alamos. For a heavily beam-loaded linac as proposed for the spallation breeder, the manifold concept may not be appropriate. With an energy gradient of, say, 1.5 MeV/m and a beam current of 300 mA, the linear energy feed density is 0.43 MW/m - one present-day klystron per metre. With such a high power density, the fractional energy change caused by the failure of a single unit could probably be accommodated by the accelerator. In fact, there may be an advantage in developing an even larger unit klystron size, say 1.5 MW, which could feed a single module 3 metres long.

Future Developments

The trends of future development of high power accelerators for spallation breeding are becoming apparent.

Beam handling in the injector beam line will require considerable development. We do not understand in detail how the behaviour of dc or bunched ion beams is affected by space-charge neutralization. Ways must be found for transporting space-charge neutralized beams without emittance growth.

The control of beam spill will require improvement in the limitation of emittance. This implies radial beam scraping and controlled dumping of the beam to limit the transverse phase space. This early in the accelerator. It also implies chopping or more sophisticated bunching schemes to eliminate that portion of the longitudinal phase space that will not be accepted. In short, we should learn how to clean up the beam early so that less will be spilled at higher energies.

It would be desirable to reduce the injector voltage to ease problems of dc operation of accelerator columns at high currents. At the same time the rf frequency of the drift-tube linac should be raised above 50 MHz to 150-200 MHz where high efficiency klystrons can be conveniently used and where the frequency ratio between the drift-tube and coupled-cavity structures can be as low as 3 or 4. Recent work at Los Alamos has shown that an application of alternating phase focusing should allow the use of an injector voltage as low as 200 keV and a frequency of 150 MHz for a steady current of 300 mA.

For 300 mA operation we will have to develop new beam diagnostic devices such as non-intercepting beam position monitors and if possible beam profile monitors.

A large effort is already underway at LAMPF to understand the beam halo phenomenon at intermediate energies. We can look forward to continued development of structures not only for the improvement of the manufacturing procedures but also to improve beam handling, for example, by the incorporation of electromagnetic focusing within coupled cavity structures. The PIGMI program at Los Alamos promises to produce important innovations in structure design especially suitable for the low energy section of the high power accelerator.

The dominant importance of the rf power system will result in some increase in klystron efficiency. It will also be necessary to determine the best module size for a heavily beam-loaded linac; in addition to the focusing constraints on module size, the matching of the load of a module to a single rf power source for economy and reliability must also be taken into account. There is a need to develop a scheme to reduce or cope with the power reflected to the source as the transition is made from only to 90% beam loading. This could take the form of a motor-driven variable coupler to effect a dynamic match, or an auxiliary microwave network or a specially designed output cavity in the klystron capable of absorbing its full reflected power while operating. The characteristics of the target-reactor will undoubtedly require that the beam current be run up slowly over a period of many minutes. The accelerator control system including beam transport, structure resonance, field amplitude and phase control, must be capable of accurately tracking the slow run-up conditions as well as any fast disturbance.

Conclusions

The prospect for high power accelerators for spallation breeding of fissile materials has been enhanced in recent years by developments at several research accelerator installations and by experiments with low power 100% duty factor linacs. It appears likely that beam spill can be controlled sufficiently to allow hands-on maintenance.

Nevertheless, considerable development remains to be done especially in the injector area, low energy beam handling, the initial acceleration and emittance control of the beam. Methods and devices need to be developed for handling large amounts of rf power under a wide range of operating conditions. High efficiency, reliable and cheap MW klystrons in the 200-600 MHz range need development; none of the present beam to necessity technological developments - effective use of existing techniques will produce the desired results.

References

1. R.H. Goeckerman and I. Perlman, Phys. Rev. 73, 1127 (1948).