BNL 33020

# THE SPALLATOR - A NEW OPTION FOR NUCLEAR POWER

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JUNE 1983

DEPARTMENT OF NUCLEAR ENERGY
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UPTON, NEW YORK 11973

PREPARED FOR
UNITED STATES DEPARTMENT OF ENERGY
UNDER CONTRACT NO. DE-AC02-76CH00016

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# THE SPALLATOR - A NEW OPTION FOR NUCLEAR POWER

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## Abstract

The principles of the spallator reactor are reviewed. Advances in linear accelerator technology allows the design and construction of high current (hundreds of mA) continuous wave high energy (thousands of MeV) proton machines in the near term. Spallation neutronic calculations building on existing experimental results, indicate substantial neutron yields on uranium targets. Spallator target assembly designs based on water cooled reactor technology indicate operable efficient systems. Fuel cycles are presented which supply fissile material to thermal power reactors and reduce fission product waste. Preliminary comparative analysis indicates an economically competitive system in which a single purpose self-sufficient spallator supplies fuel to a number of LWRs. The spallator assures a long-term LWR power reactor economy. International interest in advancing the technology is indicated.

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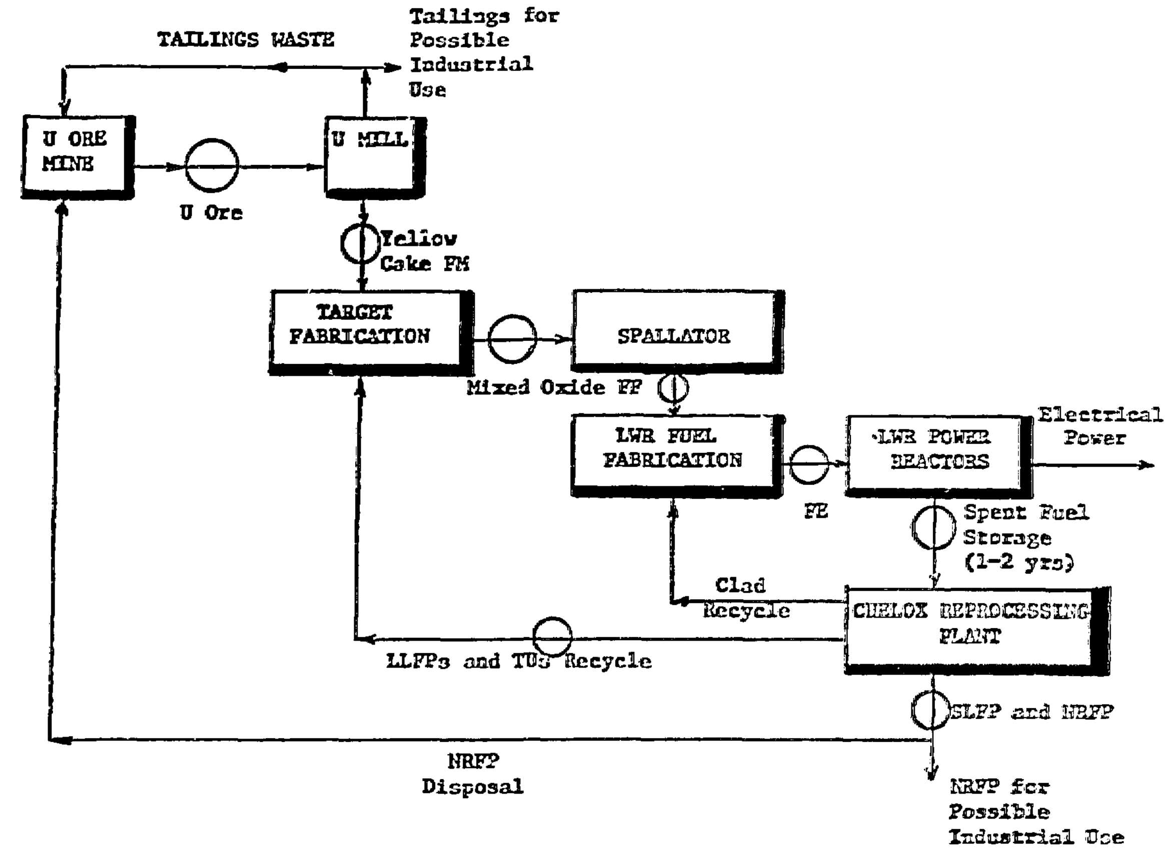


Legend

— Storage
FM — Fertile Material (U-238)
FF — Fissile Fuel (Pu-239, U-235, TUs)
NRFP — Non-radioactive fission product
SLFP — Short-lived fission products (<2 yrs)
LLFP — Long-lived fission products (Cs, Sr, Kr, I, etc.) 2 yr.
TU — Transuranics (Pu, Am, Cm, etc.)
FE — LWR Fuel Element

APEX NUCLEAR FUEL CYCLE
for U/Pu fuel cycle

Includes 1) Spallator for generating Pu fissile fuel, 2) Chelox reprocessing for recycling radioactive waste, 3) LWRs for generating power and eliminates enrichment and need for long-term geological-age storage of long-lived radwaste. System can be modified for application to the Th/U-233 fuel cycle.

FIGURE 8

THE SPALLATOR - A NEW OPTION FOR NUCLEAR POWER

## I. Introduction

The three major problems facing the long-term acceptance of nuclear power by the industry and the public include (1) the safe operation of nuclear power reactors (2) the long-term supply of fissile fuel and (3) the management and disposal of radioactive waste material. The approach to the safety problem involves improved design, construction and operation of light water reactors (LWRs) being pursued by the industry and monitored by the Nuclear Regulatory Commission (NRC). Present U.S. policy concerning the second problem is being advanced through the demonstration of the fast breeder reactor, and the current solution to the third problem involves geological age storage of long-lived radioactive fission product waste.

The liquid metal fast breeder (LMFBR) has had a long development history and has experienced much delay due to technical and economic difficulties in the U.S. An alternative to breeding fissile fuel in fission reactors is the concept of a fusion-fission hybrid system.[1] Neutrons from the fusion of deuterium and tritium in a plasma are absorbed in a surrounding fertile blanket material containing either uranium (U-238) or thorium (Th-232) for conversion to fissile material, (Pu-239 or U-233). The problem with this concept is that fusion will take many years (>30 yrs) to be proven a viable technology.[2] An energy producing fusion plasma demonstration is yet to be demonstrated. Another option which was initially employed at the dawn of the nuclear age[3] is to use spallation neutrons produced by accelerator driven protons or deuterons impinging on a heavy metal target. The spallator neutrons are then absorbed in naturally occurring fertile material in the target to produce the fissile fuel needed for power reactors. Advances in linear accelerator technology and new data on neutron yields makes this a new near-term technology option. The proton accelerator with the fertile target assembly is termed the Spallator. The linear accelerator (linac) is the accelerator of choice for producing the high energy protons. Linac technology has advanced through its extensive use in high energy physics research over the past 40 years to the point where it is believed that an efficient continuous wave high current production machine can be reliably constructed and operated. Heat development due to the spallation and fission reactions taking place in the target assembly is used to generate electrical power to drive the linac. The Spallator then becomes an independent self-sufficient plant producing nuclear fuel for thermal power reactors presently used by the utility industry, particularly the light water reactors (LWRs). The Spallator thus breeds fissile fuel from abundant fertile material and the long term supply of fissile fuel is then assured. To complete the nuclear fuel cycle, it is necessary to reprocess the spent fuel for purposes of extracting the fission products, recycling the unburned fissile material and adding fresh makeup fertile material. Figure 1, gives a schematic of the overall fuel cycle for the Spallator/power reactor system.

## II. Accelerator Technology

From the time, in the early 50's, when accelerators were proposed for the production of fissile material, accelerator technology has come a long way. The growth of the technology can be attributed wholly to government funding for basic research in nuclear and elementary particle physics. Among the many types of accelerators developed, one in particular offers the potential to accelerate large beam currents (many mA), continuously, to very high energies (thousands of MeV's), that is, the linear accelerator or linac.

The basic capability of the linear accelerators has been demonstrated by the operating performance of the linac injectors for high energy proton synchrotrons, such as those at Brookhaven, Fermilab, CERN, Argonne, and elsewhere. Peak beams intensities in excess of 100 mA have become routine, and good reliability has been demonstrated. Although these synchrotron injectors have not been required to run at a 100% duty factor, there is no fundamental reason that such operation cannot be achieved if sufficient rf power and cooling are provided. The Los Alamos Meson

Physics Facility (LAMPF) operates at a duty factor of 10%. In fact, a 7.5 MeV, 30-mA deuteron linac was successfully operated at 100% duty factor almost thirty years ago as part of the Material Testing Accelerator (MTA) project;[3] and moreover, a 35-MeV, 100-mA deuteron linac at 100% duty factor is being built now at the Hanford Laboratory for the Fusion Materials Irradiation Testing Facility (FMIT).[4,5] Table 1 lists these accelerators with their relevant parameters.

The accelerator design for the Spallator would not be very different from those mentioned above and would use the collective experience gained in the design, construction, and operation of these existing accelerators and on new accelerator technology developed during the past ten years. The design specifications lie well within the state-of-the-art. No fundamental problems are anticipated. Experience with operating linacs indicates that such machines can be operated without appreciable beam loss during acceleration so that residual radiation will not handicap maintenance of the machine. The main characteristics of the Spallator linac are given in Table 2.

(a) The Injection System

In the past, all linear accelerators have relied on the use of 500 to 800 keV (Crockroft-Walton) pre-accelerators containing duoplasmatron ion sources. The requirement for high voltage was dictated by limitations of drift-tube linacs concerning physical design and beam acceptance into the machine. The dc ion beam extracted from the source was accelerated to this 500 to 800 keV, then chopped, bunched, and matched to the desired conditions before injection into the accelerator. Typical beam capture efficiencies were about 70%.

New developments in the technology, promise substantial improvements in the cost and performance of new facilities. In particular, the invention of the Radio Frequency Quadrupole (RFQ) pre-acclerator eliminates the need for high voltage Cockcroft-Waltons and increases the linac acceptance because of the higher injection energy (~2 MeV). Typical beam capture efficiencies can reach 95%.

The RFQ accelerating structure, invented by Kapchinskii,[6-8] is being developed in this country at Los Alamos Scientific Laboratory.[9-10] Prototypical experiments have demonstrated the capability of the device to meet expected performance requirements. The use of the RFQ in any new linac injection system will greatly simplify the entire bunching and matching section. In addition, the ion source will deliver the beam to the RFQ at ~200 keV instead of the ~750 keV previously required.

Ion sources have also seen large improvements over the last decade. Existing linacs depend on duoplasmatron ion sources. These sources have been operated at up to 600 mA in a pulsed mode and up to 200 mA dc. Now, sources developed for neutral beam heating of fusion reactor plasmas have delivered multiampere dc beams of high quality (low emittance, low noise). These new sources are now being adapted for linear accelerators. They promise beam characteristics far superior to duoplasmatrons allowing optimum matching to the accelerator which should help minimize beam losses.

(b) Linear Accelerator

Beam dynamics theory of linear accelerators is now well understood. Preliminary calculations have been carried out for a Spallator linac with a 300 mA beam current. These conservative calculations indicate that the radio frequency should be ~150 MHz for the drift-tube linac section. This frequency could be as high as 200 MHz.

The accelerator would consist of a two stage rf linac. First, an Alvarez or drift tube section would accelerate the beam to about 150 MeV, then a socalled $\pi/2$ structure would drive the beam to its final energy (2.0 GeV).

The first stage drift-tube structure, is well developed.[11-13] It is being used for all modern proton linacs. Post-coupler compensation similar to that used in the LASL and FNAL linacs, or multistem compensation used at BNL are close to optimum for beam loading efficiency. Due to the 100% duty factor, heat dissipation and temperature control become major factors in the cavity design. However, conventional mechanical fabrication techniques using copper clad steel to act as a combined radio frequency cavity and vacuum envelope appear to be acceptable. Power would be coupled to the structure via water-cooled coupling loops. A water cooling jacket designed to maximize the surface area in contact with the cooling fluid and minimize temperature gradients would be welded to the tank's outer surface. Figure 2 shows the existing Brookhaven National Laboratory (BNL) 200 MeV Alvarez linac. At the 150 MeV energy, the Alvarez-type accelerator structure becomes inefficient. It has to be replaced by what is known as a $\pi/2$ coupled cavity structure whose efficiency increases with beam energy.

The $\pi/2$ coupled cavity structure chosen for this application is called the disc-and-washer (DAW) structure. It appears to be the best choice for a high current linac above 150 MeV. This structure--first developed in Russia[14]--has also been under development elsewhere for a number of years.[15] Besides its higher shunt impedance (higher efficiency), this structure has large bandwidth and is better able to cope with high power levels and high beam loading.

Because of the higher particle velocity and longitudinal-phase damping produced in the Alvarez section, one can operate the DAW structure at an rf frequency several times higher than that of the drift-tube section, thereby, obtaining a higher acceleration rate and higher beam-loading efficiency. Preliminary investigation indicates that a frequency of 450 MHz, an acceleration rate of ~1.5 MeV/m, and a beam loading of more than 70% can be attained.

(c) Radio-Frequency Systems

High-power rf systems using both klystron and gridded tubes have been used for pulsed accelerator applications with good success. At low frequencies, gridded tubes are preferred; at frequencies of >200 MHz, the klystron is preferable. High-power gridded tubes and klystrons are available commercially. These tubes give output powers of >1.0MW average at 450 MHz with more than 20,000-hour lifetimes. However, because of the amount of rf power required and the incentive for high conversion efficiency, tubes expressly developed for this application would be highly desirable. The development effort would be focused on obtaining tubes with high ac-to-rf power conversion efficiency and high output power. Conversion efficiencies of 70% can be easily achieved. The capital cost of rf systems decreases with increasing output power per amplifier unit; therefore, output power of up to 2 MW/power tube would be highly desirable. These power levels appear feasible.

Compared with presently operating pulsed systems, continuous wave operation brings tremendous simplification to parts of the rf system. Energy storage requirements are eliminated, and feedback control of cavity amplitude and phase is greatly simplified. However, fast crowbar and other protection features are more difficult. Provisions must also be made for possible cavity sparking and subsequent system recovery.

Redundancy in the rf system is essential for reliable operation. Each cavity may be fed directly from individual rf supplies, or it may be fed from a manifold which is--in turn--fed by the supplies. The latter arrangement has the advantage that the excitation pattern of the cavity is not affected by the failure of a redundant supply unit. Both the rf feed mode and the optimal degree of redundancy need to be studied in relation to the overall control system for the machine. Computer control systems for accelerators are well developed on existing machines. Distributed intelligence systems, where peripheral minicomputers or microprocessors carry out control functions at the location on the device, and control is distributed by a central processor, appears to be the most promising of many possible configurations. Fast control, for protection against beam loss and for the control of cavity phase and amplitude levels, must be accomplished locally with analog systems. Adequate designs for these systems have been demonstrated on existing accelerators with microsecond response time.

(d) Facilities, Maintenance, and Reliablity

The linear accelerator described above would be housed in an earth-shielded tunnel, the rf power equipment and auxiliaries being in an adjacent, light, conventional structure. The radiation shielding around the accelerator tunnel would be designed for catastrophic beam spill as well as an acceptable continuous beam loss. Figure 3 shows a cross section of the accelerator tunnel and adjacent equipment gallery.

Properties of linear accelerators preclude operation without some beam loss. The ablity to control beam losses in cw, high current machines is essential to allow hands-on repair and maintenance. Beam loss control can be achieved by combining two approaches to the linac design: firstly, the design parameters should be very conservative, especially with regard to tolerances and allowances that may affect beam loss; the rf frequency, is chosen to allow for large beam aperture in drift tubes, the frequency transition energy, synchronous phase angles, transverse and longitudinal magnetic and electric gradients, and all other pertinent parameters should be chosen to maintain the beam bunches during acceleration in only a small fraction of the stable phase region. These steps would make allowance for any errors and tolerances required for construction. Secondly, the proton beam should undergo scraping and cleaning at several stages during the acceleration process. This would be accomplished by leaving gaps in the accelerator, which would contain scrapers in heavily shielded areas. The intent is to lose, in a controlled manner, that portion of the beam which has fallen outside given tolerances in the phase space region in localized areas where remote handling would be used for servicing.

The design and execution of the accelerator would be directed to achieving the same degree of reliability found in existing facilities (e.g., >90% at BNL, >85% at LAMPF, and >90% at SLAC). BNL operation during a 10 year history of the 200-MeV LINAC indicated that it averaged >90% of scheduled time. The Spallator would be designed to achieve 80% plant factor at a conservative power input to beam power output efficiency of at least 50%. Based on performance of the existing facilities mentioned above, this goal should be achievable.

## III. Spallation Neutronics

The collision of a high energy nucleon (proton or neutron) or pion with an atomic nucleus induces a variety of reactions. When a sufficient amount of momentum is imparted to an individual nucleon or pion, it can be driven (Spalled) out of the nucleus. The nucleus is then left in an excited state. In either event, the excited nucleus will decay via various possible channels: evaporative emission of particles (i.e., nucleons, pions, light atomic nuclei), $\gamma$-rays, and fission (for heavy nuclei with sufficient excitation energy). If the secondary particles emitted during the intranuclear-cascade process have enough energy, they can excite or cause spallation in other nuclei, producing an inter-nuclear cascade.

A number of experiments have been carried out to investigate the reactions induced by high energy particles. Of particular interest is how the yield of neutrons (which can be captured to produce fissile fuel) varies with the type and energy of the bombarding particle, and the type of target. Figure 4 shows neutron yield for protons as a function of energy and type of target, as measured by Fraser, et al.[16] Low Z materials (e.g., Be) have low neutron yields, since the principal neutron production channel for light nuclei is direct spallation, which has a low probability. High Z materials (e.g., Pb) have much greater neutron yields. The principal neutron production channel for heavy nuclei is evaporation, which has a high probability. Typically, several neutrons boil off from each excited compound nucleus.

In these experiments, the neutron yield from uranium targets is approximately a factor of two higher than from lead. This occurs because additional neutrons are generated by neutron induced fast fission of uranium. The average energy of the evaporated neutrons is high (about 5 MeV) and they cause substantial fast fission, even in normally non-fissionable $^{238}U$. A neutron yield of ~40 neutrons per GeV of particle energy was measured for protons incident on uranium at 1 GeV. By way of comparison, the net neutron yield in fission is only ~5 per GeV of energy release.

Neutron yield can be increased by using larger targets and/or targets with some fissile content (i.e., $^{235}U$ or $^{239}Pu$), or by using other types of particles (e.g., deuterons or tritons). The last option appears undesirable, even though neutron yield can be increased by 20 to 30%. Accelerators for deuterons and tritons are more difficult to construct, and activation is more of a problem.

Larger targets substantially increase neutron yield. In Frazer, et al's experiments,[16] target rod diameters were kept small (e.g., 10 cm) so that the generated neutrons could readily escape from the target into a surrounding water tank. The experiment was aimed at a high flux by neutron source, not a fissile fuel producer. Neutron multiplication by fast fission and (n,2n) reactions was substantially lower than it would have been in a neutronically thick target.

Neutron yield measurements for protons in large blocks of uranium (60 x 60 x 54 cm) were carried out by Vasil'kov.[17] The blocks were reflected with lead. Analysis of measurements were made at two proton energies, 400 and 660 MeV, and are summarized in Table 3. Experimental neutron yields (i.e., capture in $^{238}U$) are much higher than those of Frazer. An energy of 660 MeV, for example, yield is ~70 neutrons per GeV of particle energy, considerably greater than the ~40 measured by Frazer at a higher energy, 1 GeV.

The yield is quite non-linear with proton energy, increasing by over a factor of two when the energy increases from 400 MeV to 660 MeV. At lower energies, i.e., ~200 MeV, yield drops to a very small value, because most of the proton energy is lost to non-productive coulomb collisions. Neutron yield per GeV of particle energy will increase above 660 MeV, since a larger fraction of the proton energy goes into productive excitation of the nucleus. For particle energies >1 GeV, neutron yield per GeV becomes essentially constant, however. Although absolute yield per incident particle continues to increase, the efficiency (neutrons per unit energy) becomes constant. Experimental data is limited and generally taken on idealized targets. These are not like the ones that would be used in a production spallator, where the effects of structure, coolant, and leakage must be taken into account.

Analytical calculations of neutron yield can be made by the Monte Carlo method, using nuclear meson transport codes developed at Oak Ridge and Brookhaven (U.S.)[18,19] and Dubna (U.S.S.R.).[20] The codes directly model the nuclear interaction and trace the fate of all particles from the point of origin to capture by a nucleus, decay (for mesons), or leakage from the target. Although the total number of all elastic and inelastic collisions of the shower of particles with nuclei is very large and rises rapidly with the primary particle energy, modern computers permit reasonably accurate calculations, within a few percent statistical error, with a practical amount of computer time.

In our calculations of neutron yield, the NMTC/BFIS[21] Monte Carlo code is used to calculate all high energy reactions with excitation energy above 15 MeV. This version includes the effects of high energy fission, which is not taken into account in the original NMTC code, using Fong's model[22] based on statistical equilibrium at the scission point. In the energy range under 15 MeV, only the reactions induced by neutrons are calculated, using neutron transport codes such as ANISN[23] (1-dimensional) and TWO-TRAN[24] (2-dimensional) or the Monte Carlo code MORSE[25] (1 to 3 dimensions). The cross section set is taken from the DLC-37 library[26] which is based on the ENFB/D-IV file.[27]

Analytical predictions of neutron yield for Vasil'kov's conditions are compared with the experimental data in Table 3. They generally underestimate neutron yield. Garvey's calculations[28] substantially underestimate yield, principally because high energy fission is not included. In our old calculation for the 660 MeV case for example, which did not include high energy fission, a neutron yield of 28 was obtained, quite close to Garvey's value.

At higher proton energies, neutron yield should increase substantially. Our analyses predict that the neutron yield in large natural uranium blocks would be 110 neutrons per GeV of particle energy for protons incident at 1 GeV. Above 1 GeV, neutron yield per unit amount of energy is essentially constant.

Fraser has made additional experiments using protons at 480 MeV on uranium targets[29] of varying effective diameters. Analyses of these experiments are described in more detail elsewhere.[30] In general, the analytical predictions of neutron yield were smaller than the experimental values, except for the single rod case. Neutron yield increased with effective diameter of the assembly. Neutron yield is measured in Fraser's experiments as thermal captures in a water tank surrounding the assembly, while in Vasil'kov's experiments it is measured as productive captures in $^{238}U$. As targets became larger, a larger fraction of the generated neutrons will be captured in $^{238}U$. This effect, plus the larger target size in Vasil'kov's experiments, help to account for the difference in yields. Vasil'kov's results are more directly relevant to fissile production rate in spallators.

Russell[31] has recently measured neutron yield on a small uranium target, using the 800 MeV proton beam at LAMPF. We have analyzed this experiment and find that the experimental values are slightly smaller (~10%) than the predicted values. Alsmiller's[32] analyses show similar results.

In real Spallator reactors, the effects of structure, coolant, and leakage (which tend to decrease neutron yield) must be analyzed together with the effects of fissile content in the target (which tends to increase neutron yield). In addition, the energy released in the target per unit beam energy is important. For a 50% energy efficient accelerator and LWR-type power cycles, enough energy will be released in the target to generate the electrical power needed to provide the power to operate the accelerator.

Table 4 compares the fissile production rate and the energy release rate for various target materials and coolant. The target is similar to that described in the following section, with Zircaloy pressure tubes (CANDU type) and cladding. Net fissile production rate is shown, (that is, total production minus consumption). Calculations are made for a proton energy of 1.5 GeV, but yields are normalized per GeV of incident particle energy.

Uranium metal has the highest fissile production of the three fuels. Dilution by oxygen in $UO_2$ reduces the yield, while Th has a much lower fission cross section than $^{238}U$. The fissile fuel produced from Th targets ($^{233}U$) is neutronically superior to $^{235}U$ in reactors, however, and less of it is needed for makeup. Thus, essentially Th target Spallators are comparable to uranium targets in their ability to sustain a given number of power reactors.

In the calculation of nuclear reactions above 15 MeV with the NMTC code, the nuclear model is not suitable for light nuclei other than ordinary hydrogen. Consequently, $D_2O$ is assumed to act like $H_2O$ for reaction energies above 15 MeV. It appears likely that a more accurate calculation would raise fissile production rates from the $D_2O$ moderated cases in Table 4 by 5 to 10%.

Practical Spallators will have substantial fissile content, on the order of 2 to 3%, since they use spent fuel from the LWR reactors and essentially reenrich the fuel for recycle to the power producing reactors. Fissile production rates in Table 4 are calculated for targets with depleted uranium (0.3% $^{235}U$). Our recent calculations indicate that increased fissile content in the target will not change the neutron yield and net fissile production rate. The increased fissile content will produce increased energy released in the target sufficient to supply power to the accelerator.

Additional experimental data are needed to more fully define the neutronics of Spallator reactions; however, the analytical predictions appear reasonably accurate, and give results that are very encouraging.

## IV. Spallator Targets

In some ways, Spallator targets will be similar to conventional nuclear reactors, and in some ways quite different. When the high current, high energy particle beam interacts with the target, copious quantities of neutrons and heat are generated. Target design is shaped by the objectives of maximizing the yield and utility of neutrons (which are captured to generate fissile fuel), while keeping heat removal requirements and radiation damage effects with-in practical limits.

Like nuclear reactors, Spallator targets for the production of fissile fuel contain uranium, and will inevitably have a substantial inventory of fission products. Cooling and safety systems are thus required to ensure adequate heat removal at all times, including after shutdown.

Spallators with non-uranium primary targets are possible, such as the lead target design developed by BNL,[33] in conjunction with the Nuclear Alternative Systems Assessment Program NASAP effort.[34] Such designs do not have an after heat removal problem in the primary target; however, it is not possible to eliminate all fission in the secondary fertile uranium region where the neutrons are captured. Thus adequate cooling and safety systems are still needed, though their requirements are considerably less.

Spallators are also of great interest for high flux neutron research. In these devices, it is not necessary to use uranium, so that there is no fission product hazard, and no concern about aftercooling. For example, the proposed SNQ spallation facility[35] in the Federal Republic of Germany would generate neutron fluxes comparable to these in high flux research reactors, using a non-uranium target.

The fissile production rate in Spallators with non-uranium primary targets is only about half that with uranium primary targets, and their fissile fuel unit production cost is correspondingly greater. For this reason, production Spallators will probably use primary uranium targets.

In contrast to conventional reactors, however, Spallator targets are strongly subcritical. They cannot have criticality accidents and do not require safety or control rod systems. Flux and power distributions are primarily determined by proton slowing down characteristics, rather than by neutron transport in the lattice. In addition, neutron production is not strongly dependent on the thermal cross section properties of the lattice, therefore, the designer has more freedom in selecting materials than is the case with conventional reactors.

Figure 5 shows the proposed design for a Spallator target. The triangular shaped cavity forms a hohlraum for the neutrons generated by the particle beam, and minimizes leakage. The proton beam enters through a relatively small opening at the left of the cavity, and impinges on a lattice of pressure tubes containing target assemblies.

Prior to entering the target cavity, the proton beam is defocused by a quadrupole magnet. By the time the beam hits the pressure tube lattice, the beam envelope has expanded into a vertically-elongated narrow ellipse, with the long axis running in the same direction as the pressure tubes. The elliptical beam is swung horizontally back and forth across the target lattice by a second magnet, at relatively high frequency (e.g., 1 kHz). The temperature variation in the target assemblies and coolant is very small during the beam swing, less than a tenth of a degree Kelvin. The thermal-hydraulic response of the target lattice will be steady state, for all practical purposes.

The target lattice is similar to that in CANDU reactors,[36] except that the pressure tubes are closely spaced and there is no $D_2O$ moderator between them. Pressure tube orientation can be horizontal, as in most CANDU reactors, or vertical, as in the Gentilly reactor.[37] Typical Spallator target assemblies, shown in Figure 6, are very similar to CANDU assemblies. The rod bundles can be loaded and unloaded while the Spallator is operating, as in the CANDU reactors. The fueling machine is simlar to the CANDU machine, except that the attaching head is redesigned because of the closer pressure tube spacing.

The proton beam first strikes the face of the main lattice at the rear of the target cavity. The lattice is thick enough (e.g., 2 meters) to stop virtually all of the protons. Shielding behind the lattice reduces residual radiation to an acceptable level for personnel. Collisions cause the protons to deflect somewhat from their original trajectory as they traverse the lattice, but back-scattering from the target face is negligible, because of their very high momentum.

Neutrons generated near the target face can leak out, however. The effect of this leakage is minimized by placing additional rows of pressure tubes along the sides of the target cavity. Neutrons leaking from the primary target lattice interact with the fuel assemblies in this secondary region, producing fissile fuel. The upper and lower surfaces of the target cavity are lined with neutron reflecting graphite.

Three-dimensional Monte Carlo neutronic calculations of a Spallator target cavity have been carried out. The neutron yield for the actual target/cavity configuration is slightly less, ~5%, than the yield calculated for an idealized one-dimensional configuration with no neutron leakage. This indicates that the cavity hohlraum does effectively conserve neutrons and minimizes leakage.

There is a wide range of coolant options for the Spallator, including pressurized water or boiling water ($H_2O$ or $D_2O$), organic, gas (e.g., He or $CO_2$) and liquid metal (e.g., Na). The low-pressure coolants (organic or liquid metal) are attractive, since tube wall thickness and stress can be reduced. In our design, however, we have concentrated on existing technology, pressurized and boiling water systems, using light water ($H_2O$). The slightly higher neutron yield with heavy water ($D_2O$) coolant probably is not economically justified. The pressurized water coolant system would be virtually identical to the present CANDU system, while the boiling water system would be similar to present BWR systems. Vertical pressure tubes would be used with boiling water coolant, as in the Gentilly reactor.[37]

There is also a wide range of material options for the pressure tubes and fuel cladding, since neutron yield is not determined by criticality. For example, analyses show that stainless steel, which severely degrades breeding ratio in conventional LWR's, can be used in Spallators without significantly affecting fissile production rate. However, our designs have used Zircaloy for the pressure tubes and cladding, because of the large amount of technical data available on it.

Target and power cycle parameters for the Spallator are summarized in Table 5. As presently configured, the target is strongly based on CANDU technology, using similar types of pressure tubes and fuel assemblies, similar materials and coolant (except that $H_2O$ is used instead of the more costly $D_2O$), and similar fuel handling equipment and management procedures. The high plant factors achieved in CANDU reactors (over 90% in some cases) as a result of on-line fuel reloading and shuffling should also be practical in Spallators. A conservative 75% plant factor has been assumed in our study.

In effect, the Spallator target has a vacuum calandria instead of the $D_2O$ moderator calandria used in CANDU reactors. This appears practical, with the tube/calandria seals acting to prevent vacuum leaks rather than $D_2O$ leaks. Some minor in-leakage to the target vacuum chamber will probably occur through seals as well as small cracks in pressure tubes. Vacuum quality in the cavity does not have to be high; a vacuum of $10^{-3}$ Torr, for example, is quite acceptable. High vacuum is required in the accelerator structure; however, there is a long (~100 meter) transition section between the accelerator and the target building, so that differential pumping can easily reduce pressure to the $10^{-5}$ to $10^{-6}$ Torr level required in the accelerator.

Safety considerations for the accelerator will be similar to those in conventional nuclear reactors, (in particular CANDU's) with the exception that criticality accidents are not of concern. Emergency cooling systems will be required to ensure that adequate cooling is maintained if the main coolant pumps or pressure tubes fail. High-and low-pressure injection systems (both in duplicate) will be needed, with independent pumps.

The target containment building (Figure 7) will be similar to standard reactor containment structures, with isolation valves for the beam line, residual heat removal systems, sprays, etc. Construction and licensing procedures will be similar to those for conventional reactors, as will unit costs for heat exchangers, steam generators, turbine generators, etc. Overall unit power generation costs in \$/kW(e) for the Spallator will probably be similar to those for conventional reactors, i.e., ~\$1000/kW(e) (1980 dollars).

Fuel and cladding residence times are short, compared with the time necessary for serious materials damage by neutrons and protons in the target to occur. Neutron damage effects on Zircaloy have been extensively investigated, and the pressure tubes should be suitable for service over the 30-year life of the Spallator. Proton damage effects are less certain. High energy proton fluence is approximately an order of magnitude smaller than energetic neutron fluence (>0.1 MeV), and displacement damage effects from protons should be small compared with those from neutrons. Because of the large frontal area of the target the proton current per unit area is very small, on the order of 2 microamps/cm$^2$.

Interstitial H and He generation in pressure tubes by (p,2p) and (p,$\alpha$)-type reactions are a potential problem. However, preliminary estimates indicate service life of at least 10 years before embrittlement effects could become troublesome for tubes in the front part of the target. It could be feasible to periodically replace pressure tubes, if required. Large numbers of pressure tubes with hydrogen cracking problems were replaced in some CANDU reactors, for example. Alternatively, the target frontal area could easily be increased, which would reduce neutron and proton damage rates. The target size, indicated in Table 5, was chosen to have a maximum power density similar to that in present conventional reactors. Target size could easily be made larger, however.

Material irradiation tests at representative proton/neutron fluence conditions are needed before a detailed engineering design of a Spallator can be made. Fortunately, these data can be obtained in a few years using presently available accelerators such as LAMPF. The 800-MeV, 2 mA beam has sufficient energy and intensity to test reasonable size samples (i.e., ~100 $cm^3$) at the integrated fluence conditions characteristic of 10 to 20 years Spallator operation.

Overall, the target system in the Spallator appears relatively straighforward. It is based for the most part on existing CANDU technology. Materials performance in the proton beam is probably the principal uncertainty, and this could be resolved in a short time by irradition tests in existing accelerators.

## V. Spallator-Power Reactor Fuel Cycle

There are a number of alternative fuel cycles that can be advantageously used in applying the Spallator for production of fuel for LWR power reactors. One example, compatible with present day practice, is described here. Zircaloy clad U metal target elements cooled by light water in Zircaloy pressure tubes are assumed for the target assembly. Referring to Figure 1 and assuming an equilibrium fuel cycle, spent fuel from the LWRs containing approximately 2.5% fissile material (Pu-239, Pu-241 and U-235) is sent for refabrication into a target element. Depending on the design of the Spallator target, the spent $UO_2$ fuel could be inserted directly into the Spallator target or reprocessed for purposes of recycling and increasing the Pu concentration in the target, thus enhancing the Pu yield. In the present example, the spent $UO_2$ fuel is not reprocessed prior to being placed into the target. In the target there is a net production of Pu which increase the content from 2.5% to approximately 3.5% fissile material. The enriched material from the target is then sent for reprocessing to eliminate the fission product waste. Conventional Purex reprocessing of spent fuel uses acid dissolution of the fuel elements and tributyl phosphate (TBP) for separation and concentration of the U and Pu.[38] The separated U and Pu with the addition of makeup natural $UO_2$ are fabricated into fresh LWR fuel elements. The fission product waste is stored in tanks for several years and is eventually disposed of by long-term storage in geological-age formations.

An alternative fuel cycle named APEX which recycles the long-lived fission product waste so as to avoid geological-age storage of fission product waste is shown in Figure 8.[39] In this fuel cycle which is uniquely suited to the utilization of the Spallator only the short-lived (≤2 yr half-life) and non-radioactive fission products (SLFP and NRFP) are extracted from the spent LWR fuel and the long-lived fission products (LLFP, mainly Cs and Sr) and the transuranics (TRU, mainly Pu, Am and Cm) are recycled without separation, to the Spallator, to be reenriched with fissile Pu for makeup into fuel elements for the LWR power reactors. The short-lived and non-radioactive fission products are stored in tanks for periods of 10 to 20 half-lives (~20 to 40 yrs) for decay to background levels where they can be returned to the U ore mines or disposed of in a more conventional manner. Because of their low neutron cross sections [<1 barn), the long-lived fission products will reach equilibrium concentrations mainly through the process of decay. The transuranics on recycling reach equilibrium concentration through the process of fission. Because of their high thermal neutron cross sections (100's of barns) the transuranics reach equilibrium concentration values in a relatively short period of time due to transmutation of the even mass-numbered isotopes and by fissioning of the odd mass-numbered isotopes.[39] Since only the non-radioactive stable fission products are extracted from the fuel cycle, long-term storage of waste in geological-age formation could therefore be avoided. The concentration of fissile fuel will be increased by production of Pu-239 from U-238 in the Spallator and the Pu-239 is fissioned (burned) in the LWR reactors to produce power.

The APEX flowsheet also indicates the use of an alternative to the Purex process for reprocessing of fuel. A β-diketonate chelating agent could potentially separate the short-lived and non-radioactive fission products in a non-aqueous system.[40] The Pu and transuranics would remain in the $UO_2$ without separation.

Because of the small neutron cross sections of Cs-137 (0.1 barn) and Sr-90 (1.0 barn) which have half-lives of approximately 30 yrs, the inventory of these long-lived fission products will buildup in the fuel cycle. In order to reduce the inventory and essentially reduce their effective half-lives it is possible to transmute the long-lived isotopes in a specially designed high flux Spallator target assembly. The rate of transmutation of the radioactive isotope is presented by,

$$\frac{dn}{dt} = n\ (\sigma\ \phi + \lambda)$$

where n is the number of fission products atoms remaining, $\sigma$ is the neutron cross section ($cm^2$), $\phi$ is the neutron flux (neutrons/$cm^2$-sec) and $\lambda$ is the isotope decay constant ($sec^{-1}$). In order to transmute the Cs-137 and Sr-90 at a rate 10 times faster than the decay rate, a neutron flux of $10^{17}$ n/$cm^2$-sec is required. A Spallation target having this flux magnitude has been designed, consists of a liquid Pb or solid $UO_2$ primary target surrounded by $Cs_2O$ and SrO containing blanket, a graphite reflector and cooled with heavy water ($D_2O$).[41]

Based on the specific target design given in Table 5, Table 6 gives the production capacity and characteristics of a Spallator employing a 2 GeV proton at a beam current at 300 mA. The beam power is thus 600 MW. At a reasonable accelerator efficiency of 50% (power input to beam power output), 1200 MW(e) is needed to drive the accelerator. A U metal/Zr clad target element inside of a pressurized Zr water cooled tube with a fuel to moderator ratio of 2.37, yields a net production of 94 fissile atoms/GeV incident proton. This translates to 3300 kg/yr of Pu-239 or enough Pu capacity to supply 9-1000 MW(e) conventional power LWRs at a 75% plant capacity factor and 0.6 reactor conversion ratio. The target is also designed with a power producing zone so that 3600 MW(t) heat is generated in the target which is used to produce 1200 MW(e) of electricity by means of a steam power cycle. This amount of power is enough to drive the linac thus making the installation self-sufficient. No external power source is required except for startup. The fissile fuel content in the spent fuel from the LWR is in the order of 2.5% and the concentration in the fuel fed to the LWR is enriched to 3.5%. An LWR power reactor requires a Pu-239 makeup of approximately 360 kg/yr. Fuel shuffling in the target will be required to maintain a level power density distribution.

Based on the above capacity characteristics, a preliminary comparative economic evaluation of the Spallator with respect to other systems can be made. An estimate of the Spallator construction cost is given in Table 7. The linear accelerator estimate is based on construction costs for existing research machines[33] and has been escalated to 1980 dollars. The target is essentially a subcritical assembly resembling a power reactor without control rods and therefore its cost estimate is comparable to a power reactor assembly. Table 8 shows a comparative lifetime capital investment estimate for four cases each generating an equalized total amount of power of 9000 MW(e) as follows: 1) A Spallator providing fuel for 9-1000 MW(e) LWRs, 2) 9 conventional 1000 MW(e) LWR reactors supplied with enriched U-235 fuel, 3) 9-1000 MW(e) LWRs with Pu recycle and 4) an LMFBR breeder/LWR cycle which requires 6-1000 MW(e) breeders providing enough fuel for 3-1000 MW(e) LWRs based on a 20 year breeder Pu doubling time, the combination producing a total power output of 9000 MW(e). Based on these reasonable cost assumptions, the Spallator/LWR economy indicates a 14% lower total lifetime capital investment than the fast breeder/LWR economy. This mainly results from the assumption that the present projected cost of a breeder is 70% greater than an LWR.[42] The investment in the Spallator is less than the total incremental investment in the 6 breeders supplying 3 LWRs. Even at a 30% breeder incremental cost projected for the long-term, the Spallator is still competitive with the breeder system. Although the inventory of fissile material is higher for the breeder than for the LWR, the inventory required for the Spallator in addition to the LWRs will be about the same as for the breeder systems. Reprocessing and fuel fabrication will also be about the same for these two cases. One can argue that the breeder is much more technically advanced than the Spallator and that a development cost must be added.

A development estimate of $0.1 $\times 10^9$ added to the Spallator would not change the conclusion that the Spallator/LWR system is competitive with the LMFBR/LWR system.

It also appears from Table 8 that the Spallator is highly competitive even with the present U-235 fuel enriched LWRs with no recycle and also competitive with Pu recycle. Furthermore, the Spallator breeds fissile fuel, while the U-235 enrichment essentially depletes the natural fissile material and thus eventually must be replaced with a breeding system.

## VI. International Interest

In addition to the studies that have been performed in the U.S. several studies of Spallators have taken place in other countries. There has been a continuing interest in Canada to develop a Spallator for breeding fuel for the CANDU reactors especially for the U-233 thorium fuel cycle.[44] A long-range program exists to prove out the accelerator design and construction in several stages. The first stage is to prove out a full current cw machine at 300 mA and low energy 10 MeV; the second stage is to raise the energy to 200-MeV and the final stage is to raise the energy to 1000 MeV where production design conditions can be proven.

In Germany, at Julich a Spallator is to be constructed as a research machine to produce an intense source of neutrons (SNQ).[43] The design, a low current time average 5 mA beam with full energy of 1.1 GeV is designed to impinge on a rotating lead target for better heat and radiation dissipation. Time average fluxes of $7 \times 10^{14}$ n/cm$^2$ sec and peak fluxes in the order of $1.3 \times 10^{16}$ n/cm$^2$ sec are expected. This research neutron source could act as a forerunner of larger production Spallators.

In Japan, studies have been conducted on a fluid molten salt target containing fertile material to obtain better heat transfer in the target and produce maximum yields of fissile material by continually proces ing the molten salt stream[45]

In the Soviet Union, there has been interest in measurement of the neutron yields in large targets[46] which can serve as a basis for Spallator designs.

## VII. Summary

The advantages of the Spallator/LWR nuclear power economy in conjunction with the APEX fuel cycle are as follows:

1. The Spallator is a single purpose machine which essentially enriches spent LWR fuel and assures a long-term supply of fissile fuel for the presently acceptable LWR power reactor economy. One 600 MW(e) Spallator can supply fuel for at least 9 other 1000 MW(e) LWRs.

2. With the Spallator, the utilities need not replace their present LWR power reactor technology with a new power reactor technology, e.g., the LMFBR, which is still a long way from being accepted by a regulatory agency in the U.S.

3. The Spallator is based on a near term technology of linear accelerators and target assemblies as compared to a fusion plasma combined with a fissile fuel producing blanket concept (fusion-fission hybrid) which is yet to be demonstrated in a scientific feasibility experiment.

4. The Spallator fissile fuel producer is an independent self-sufficient machine which does not require power from the utility grid, as compared to enrichment plants which consume power or to the liquid metal fast breeder which produces power for the grid.

5. The projected economics of the Spallator is competitive with the fast breeder.

6. The Spallator target is a subcritical assembly which shuts itself down when the proton beam is lost. By supplying a number of LWRs, the incremental risk due to operation of the Spallator is minimized.

7. The APEX fuel cycle in conjunction with the Spallator extracts only the stable fission product waste and recycles the transuranics and long-lived fission products which reduces the need for long-term geological age storage of nuclear waste material. A high flux Spallator can transmute and further reduce fuel cycling inventory of the long-lived fission products.

Although a considerable development effort and probably more than a decade would be needed to bring the Spallator into production, it is a highly worthwhile effort considering that this technology could be more acceptable to both the public and industry in projecting a long-term nuclear power economy.

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TABLE 1

PARAMETERS OF RELEVANT ACCELERATORS

| Accelerator Laboratory | Type | Ion Type | $E_{max}$ MeV | $I_{max}$ Amp. | Duty Factor % | Status |
|---|---|---|---|---|---|---|
| LASL-LAMPF | linac | proton | 800 | 0.020 | 12 | op. |
| LLL-A48 | linac | deut. | 7.5 | 30 | 100 | op. |
| BNL-AGS | linac | proton | 200 | 0.2 | 0.5 | op. |
| FNAL | linac | proton | 200 | 0.3 | 0.2 | op. |
| HEDL-FMIT | linac | deut. | 35 | 0.1 | 100 | under constr. |

TABLE 2

BASIC LINAC DESIGN PARAMETERS FOR THE SPALLATOR REFERENCE CONCEPT

| | |
|---|---|
| Final energy | 2000 MeV |
| Beam Current | 300 mA |
| Duty factor | 100% |
| Efficiency Energy Output/Input | 50% |
| Injection System: | |
| Energy | 2 MeV |
| Ion source, protons | bucket type |
| Buncher, preaccelerator | RFQ |
| Drift-tube linac: | |
| Energy | 2 to 150 MeV |
| Frequency | 150 MHz |
| Accelerator gradient | 1.25 MeV/m |
| Disc- and washer-linac: | |
| Energy | 100 to 2000 MeV |
| Frequency | 450 MHz |
| Accelerator gradient | 1.5 MeV/m |
| Total accelerator length | 1500 m |

TABLE 3

ANALYSIS OF VASIL'KOV's EXPERIMENT FOR HIGH ENERGY PROTONS INCIDENT ON LARGE URANIUM BLOCK

| | Proton Energy MeV | Experiment | BNL Calculation | Garvey's *(28) Calculation |
|---|---|---|---|---|
| Capture $^{238}U$ | 660 | 46.0 ± 4.0 | 42.6 ± 4.8 | 29.9 ± 1.6 |
| Fission $^{238}U$ | | 14.6 ± 1.3 | 11.3 ± 1.2 | 5.2 ± 0.3 |
| $^{235}U$ | | 3.9 ± 0.4 | 2.44 ± 0.2 | 1.6 ± 0.1 |
| Total fission | | 18.5 ± 1.7 | 13.74 ± 1.4 | 6.8 ± 0.4 |
| Total Yield | | 64.5 | 56.3 | 36.7 |
| Capture $^{238}U$ | 400 | 22.1 ± 2.4 | 16.2 ± 2.0 | 10.9 ± 0.6 |
| Fission $^{238}U$ | | 7.0 ± 0.8 | 4.5 ± 0.6 | 2.1 ± 0.6 |
| $^{235}U$ | | 1.9 ± 0.2 | 0.96 ± 0.1 | 0.7 ± 0.1 |
| Total fission | | 8.9 ± 1.1 | 5.46 ± 0.7 | 2.8 ± 0.2 |
| Total Yield | | 31.0 | 21.6 | 13 / |

*High energy fission is not included in the calculation.

TABLE 4

FISSILE MATERIAL (Pu OR $^{233}U$) PRODUCTION MODE

| Fuel | Moderator | Neutron yield >15 MeV reaction | Net fissile element[a] production rate atoms/GeV-p | Total fission energy[b] GeV/GeV-p | Total[c] Energy GeV/GeV-p |
|---|---|---|---|---|---|
| $UO_2$[d] | $H_2O$ | 51.25 ± 3.75[e] | 60.94 ± 4.46 | 2.85 GeV | 3.65 |
| | $D_2O$ | | 59.48 ± 4.35 | 2.20 | 3.0 |
| U[d] | $H_2O$ | 71.79 ± 3.59[e] | 93.58 ± 4.68 | 3.74 | 4.54 |
| | $D_2O$ | | 97.38 ± 4.87 | 3.81 | 4.61 |
| Th | $H_2O$ | 57.10 ± 3.03 | 59.06 ± 3.13 | 1.08 | 1.88 |
| | $D_2O$ | | 59.61 ± 3.16 | 1.04 | 1.84 |

Calculated for incident proton energy of 1.5 GeV; the above values are normalized per GeV proton energy.

[a] Production of fissile element (e.g., $^{239}Pu$) minus consumption of fissile element ($^{235}U$).
[b] 200 MeV fission energy is assumed in target.
[c] Total Fission and beam energy in target (includes endothermic energy requirements for beam-induced neutron release from target nuclei).
[d] Depleted uranium (0.3% $^{238}U$).
[e] In NMTC (BNLF) calculation, deuteron atom is treated as hydrogen atom, stripping reaction will increase neutron yield (probably 5 to 10%).

NOTE: Volume fractions are: fuel (0.64), moderator, (0.27), and tube/clad (0.09).

TABLE 5

SPALLATOR TARGET PARAMETERS

| | |
|---|---|
| Beam Energy | 2 GeV |
| Beam Current | 300 mA |
| Target Power | 3600 MW(th) |
| Electric Generation | 1200 MW(e) |
| Primary Target | |
| Height (Along Tubes) | 3 meters |
| Width | 5 meters |
| Depth (100% d.f.) | 1 meter |
| Driven Subcritical Zone | |
| Width | 6 meters |
| Depth | 1 meter |
| Moderator/Fuel Ratio | |
| Primary Target | 0.5/1 |
| Driven Subcritical | 2/1 |
| Peak/Average Power Ratio | 1.5/1 |
| Average Power Density | 110 kW/liter |
| Fuel Rod Diameter (Both Zones) | 0.42 in. |
| Pressure Tube Diameter, o.d. | 6 in. |
| Pressure Tube Wall Thickness | 0.18 in. |
| No. of Rods in Fuel Assembly | 124 |
| Fuel Assembly Length | 20 in. |

TABLE 6

THE SPALLATOR

Accelerator Spallation Reactor

Production Capacity and Design Characteristics

| | | |
|---|---|---|
| Proton Energy | - | 2 GeV |
| Net Fissile Atom Yield for U/Zr clad-$H_2O$ cooled | - | 94 Fissile Atoms/GeV-Proton |
| Current CW | - | 300 mA |
| Beam Power | - | 600 MW |
| Accelerator Efficiency | - | 50% |
| Power to Accelerator | - | 1200 MW(e) |
| Power Generated in Target | - | 3600 MW(t) (Self-Sufficient) |
| Plant Factor | - | 75% |
| $Pu^{239}$ Fissile Fuel Production Rate | - | 3300 kg/Yr |
| Fissile Fuel Needed for 1-1000 MW(e) LWR 75% P.F. and 0.6 C.R. | - | 360 kg/Yr |
| No. of 1000 MW(e) LWRs Supported | - | 9 |

TABLE 7

THE SPALLATOR

Accelerator Spallation Reactor

Capital Investment
1980 Dollars

| | | |
|---|---|---|
| Linear Accelerator = \$1000/KW(e)* x 600 MW = | | $\$600 \times 10^6$ |
| Target = 1200 MW(e) x \$1000/KW(e)* | = | $1,200 \times 10^6$ |
| | Total Cost | $\$1,800 \times 10^6$ |

* Based on ref. [2] and [6]. Earlier estimates indicated a unit cost for the accelerator of \$560/KW(e) of beam power. For this comparative estimate we practically doubled the cost to \$1000/KW(e) to account for escalation and contingencies.

** Target cost is assumed to be equal to an LWR power reactor in terms of unit power generation.

## TABLE 8

## NUCLEAR ENERGY ALTERNATIVE SYSTEMS COMPARISON

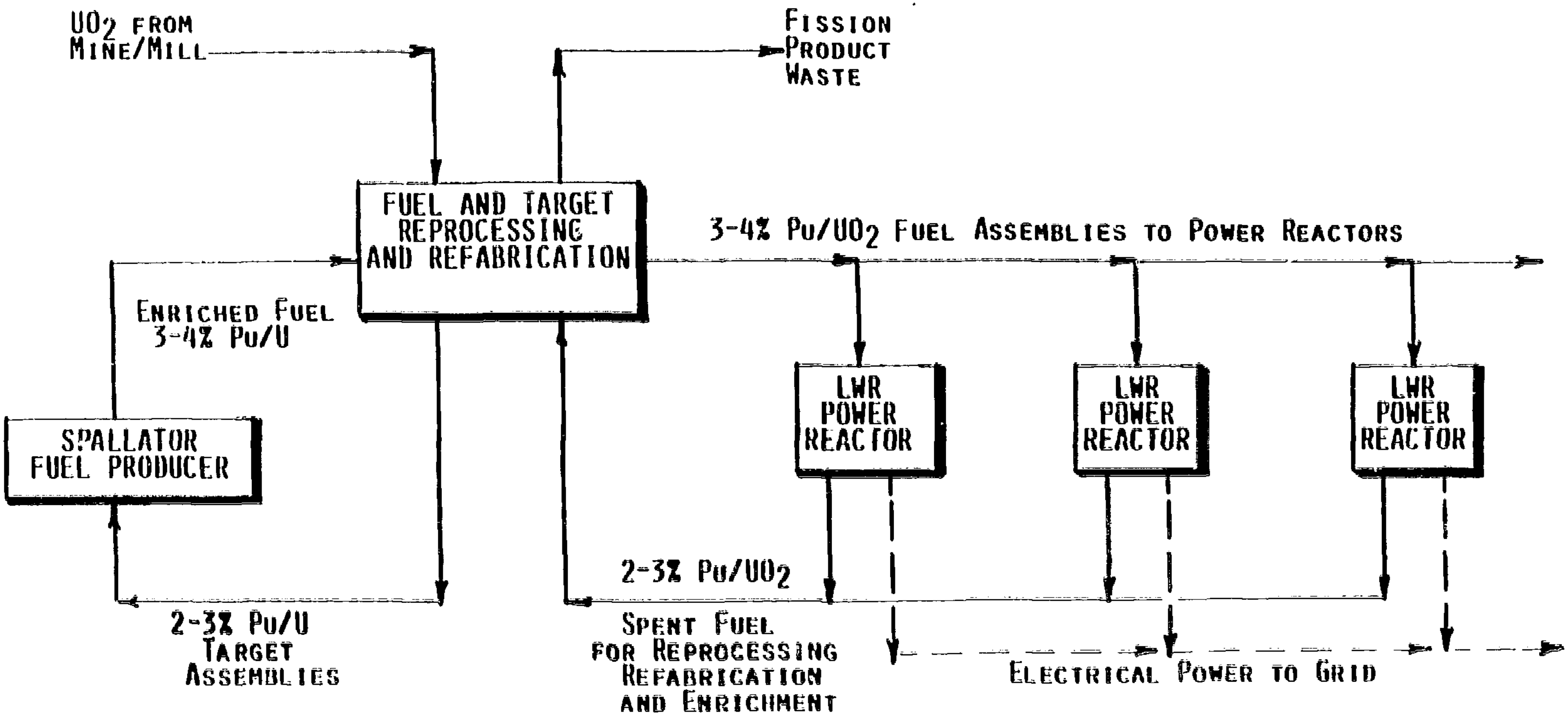
Lifetime Capital Investment 1980 Dollars

| | | Spallator 1 S/9 LWRs | LWR No Recycle | LWR With Recycle | Breeder (LMFBR) 6 Breeder/3 LWR |
|---|---|---|---|---|---|
| No. of Reactors (1000 MW(e)) | | 9 | 9 | 9 | 9 |
| Capital Cost ($1000/KW(e)) | LWRs | $9.0 x 10^9$ | $9.0 x 10^9$ | $9.0 x 10^9$ | $3.0 x 10^9$ |
| | Breeders | ———— | ———— | ———— | $10.2 x 10^9$* |
| Capital Cost of Spallator | | $1.8 x 10^9$ | ———— | ———— | ———— |
| Nat. U Feed (30 Yrs) | | Negligible | 54,000 MT | 18,000 MT | Negligible |
| Enriched Fuel - MT U-235 | | ———— | 243 MT (3.0%) | 81 MT (33%) | ———— |
| Total Cost of Nat. U Feed at $40/lb | | ———— | $4.3 x 10^9$ | $1.4 x 10^9$ | ———— |
| Cost of Enrichment, $100/SWU | | ———— | $2.9 x 10^9$ | $1.6 x 10^9$ | ———— |
| Fissile Material Inventory*** | | 61 MT | 47 MT | 47 MT | 59 MT |
| Fissile Inventory Cost at $40/gm | | $2.4 x 10^9$ | $1.9 x 10^9$ | $1.9 x 10^9$ | $2.3 x 10^9$ |
| Cost of Reprocessing Plant** | | $0.3 x 10^9$ | ———— | $0.3 x 10^9$ | $0.3 x 10^9$ |
| Cost of Fuel Fabrication Plant** | | $0.3 x 10^9$ | Negligible | Negligible | $0.3 x 10^9$ |
| Cost of Waste Storage | | Negligible | $1.4 x 10^9$ | Negligible | Negligible |
| Total Cost | | $13.8 x 10^9$ | $19.5 x 10^9$ | $14.2 x 10^9$ | $16.1 x 10^9$ |

* There is a projected 70% cost differential between a 1000 MW(e) LWR ($1 x 10^9$) and a (1000 MW(e) LMFBR (1.7 x $10^9$).

** Estimated total cost of reprocessing plant is $1.5 x 10^9$ for reprocessing fuel from 60 LWRs. Hot Fuel Fabrication Estimated to be Equal to Reprocessing.

***Fissile Material Inventory for 1 S/9 LWRs = 61 MT (23.4 in/out of LWR; 6.5 in/out Spal) for 5 Breeder/3 LWRs 59 MT (29.4 in-core and 29.4 out-of-core) - (1 LWR core contains 2.6 MT; 1 LMFB core contains 3.6 MT).




Spallator Supplying Fuel for Light Water Power Reactors (LWRs)

Figure 1

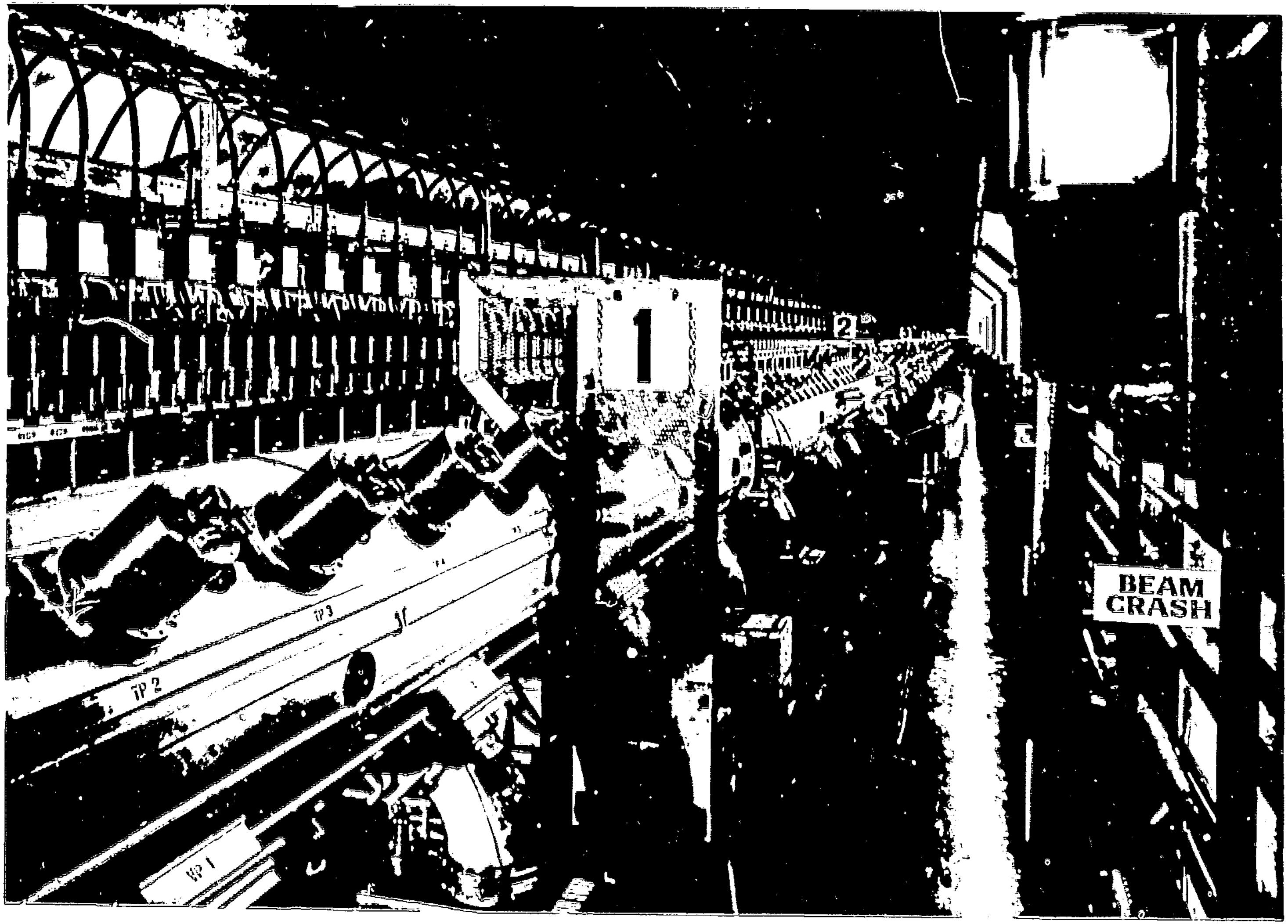
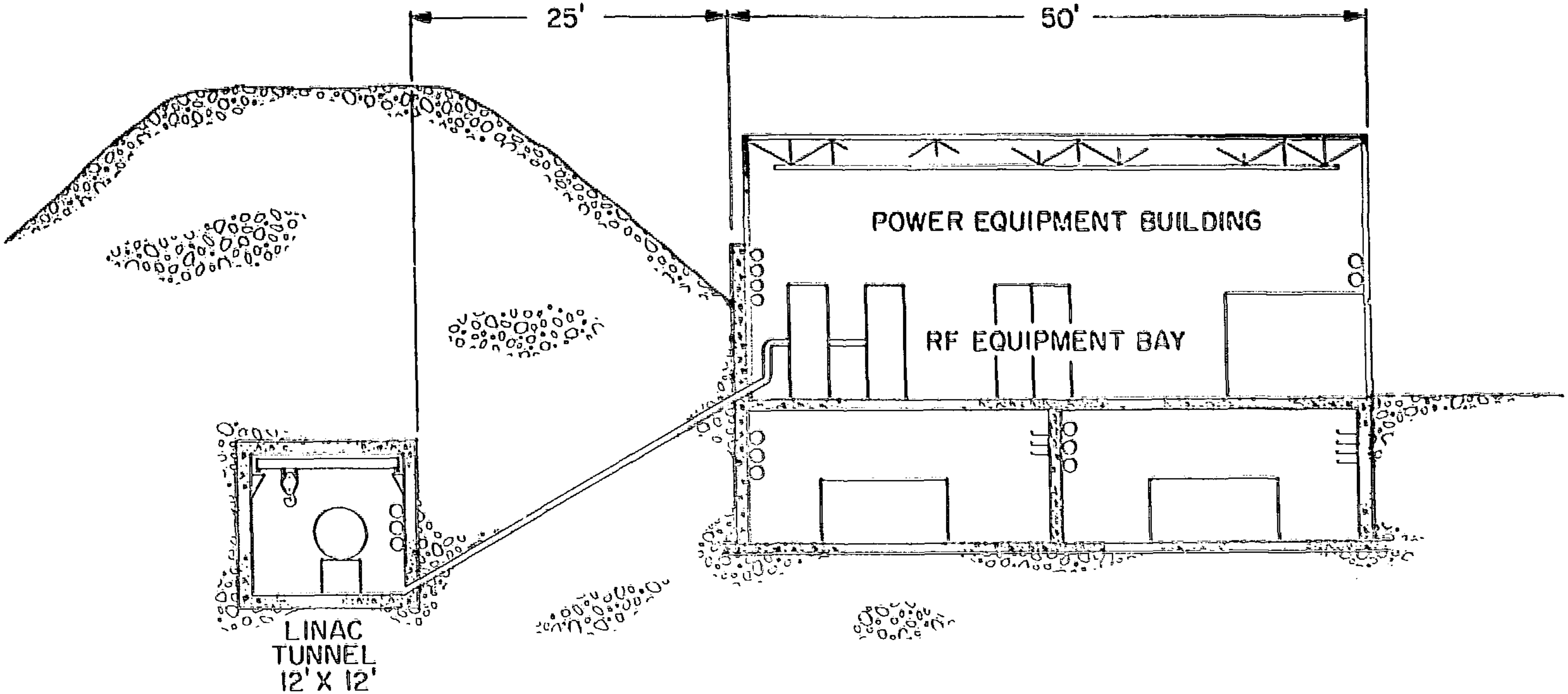
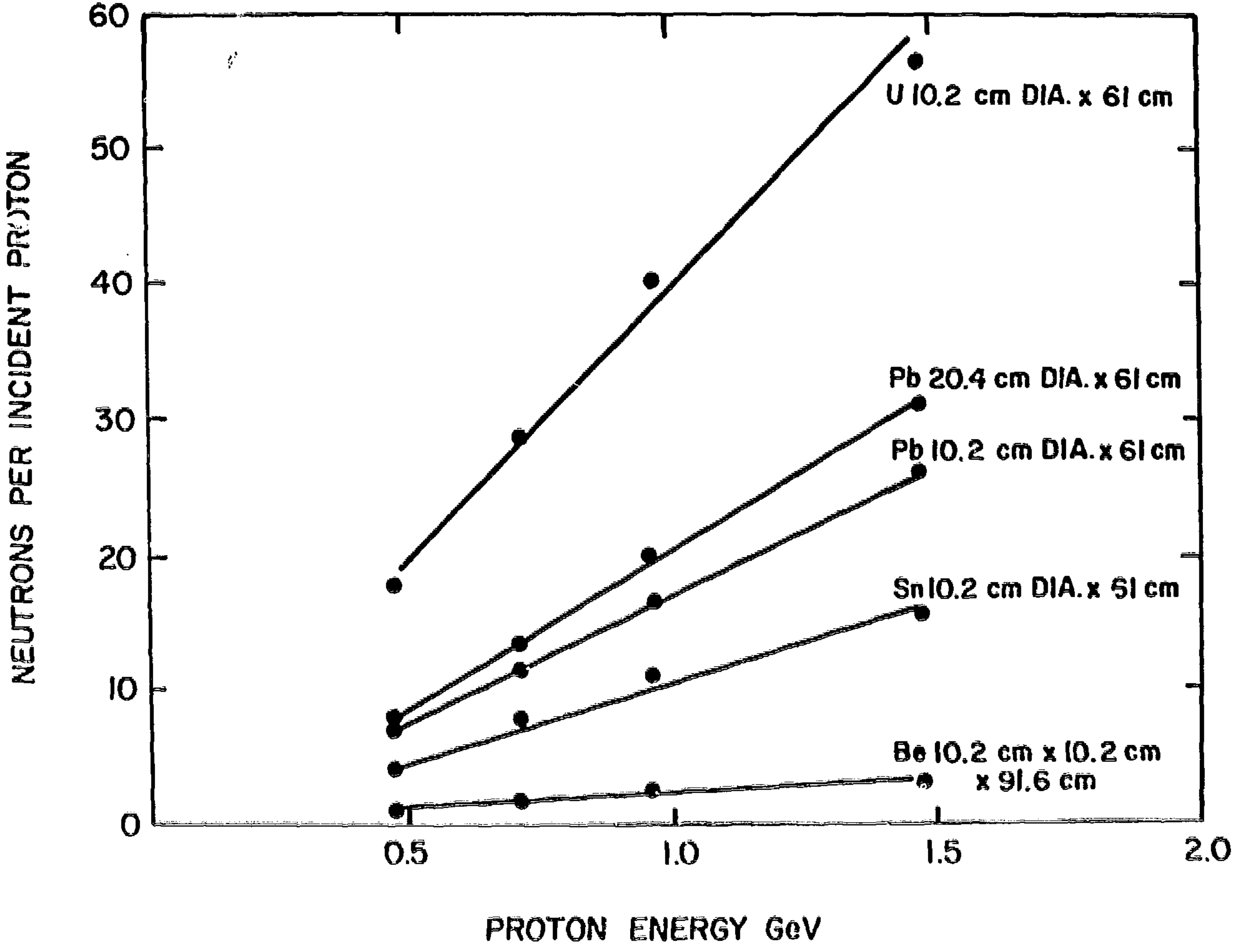



FIGURE 2. Brookhaven National Laboratory 200 MeV Proton Linac.



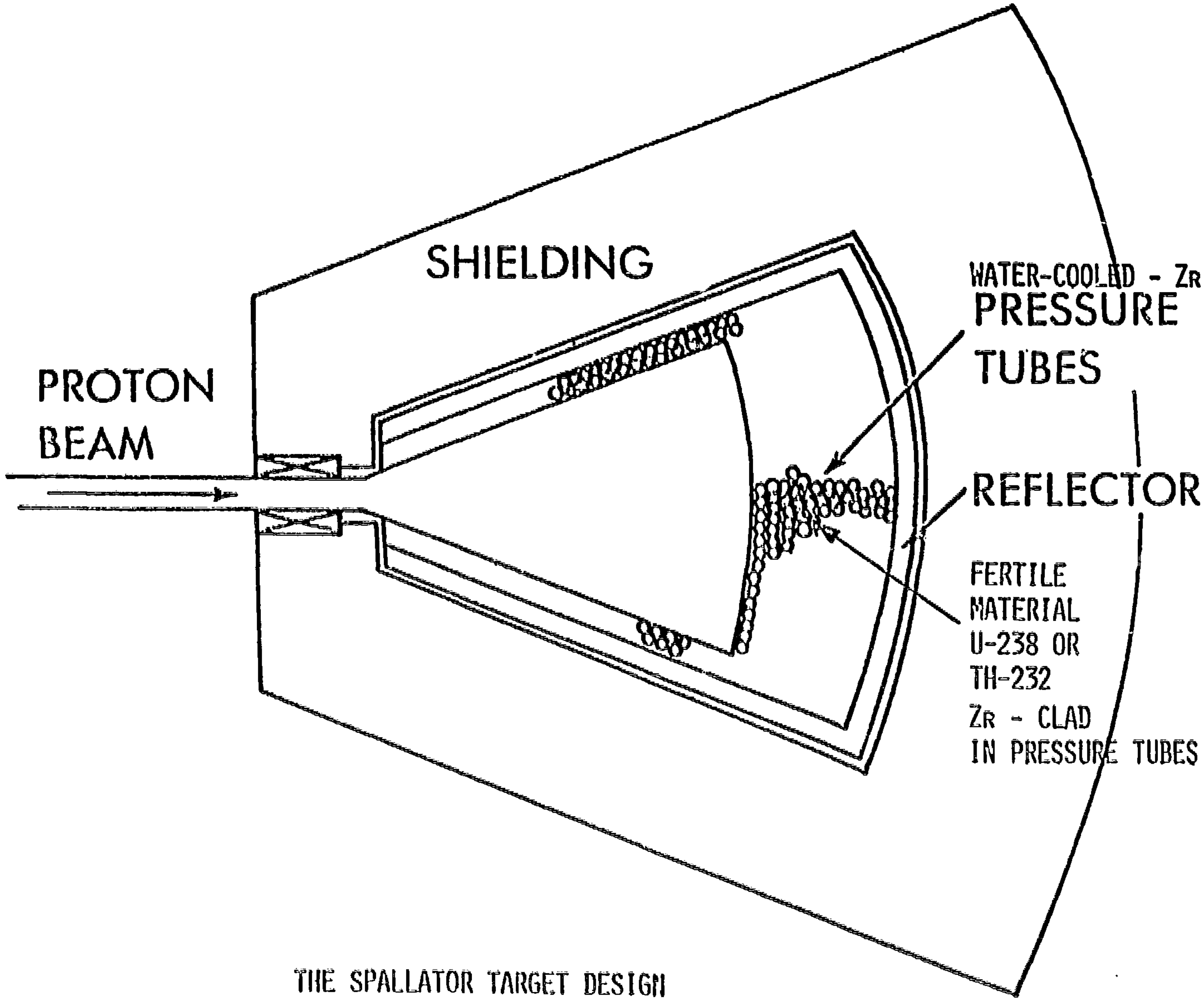

LINEAR ACCELERATOR CROSS SECTION

FIGURE 3



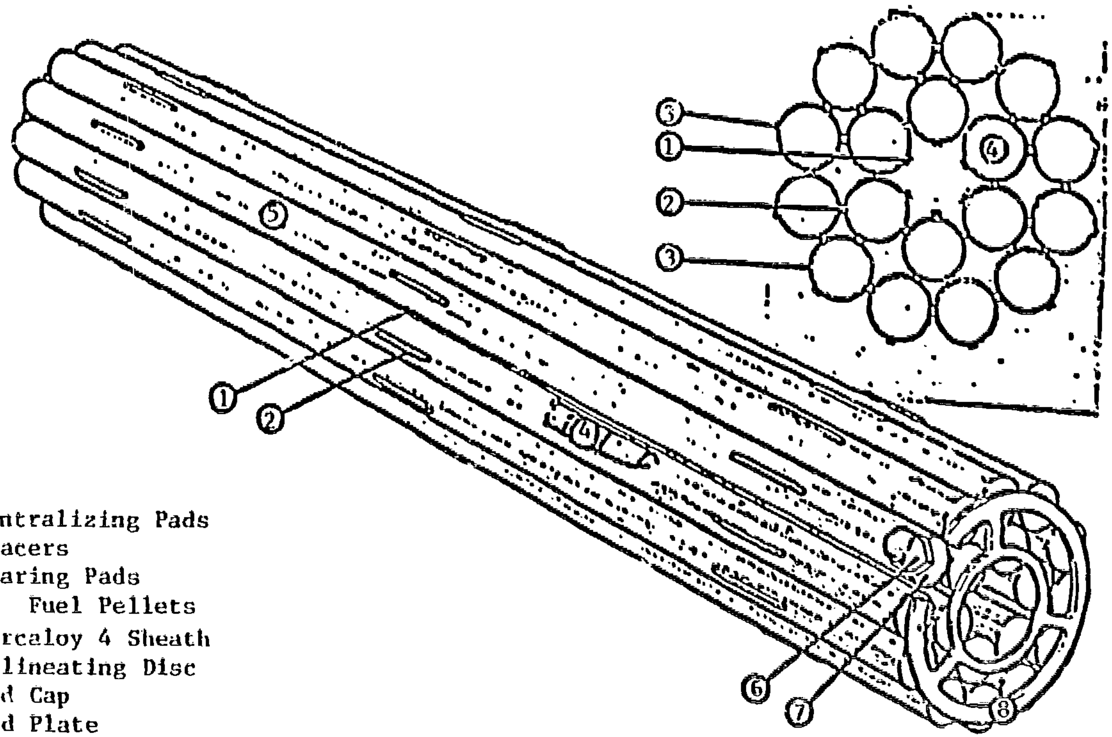

EXPERIMENT YIELD OF NEUTRONS BY BOMBARDMENT OF A HEAVY METAL TARGET WITH HIGH ENERGY PROTONS

FIGURE 4




THE SPALLATOR TARGET DESIGN

FIGURE 5

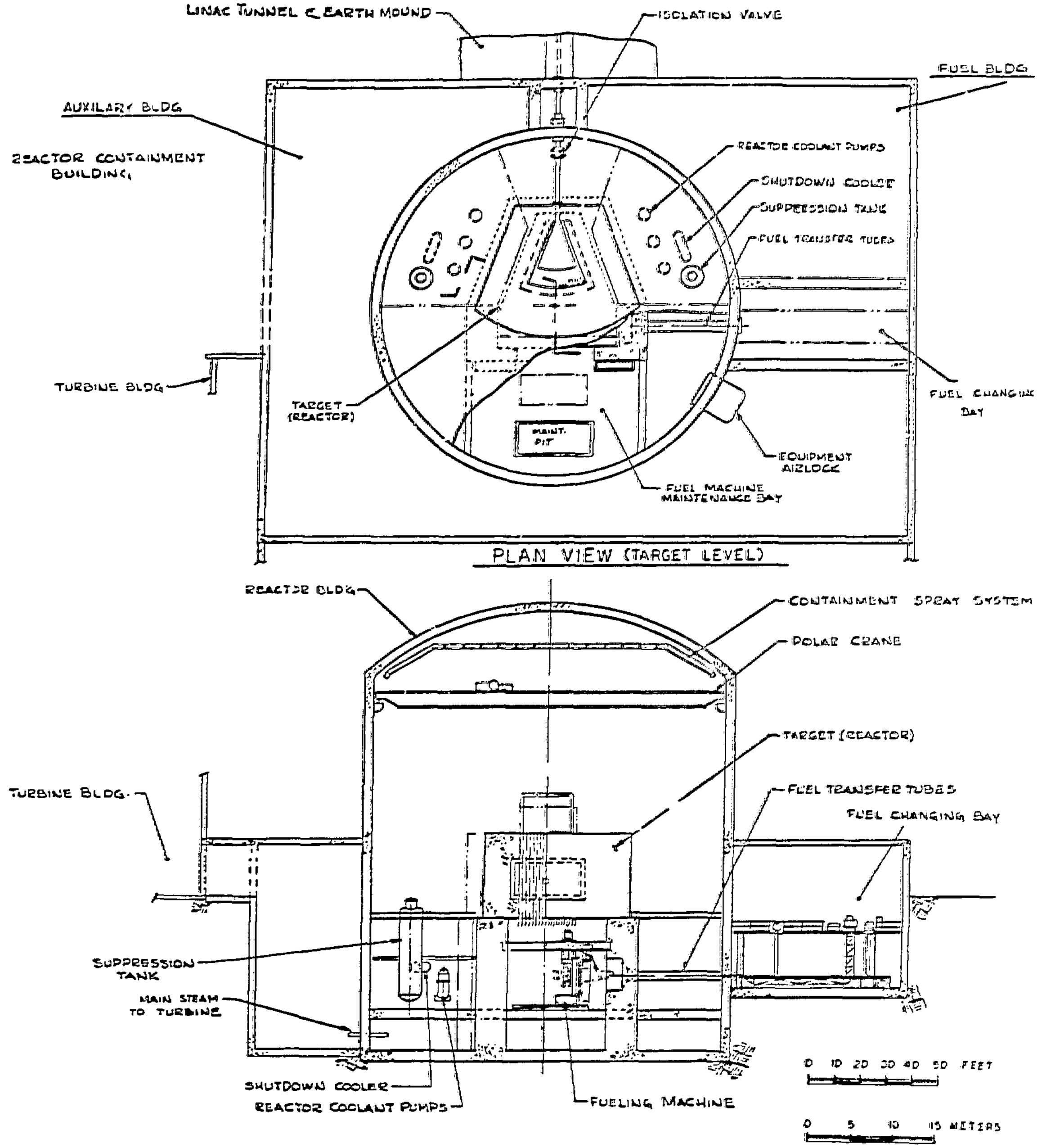



1. Centralizing Pads
2. Spacers
3. Bearing Pads
4. U Fuel Pellets
5. Zircaloy 4 Sheath
6. Delineating Disc
7. End Cap
8. End Plate

18 ELEMENT FUEL BUNDLE

SPALLATOR TARGET ASSEMBLIES

FIGURE 6




TARGET CONTAINMENT BUILDING

FIGURE 7