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SPALLATION-BASED SCIENCE AND TECHNOLOGY AND ASSOCIATED NUCLEAR DATA REQUIREMENTS

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ABSTRACT

Rapid advances in accelerator technology in recent years promise average proton beam currents as high as 250 mA with energies greater than one GeV. Such an accelerator could produce very high intensities of neutrons and other nuclear particles thus opening up new areas of science and technology. An example is the efficient burning of transuranic and fission product waste. With such a spallation-burner it appears that high-level waste might be converted to low-level waste on a time scale comparable to the human lifespan at a reasonable additional cost for electric power generation. The emphasis of this paper is on the design of a high power proton target for neutron production, on the nuclear data needed to operate this target safely and effectively, and on data requirements for transmutation. It is suggested that a pilot facility consisting of a 1.6 GeV accelerator and target operating at 25 ma is the next major step in developing this technology. Bursts of protons near the terawatt level might also be generated using such an accelerator with a proton accumulator ring. Research prospects based on such proton bursts are briefly described. The status of established nuclear data needs and of accelerator-based sources for nuclear data measurements is reviewed.

1. INTRODUCTION

Among the advances in accelerator technology in recent years, perhaps the most impressive is the technical base for r.f.-driven proton linacs with beam power far beyond demonstrated technology. The Los Alamos National Laboratory in collaboration with the Brookhaven National Laboratory have been evaluating a 250-ma 1.6-GeV 400-MW accelerator/target for the production of tritium as a backup to a new production reactor facility. The concept represents an advance in

accelerator and target beam power of a factor of 400 beyond the one milliamp average current of the Los Alamos Meson Physics Facility (LAMPF). This facility, which is shown in Fig. 1, is presently under review by the U.S. Department of Energy. The target proposed by the LANL/BNL collaboration is an array of rods of neutron production and conversion material with flowing coolant similar to that found in reactors.

REFERENCE APT SYSTEM FOR GOAL TRITIUM PRODUCTION

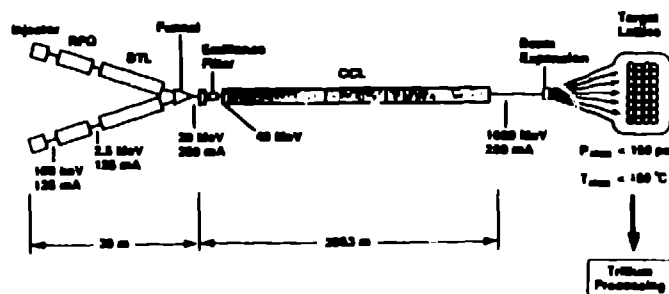


Fig. 1 Layout of the 400-MW beam power accelerator considered for tritium production.

While the reactor-like array appears practical for the proposed application, alternative concepts might make even better use of the special features associated with neutron generation by spallation. These include a much lower heat generation of 30 MeV per neutron for a lead or bismuth target compared with 200 MeV per useful neutron for fission, and the capability of using a flowing liquid target

which allows heat transfer outside of the neutron flux rather than inside as with the reactor. The direct result of both of these advantages is the possibility for a substantially higher neutron flux than is practical in most reactors. In addition the flexibility in reactor core design is severely restricted by criticality and the need for a flat energy density profile. The spallation source is not bound by these constraints. The spallation source also generates substantially less radioactive waste product than a reactor of comparable capability and with the flowing target much less of the radioactive inventory is in the source region. This lower inventory, the absence of a criticality condition, and the ability to quickly adjust the power level in the target by controlling the proton beam current are very attractive safety features.

In order to bring the many aspects of high power spallation target design into better focus, a representative target design is described. Data needs, technology applications, and safety are evaluated with respect to this design. The target offers extraordinary new prospects for transmutation-based technology such as the burn-up of reactor waste and the production of tritium for development and deployment of fusion power reactors. A waste stream from the target might be avoided by taking advantage of neutron capture in the target to burn spallation products back toward their Pb-Bi parents.

Since the handling of reactor waste is so important to the future of commercial nuclear power, the role of the thermal/epithermal spallation neutron source for waste transmutation is considered here in some detail. The nuclear data requirements for implementation are also reviewed. A protocol is outlined in which commercial reactor waste is chemically partitioned into six categories: (1) uranium isotopes, (2) plutonium isotopes, (3) higher actinides, (4) stable fission products, (5) fission products with half-lives less than 30 years, and (6) fission products greater than 30 years. The uranium isotopes are saved for reuse, the stable fission products are stored as low level waste, the higher actinides and > 30-year fission products are burned promptly to high conversion and recycled, and the < 30-year fission products are stored for a period of about 60 years and then partitioned and burned to high conversion with recycle. The spallation/burner might make possible the conversion of commercial reactor waste to stable low level fission product waste on a time scale comparable to the human lifespan with a reasonable cost addition to nuclear electric power generation.

A pilot scale accelerator-based facility at the 250-ma, 1.6-GeV, 10% duty factor, 40-MW level is described for demonstrating the new

technologies and research made possible by a neutron flux at the 10^{16} n/cm²-s level. The list of research topics possible with such a facility is quite lengthy and reaches across a broad range of nuclear, condensed matter and fundamental physics. The usefulness of such an accelerator for driving a storage ring capable of storing a substantial portion of the beam and compressing the beam into pulses in the sub-microsecond range is described.

II. TARGET DESCRIPTION

In order to obtain the highest neutron flux level it is desirable and perhaps necessary to use a flowing liquid heavy metal target. Such a target geometry is shown in Fig. 2. A lead-bismuth eutectic is selected for this although the neutron output per proton is a factor of about two lower than for uranium. A liquid uranium target would greatly complicate the technology. The flowing target allows the use of a small diameter proton beam but results in such a high proton beam areal density that a window between the target and the accelerator vacuum seems impractical. The requirement for a windowless target requires that the beam from the accelerator impinge from above on a vertically flowing target(1). The flowing metal is pumped upward in a concentric cylinder around the target and is turned into the downward direction after which it falls by gravity forming a meniscus below the turnover point. The diameter of the metal target for a 400-MW proton beam at 1.6 GeV is 100 cm; the proton beam is expanded to a 60-cm diameter before it strikes the target. The expansion of the proton beam to this diameter after bending the beam into the vertical direction requires a path length of at least ten meters. The 1.6-GeV beam has a range of about one meter in the metal. Neutrons are produced throughout this length with the production being highest at the top and decreasing approximately linearly through the one-meter effective target length. The lead flows downward to a pump and then through a water cooled heat exchanger before returning to be bombarded again. About one fourth of the lead is in the vertical target column. Neutrons from the target are moderated first by inelastic scattering in the lead and then by other moderator in the working volume. D₂O is chosen as the moderator since D₂O is an effective coolant and allows peaking of the neutron flux farther from the lead than would an H₂O moderator. It also is more favorable to the neutron economy than is an H₂O moderator. The working volume contains encapsulated rods of the material to be transmuted.

The height of the beam expander might be a disadvantage in that it could require underground siting of the major portion of the target facility. However it has the advantage that the water-cooled length becomes an

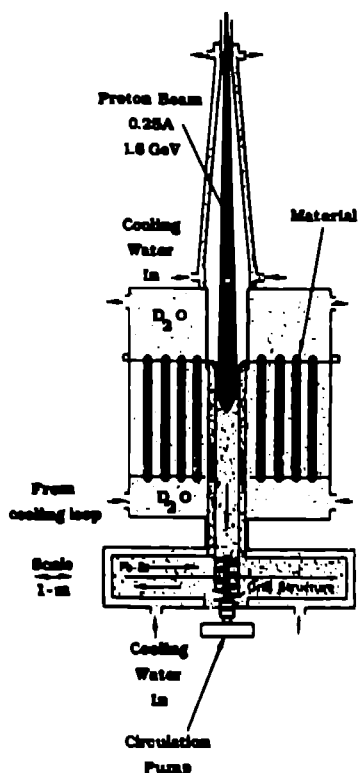


Fig. 2 Elevation view of the flowing Pb-Bi eutectic target for spallation neutron production.

effective collector for volatile spallation and fission products, the largest of which will be mercury. It is expected that these will collect and flow downward meeting the cooled lead at the outside of the top of the target and returning to the lead stream. The pumps on the beam transport system should therefore see only ^3H and the radioactive nuclides of Kr and Xe. The activity of these materials probably is too high to exhaust into the atmosphere and should be collected cryogenically for elimination either by natural radioactive decay or by later burning.

It is expected that the lead target can be operated with a minimal waste stream. The beam will generate spallation product nuclei with masses close to that of lead. Also about 10% of the neutrons will be generated from fission of the lead implying a fission product production rate which is about 3% of that of a reactor generating the same number of useful neutrons. As described above, nearly all of these will remain in the lead which is necessarily located in a very high flux region of the target. Over time a quasi-equilibrium will be established between the production of these isotopes and their successive neutron capture back toward lead. Eventually the primary change in the target with irradiation will be the reduction of the nuclear mass of lead-bismuth from about 208

to 207 and so on. The reduction of nuclear mass by one unit will require 50 years at a beam power of 400 MW. The lowest stable isotope of lead is ^{204}Pb . Therefore it appears that a single lead loading might be used over hundreds of years in successive generations of spallation-burners without a waste stream. If it is found that the build-up of product nuclei in the lead is bothersome, one could extract the stable elements such as gold continuously by diverting a portion of the flowing lead through chemical separation facilities.

The generation of a high neutron flux is essential for efficient transmutation. An estimate of the flux from a Pb-Bi spallation target has been made using theoretical and experimental results obtained from a flowing lead-bismuth target study conducted for the SIN facility(2). In that study isoflux profiles in a D_2O moderator for thermal neutrons produced from a 590-MeV proton beam were obtained. A 15-cm diameter Pb-Bi target was located inside a 20-cm diameter moderator surface. Approximately four times as many neutrons would be produced per proton for a 1.6 GeV target and the range of the proton beam would increase from 20 cm to 100 cm. Assuming a straight-line dependence of neutron production from maximum to zero over the 100 cm and using superposition, the flux can be estimated for a 1.6 GeV beam on a target of the same configuration. The result is shown in Fig. 3 for a beam current of 25 mA. The pumpkin-shaped curves are displaced slightly upward from the target center as expected and are stretched away from circular in the vertical direction. Note that the flux at the highest point reaches almost 5×10^{15} n/cm 2 -s. This high flux region appears at a radius of 20 cm where there is also an epithermal neutron flux lower by about a factor of five. At a radius of 80 cm the thermal flux is lower by about an order of magnitude. The highest flux region (above 4×10^{15}) extends over a volume of about 100 liters.

The isoflux curves for a 250 mA target have not yet been determined. In this case the diameter of the lead target will have to be increased to at least 60 cm to maintain a practical lead flow rate. Although the total neutron production must increase by a factor of ten, the larger radius will not allow a proportionate increase in the neutron flux. However a flux of at least 1×10^{16} n/cm 2 -s appears likely. This estimate can be readily verified using the 800-MeV LANPFF proton beam for an isoflux measurement on a 60-cm diameter target surrounded by D_2O and using source superposition as described above to extrapolate to a 1.6 GeV beam energy.

III. BURN-UP OF NUCLEAR WASTE

The 400-MW accelerator produces about 7.5×10^{19} n/s. If leakage and parasitic capture are kept to low levels, the transmutation rate in

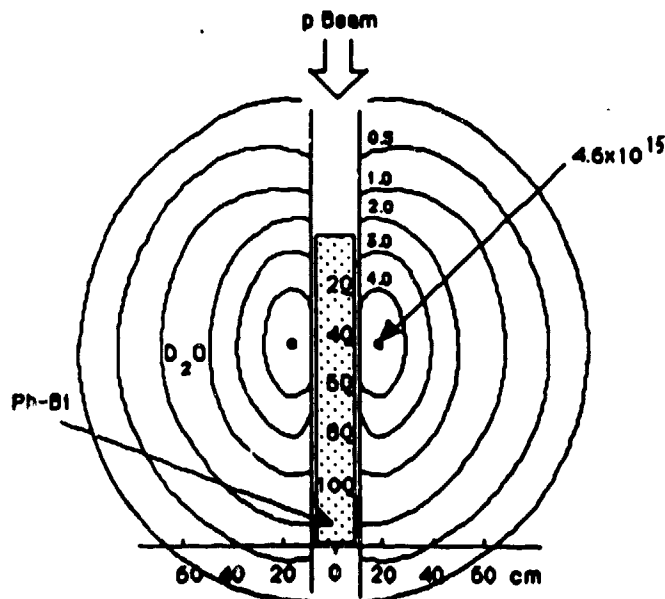


Fig. 3 The time average thermal neutron isoflux profiles for a Pb-Bi eutectic flowing target for a beam energy of 1.6 GeV and a proton current of 25 ma. The shaded column in the center is the metal target with dimensions along the vertical in cm with zero marking the top of the liquid metal. The dimension in the horizontal direction is in cm.

nuclei per second is the same regardless of how low the absorption cross section might be. However the fraction of the nuclei in a sample burned in a given time depends not on the neutron production rate but on the product of neutron flux and absorption cross section. Therein lies the advantage of a spallation-burner over a reactor. A power reactor is optimized for power production over a large volume with a uniform power distribution. The flux typically is about 10^{14} n/cm²-s. With a peak flux of around 10^{16} n/cm²-s the rate of material conversion for a spallation source can be higher by a factor of 100 for the same cross section. For the burn-up of fission products, this rate advantage is all important since the half-life for the material in the neutron flux must be much less than its natural half-life. For a significant impact the half-life in the burner neutron flux should be less than a few years for all of the nuclei to be burned.

These points are illustrated in Fig. 4 which shows the relationship between the half-life inside a neutron flux $T'_{1/2}$ given on the ordinate and the natural half-life $T_{1/2}$ on the abscissa. The curves are calculated for a flux of 5×10^{15} n/cm²-s and for several different cross sections using the relationship

$$T'_{1/2} = T_{1/2} / (1 + \phi \sigma T_{1/2} / 0.693) \quad (1)$$

where ϕ is the neutron flux and σ is the absorption cross section. Eq. 1 follows directly from the relationship

$$\lambda' N = \lambda N + \phi \sigma N \quad (2)$$

where λ' and λ are the induced and natural decay constants and N is the target nuclear density.

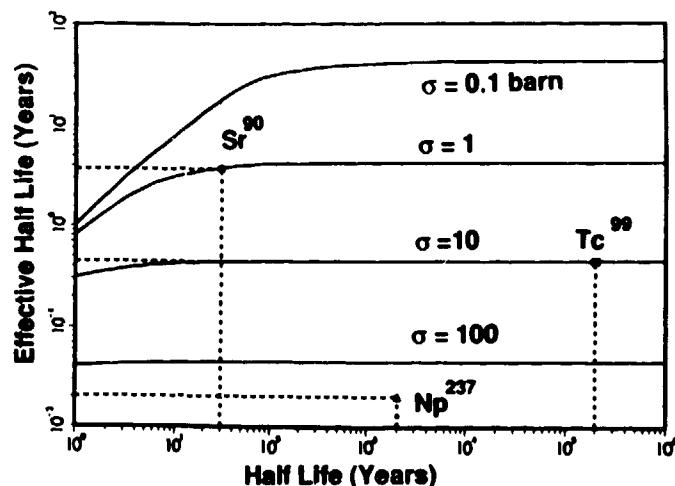


Fig. 4 A comparison of the effective half-life of a nucleus in a 5×10^{15} n/cm²-s flux given on the ordinate with the natural half-life given on the abscissa for several different cross sections. The curves may be used for different fluxes as described in the text.

As an example of the importance of the high flux requirement for burn-up, consider the isotope ⁹⁹Tc with a natural half-life of 2×10^5 years and a cross section of ten barns. In a 10^{14} n/cm²-s flux the half-life is about 20 years while in a 10^{16} n/cm²-s flux the half-life is about 10 weeks. For this nucleus the reactor neutron flux changes the lifetime by a large amount but not enough to be useful. For 30-year ⁹⁰Sr the corresponding lifetimes are 29.9 years and 3 years. The lower flux offers no advantage over natural decay whereas the higher flux offers a significant advantage for a reasonable irradiation time.

The case of ¹³⁷Cs with a half-life of 30 years is somewhat special in that the thermal capture cross section has been thought to be quite small at 0.11 barns, although a higher cross section of 0.25 barns has been reported recently(3). In order to achieve an effective half-life of no more than two years, one must achieve a thermal flux in the target of 2×10^{16} n/cm²-s and must get as much conversion from the epithermal region as from the thermal region. Flux estimates for the full 250 ma of beam

current indicate that fluxes above the required level can be achieved. Estimates of the flux and cross section in the epithermal range support the required level of epithermal conversion for ^{137}Cs . However isotope separation before irradiation will be required to make the burning of both ^{90}Sr and ^{137}Cs practical.

For the actinides several successive neutron absorptions might be required before destruction of the nucleus by fission. For an absorption cross section of 100 barns the time between successive neutron absorptions on the same nucleus is about 10 days for the spallation flux compared with about 3 years for the reactor flux.

The burn-up of nuclear waste probably must meet several criteria to be of interest. (1) Both fission product and higher actinide waste must be burned effectively. (2) Conversion of high level waste to low level waste must be accomplished in a time comparable to the human

lifespan. (3) The cost of waste burn-up must be a modest increment on the cost of nuclear electric power generation.

The effectiveness and cost of spallation-burn-up of power reactor waste may be estimated for the protocol illustrated in Fig. 5. A power reactor operating at the relatively low flux of 10^{14} n/cm²-s burns actinide fuel producing heat and also slowly transmuting the actinides to higher mass. In addition it burns the high cross section fission products to low cross section nuclei some of which will be unstable. For this reason virtually none of the abundant fission product nuclei have high thermal cross sections. Hence, the need for a high thermal flux for effective burning rates. After a 10-year cool down period the nuclei are chemically separated into five classes; (1) the U and Pu which can be further used as nuclear fuel, (2) the higher actinides, (3) fission products with $T_{1/2} > 30$ years, (4) the fission products with $T_{1/2} < 30$ years, and (5) the stable fission products.

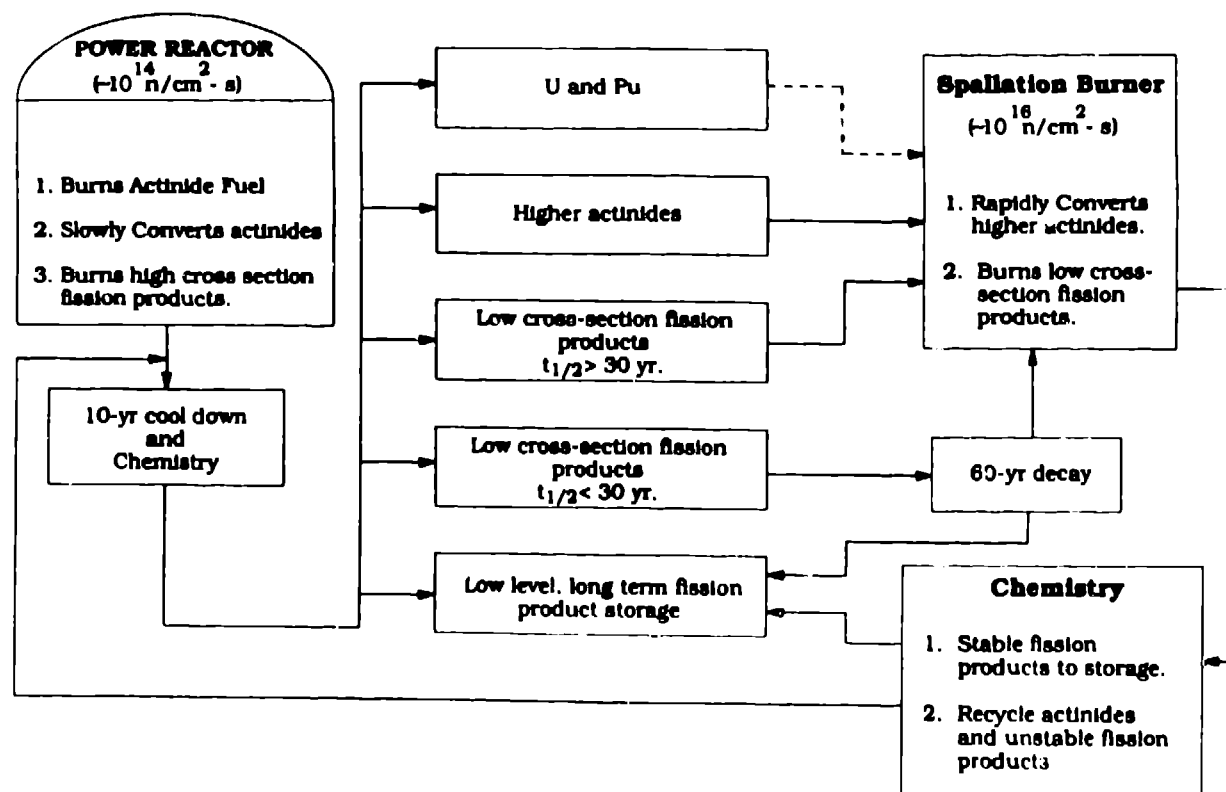


Fig. 5 Protocol for implementation of a spallation burner driven by a 400-MW proton beam for burn-up of all high level power reactor waste on a time scale comparable to the human lifespan.

In Table 1 the annual production of fission products from a 3-GWT PWR with $T_{1/2} > 30$ years are listed for fuel burned to 33,000 megawatt-days per metric ton of uranium (MWd/MTU) after 10 years of decay. The important nuclei ^{90}Sr and ^{137}Cs with $T_{1/2} = 30$ years are included. The total number of nuclei to be burned is found to be 45.7×10^{25} . Table 2 shows the higher actinide and plutonium production under the same condition as Table 1 along with the total nuclides in each category.

Plutonium is included since it may be used to boost the neutron rate available for burn-up. The number of higher actinide nuclei is found to be 8.7×10^{25} . These figures for the production of higher actinides and fission product nuclei when compared with the neutron production rate of a 400-MW spallation-burner of 2.3×10^{27} neutrons/year suggest the practicality of a spallation-burner. This suggestion may be made more concrete with the more quantitative estimates which follow.

Table 1. PWR FISSION PRODUCTS* WITH $T_{1/2} > 30$ YEARS.

Nuclide	Kg/yr	Half-life (yrs)	Cross section (barns)	Atoms ($\times 10^{25}$)
^{79}Se	0.19	6.5×10^4		0.13
^{90}Sr	13.5	29	0.9	8.97*
^{93}Zr	23.3	1.5×10^6	2.5	15.0
^{99}Tc	25.1	2.1×10^5	20	15.2
^{107}Pd	7.4	6.5×10^6	1.8	4.1
^{116}Sn	0.91	1×10^5	0.14	0.46
^{129}I	5.87	1.6×10^7	27	2.73
^{135}Cs	9.47	3.0×10^6	62	4.22
^{137}Cs	30.9	30	0.11	13.5*
^{151}Sm	0.38	90	15200	0.16
^{59}Ni	2.0	7.5×10^4	93	2.11
^{63}Ni	0.38	100	24	0.36
^{93}Zr	1.85	1.5×10^6	2.5	1.19
^{94}Nb	0.09	2×10^4	15	0.07
Total				45.7×10^{25}

* These amounts are annual production for a PWR running at 3 GW thermal with fuel burned to 33,000 megawatt-days per ton requiring the removal of 33 MTU spent fuel per year.

* Not included in the sum; half-lives under 30 years.

Table 2. PWR TRANSURANIUM WASTE NUCLEI*

Nuclide	kg/year	Half-life (yrs)	Atoms ($\times 10^{25}$)
^{237}Np	14.5	2.1×10^6	3.66
^{241}Am	16.6	432	4.13
$^{242\text{m}}\text{Am}$	0.022	141	
^{243}Am	2.99	7.4×10^3	0.73
^{243}Cm	0.011	28.5	
^{244}Cm	0.58	18.1	<u>0.13</u>
Total			8.65×10^{25}
^{238}Pu	4.52	88	1.13
^{239}Pu	166	2.4×10^4	41.6
^{240}Pu	76.7	6.6×10^3	19.2
^{241}Pu	25.4	14.4	6.4
^{242}Pu	15.54	3.8×10^5	<u>3.9</u>
Total			72.2×10^{25}

* These amounts are annual production for a PWR running at 3 GW thermal with fuel burned to 33,000 megawatt-days per metric ton requiring the removal of 33 MTU spent fuel per year.

The burning of the actinides is somewhat complicated by the fact that for thermally fissile nuclei fission always competes with capture, that about half of the nuclei have negligible fission compared to capture, and that the dominance of fission and capture alternate in an isotopic series. Neutrons are generated in the fission process and absorbed in the capture process. Since the objective is to destroy the nucleus by fission, simple terms must be developed which give the average number of neutrons required to destroy by fission the plutonium isotopic mixture and the higher actinide group. The following terms based on the alternating isotopic sequence give the average number n_1 of neutrons required for fission for four classes of initial target nuclei:

Fissile target ($^{239,241}\text{Pu}$, ^{242}Am , ($^{243,245,247}\text{Cm}$)

$$n_0 = -(\nu - 1 - 2\alpha) \quad (3)$$

Non-fissile target class 1 ($^{238,240}\text{Pu}$, ^{241}Am)

$$n_1 = -(\nu - 2 - 2\alpha) \quad (4)$$

Non-fissile target class 2 (^{237}Np , ^{243}Am)

$$n_2 = -(\nu - 3 - 2\alpha) \quad (5)$$

Non-fissile target class 3 (^{242}Pu)

$$n_3 = -(\nu - 4 - 2\alpha) \quad (6)$$

The quantity ν is the average number of neutrons emitted per fission, which varies slowly for the transuranic nuclei and is taken to be 2.91 - a value midway between that for the nuclei ^{239}Pu and ^{241}Pu . The quantity α is the capture to fission ratio for the fissile nuclei. It varies more for the fissile nuclei than does ν , but it is nearly the same for ^{239}Pu and ^{241}Pu and we take it to be 0.36. Note that n_1 does not depend on cross sections - only on the ratio of the cross sections α and on ν . These parameters substituted in Eqns. 3-6 then give for the average number of neutrons required to cause eventual fission of the initial nucleus the values $n_0 = -1.2$, $n_1 = -0.2$, $n_2 = +0.8$, and $n_3 = +1.8$. (A negative number means that there is a net generation of neutrons rather than a net absorption.)

Using the above estimates the average number of neutrons required to induce fission can be calculated for the isotopic composition of the higher actinides and the plutonium given in Table 2. The plutonium mixture generates 0.82 neutrons per nucleus burned, the higher actinide group generates -0.31 neutrons per nucleus burned. For the fission products -1.0 neutrons are generated per nucleus burned. These figures, which are averages over the isotopic mixture, should allow the higher

actinide burn-up rates to be calculated to an accuracy of about 10%.

It is worth pointing out that these burn-up calculations are applicable to fluxes below about 5×10^{15} n/cm²-s. At higher fluxes the burn-up rate of the higher actinides can be much higher perhaps even approaching an uncontrolled runaway. The runaway condition comes about because of the 2100-barn fission cross section of the ²³⁸Np with a half-life of 2.15 days. In a high flux the ²³⁸Np can be produced at a higher rate than it decays to ²³⁸Pu. When the fraction of ²³⁸Np exceeds a few percent, the loading of higher actinides might become supercritical. Careful studies are required to take full advantage of the ²³⁸Np in enhancing the burn-up efficiency while maintaining safe control of the reaction rate.

IV. BURN-UP RATES AND COSTS

First the burn-up rate for the higher actinides is shown to be very high. With an annual neutron production rate by spallation of 2.3×10^{27} nuclei, an annual PWR higher actinide production rate of 8.6×10^{25} , and the requirement of 0.31 neutrons to destroy one nucleus, the spallation source could theoretically destroy the higher actinide output of 84 PWR's! This rate would require scaling back the accelerator current since the thermal power from generation of fission at this rate corresponds to 7.75 GW.

For the longer lived fission products, the annual production rate of 6.8×10^{26} nuclei implies a burn-up rate of 3.4 PWR's per year. In order to improve this rate we transfer the ⁹⁰Sr and the ¹³⁷Cs to the $T_{1/2} < 30$ year group and allow this group to decay for a period of 60 years. After that time these two isotopes dominate the shorter-lived group and the remaining amount in the short-lived group has been reduced by four to 5.6×10^{25} nuclei. When this is added to the longer lived group of 4.7×10^{25} nuclei, the burn-up rate for 50.3×10^{25} nuclei becomes 4.6 PWR's.

The rate could be enhanced still further by adding the plutonium isotopic mixture to the spallation target to boost the neutron production. Setting an upper limit of 3 GWT to the spallation target power allows the generation of 8.1×10^{19} fissions per second each of which produces on average 0.82 neutrons. The annual production rate of neutrons by fission then becomes 2.1×10^{27} which compares with the 2.3×10^{27} produced by spallation. The fission product burn-up rate then becomes 8.8 PWR's. However now the target itself is generating fission products at the rate of about 0.87 PWR's so that the rate must be reduced by 0.87 and becomes 7.9 PWR's. Note however that if the 3-GWT power were converted to accelerator beam power using efficiencies of 40% and 45% for

heat to electrical and electrical to beam power conversions respectively, the accelerator-produced neutron rate would increase by 35%. This would result in a net burn-up rate of more than 10 3-GWT power reactors. At this rate the incremental cost from burning up all of the nuclear waste might well be modest and acceptable to the consumer.

The impact of two burn-up scenarios is shown in Fig. 6 where the activity of fuel removed from a 3-GWT reactor is shown as a function of time(4). Spent fuel assemblies will decay down to the radioactivity level of uranium ore after about 10^5 years. The situation is little changed by plutonium recycle. Prompt burning of the actinides, which appears practical with very high efficiency using the accelerator, leaves only the fission products which will reach the activity of the ore in about 1000 years. By burning the fission products as well allowing a 60-year decay period for the ¹³⁷Cs and ⁹⁰Sr followed by ten two-year cycles of 50% burn-up, the ore level can be reached in only 100 years. Note that the chemical processing selectivity does not have to exceed 1 in 1000 to achieve this objective.

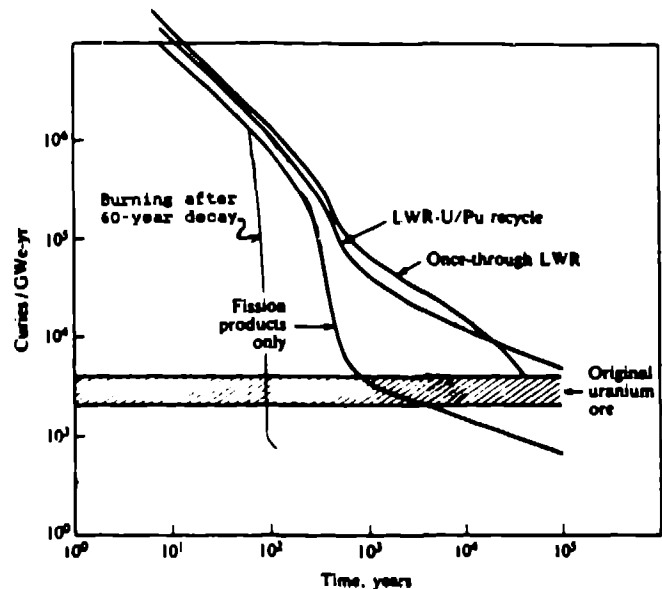


Fig. 6 The decay of waste from a 3-GWT power reactor. The once-through LWR and Pu-recycle do not involve the burning of waste. The other two curves show radioactivity levels for burn-up of higher actinides only (fission products remaining) and the burn-up of all radioactive wastes.

In summary the spallation-burner appears to be capable of the following:

1. Burn-up of all high level fission product and actinide waste to low level fission product

waste with residual activity below that of uranium ore.

2. Accomplishing the burn-up at a reasonable incremental cost to the consumer.

3. Completing the burn-up of the waste on a time scale comparable to the human lifespan.

V. DATA NEEDS FOR THE SPALLATION-BURNER

The data requirements for the spallation-burner are substantially different from those for a reactor. In a reactor criticality, breeding ratio, and fuel efficiency have required cross section measurements often with requests for accuracy in the 1% range. However the principal requirements for the spallation-burner regard the neutron spectral shape requirement, the irradiation time, and the position distribution of the various waste nuclei in the neutron flux. The cross sections are therefore not required at high accuracy. However most of the nuclei will be unstable and this will be a serious complication to the measurements. Most of the neutrons from the spallation process are born at energies in the 1- to 5-MeV range from the boil-off nuclear process. This spectrum is softened into the keV range by inelastic scattering in the Pb-Bi before reaching the D₂O. The D₂O moderates the neutrons into the thermal range. Near the lead-D₂O interface the moderation is incomplete so that the spectrum extends from thermal to around 100 keV. By the time the neutrons have traveled about 50 cm from the Pb into the D₂O, the spectrum is fairly well thermalized. Beyond this distance little transmutation will take place outside of the thermal range. Capture cross sections differential in energy are therefore needed from thermal to about 100 keV. Information that can be obtained from theory about these cross sections is limited since for most of the nuclides the cross section is dominated at thermal by a few resonances with unpredictable parameters. At keV energies, standard theoretical models may be more appropriate for capture cross section estimation. The nuclear data fall into five groups which are discussed separately below in order of priority.

Spallation Neutron Production Rate

The accuracy of neutron production by spallation may be uncertain by as much as 20% at 1.6 GeV. Calculations of target performance now rely on the intranuclear cascade evaporation code HETC for spallation neutron production, on Monte Carlo (eg. MCNP) for transport through the lead, and on discrete ordinate (SN) for neutron moderation and transport in the D₂O. A careful benchmark experiment measuring the thermal and epithermal flux distribution and absolute intensity in the D₂O is highly desirable at an energy as close to 1.6 GeV as possible.

Similarly more accurate measurements of neutron production from other Pb-Bi target geometries would also be desirable.

Fission Products

Capture cross section are required for the fission products of Table 1 along with that of some of the nuclei in the capture chain. For some nuclei such as ⁹⁰Sr, burn-up is complicated by the presence of lighter stable isotopes (⁸⁸Sr) which can be burned along a nuclide chain into the unstable nucleus. As many as 30 nuclides must be measured for complete information on target arrangement and detailed burn-up rates.

Structural Materials

The structural materials of concern are the walls separating the Pb-Bi from the D₂O and the cladding for the waste. The very high neutron flux will necessarily transmute a substantial fraction of the structural material in a relatively short time. Therefore it is desirable to use materials which can handle several successive neutron captures on the same material without substantial chemical change or activation. Any material with a substantial (n,p) or (n,α) cross section, such as nickel, should be avoided in order to keep hydrogen and helium build-up to a minimum. There might be as many as ten nuclides in this class requiring measurement.

Spallation Products

It is highly desirable to avoid a waste stream from the lead target. An equilibrium condition is discussed earlier in which the high neutron flux transmutes spallation product nuclei to higher mass at about the same rate at which fresh spallation nuclei are being produced. The target design keeps all but the gaseous products in the Pb-Bi liquid so that such transmutation can take place continuously. It is also useful to calculate the decay heat curve for the spallation target in case of Pb-Bi circulator pump failure. The spallation products generally have a nuclear mass above 160. In addition fission products, which are mostly lighter than spallation products, are produced at about 3% of the rate of a FWR running at 3-GWT. The time scale for approach to the equilibrium condition is not known. This time-scale information could be calculated from the cross sections since the spallation product distribution is fairly well known. About 20 nuclides in this class should be measured.

Unstable Bi and Po Isotopes

The high neutron flux will give rise to successive neutron capture on the same starting nucleus of ²⁰⁸Pb and ²⁰⁹Bi resulting in the generation of several unstable nuclides of Bi

and Po which then cycle back to Pb and stable Bi by alpha decay or beta-decay-like processes. It appears that an equilibrium around this cycle will be established in about one year. The equilibrium distribution would be of interest for calculating the decay heat in case of the Pb-Bi circulator pump failure.

Actinides

Cross sections for all of the actinides have been measured with more than adequate accuracy owing to the long existing need for accurate data in calculation of criticality, breeding ratio, etc. for all classes of reactors.

Measurement Facilities

The measurement facilities available presently consist of intense variable energy monoenergetic neutron generators for use in the mid-keV to 20-MeV range, pulsed electron linacs for neutron measurements from the higher eV to the lower MeV range, and, more recently, pulsed spallation sources which have their greatest superiority in the thermal to lower keV range and in the 1- to 400-MeV range. The demand for nuclear data appears not to be as strong as it was in the prime years of fission reactor

development. Several facilities have been under pressure to reduce their activity and unfortunately a couple have been closed. The data needs outlined above appear to justify a continued effort in nuclear data measurements and the maintenance of skills necessary to respond to a demand for data such as that which would be associated with a serious spallation-burner program.

VII. A SPALLATION-BASED TECHNOLOGY DEMONSTRATION CENTER

Although LAMPF at Los Alamos was built 20 years ago, it is still the world's highest power proton linac. The linac for the proposed tritium production facility operates at twice the energy and 250 times the LAMPF average current. Because of this large step in accelerator and target size, it seems prudent to make an intermediate step in accelerator power before constructing the proposed 400-MW version. A more modest accelerator also would make possible the demonstration of nuclear waste burn-up at the pilot-model level and would provide the base for the wide spectrum of other science and technology reviewed briefly above. Fig. 7 shows a layout for a demonstration center for spallation-based technology.

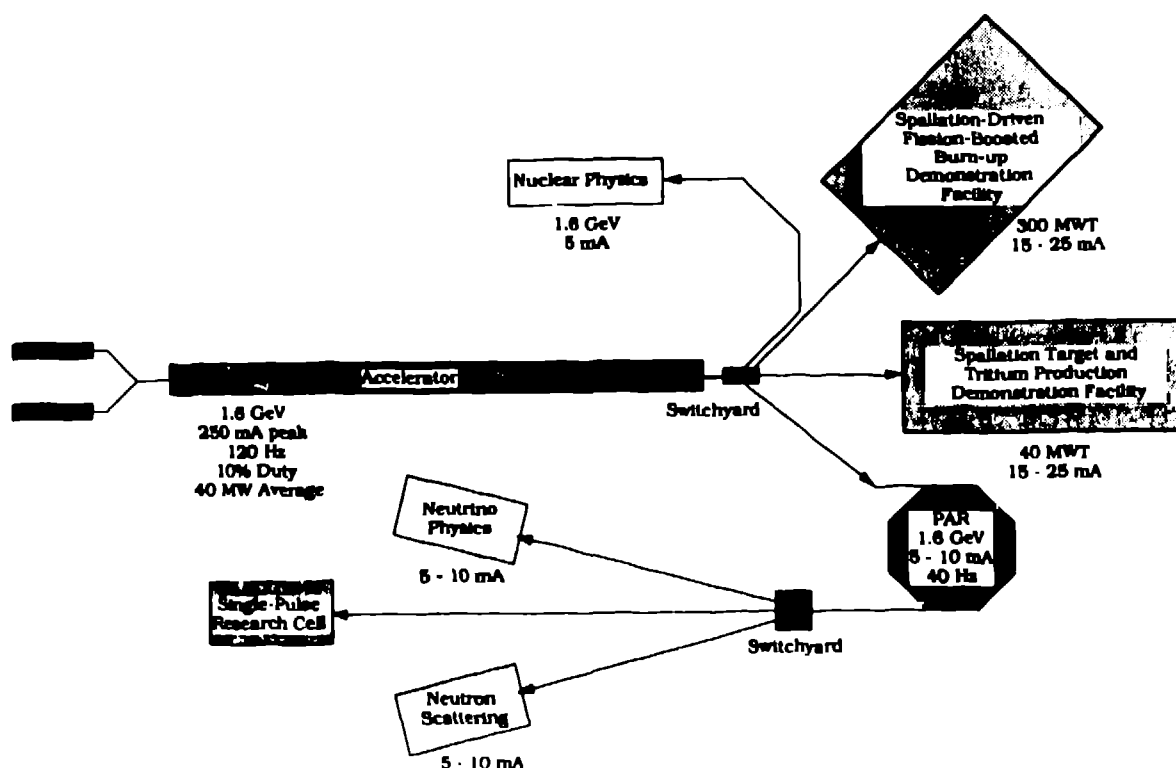


Fig. 7 Layout for a demonstration center for spallation-based technology.

The accelerator operates at 1.6 GeV with a peak beam current of 25 ma, a repetition rate of 120 Hz, and a duty factor of 10% for an average beam power of 40 MW. At this performance level it should be possible to achieve a steady-state neutron flux of 10^{16} n/cm²-s outside the lead target at the straight-ahead target facility. This facility could be used to demonstrate the spallation target integrity and practicality for tritium production. The second target, located in the figure above the first, would be devoted to demonstration of higher actinide and fission product waste burn-up. The thermal power of this facility would be in the 300-MW range since the higher actinides would be burned by fission.

The figure also shows a beam line which should make possible a major step in capability for nuclear physics research.

The proton accumulator ring (PAR) shown in the lower half of the figure would provide beam for three world-leading research facilities. Such a ring greatly increases the power of a GeV-range high power proton linac for research and technology. While the peak proton current in r. f. linacs has not exceeded 30 ma, proton storage rings allow multiplications in proton current by about three orders of magnitude. The most intense pulsed proton current to date is that achieved at Los Alamos for LANSCE. The present performance level is an average current of 60 microamps, at a repetition rate of 20 Hz for approximately triangular pulses with a 0.25 microsecond width at the base. This translates to a peak current of 24 amperes in the ejected proton pulse. The construction of storage rings making possible proton currents at this level has been driven by the need for intense pulsed neutron bursts for neutron scattering studies in material science. These intense neutron bursts also have been shown to be valuable for nuclear data measurements, for forefront studies in fundamental neutron physics and for materials science studies using pulsed muons. Other exciting prospects include the production of ultracold neutrons, the development of polarized neutron fields with fluxes many orders of magnitude higher in the neutron field than is possible in a polarized neutron beam, and the prospect for a practical neutron-neutron scattering experiment. The next generation of storage rings should be powerful sources for neutrino physics assuming reasonable extrapolations from demonstrated technology.

However the forefront least explored and developed is that requiring intense single bursts of protons. The peak power of the present PSR bursts driving LANSCE is almost 20 gigawatts. If the performance of the next generation of rings were improved by a factor of 30 using higher energy, larger aperture, and improved injection, the power would approach a terawatt with a total stored energy nearing 100 kilojoules. Such power and energy opens up the

prospect for driving new lasers possibly pushing to x-ray and gamma-ray wavelengths. The possibility of laboratory fusion based on the confinement of an intense proton burst for plasma heating using pulsed megagauss magnetic fields should be investigated. More details about these and other prospects are provided elsewhere(5).

The study of materials dynamics using neutrons is an exciting forefront opened recently by measurements at Los Alamos. The LANSCE intensity is already high enough to allow the study of neutron resonances and powder diffraction using single LANSCE pulses. Fig. 8 shows Bragg diffraction edges for an iron sample measured(6) with a single pulse from LANSCE. The pattern of the edges gives the crystal structure, the spacing gives the lattice constant, the height of the edges gives the temperature, the distribution in edge heights gives the texture (non-random orientation of microcrystals) and the slope of the edges measures strain at the microcrystal level. The technique promises dynamic materials studies in the 10^{-5} to 10^3 second range. With optimized geometry and the present LANSCE performance the technique probably could be pushed into the few microsecond range.

In summary the addition of a storage ring to a GeV-range proton linac broadens the spectrum of science and technology studies several times beyond that possible with the linac alone.

The accelerator should be designed with the expectation that it will reach its beam current objective soon after completion of construction and that it will operate with greater than 90% reliability. The facility should stabilize into an operation mode satisfactory for the spectrum of facilities suggested. The substantial investment in the accelerator can be written off over a much longer time period than is expected for demonstration of the tritium production and waste burn-up technologies because of the broad range of other long term research included. It is worth noting that the number of proposed beam lines and facilities is essentially the same as that presently being served effectively by LAMPF.

IX. CONCLUSION

Recent advances in r. f. linac technology appear to make practical accelerators with average beam intensities up to 250 ma for energies in the lower GeV range and beam powers of hundreds of megawatts. Perhaps the most important application of such an accelerator is in the burning of high level fission product and actinide waste from commercial power reactors using thermal neutron fluxes of 10^{16} n/cm²-s or higher. Consideration of this prospect

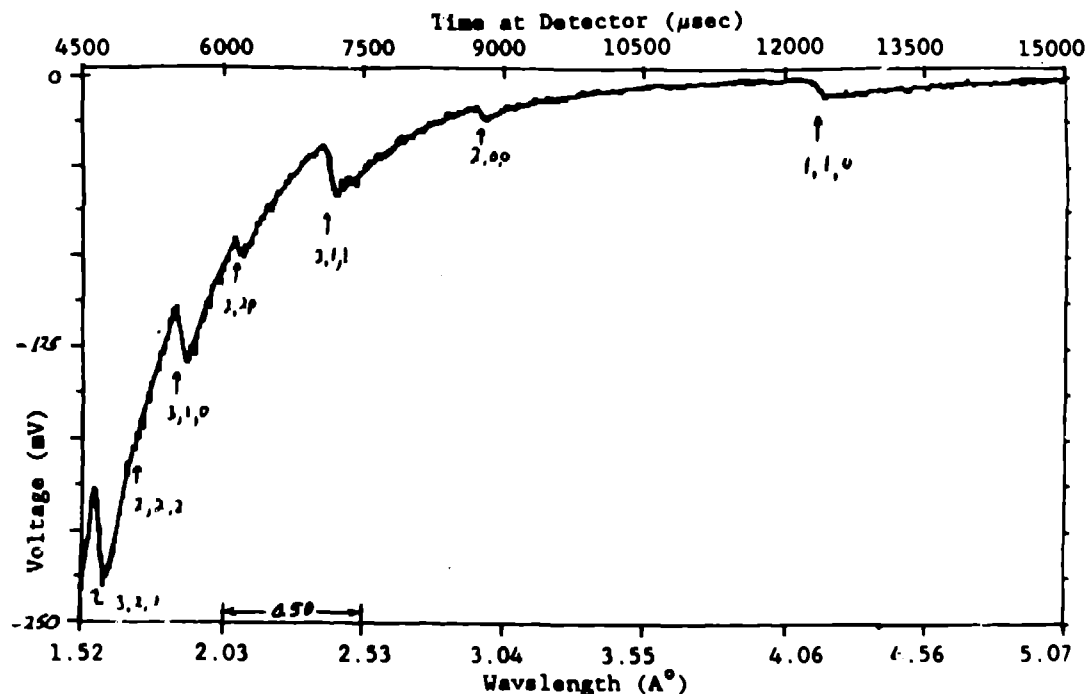


Fig. 8 The figure shows the Bragg edges measured in transmission using a single LANSCE pulse for a sample of polycrystalline iron. The Miller indices shown at the breaks indicate the lattice planes for the iron cubic lattice. The lower abscissa is the neutron wavelength; the upper is the time at which the transmitted neutrons reached the detector. The neutrons were measured in a detector converting neutron intensity to negative current. Therefore zero at the top of the figure corresponds to low intensity or low transmission. The transmission increases toward the bottom of the figure.

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indicates that burn-up could be accomplished on a time scale comparable to the human life span and probably at an acceptable incremental cost to nuclear power generation. The optimization of this process requires a large amount of nuclear data on fission and spallation products.

A center for spallation-based technology is proposed with the high power accelerator operating at an average beam power of 40 MW as the driver and pilot-level programs for tritium production and high level waste burn-up being the primary technology development programs. The great enhancement in research prospects when a proton storage ring is coupled to the high current proton linac is described. The facility carries in parallel a broadly based research program including materials science, nuclear physics, and new prospects such as the exploration of new laser and fusion concepts.

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