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REPETITIVELY PULSED ACCELERATOR BOOSTERS

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I. INTRODUCTION

Several years ago it occurred to us that a very high peak power level short burst reactor could be built by bombarding a supercritical fast reactor with the electron beam from a high current linear accelerator. This approach is different than that used in the design of the Harwell Linac booster which runs at relatively low multiplication and peak power levels, at very short pulse widths, and at relatively high repetition rates for intermediate energy neutron spectroscopy. The concept of the high flux booster has been explored for the last three years in a theoretical and experimental program conducted at General Atomic for the Defense Atomic Support Agency.* The objective of this work has been to study the production of single very high intensity pulses with controllable pulse width. This type of device was desired for diagnostic studies of transient radiation effects in electronic components.

The results of the above mentioned program are summarized below; this is followed by a discussion of an idea for a very high intensity booster (having special advantages in the thermal neutron energy range) which is an outgrowth of this program.

II. RESULTS OF DASA WORK

The objective of this program has been to determine the characteristics of the fission power pulse when a high current of electrons is stopped in a supercritical fast assembly of fissionable material. The program has included studies of the fundamental neutron production mechanisms - (target studies in Pb, U^{238} , U^{235} , U^{233} , and Pu^{239}), calculations of the high fission power levels of various possible assembly configurations using coupled neutronic-hydrodynamics codes, an analysis of accelerator capabilities for this application, and a series of prototype

*Contract DA-49-146-XZ-171

test experiments conducted with a 55 Kg spherical critical assembly of U^{235} on the General Atomic Linac. This work has been performed somewhat intermittently since 1961 and is described in DASA report 1420.⁽¹⁾ Only conclusions relevant to the design of higher repetition rate pulsed boosters -- such as a thermal flux booster -- will be discussed here.

The neutron yield from a booster is a function of both the input neutron source strength and the multiplication or reactivity of the booster reactor. The unmultiplied neutron yield produced in the core per incident high energy electron must be known for the theoretical analysis of the booster. Miscellaneous neutron yield information has accumulated for a number of the fissionable elements over the years.⁽²⁾ Some of this information is incomplete and contradictory. General Atomic undertook the study of neutron production in thick and thin targets of U^{238} and U^{235} , and thin targets of Pu^{237} , and U^{233} as a function of electron energy. Unfortunately there exist some rather serious disagreements in the interpretation of our yield data also. Qualitatively the target materials appear to rate in the following order according to increasing neutron yield, U^{238} , U^{235} , Pu^{239} , and U^{233} , although a recent interpretation of the same data by MacGregor⁽³⁾ would indicate that all target materials may have the same neutron yield at the same electron energy. Further information would indicate that the target neutron yield per incident electron increases significantly with bombarding energy.^(1, 3) Figure 1 compiles some of the published and unpublished data for neutron yields produced by electrons incident on U^{238} . The wide disparity in answers is typical of data available today on many photo induced reactions. However, in the calculations which follow we have been careful to take conservative yield data so as not to make the devices appear overly optimistic.

Fig. 1 -- Photoneutron yield from U^{238} target

Pulsed reactors of the type we are discussing may be characterized by the parameters of pulse width and peak power level. A variety of operating parameters are available for adjusting either or both the fission peak power and the pulse width. These include the accelerator current, energy, and pulse width, the booster geometry, lifetime, and reactivity. Figure 2 shows the tremendous range of operating parameters which may be covered by these advanced devices. The abscissa is the pulse width (full width at half maximum power) of the fission neutron pulse. The ordinate gives peak power in megawatts. Three accelerator boosters are considered. The first accelerator is a typical L-band linac with 20 megawatts of beam power. With this presently available accelerator very high fission power of close to 1000 megawatts appears to be possible for a simple GODIVA type booster. The second device consists of a 6-section UHF linac operating at 200 MeV and 1 ampere of current into a GODIVA. The third device considered is the same advanced accelerator pulsing a spherical U^{233} assembly, which has a shorter lifetime than U^{235} . The two solid lines on the right are the performance curves for GODIVA burst reactors. The accelerator pulsed reactors may be operated at any point under the maximum performance curves drawn by proper selection of device parameters. Thus, exceedingly high peak power levels at pulse widths less than roughly 10 μ sec are possible with a practical electron accelerator pulsed fast assembly combination. We will not discuss here the availability or economics of electron accelerators such as those used in the calculation of Fig. 2 for this application since there are presently so many possible choices.

The feasibility of the above pulsed reactor concept has recently been subjected to experimental check using a spherical U^{235} critical assembly placed on the General Atomic L-band linac. The experiments were conducted in our critical assembly room shown in Fig. 3. The electron beam from the linac was piped to this area for single shot pulsing

Fig. 2 - - Peak power of accelerator booster versus burst length

Fig. 3 -- General Atomic Linac and fast critical experiment facilities

of the uncooled reactor. The assembly and assembly machine are shown in Fig. 4. The characteristics of a typical burst are shown in Figs. 5a, b and 6. Figure 5a shows the electron beam burst for 0.3 ampere of peak current and a 5 microsecond pulse width, and Fig. 5b shows the fission power trace which reaches a peak power of 300 megawatts even for the rather modest electron beam conditions used. The buildup and decay time constant are about $1.6 \mu\text{sec}$; characteristic of this assembly having a multiplication of about 250. Figure 6 shows another very interesting test that was performed on shock wave generation in the device. The calculated reactor surface velocity is shown as a function of time after the start of the electron pulse. The coupled neutronics-hydrodynamics code CONEC modified to include a local pulsed source was used. The beam heating effect was measured separately by recording the pressure wave in a piezoelectric detector touching the central section of the three-section critical assembly with the other sections removed (low multiplication). The surface velocity produced by both electron beam heating and the distributed multiplication are also shown in Fig. 6. The agreement between theory and experiment is still not very good in part of the time region, possibly because the calculational model assumes a solid sphere, whereas in practice the sphere is composed of five separate sections. An important part of the job of trying to understand transient burst reactor performance is to study the transient shock problems in these devices since stress limitations can be critical in establishing the ultimate capabilities of such devices. The piezoelectric probe would seem to be a very valuable tool to use in these studies. Although all diagnostic studies of the accelerator booster at General Atomic have been discontinued some further work to study the neutronics alone is planned. These experiments consist of the basic reactor physics measurements of the fast and epithermal neutron spectra leaking from the booster by time of flight and are planned for execution this spring.

Fig. 4 -- Assembly machine, U^{235} ball in fast critical experiment room

Fig. 5(a) -- Linac electron pulse (top)

Fig. 5(b) -- Fission power pulse (bottom)

Fig. 6 -- Surface velocity of U^{235} ball versus time after the accelerator pulse

III. GENERAL DISCUSSION OF REPETITIVELY PULSED ACCELERATOR BOOSTERS

In Fig. 2 the large peak power levels attainable with an accelerator booster lead one to speculate on the potential usefulness of such devices for producing extremely high neutron fluxes for experimental physics studies. For many physics investigations it is desired to repetitively pulse a source rather than to try to complete the experiment in one burst. This simplifies data taking, permits pulse counting, and minimizes count rate losses. Up to now we have ignored the problem of average power production in boosters since heating is not usually the limiting factor in single pulse short burst reactor operation. However, in repetitive pulsed operation, heat removal provides the main limitation on the peak power. The full capability of the accelerator pulsed booster systems indicated in Fig. 2 thus cannot usually be used. To illustrate this in Fig. 7 is plotted the permissible peak power of a repetitively pulsed fast burst reactor as a function of repetition rate for a 6 μ sec burst width and both 500 kw and 5 megawatt heat removal capabilities. Five megawatts of average power is probably close to that ultimately obtainable in the core of a small liquid metal cooled reactor if this limit is established by heat transfer from the fuel elements. Even this might have to be obtained by using molten lithium for heat transfer. Clearly a large range of peak power levels between 100 megawatts and 100,000 megawatts can be attained. For reference the Soviet IBR⁽⁴⁾ repetitively pulsed reactor runs at 23 megawatts peak power and the proposed SORA⁽⁵⁾ reactor at 40 megawatts.

To attain the peak power levels indicated in Figs. 2 and 7 for accelerator pulsed boosters it is generally necessary to operate in the range of reactivity from delayed critical to prompt critical. Obviously the reactor multiplication cannot be permitted to remain constant between bursts or the reactor power level would increase without bound so that

Fig. 7 -- Allowable peak power of accelerator booster versus repetition rate

a method of varying the reactivity periodically to coincide with the accelerator pulsing is required. In this sense the accelerator pulsed reactor is similar to IBR or SORA except that more flexibility exists with this device than with either IBR or SORA in the method of mechanically varying the reactivity. The reactivity pulse need not be particularly short since it does not determine the fission pulse width which is largely influenced by the accelerator pulse characteristics. Actually at least two advantages have been gained here over IBR and SORA, (1) the speed with which one must mechanically vary some portion of the reactor system has been reduced by a large factor possibly as much as an order of magnitude. This is a great advantage because of the very high velocities required to move reactivity bearing components in both of the other systems, (2) the degree of supercriticality to attain a given peak reactor power has been considerably reduced by using the reactor as a booster. Very high power level performance can be attained with reactor multiplications from 100 to 1000, thus completely obviating the hazardous practice of pulsing the reactivity above prompt critical.

The neutron energy region in which this device would be useful for research purposes is really very wide. IBR⁽⁴⁾ has only 23 megawatts of peak fission power and a wide pulse of 36 μ sec but has been used for original neutron physics research from 0.001 eV to 1 MeV. However, comparisons have been made in recent years between booster sources and unboosted short pulsed accelerators, and it is generally believed that short intense bursts usually lead to higher experimental intensities than bursts from the relatively wide pulse boosters. Thus, above roughly 10 keV neutron energy it is certainly expected that the best tool for neutron research will be short pulsed high current accelerators. Below 10 keV neutron energy the matter becomes rather complex because the evaluation must consider attainable neutron flux levels and experimental details as affected by the source burst width. For neutron spectroscopy a typical arrangement might consist of a fast chopper system looking at

a moderator placed near a pulsed reactor. The fast chopper pulse width would be expected to be typically 1 microsecond. The fast reactor pulse is a few microseconds in width attaining power levels of several thousand megawatts and the epithermal neutron flux which is seen at the time of chopper opening is that corresponding to the level of a several thousand megawatt research reactor. Even though the flux levels usable by the fast chopper exceed those in presently proposed high power research reactors by nearly two orders of magnitude, it is still not clear that the flux levels in this repetitively pulsed fast reactor will exceed the advanced linac in intensity in the epithermal energy region. This situation is due to the fact that the minimum pulse width for fast chopper operation is between 0.5 and 1 μsec ; whereas pulsed beam time of flight work with linac sources can often be conducted advantageously with pulse widths of 0.01 to 0.1 μsec between 10 keV and 100 eV respectively. This disparity of a factor of ten in pulse width between choppers and linacs would have to be made up by increasing flight path lengths in the chopper experiments by about one order of magnitude for the same energy resolution over those used at linacs. Since the experimental intensity varies as the inverse third or fourth power of the flight path length, one loses the factor of 1000 gained in boosting the linac yield very rapidly in trying to obtain energy resolution comparable to that of the bare linac system. However, for many intermediate energy neutron physics experiments Doppler broadening effectively establishes the energy resolution and one might desire to use linac burst widths (unboosted) as large as 1 μsec in the 100 eV neutron energy region. In this case the chopper-linac booster combination can compete very favorably with the linac source alone.

In the energy region below 10 eV and above 1 eV, the effective moderator pulse widths begin to become comparable to the pulse width attainable with fast choppers. For this reason approximately the same path length is required for the same time or energy resolution with

either the linac pulsed source or a chopper system. The flux seen by the fast chopper still slaves to the peak reactor power so that it would appear that the fast burst reactor possibly in combination with a chopper would be an optimum way of proceeding in many experiments and that several orders of magnitude increase in intensity would thereby be obtained over chopper operation with a steady-state reactor. Obviously for chopper experiments a reactor with a power spike of approximately the same width as the chopper window width is optimum (a few microseconds) since neutrons born outside of the chopper open time generally only contribute to unwanted backgrounds. The accelerator pulsed booster with pulse widths of a few microseconds is obviously superior to a wide pulse reactor like SORA or IBR for which the fission energy in the pulse may be the same but the peak power or epithermal flux seen by the chopper is over an order of magnitude lower. However, when the moderator burst width and the time width of the chopper opening become comparable, one would normally seriously consider avoiding use of a chopper altogether. It is often possible to gain an enormous advantage in so doing since typically a fast chopper can see only a few square centimeters of source moderator whereas an area up to 100 times as large can often be viewed in a pulsed source experiment—experimental time resolution permitting.

For the study of neutron physics below 1 eV the selection of the optimum or ultimate research tool is complicated by the inclusion of the thermalization and neutron diffusion times in the pulsed moderators which ultimately may tend to limit time resolution, possibly more than the pulse characteristics of the driving reactor. In fact, it has been stated by both Raievski⁽⁵⁾ and Brunin⁽⁴⁾ that one need not strive for reactor pulse widths of less than 30-50 μ sec, or so, since the over-all neutron pulse width is determined by the properties of the moderator used to thermalize the fast neutrons and not by the pulsed reactor. It is at this point we would like to take exception with arguments advanced by others and to point out

that the shorter pulse accelerator booster is indeed superior to a device like SORA for all neutron energies below 10 eV even for subthermal and cold neutron physics.

IV. POTENTIALITIES OF A THERMAL FLUX BOOSTER

4.1 GENERAL

The generally high power levels attainable with repetitively pulsed fast boosters have been discussed in previous sections, together with general advantages of this device over other types of pulsed reactors. The consideration of this device in connection with production of very high intensities of thermal and cold neutrons is a complex subject because it is intimately interwoven with the design of an optimum neutron moderator. For example, it is not clear at first whether a short 5 μ sec burst reactor having 10 times the peak power of a longer burst reactor (50 μ sec) gives either higher instantaneous thermal fluxes or a narrower neutron burst. However, fairly conclusive arguments can be made on the basis of simplified analysis to indicate qualitatively that appreciable gains in neutron intensity, experimental flexibility, and device safety are attainable using accelerator pulsed boosters. The main areas of consideration are: (1) the flux levels obtainable, (2) burst shapes, (3) methods of varying the reactivity periodically, (4) background considerations, (5) reactor safeguards, and (6) repetition rates.

First, of course, one of the strongest motivations for pursuing this approach is the limitation placed upon flux levels obtainable from steady-state research reactors because of heat removal and fuel element burnup. Many experiments, however, do not require steady-state flux conditions. This is especially true of reactor chopper experiments where the reactor flux is utilized by the chopper over a low duty cycle (one percent) and the steady-state reactor only serves as a source of background

over most of the duty cycle. Thus, the idea of concentrating the reactor power in intense pulses with low power in between accomplishes at least three major objectives, (1) the average power of the reactor is reduced, (2) high peak neutron fluxes for chopper or pulsed moderator sources are provided, and (3) low background exists in between pulses.

4.2 THERMAL FLUX LEVELS ATTAINABLE

Thermal flux levels of greater than or equal to 10^{15} n/cm²/sec have been postulated for the new round of high flux research reactors in the planning stage or under construction in this country.⁽⁶⁾ Thus, it would appear a desirable objective to attain instantaneous flux levels with a repetitively pulsed booster in excess of 10^{16} n/cm²/sec. Qualitatively it seems possible to obtain or exceed this objective for reasons outlined below. However, it is not really clear that this should be the objective of a research reactor development program since it would appear more important to optimize conditions for the production of maximum neutron flux in the energy region desired for experimental study. It does not follow that a high total thermal flux level of 10^{16} n/cm²/sec guarantees that this will happen. For example, if one desires a high instantaneous flux of cold neutrons ($E_m < .01$ eV), one would never know whether this had been attained by simply considering the integrated flux produced in a moderator

$$\phi_{th}(T) = \int_0^{0.3\text{eV}} \phi(E;T)dE \quad (1)$$

Most of the integral in equation 1 comes from energies above 0.01 eV. The flux in the relevant low energy range of interest may actually peak at a time considerably later than the integrated thermal flux peak. It would thus appear desirable to study the potentialities of repetitively pulsed reactors from the standpoint of optimizing the quantity $\phi(E_o, T, X)$

in the energy range of interest. These problems of space (X), time, and energy are barely soluble theoretically in idealized one dimensional geometries by present day computational techniques. Of course, some insight into this problem can be obtained from theory but measurements are badly needed to determine actual flux levels.

Qualitatively it should be clear now why emphasis is often placed on reactor peak power levels since this quantity does serve as a meaningful guide to the performance capabilities of pulsed reactors without complex consideration of the details of the space time energy problem for the moderator. However, something can be said about thermal flux levels in repetitively accelerator pulsed booster reactors. The gross peak thermal flux level in a moderator placed near a fast reactor depends on the time dependent fast neutron leakage from the reactor, the geometrical coupling between the reactor and the moderator, and the slowing down and thermalizing properties of the moderator. For our purposes here we will make the idealization that the burst of fast neutrons will not be appreciably influenced by the neighboring moderator. Thus, the time dependence of the accelerator booster power we are considering is given approximately by the following equations:

Linac on

$$P(T) = P(T_0)e^{\alpha(T-T_0)} + \frac{S'}{\alpha} \left(e^{\alpha(T-T_0)} - 1 \right) \quad T < T_1 \quad (2)$$

Linac off

$$P(T) = P(T_1)e^{\alpha(T-T_1)} \quad T > T_1 \quad (3)$$

The variables are defined as follows:

$$S' = \frac{Shkw}{v\ell}$$

S = Linac produced neutron yield

h = heat generated per fission (joules)

k = prompt multiplication constant (assumed constant here during accelerator pulse)

w = ratio of importance weighting of the external source to the importance weighting of the fundamental mode.

ν = number of prompt neutrons produced per fission

ℓ = prompt neutron lifetime

T_o = time

$P(T_o)$ = metal reactor power level at time when accelerator is turned on

T_o = time when accelerator is turned off

$$= \frac{k-1}{\ell}$$

The power level thus varies in much the same way as shown below,

and it would be expected that the fast neutron leakage into the moderator will have about the same time dependence. Thus, to a rough approximation the thermal flux in the moderator can be thought to follow the two group expression neglecting slowing down time

$$\frac{d\phi_{th}(T)}{dT} = k P(T) - \lambda \phi_{th}(T) \quad (4)$$

This expression can only be considered illustrative since the flux $\phi(T)$ in the moderator is not really describable by a simple exponential dieaway. The solution to equation 4 may be obtained after insertion of equation 2 and 3 for $P(T)$ namely

$$\phi_{th}(T) = \frac{kS'}{\alpha\lambda} \left(\frac{\alpha e^{-\lambda T}}{(\alpha+\lambda)} + \frac{\lambda e^{\alpha T}}{\alpha+\lambda} - 1 \right) \quad T < T_1 \quad (5)$$

$$\phi_{th}(T) = \frac{kS'}{\lambda(\alpha+\lambda)} \left[1 - e^{+\lambda T_1} \right] e^{-\lambda T} + \frac{kS'}{(\alpha+\lambda)\alpha} \left[1 - e^{-\alpha T_1} \right] e^{\alpha T} \quad T > T_1$$

In the present form qualitative conclusions are hard to draw from equation 5 regarding peak thermal flux levels. However, let us consider the limiting cases which actually happen to conform to cases of practical interest. Case I is for $|\alpha| \leq |\lambda|$ and Case II is for $|\alpha| \geq |\lambda|$. Case I is that for a hypothetical reactor having a burst width comparable or longer than the longest thermal lifetime. It is indeed quite similar to the situation in the SORA reactor. Case II is the case of the accelerator booster where the pulse is always shorter than the thermal moderator lifetime. The resulting pulse shape for the thermal and fast spikes are shown for Case I in Fig. 8a while those for Case II are shown in Fig. 8b. Advantages of the shorter reactor pulse are thus apparent in that the peak thermal flux in Case II is essentially twice that in Case I and the pulse width is less than half that of Case I. A relatively long thermal dieaway time of 50 μ sec was used so as not to unfairly bias the comparison in favor of the accelerator booster.

In detailed evaluation of the thermal flux produced in a moderator a consideration of prime importance is that of the coupling of the neutron flux from the reactor to the moderator. A compact fast reactor with large fast neutron leakage usually produces considerably higher usable thermal fluxes in an adjacent moderator than a dilute thermal system operating at the same average power level. Assuming comparable reactor external moderator neutron coupling, the factor which seems to be relevant in determining peak thermal flux is the total fast flux impinging on a

Fig. 8(b) -- Thermal pulse shape for narrow reactor power pulse

Fig. 8(a) -- Thermal pulse shape for wide reactor power pulse

moderator in a time equal to about one thermal dieaway time. Thus, one would expect peak thermal fluxes produced by pulsed devices to be scalable on the basis of total fissions (watt-sec) per burst. Assuming again a thermal source dieaway time of 50 μ sec, the relevant fission levels are as follows for these pulsed reactors.

1. Present SORA Design - $\phi_{th} \propto 40 \times 10^6$ watts $\times 50 \times 10^{-6}$ sec = 2000 watt-sec.
2. IBR - $\phi_{th} \propto 23 \times 10^6$ watts $\times 36 \times 10^{-6}$ sec = 828 watt-sec
3. Booster - $\phi_{th} \propto 10,000 \times 10^6$ watts $\times 6 \times 10^{-6}$ sec = 60,000 watt-sec.

If peak thermal fluxes for an accelerator booster are scaled up using the above criteria from those calculated for SORA, fluxes greater than 10^{16} n/cm²/sec and possibly as high as 6×10^{16} n/cm²/sec are indeed obtained. If one wishes to use the Russian published data from the 1964 Geneva Conference,⁽⁴⁾ one finds that an 828 watt-second pulse produces a peak thermal flux of 2.8×10^{14} n/cm²/sec in a moderator. Thus, the above accelerator booster would be expected to produce fluxes of at least 2×10^{16} n/cm²/sec. If repetition rate could be sacrificed, at least a factor of three increase in peak thermal flux could be obtained by increasing linac pulse width utilizing the same heat transfer system.

In addition, we have made an approximate calculation of the peak thermal flux shape $\phi(E, X_m, T_m)$ in a one-dimensional geometry. The idealized geometry, shown in Fig. 9, consists of a 7-centimeter radius spherical U²³⁵ core surrounded by 3 centimeters of B¹⁰ and a thick LH₂ moderator. LH₂ may not be a practical moderator for this application, but it is one of the few cold moderators for which a complete and semi-realistic scattering kernel exists for use in the theoretical analysis. Arbitrary selection of thermal scattering cross sections (such as free hydrogen gas) for the calculations can lead to totally misleading results. The thermal spectra at the time of peak flux intensity produced by the

Fig. 9 -- Idealized geometry for calculating thermal fluxes

type of accelerator burst we have been considering are shown in Fig. 10 for three different moderator conditions: (1) 15-cm thick moderator unpoisoned, (2) 15-cm moderator poisoned with $1/v$ absorber to reduce the thermal lifetime, and (3) 5-cm moderator unpoisoned. If one integrates these spectra from zero to 0.3 eV, one obtains peak flux levels of over 10^{16} n/cm²/sec in this example. Thus, instantaneous thermal flux levels which would require at least a 500-megawatt steady-state thermal research reactor can be produced at an average power level of only 5 megawatts. It must be stressed again in the case of cold moderators that the above means of evaluating source intensity is at best qualitatively relevant since it does not reflect the abundance of the lower energy neutrons. It is important to note in Fig. 10 that the poisoned moderator did not really attenuate the peak value of the cold neutron flux much (however, its reduction of the pulse width of the system is far more pronounced). This important observation may be generally true for other moderators at other temperatures. It is true, however, that the spectral shapes shown above may possibly bear only a slight resemblance to those which will prevail in a practical cold source. In many of the cold moderators, liquid parahydrogen is a prime example, the transport mean free paths are very long and the spectrum is dramatically changed by small geometrical variations in the moderator vessel or its surrounding which affect the neutron leakage from the vessel. This effect can be seen qualitatively for steady-state spectra calculated in liquid parahydrogen (diffusion theory approximation) shown in Fig. 11, where the size of the hydrogen container (geometric buckling B^2) is varied.

4.3 PROMPT BURST SHAPES

In evaluating the importance of neutron burst shape, a great deal of attention must be paid to the experiments which use an intense pulsed source of neutrons. There are basically two ways of using this type of source:

(1) with a chopper to establish the experimental time resolution, and (2)

Fig. 10 -- Peak neutron flux shapes for various LH₂ targets

Fig. 11 -- Steady state thermal spectra in LH_2 as a function of container size (bucklings - B^2)

without a chopper — the pulsed moderator mode of operation. In the first case the chopper is synchronized to open at the time of peak intensity for the neutron energy range under study. This time may vary because of differences in slowing down times. Obviously for maximum effectiveness, the chopper must be placed near the moderator. The detailed burst shape of the moderator pulse is really of little importance in chopper experiments except possibly in very short flight time experiments where a long decay of the prompt pulse might produce a time dependent background during the counting interval. If, however, it is desired to use a pulsed reactor without a chopper for experiments, in order to avoid losses of intensity due to small chopper apertures, the moderator pulse width at all relevant neutron energies becomes a major consideration. In fact, experimental counting intensities will depend strongly on the neutron burst width obtainable. In most time of flight experiments the counting intensity depends on the inverse cube to fourth power of the required flight path length. The flight path length is determined by the experimental requirements for time or energy resolution. For thermal neutron physics the time uncertainty is usually established by the over-all source characteristics rather than those of the detector. A decrease by a factor of two in source pulse width means that a typical experiment can be performed on a flight path one half as long at an intensity increase of at least eight. Improvements in pulse width for pulsed reactors are therefore very important.

It was pointed out in the last section that the general problem one must solve for a pulsed reactor-moderator combination is that of the space, energy, and time dependent flux. It is possible to estimate by the time moments method⁽⁷⁾ what this flux looks like and what the effective pulse width is. However, this complex calculation is not required to understand qualitatively the value of a shorter pulse accelerator booster for thermal neutron production. Let us first define a simple calculational quantity which is a measure of the burst pulse width at any neutron energy. This quantity is the moderator mean emission time $\overline{T(E)}$ for neutrons of energy E and is defined as

$$\bar{T}(E) = \frac{\int_0^{\infty} \phi(E, T, X) T \, dT}{\int_0^{\infty} \phi(E, T, X) \, dT} \quad (6)$$

In an exponentially decaying flux this is the mean lifetime or time for the flux to fall by a factor of e in intensity. For other time dependences it is not so easily visualized, but it can usually be regarded as an index of the moderator pulse width. $\bar{T}$ is a quantity which can be readily calculated from the time independent transport equation. If we now calculate this time for a typical liquid hydrogen target, we obtain the curve shown in Fig. 12. The slowing down time (no neutron diffusion) is also indicated in Fig. 12, since it is a lower limit on the pulse width obtainable for a moderator. It is qualitatively clear from these calculations that the experimental burst width is seriously extended over most of the useful thermal energy regions if the moderator sees a reactor pulse of 50 microseconds width as in SORA. At neutron energies above 0.005 eV the basic moderator pulse width (full width at half maximum) has been more than doubled or the intensity available for the same energy resolution reduced by an order of magnitude. Curves of the neutron pulse widths for both SORA and an accelerator booster (LH_2 target) are given in Fig. 13. At 0.02 eV, for example, a moderator pulse width of about 15 μsec may be attained, a factor of nearly 4 less than the pulse width of the SORA system and intensities available at comparable time resolution fall for SORA by a factor of 64 at least.

An accelerator pulsed fast reactor would not extend the inherent moderator pulse width below 0.1 eV and as we have shown can provide higher peak thermal fluxes than SORA at the same average reactor power level. It can be seen from Fig. 13 that accelerator booster pulse widths of 10 microseconds are probably the maximum desired so that the time resolution of the device is not destroyed at higher neutron energies. It should be realized that the pulses we are describing are, although not

Fig. 12 -- Mean emission times for targets

Fig. 13 -- Pulse widths for SORA-LH₂ moderator
and accelerator booster-LH₂ target

perfectly shaped, very useful for high resolution neutron spectroscopy. Better than one half percent energy resolution would be obtainable over the entire neutron energy range with the LH_2 source of Fig. 13 using a flight path length of 10 meters.

A similar analysis may be performed for a conventional room temperature water moderator from which it is clear that above energies of 0.1 eV the moderator pulse width is extended by at least a factor of two by a reactor pulse of 50 μsec . Thus, it would seem very desirable in advanced pulsed reactor design to minimize the pulse width of the reactor.

4.4 METHODS OF VARYING REACTIVITY PERIODICALLY

For high flux repetitively pulsed fast reactors it is necessary to vary the reactivity of the device in some mechanical fashion. In conventionally designed devices such as IBR and SORA, the reactivity is varied from many dollars (6 to 15 β) below delay critical to above prompt critical by (0.1 β). In IBR two wheels each containing a portion of the reactivity are spun at high speeds through the core in order to put the reactor on a prompt period for a given time and then abruptly reduce the power by approximately five orders of magnitude. In SORA it is planned to rotate one wheel of reflector material past the surface of the reactor core at a speed of 300 meters per second. The reactor is thus put on a prompt positive period attaining a power level of some 40 megawatts for 50 μsec , but falling to a power level of less than 100 kilowatts between pulses.

The wheel performs at least three functions in the impulse reactor: (1) it varies the reactivity above prompt critical in order to produce the power pulse, (2) it drops the reactivity out of the supercritical region to shut off the power surge, and (3) it actually reduces the reactivity many dollars below critical in order to limit the experimental background produced by multiplication of delayed neutrons. To obtain a 20-40-megawatt power spike, the background neutron level must be multiplied by a

factor of about 1000. This requires that the reactivity be held above prompt critical for about a hundred microseconds if the reactor period is 10 microseconds or more. Thus, the properties of the rotating wheel for a SORA reactor must be such that the reactor remains a controlled and safe amount above prompt critical for the relatively long time it takes for the power level to build up. Exactly how it is proposed to do this is not known. The reactor peak power actually starts to decay when the assembly reactivity becomes subprompt critical.

For the accelerator pulsed booster a mechanical device may be used to periodically vary reactivity above delayed critical conditions sufficiently to obtain the desired power level. Prompt multiplications of between 200 and 1000 seem to be required to attain the fission power levels stated previously. Thus, the moving device is not needed to shut the reactor off or define the pulse width. The linac pulse essentially defines the fission burst shape. Therefore, the speed of the mechanism needed to vary reactivity does not approach that required for SORA or IBR. It is believed that sizable speed reductions of a factor of two or more can thus be effected in moving components associated with repetitively pulsed reactors. This fact opens up again the whole subject of how to vary the reactivity since mechanical systems which are inherently too slow for the SORA or IBR operation can now be considered.

4.5 BACKGROUND CONSIDERATIONS

One of the advantages of the repetitively pulsed booster (IBR, SORA) in contrast to, say, a booster of the present Harwell type is that the reactor multiplication is high when the accelerator neutrons are produced but low when the delayed neutrons are produced. In fact, in IBR the background power level between pulses is dropped to a nearly insignificant level. For many time of flight experiments the signal-to-background counting rates in a channel are proportional to the peak reactor power at time zero and inversely proportional to the background power

level existing at the times of neutron detection. The relevant background, for example, might be produced by fast neutron leakage through shielding and production of inelastic gamma rays in the structure of a detector housing. The interpulse power levels can be determined from the following general expression, giving the fraction of the fission energy included in the prompt power pulse:

$$\frac{\text{Prompt Pulse Energy}}{\text{Total Energy}} = 1 - \frac{\beta}{\epsilon}$$

β = is the effective delayed neutron fraction and ϵ is the reactivity below prompt critical attained on the average between pulses. It is measured in units of β . For IBR ϵ was about 15β , for SORA ϵ is 6β . The ratio of peak power-to-background power level between pulses is 10^5 for IBR and 10^3 for SORA. One of the two orders of magnitude improvement of IBR over SORA is due to pulse width and degree of subcriticality, the other is artificial being due mainly to a lower repetition rate. For an accelerator pulsed booster, in view of the increased flexibility in the design and the relaxed mechanical restrictions on varying reactivity, it is believed that one can exceed the degree of subcriticality of SORA between pulses and improve the background conditions for experiments to be more nearly in keeping with those of IBR. A large advantage is attained in this regard over most of the neutron energy region above 1 eV over steady state reactions because of the narrower effective pulse width of the accelerator booster and corresponding higher peak flux. It is expected that signal-to-background ratios of at least 10^4 could be obtained.

An idea of the advantage gained in signal to noise ratio in a pulsed reactor over a steady state reactor may be obtained by examining typical chopper experiments. The total number of signal counts obtained in a chopper experiment is proportional to the peak reactor power when the chopper is open multiplied by the chopper window width (ΔT_c). The total background obtained in the counting channels is proportional to the reactor power when the counting channels are open times the interpulse

period (τ), assuming the time of flight counting channels are open most of the time τ . Thus for a steady state reactor

$$\frac{\text{Signal}}{\text{Background}} = \frac{k \Delta T_c P(\text{Steady State})}{\tau P(\text{Steady State})} = \frac{k \Delta T_c}{\tau}$$

In a pulsed reactor

$$\frac{\text{Signal}}{\text{Background}} = \frac{k \Delta T_c P_a (\text{in pulse})}{\tau P_b (\text{between pulses})}$$

For IBR, SORA, or an accelerator booster P_a/P_b is typically 10^3 to 10^5 (as mentioned previously) and the experimental signal to background is improved by exactly this large factor using the pulsed reactor.

One of the great advantages of the repetitively pulsed accelerator booster over the SORA type of reactor is the ease with which experimental background corrections can be made. The accelerator may be triggered on alternate reactor pulses and the time dependent background accumulated on those pulses for which there has been no accelerator pulse. It would thus seem possible to instrument many experiments for automatic background subtraction.

4.6 REACTOR SAFEGUARDS

The pulsed thermal flux booster is a device that has the potential of being used by a large number of experimenters simultaneously. A number of reactor facility designs are possible for thermal neutron physics experiments but all have in common the placement and use of experimental devices near (within ten meters) the reactor. Thus, for a research reactor of this type to be useful it must be safe enough to be placed in an inhabited area. It is believed that the accelerator booster offers distinct advantages over a superprompt critical booster in this regard. In the previous sections it was shown that the mechanical techniques for varying the reactivity of an accelerator booster are not as difficult as those required for operation of superprompt critical pulsed reactors IBR and SORA. Not only is the reactivity attained above delayed critical considerably less but the speed of component movement has been reduced considerably. In fact, in the case of the SORA, if the moving reflector were to stop in its most reflective position the core would melt down before normal scram mechanisms could operate. For the accelerator booster, if a rotating reflector were used and stopped in the most reflective position, the reactor would go on a one second period at most and normal shut down mechanisms would have ample time to operate. In addition for the case considered, wheel design would not be as critical a problem as for the superprompt critical device where slight flutter or wobble in the wheel could cause large and dangerous fluctuations in the reactivity level above prompt critical. A third safeguards consideration in the single wheel device (SORA) is the fact that the wheel speed must be rigorously maintained since ten percent changes in speed can cause increases of a factor of two to three in peak power level and in turn average operating power level, which may overload the heat removal equipment or overheat the core seriously.

4.7 REPETITION RATES, REPRODUCIBILITY, AND GENERAL FLEXIBILITY

It is possible that experimenters using a boosted reactor would all desire a single pulse repetition rate, but this is usually not an optimum situation for all neutron experiments (for example, overlap criteria for neutron time of flight experiments differ). Of course, a reactor like SORA can provide a range of repetition rates but in this case the pulse width varies inversely with the repetition rate. Additional provision must be made to adjust the reactivity of the core when the wheel speed is reduced; otherwise the reactor power level will try to climb, for example, by another factor of 1000 on a speed decrease of a factor of two. With a repetitively pulsed accelerator booster, however, one does not have these problems. A wheel may be run at constant speed and the accelerator pulsing adjusted to control the neutron burst rate. On wheel pulses unaccompanied by linac pulses, the reactor merely multiplies the background level present which can be measured at that time if desired.

It should be apparent from the previous discussion that the reproducibility of burst characteristics for a repetitively pulsed fast reactor like SORA or IBR depends strongly on the mechanical characteristics of the system. Very slight speed variations or spatial fluctuations can easily cause 10 percent peak to peak power variations. On the linac driven system these same effects are of lesser importance and the pulse to pulse reproducibility of linac energy and current are most important in considering reproducibility. In a normally operating high current linac these variations are quite small and should produce no more than five percent fluctuations in power level of the accelerator booster.

A further element of flexibility afforded the experimenter with the accelerator booster is the possibility of rapidly varying the reactor intensity without adjusting reactivity levels. This can be done directly by controlling the linac beam current or pulse width on a pulse to pulse basis, if desired.

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V. CONCLUSIONS

It is apparent from the previous discussion that the potentialities of a repetitively pulsed linac booster are very great. However, in our discussions certain critical design areas have been passed over rather superficially either due to the lack of the necessary input data to use in making concrete predictions or due to incomplete analytical tools for calculating performances. Therefore, it is believed that before an optimum device of this kind can be built certain technical problems must be studied and solved. Some of these problems are briefly reviewed below:

1. Source or target yields of the photoneutron interactions in the fissionable elements must be pinned down experimentally up to and hopefully above 100 MeV electron energy and compared with thick target calculations using fundamental cross sections. Factors of two uncertainty exist between target yields from different isotopes at the same energy and between yields for the same isotope at widely spaced electron energies.
2. A theoretical model or calculational procedures for determining detailed fast and thermal burst shapes and yields must be formulated and tested. This may include a variation of a standard coupled neutronics - hydrodynamics code such as CONEC and also a transport description of moderator slowing down.
3. Absolute energy dependent leakage flux levels and emission times from pulsed moderators should be studied experimentally in clean geometries and compared to analytical predictions so that optimum pulsed neutron sources for various energy ranges can be intelligently designed. Moderator poisoning, shaping, and movement to enhance flux levels and burst shapes should be investigated.

This work should be done with a multiplying system to include interaction effects.

4. The effect of reflectors or shield environment on the reactor or moderator pulse width or time dependence should be studied experimentally in typical mock-ups.
5. Further tests of shock patterns set up in centrally pulsed multiplying assemblies should be made to guarantee that the material stress limits are not exceeded during short transient bursts.
6. A simple wheel or other mechanisms for varying reactivity should be tested experimentally to validate the theoretical procedures used for calculating the optimum performance of these devices and in an effort to arrive at a device design which will minimize interpulse background.

Although a systematic approach such as that outlined above is required to develop an optimum device, a very high flux prototype device operating at about 10% of the ultimate average power level is completely practical today. Most of this extensive feasibility and prototype test program mentioned above can be carried out with existing facilities available now in this country.

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