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FEASIBILITY OF UTILIZING A MICROTRON ELECTRON ACCELERATOR FOR NUCLEAR MATERIALS ASSAY

by
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I. INTRODUCTION

The use of a bremsstrahlung interrogation beam for surveillance of fissionable material can, in principle, offer advantages in certain practical applications. Gamma ray beams can be intense and penetrating and can be collimated as a narrow incident beam. They also suffer minimal multiple scattering and show no special sensitivity to hydrogen content. At energies well above the detectable threshold for photofission (roughly 5.5 MeV), the photofission cross sections as a function of energy all have approximately the same shape. Thus, while the total number of fissions per unit of incident bremsstrahlung radiation can be determined, it is not easy to identify the appropriate source isotopes producing the fissions. In principle, the analysis of the delayed neutron time behavior permits one to separate U^{238} from U^{235} and Pu^{239} with some some accuracy, but U^{235} and Pu^{239} cannot be separated from one another by this method, as their decay times are very similar.

One way that distinctive signatures can be obtained is to work at bremsstrahlung end-point energies very close to the actinide experimental fission thresholds (5-6 MeV). The U^{235} and Pu^{239} photofission cross sections have quite different energy dependences near these thresholds (see Figures 1 and 2), and measurements at two different energies can give distinctive signatures. However, to take advantage of the behavior near threshold, the energy spread of the interrogating electron beam must be made very small and stable. The Pu^{239} cross section near 6.5 MeV varies by a factor of 2 for $\Delta E = 0.3$ MeV. Thus the interrogating beam should have an intrinsic electron energy spread of no more than 0.1 MeV, and an energy stability and reproducibility commensurate with this value. It may be possible to develop assay techniques where a very stable low energy resolution electron beam can be used, but up to now this has not been established.

There are other advantages in working near the fission threshold. Competing processes with fission such as (γ, n) are minimized. Also, the

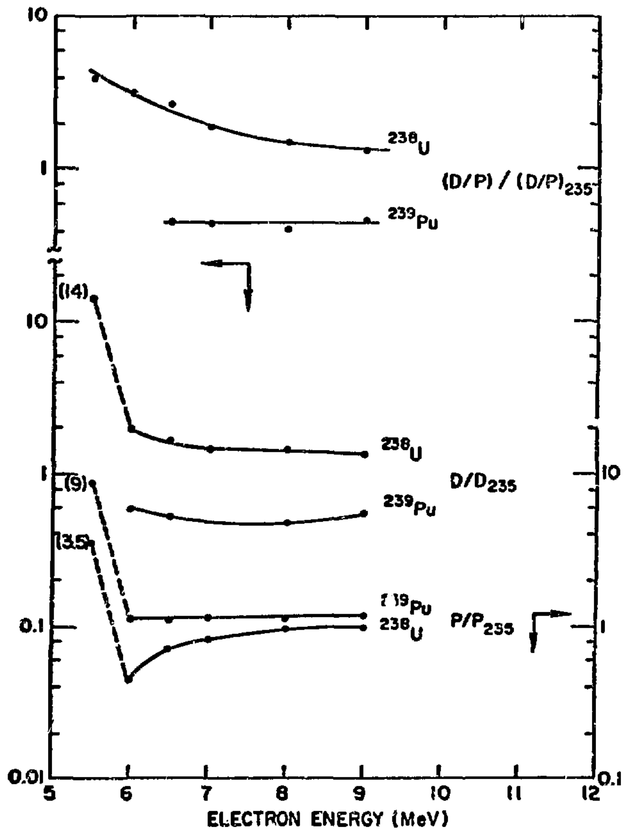

Fig. 1. Measured discrimination ratios. (GGA program data)

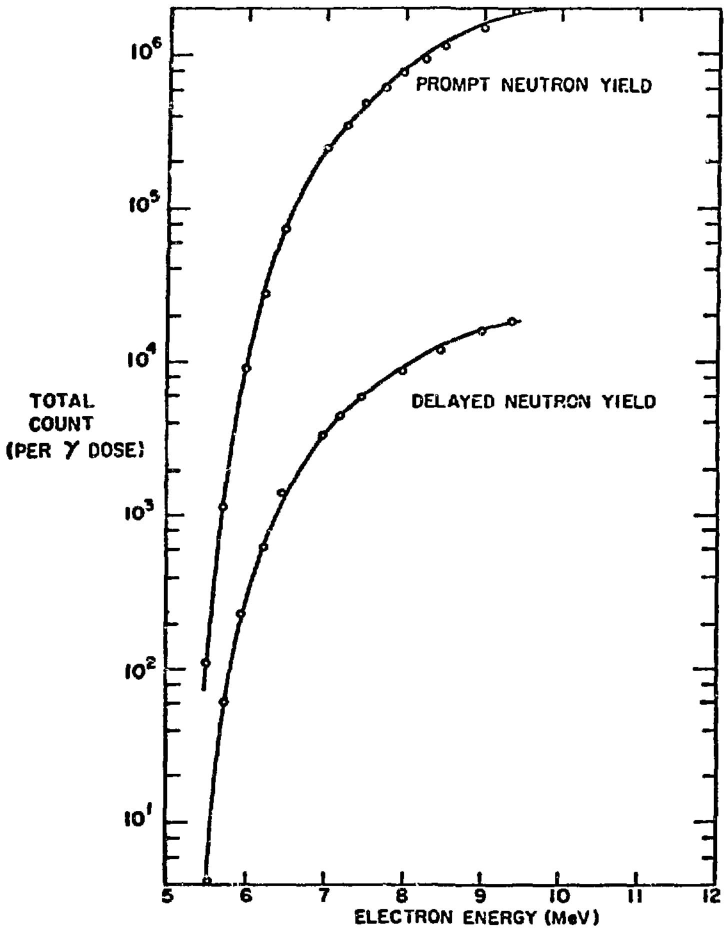

Fig. 2. Prompt and delayed neutron yield vs electron energy for ^{238}U. (GGA program data)

radiation shielding problems are more easily handled. This is important when considering a mobile facility.

Although electron linacs have the advantage of high beam currents, they have the serious disadvantages of having a rather large and variable energy spread, energy instability, and angular divergence of the output beam. Good energy resolution requires an elaborate injector pre-buncher system and a magmetic analysis system for the extracted beam. To obtain a resolution width of 100 KeV on a Linac, a defining slit arrangement must be used in conjunction with a bending magnet, and most of the electron beam must be discarded. The stray radiation from the discarded beam introduces serious shielding problems.

In order to investigate the performance requirements for the linac in more detail, consider the following example for an electron energy of 8 MeV. The output beam is passed through a 30^{o} bending magnet which is set to focus 8 MeV electrons. The energy spectrum of the electron beam before magnetic analysis has a Gaussian shape with a full width at half maximum of 10%. Defining slits would normally be placed at the focal point of the magnet. It can be shown that second order corrections are small, and that simple first-order magnetic optics gives a reliable calculation of the above example. When this calculation is carried out, we obtain the results shown in the following table:

Table 1

Beam Analyzing Efficiencies for an 8 MeV Electron Beam Passed Through a 30^{o} Bending Magnet. The Incident Beam has a Gaussian Distribution with FWHM = 10%

Beam Divergence	Energy Spread (FWHM)		Efficiency (% through slit)
	Slit Width	0.05"	
2 mr radian		0.12 MeV	14%
5 mr radian		0.17 MeV	13%
10 mr radian		0.34 MeV	13%
	Slit Width	0.1"	
2 mr radian		0.24 MeV	24%
5 mr radian		0.20 MeV	26%
10 mr radian		0.34 MeV	27%
	Slit Width	0.2"	
2 mr radian		0.56 MeV	64%
5 mr radian		0.44 MeV	50%
10 mr radian		0.40 MeV	48%

From the results shown in the table, we see that in order to have a narrow energy spread requires both a small angular divergence and a narrow slit width. To obtain ΔE = 100 KeV, the beam divergence can be no greater than 2 milliradians This implies the rather severe restriction that an electron gun and injector system, operated at 100 KeV injection energy, collimate the electron beam to within $\pm 2^{\circ}$. With the slits set to accept $\Delta E = 100$ KeV, about 12% of the accelerated electron beam will pass through the slits as useful beam. The other 88% of the beam must be captured and shielded so as to prevent it from causing an unwanted background.

It is thus important to consider alternatives to using the traveling wave electron linac as a high-resolution source of electron current. One approach (mentioned previously) is to emphasize the development of assay techniques that do not require a high-resolution electron accelerator. A second approach is to work with an accelerator which has inherently high resolution. The microtron is such a device. Although its development as a radiation source has never been emphasized in this country, the device has been used very successfully on a wide variety of applications in the Soviet Union. The device has the additional advantage that it does not involve costly components such as klystrons and thus might be produced as an inexpensive accelerator. Actual operational experience with these devices in typical safeguards assay applications is lacking at present. Nevertheless, if active methods of nuclear materials assay are to be pursued,the need for improved radiation sources is apparent and this device appears to offer itself as a simple inexpensive source.

Recently, the suggestion has been made that it might be possible to find one type of accelerator to perform both neutron and gamma interrogation. As will be seen from these studies, a low-energy high-resolution electron machine may be able to do this job. In this evaluation, the machine operation is described in Section II, its advantages in Section III, disadvantages in Section IV, and recommendations in Section V.

II. PRINCIPLES OF OPERATION

Figure 3 shows the electron orbits in a microtron. The electrons are injected into an R. F. (microwave) cavity (or cavities) and are accelerated to an energy of the order of 1 MeV for machines of interest to us. After leaving the R. F. cavity, the electrons perform an approximately circular orbit in a fixed magnetic field, returning to the R. F. cavity after each orbit. The machine design is such that the electrons return in a time corresponding to integer multiples of the R. F. period so as to remain in phase. In fact, the change in orbit period is directly proportional to energy change. Although the necessary energy gain is acquired by those electrons which reach the gap at a particular voltage phase, phase stability is operative, and electrons somewhat ahead or behind the synchronous phase acquire the correct energy gain as in a synchrotron. The lowest energy allowable for the first orbit is determined by outside dimensions of the R. F. cavity R_c and magnetic field such that

$$2R_{electron} > R_c$$

allowing electrons in the first orbit to return to the cavity for further acceleration.

The electrons follow circular orbits, having a radius of curvature given by the cyclotron equation

$$\frac{Hev}{c} = \frac{mv^2}{\rho}$$

where

ρ = radius of curvature in cm

v = velocity of electron in cm/sec

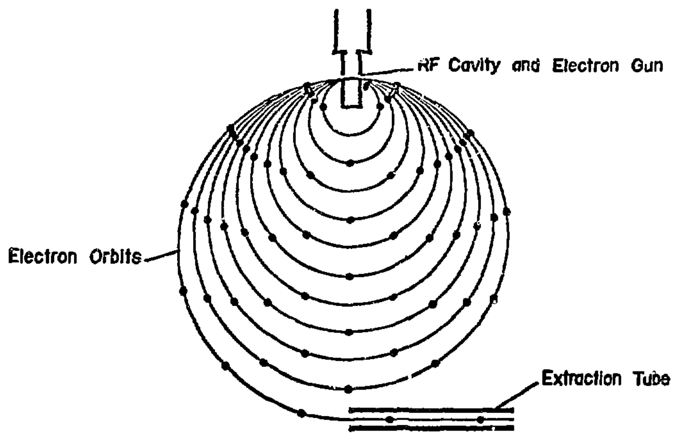

Fig. 3. Conventional circular microtron.

c = velocity of light in a vacuum (3×10^{10} cm/sec)

e = electron charge (4.8×10^{-10} E.S.U.)

m = relativistic electron mass (gm)

H = magnetic field (gauss).

The electrons pass through a cavity once each revolution. The r.f. period

$$T = \frac{1}{f}$$

thus sets the timing for the whole microtron.

Since we must use relativistic equations to follow the electron motion, it is convenient to work with the standard relativistic notation:

$$\beta = \frac{v}{c}, \ \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

The electron mass is

$$m = \gamma m_o$$

The cyclotron equation becomes

$$He\beta = \frac{m_o \gamma c^2 \beta^2}{\rho}$$

or

$$H\rho = \frac{m_o c^2}{e} \gamma\beta$$

It is convenient to define

$$Q = 2\pi \frac{m_o c^2}{e} = 10,700 \text{ Gauss cm.}$$

Now assume that the electrons are injected through the cavity. We can speak of the energy of the electron in units of γ.

$$E = mc^2 = \gamma m_o c^2$$

Thus, γ is the electron energy in units of 0.511 MeV. Similarly, we denote the energy gain in passing through the cavity as

$$\Sigma = \Delta E = \Delta m_o c^2$$

Thus Σ is the energy gain in units of 0.511 MeV. If the electron is injected with energy γ_o into the cavity, it will receive additional energy Σ. Hence, the total energy for the first orbit will be

$$E = (\gamma_o + \Sigma)\, m_o c^2$$

The time for the first orbit must be a multiple of the r.f. period T.

$$t_1 = \mu T$$

The time for succeeding orbits must be longer than the time for the first orbit by some other multiple.

$$t_2 - t_1 = \nu T$$

The time for the k th orbit is

$$t_k = \{\mu + (k-1)\nu\}\, T$$

Now for the first orbit, we have

$$t_1 = \frac{2\pi\rho_1}{v_1} = \frac{2\pi mc}{eH} = 2\pi \frac{\gamma m_o c^2}{e\,Hc} = \frac{\gamma Q}{Hc}$$

Thus,

$$t_1 = \mu T = \frac{Q}{Hc}\,(\gamma_o + \Sigma)$$

For the second orbit

$$t_2 = (\mu + \nu) \quad T = \frac{Q}{Hc}(\gamma_o + 2\Sigma)$$

and for the kth orbit

$$t_k = \{\mu + (k-1)\nu\} \ T = \frac{Q}{Hc}(\gamma_o + K\Sigma)$$

We assume that the timing is perfect, so that the full energy Σ is imparted to the electron on each orbit. By comparing the first and second orbits, we have

$$t_2 - t_1 = \nu T = \frac{Q\Sigma}{HC}$$

Solving this equation and the equation for T_1 simultaneously yields this energy increment

$$\Sigma = \frac{\gamma_o \nu}{\mu - \nu} \ .$$

Thus, if we assign an integer to ν (usually $\nu = 1$) and if we fix Σ (usually as high as possible), then the value for H is determined. We write this equation as

$$\frac{HcT}{Q} = \frac{H\lambda}{Q} = \frac{\Sigma}{\nu} \tag{I}$$

where $\lambda = cT = 10$ cm typically (S-band).

Substitution of the value for Σ into equation I gives us the requirements for H.

$$\frac{H\lambda}{Q} = \frac{\gamma_o}{\mu - \nu} \tag{II}$$

We must have $\mu > 1$ from this result. Thus, the first path must include two or three r.f. wavelengths. If we have H already fixed, then this equation determines γ_o, the injection energy. Or, we can work the other way. Fixing μ and ν at integral values, we can vary γ_o over the range of the injector. For each γ_o, we must set H from equation II. Then we must set Σ from equation I. Thus, the output energy of the microtron is variable over a limited range.

$$E = (\gamma_o + N\Sigma)M_o c^2$$

Next, consider the race-track microtron shown in Fig. 4. This differs from the circular microtron in having a total field-free drift distance D added to each orbit. This is accomplished by producing the magnetic field with two or more separated pole pieces. This design provides more feasibility in magnet requirements allowing easier injection and weight reduction among other improvements. The time to traverse an orbit is

$$t = \frac{2\pi\rho + D}{v} = \frac{Q\gamma}{HC} + \frac{D}{\beta C}$$

Thus, for the first two orbits, we have

$$t_1 = \mu T = \frac{D}{\beta_1 C} + \frac{Q}{HC}(\gamma_o + \Sigma) \tag{III}$$

$$t_2 = (\mu + \nu)\ T = \frac{D}{\beta_2 C} + \frac{\Omega}{HC}(\gamma_o + 2\Sigma) \tag{IV}$$

In the case of the circular microtron, choosing γ_o led to unique choices for H (from II) and for Σ (from I). For the racetrack microtron, the distance D gives another free parameter. Thus, for a given value γ_o, we can pick any any value for Σ , and then adjust D and H so as to satisfy III and IV. This will give perfect synchronization in the first two orbits. Succeeding orbits will not be perfectly synchronized, since the value of β will change slightly for each orbit. This lack of synchronization is not serious because only a few orbits are necessary before the beam attains the full output energy.

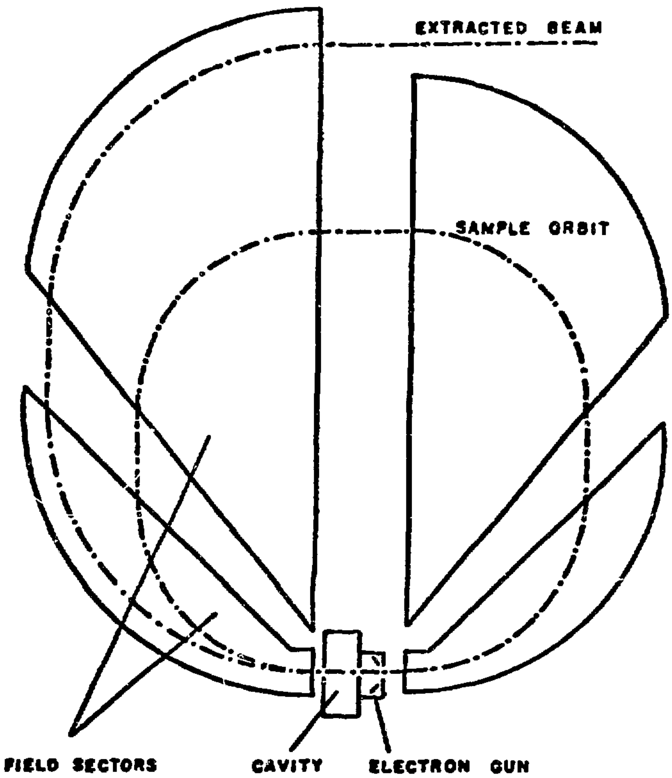

Fig. 4. Racetrack microtron. A typical orbit and the final orbit are shown. Injection is from the gun placed right next to the accelerating cavity.

III. THE PRESENT STATUS OF MICROTRONS

A microtron for safeguards purposes should have an energy range of 4-8 MeV and should have an average beam power of about 100 watts. It should also have very high energy resolution. This last requirement is not very well by all microtrons. The paper "Energy Spectrum of the Electron Beam in a Racetrack Microtron" by Sells, H. Forelich, and E. Branne, Journ. Appl. Physics 36, 3264 (1965) shows that for a 6 MeV microtron, 50% of the output current is within ± 17 KeV and 90% is within ± 37 KeV. The best result that can be obtained with a linac, using a very elaborate injector buncher system and output beam analyzer system, is to put about 10% of he accelerated beam within possibly a ± 60 KeV energy bin.

The microtron at Western Ontario has been operated at energies from 4 to 6 3 MeV and the feasibility of a commercial machine is being investigated The microtron at the University of California, Berkeley, has an energy range at present of 6 7. 5 MeV. A commercial machine manufactured by Scanditronix in Sweden provides electron beams varying in energy from 6. 1 7 1 MeV. Russians microtrons have been typically operated between 6 and 13 MeV Thus, it is apparent that the energy range of 5 to 8 MeV is one that easily accessible for a microtron installation.

An average beam power of 100 watts is a more difficult achievement for a microtron. Nevertheless, it is a goal that should not be impossible to attain. The Western Ontario microtron which has a race track configuration has a 2 μsec pulse, 40 ma in the output beam at 6. 3 MeV. Hence a pulse repetition rate of 200 would be required to give 100 watts of beam power.

The Berkeley microtron has a 1 μsec pulse width, 60 pulses per second repetition rate, 12 ma in the output beam at 7. 5 MeV. This represents an average beam power of 5 watts. The machine is patterned after that at Western

Ontario University machine and is of the sector strong focusing type. The overall size is 20 in. with 13 in. used for orbits. The magnet gap is only about 1/4 in The accelerator specifications are shown in the following table. The overall cost of designing and building the Berkeley machine was less than $50,000 several years ago. A detailed list of the operating characteristics is included in Appendix I.

The Berkeley accelerator has been used primarily for the study of the prompt bission neutron emission process for U^{235}. A bremsstrahlung x-ray beam was produced in a gold target. These x-rays fissioned a U^{235} sample and the resulting neutrons were counted with a BF_3 paraffin (long counter) detector.

A Russian microtron has been constructed that has a 2.5 μsec pulse, 400 pulses per second, a beam energy of 10 MeV, and an accelerated pulse current of 50 ma. The average beam power is 500 watts. The average power to run the machine was 15 kw, so the overall electrical efficiency of the machine is as low as an electron linac, which is not surprising. The R. F. efficiency is about 35%.

The commercial machine "Microtron M7" manufactured by Scanditronix produces 7 MeV beams in pulse widths from .05-5 μsec at rates up to 200 p/sec average current during a pulse is 200 ma. The cost of this machine is about $137,500. This machine is somewhat more versatile than really required for safeguards assay applications, so a lower cost might well be possible in those cases.

For microtrons the electron beam extraction efficiency can be very close to 100%. The beam extraction is effected by locally removing the magnetic field at the final orbit with a soft iron tube. The spacing between orbits is typically 3 cm.

One of the major operation al problems of microtrons is the electron gun or cathode lifetime, and the Russians have done much to improve this. Typical electron capture efficiency for simple electron cathodes is ~ 5% and can be increased to 10% with the Russian horizontal slotted cathodes. This limits the present currents without external injection to 100 ma while theoretical limits set by the accelerator itself are nearer to 1-10 ampheres. Thus, at present, the Russians have shown that for a 100 ma peak beam current 2 μsec pulse one can obtain a 0.2 x .4 cm spot with an angular divergence of 1.5 milliradians.

A somewhat different class of microtron has been built in the Soviet Union at OIYAI. It operates on the second frequency mode rather than the fundamental. It is a 30 MeV, 60 ma device with a higher magnetic field and small magnet. It is reported that energy control is even better with this machine than with the conventional microtron.

A microtron accelerator optimized for safeguards applications would have the following approximate specifications:

Energy Range	4 MeV - 8 MeV
Peak Current	50 - 200 milliamperes
Pulse Repetition Rate	120 pps - 180 pps
Pulse Length	2 μsec
Energy Resolution	30 - 40 KeV

These ratings are quite typical of present microtron designs.

IV. ADVANTAGES OF THE MICROTRON FOR SAFEGUARDS ASSAYS

In considering the advantages or disadvantages of any new radiation source or technique for safeguards, one must pay special attention to the detailed applications. At the present time it appears that passive methods of assay are most usually applied in fuel assay investigations. Active methods of nuclear materials assay, which could employ the microtron source, would have to be superior to competing methods on a number of counts including:

1. Capital cost
2. Operating costs
3. Simplicity, ease of operation
4. Reliability
5. Need for expensive peripheral support equipment
6. Availability of new techniques based on the sources provided
7. Portability
8. Precision obtainable in assays
9. Flexibility

(1) Capital Costs. Based on experience of those who are building these devices at Western Ontario University, the University of California at Berkeley, the University of Illinois, and Scanditronix, the microtron has been found to be a relatively inexpensive route to attaining high resolution electron beam characteristics. These machines, however, have generally been research machines and thus not subject to the stringent requirements on reliability of production devices. Development costs for a prototype production microtron for assay purposes probably would be around $100,000. Since no single component costs over a few hundred dollars, (1 megawatt magnetrons are $350), it is expected that machines other than the first one could be manufactured at a considerably lower cost. This

statement is consistent with an often expressed comment that the microtron cost is estimated to be 1/3 to 1/2 of that of a comparable Linac. Access to the Soviet microtron technology would speed up and reduce the cost of development.

(2) Operating Costs. Since accelerator parts are inexpensive, the microtron operating cost is very low and comparable to that for a Cockcroft Walton. With an internal x-ray target, the only possible machine components requiring replacement would be the electron guns. Electron guns should be as reliable as those used with Linacs, but experience to date indicates this technology is rather rudimentary for microtrons.

(3) Complexity, ease of operation. The microtron is inherently simpler to operate than a one-section Linear accelerator, since there are no phase adjustments or prebuncher adjustments. This device is about as simple as an accelerator can get.

(4) Reliability. Since all components operate at low-power and many of the microwave components have been used for years in low-power radar systems, good reliability would be expected. The reliability should be better than for traveling wave Linacs, which require 5 to 10 times as much power to attain the same beam parameters. The device also needs no magnetic beam analysis system, which eliminates a problem area concerned with the construction of vacuum hardware for high beam power applications

(5) Peripheral Support Equipment. Here one also gains an advantage in that no magnetic spectrometer is needed to produce a high-energy resolution electron beam. This auxiliary equipment on a Linac can increase the total cost of the device by at least $10,000 to $30,000, aside from providing a more complex and bulky installation.

(6) New Techniques. All assay techniques which can be performed with the Linac can be performed with the microtron. Assays performed with a microtron will contend with less background problems than similar methods using a Linac because the entire high-resolution electron beam is utilized.

(7) Portability. Machines of this sort have been typically shielded very lightly by 1/2" of lead and 12" of concrete. This is a marginal shield but qualitatively represents a great weight reduction over the shielding which must be used on a Linac for the same application. The extra shielding is for the 90% of the wasted Linac beam. Shields for Linac targets and magnetic systems run from

6" to one foot of lead plus neutron shielding. It is probably safe to say that one would save at least a factor of two in shield weight using a microtron rather than a linac in a given assay experiment. The accelerator itself is also very compact, typically fitting entirely into a volume 3' x 3' x 2' and thus easily moveable on a dolly system. A comparable "conventional" linac requires a space of about 10 ft x 6 ft x 3 ft.

(8) Precision and Speed. Precision of assay and speed of analysis are two all-important quantities as far as safeguards methods are concerned, but here, in comparing the microtron approach with other approaches, it will be necessary to be somewhat qualitative. First, on precision one finds for photo-induced methods that a very important procedure for separating responses due to U^{235} and Pu^{239} is to measure prompt and delayed neutron yield near threshold. In a Linac system, neutron background made by the large unused beam is comparable or can exceed the signal from the sample near threshold. The largest discrimination ratios appear at the lowest electron energies, so operation at slightly above 5 MeV is desirable. Techniques of assay have not been practical at energies below about 5.7 MeV to date. Since large undesirable and potentially fluctuating backgrounds should be eliminated with a microtron, one would expect to improve precision of assay considerably--by at least a factor of 2 at low electron energies ($\sim$ 5.5 MeV) and by a considerably greater factor at energies not now attainable for background reasons.

As a stable-spectrum neutron source for sub-threshold neutrons ($E_N < 1$ MeV), the microtron using (γ, d) neutrons would seem to be very promising. The peak intensity alone of this source from photodisintegration is two orders of magnitude higher than a pulsed (d, T) source. So here, too, higher assay precisions should result in greater assay speeds.

(9) Flexibility. This machine can serve very well in three general areas of non-destructive testing for safeguards:

a. Photo-induced interrogation methods

b. Neutron-induced interrogation methods (Shaped Spectrum Approach)

c. Radiography (x-ray)

The microtron is undoubtedly better than the Linac for the vast majority of photo induced assay techniques developed up to now, since the generally require a stable, high-resolution electron beam. In the case of active neutron assays, a microtron running in the energy range of 4 to 6 MeV with 100 watts of beam power has an instantaneous neutron source strength on the order of 10^{13} to 10^{14} neutrons per second. The high-energy cutoff for the neutron spectrum is 2 MeV for 6 MeV electrons and is 0.9 MeV for 4 MeV electrons. This is at least two orders of magnitude more intense than a (d, T) source and does not involve a target which must be changed repeatedly. Furthermore, the source spectrum should remain stable due to the high energy resolution of the accelerator. For radiography, the small beam spot size and angular divergence of the beam obtainable from these machines makes this machine an ideal radiographic source for fuel or sample inspections.

V. DISADVANTAGES OF THE MICROTRON FOR SAFEGUARDS ASSAYS

The microtron is an accelerator concept which has not received much attention in the United States. It is therefore in a rather rudimentary state of development. There are presently no commercial manufacturers at present. Thus,the device needs to be developed from its present laboratory status into a well-engineered reliable piece of equipment. The most difficult technical problem remaining is electron injection into the R. F. cavity. Heater burn-out on cathods for typical microtrons are reported to occur for short periods of operation. This particular engineering problem appears to be most in need of solution. Solutions to other engineering problems, including design of good vacuum envelopes, will be needed. "O" ring sealed systems are presently in use and are not desirable in production devices. Some provisions for cooling will also be needed if 100 watts of beam power is to be removed from a microtron. Thus this device is not in an advanced state of development like sealed tube (d, T) sources or Linacs and requires some effort to attain this state of development in order to be considered as a source for safeguards applications

A second disadvantage of the device is that it is basically a low current device. Although it does not appear now that high currents are necessary for nuclear materials assay work,if one has a high resolution electron beam available, higher currents may still be desirable for irradiation of large samples. Beam power levels up to 400 - 500 watts can be obtained from microtrons with a reduction in device simplicity and an increase in cost. This factor requires further serious consideration.

VI. CONCLUSIONS

1. It is fairly clear at present that no one as yet has found the ideal accelerator radiation source for assay of nuclear materials. The (d, T) neutron sources appear to have a realtively short lifetime, and require additional moderation for many common applications. The conventional traveling wave electron lines for gamma or neutron interrogation are customarily rather expensive ($150, 000), and, in addition, have a poor electron energy spectrum, necessitating magnetic spectrometers and extensive shielding. The microtron would seem to be an ideal source from many standpoints as mentioned above, but experiments, some of a materials assay nature and others concerning fundamental accelerator technology, need to be performed to see if this type of device does hold promise.

Examples of the first type of experiment are the study of the relative machine and target neutron and x-ray backgrounds from 4 to 8 MeV, and actual performance of some simple assays using prompt and delayed neutrons. Examples of the accelerator technology experiments are studies of machine-operating stability, cathode lifetime, ease of operation, and tuning. These experiments should be done first using existing microtrons.

2. As a step to develop a suitable machine for safeguards, it would be worthwhile to consider development of simple more reliable electron injectors for microtrons. The Tomsk Institute appears to have this problem under control. Since the microtron reliability factor is presently limited by cathodes and injector lifelines, it would be expedient to attack this problem first. It would appear that the electron gun reliability problem can be solved without a costly development program.

3. It is apparent that one of the most appealing ideas at present is to search for an inexpensive accelerator that provides both neutrons and

gamma beams for active nuclear materials interrogations. It seems that further thinking, along the lines of how to accomplish this, is warranted in the case of the microtron.

(4) A need also exists to make a more detailed analysis of accelerator costs generally and for the microtron in particular, including (1) parts costs, (2) design costs, (3) development costs, (4) fabrication, (5) overhead and profit, (6) cost of operation and (7) level of operating personnel. These data would be useful in objectively determining the potential market for assay systems based on microtrons.

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APPENDIX I

SPECIFICATION SHEET FOR THE BERKELEY MICROTRON

A. PERFORMANCE

Beam Particles - Electrons
Operating Beam Energy - 7 MeV
Energy Spread - 50 KeV
Beam Current (peak pulse) - - - - - - - - - - - - - - - - - - 10 mA
Beam Current (average) - 1.2 μA
First Turn Current - 45 mA
Number of Orbits - 8
Pulse Length - 1.6 μsec
Maximum Pulse Rate - 60 pps
Output Beam Size (approximate) - - - - - - - - - - - - - - - - 1/16" Diam.
Beam Emittance - 5 mm-milliradians
Beam Extraction (through iron Pipe) - - - - - - - - - - - - - 100%

B. ACCELERATOR CHAMBER

Main Chamber - 20" O.D. x 8" high, stainless steel ring, mild steel lids
Aperture (pole piece spacing) - - - - - - - - - - - - - - - - 0.28"
Volume of Vacuum Chamber (approximate - - - - - - - - - - - - $\sim$1000 inches^3
Operating Vacuum Pressure - - - - - - - - - - - - - - - - - - $\sim 10^{-6}$mm
Vacuum Pumps 1. - - - - - - - one 80 liter/sec Vac Ion pump
2. - - - - - - - one roughing pump type KC5 Kinney
Vacuum O-Rings - Viton
Beam Window - 0.001" stainless steel

C. MAGNET

Magnet Type - - - - - - - - - - - Four sector, flare focussing
Approximate Overall Dimensions - - - - - - - - - - - - - - - - 24"x32"x15"
Approximate Weight 1. Iron - - - - - - - - - - - - - - - - - - 700 lbs.
2. Copper - - - - - - - - - - - - - - - - - 50 lbs.
Pole Piece Adjustment Range (horizontal) - - - - - - - - - - - 2.5" to 4.25"
Magnetic Field Strength at Gap - - - - - - - - - - - - - - - - 1700 Gauss
Number of Coil Turns - 16,000
Power Required for Magnet (220V at 70 mA) - - - - - - - - - - 15 Watts
Magnet Cooling - None

D. INJECTION SYSTEM

Maximum Gun Voltage - 25 kV
Gun Current - 120 mA
Pulse Length - 2 μsec
Cathode - - - - - - - - Matrix type, Phillips impregnated cathode, type B
Cathode Operating Temperature - - - - - - - - - - - - - - - - 1000°C
Heater Power 12.5V at 1.2A - - - - - - - - - - - - - - - - - - 15 Watts
Cathode Life (typical) - 100 - 200 hrs.
Pulse Transformer Turn Ratio - - - - - - - - - - - - - - - - - 6.3:1
Cathode Emitting Area - 7.3×10^{-2}cm^2

E. OSCILLATOR AND RF SYSTEM

Oscillator Type - 5586 Magnetron
Tuning Range of Magnetron - - - - - - - - - - - - - - - 2700 - 2900 MHZ
Operating Frequence - - - - - - - - - - - - - - - - - - 2780 MHZ
rf Peak Power - 600 - 800 kW
Magnetron Voltage - - - - - - - - - - - - - - - - - - - 30 kV
Magnetron Current - - - - - - - - - - - - - - - - - - - 40 - 60A
Pulse Length - 3 μsec
Magnetron Cooling - - - - - - - - - - - - - - - - - - - Blower
Pulse Transformer Turns Ratio - - - - - - - - - - - - - 4.5:1
Magnetron Filament - 16V at 3.2A - - - - - - - - - - - 51 Watts
Magnet - - - - - - - Permanent Magnet, Alnico V, 2800 Gauss
Transmission Line to Cavity - - - Rectangular Waveguide, RG48/U
Approximate Distance from Magnetron to Cavity - - - 29"
Vacuum Window - - - - - - - - (Microwave Associates)- - - Glass
Isolator - - - - - - - - - - Raytheon, ISH14 - - - - 10db (nominal)
Directional Coupler - - - - - - - - - - - - - - - - - - 30db
Waveguide Pressure - - - - - - - (dry nitrogen)- - - 14 psig

F. CAVITY

Cavity Type - - - - Right Circular Cylinder - - - - TE_{010}Mode
Cavity Material - OFHC Copper
Cavity Gap - 1.090"
Cavity Q (loaded) - - - - - - - - - - - - - - - - - - - 3000
Cavity Peak rf Voltage - - - - - - - - - - - - - - - - 10^6 volts
Cavity Cooling - - - - - - - - - - - - - - Conduction and Blower
Cavity Coupling to Waveguide - - - - - - - - - Iris (0.845" Diam. Hole)

G. GUN AND RF MODULATORS

Sub-resonant Charging, Solid State Charging Diode, Solid State Reverse Diode, Pulse Line, 5C22 Hydrogen Thyratron Switches

H. SHIELDING

½" Lead Around Vacuum Chamber
12" Heavy Concrete-Block Wall Between Machine and Control Area

I DIAGNOSTICS

Faraday Cups
1. For gun Current measurements
2. For orbit position and current measurements

Cavity rf Probe
Glass Viewing Ports
Fluorescent Screen on Faraday Cup Stem for Viewing Orbits
Variable Modulator Voltage and Currents
1. Faraday Cup
2. Pole Piece Position
3. Magnetron Tuning and (voltages and currents)
4. Magnet Currents
5. Vacuum
6. Radiation Levels
7. Energy Read Out

Bremsstrahlung Foil - - - 0.080" Gold Foil
Sliding Wedge Energy Readout