SAFETY CONSIDERATIONS FOR A GENERAL PURPOSE INDUSTRIAL ACCELERATOR FACILITY

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ABSTRACT

An irradiation facility capable of housing industrial electron accelerators with beam energies of 10 MeV and beam power up to 10 kW is under construction at the Whiteshell Nuclear Research Establishment. It consists of an accelerator room, shielding maze and control room below ground level and a warehouse at street level. Shielding is provided by concrete in the maze and earth berm above the accelerator room. A conveyor system transports packaged product for irradiation from the warehouse area to the accelerator room via the maze.

The radiation hazards considered during design of the facility were radiation dose from bremsstrahlung, neutrons, activation products and radio-frequency radiation. A variety of industrial hazards including toxic gases, electrocution, pressurized systems, fire, flood and noise were analysed.

The maze is wide to accommodate a walkway and the conveyor. Extra care was taken to analyse scattering of neutrons and bremsstrahlung through the maze. Analysis with the Monté Carlo Code MCNP shows that scattered bremsstrahlung is a small component of the dose penetrating the maze, but for neutrons, the dose contribution from scattered particles is much larger than the dose from the direct penetration path. The analysis indicates that the shielding is adequate unless high neutron yield targets are irradiated.

INTRODUCTION

The Accelerator Applications Research Facility (AARF) at the Whiteshell Nuclear Research Establishment (WNRE) has been designed to house accelerators capable of delivering beams of electrons of maximum energy 10 MeV and average beam power of 10 kW.

The AARF will be used for the development of industrial processes employing radiation, and will irradiate a variety of materials including biological agents, food, toxic chemicals, pollutants, synthetic and natural materials. Materials will be irradiated in quantities appropriate to the particular experiment, ranging from a few grams to many tonnes. The applications range from purely experimental investigations to pilot-scale operations.

FACILITY DESCRIPTION

Layout

The AARF is attached to the Health and Safety Building at WNRE. It consists of a control room, shielding maze and accelerator room on one level below grade, as shown in Figure 1, and a warehousing area at street level. Both levels of the facility may be entered from the Health and Safety Building.

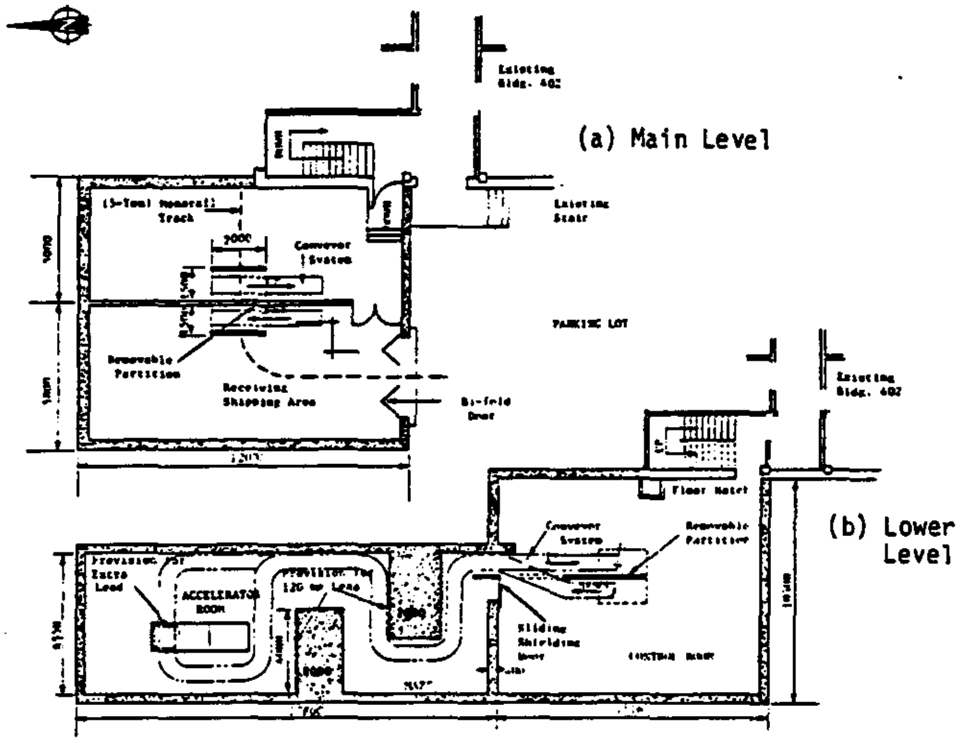

Figure 1: Accelerator Applications Research Facility at the Whiteshell Nuclear Research Establishment.

A crawl space underlays the whole basement level. This space is 1800 mm deep, except under structural beams and provides sufficient space for running services from the control room to the accelerator. The crawl space is not occupied when the accelerator is running because of high radiation fields. However, the shielding walls of the maze extend into the crawl space and are of the same thickness to prevent radiation scatter to the control room via the crawl space.

Shielding for the facility is provided on the east, west and north sides by the ground. Shielding above the maze and accelerator room is provided by 600 mm of ordinary concrete in the ceiling plus 3500 mm of earth berm compacted to a specific gravity of 1.5. The shielding between the control room and the accelerator room is provided by a maze with two walls 2000 mm thick and 4000 mm wide. The wall between the control room and the maze provides an additional 400 mm of concrete shielding against radiation scattered through the maze. The access maze to the accelerator room may be reached from the control room via a steel shielding door in the 400 mm wall.

The control room provides space for the electronic racks and control panel for the accelerator. Electrical and mechanical service panels are housed along the east wall of the control room. The access hatch to the crawl space is located in the control room. Both the crawl-space hatch door and maze access door are interlocked to prevent human intrusion with the accelerator operating.

The main floor above the control room is a warehousing area providing approximately 290 m^3 of storage space.

Facility Features

To accommodate the loading and unloading of product, a truck bay with loading dock has been provided in the warehouse. A conveyor from the warehouse level transports product packages through a hatchway in the floor of the warehouse, through the control room into the maze by way of an opening in the 400 mm control room wall. The conveyor winds through the maze, passes beneath the accelerator beam and returns back through the maze and control room to the warehouse area by the same route. The incoming conveyor leg runs below the outgoing leg in the maze to reduce the possibility of contamination of sterilized product. The conveyor legs switch to a side-by-side arrangement on the slope upwards through the control room so that the sterilized product emerges on the opposite side of a central partition from the unsterilized product still to be irradiated.

The central partition dividing the warehouse into sterilized and unsterilized areas has a removable panel over the conveyor hatchway. A five-tonne overhead crane runs along the ceiling north from the truck bay and bends east to cross over the conveyor hatchway. If the conveyor sections are removed from the hatch, accelerator components and heavy experimental equipment may be lowered through to the lower level using the crane and moved from there through the maze .o the accelerator room.

Rubber belt conveyors slope through the control room from the warehouse. The sections through the maze are independently driven roller conveyors. The two meter section under the accelerator is a stainless steel belt conveyor. All sections except the stainless steel belt are driven at a constant speed of 300 $mm\ s^{-1}$. The stainless steel section is variable speed from 0 to 600 $mm\ s^{-1}$ and may be slaved to the accelerator via the accelerator's computerized industrial controller to deliver a preset dose to product packages on the conveyor. A brake adjusts package spacing on the variable speed stainless steel belt.

Closed circuit television cameras in the accelerator room and maze are used for observing the product as it moves along the conveyors past the accelerator beam. From the operator's position at the control panel he may view the product as it slopes down from the warehouse and enters the maze and inspect it as it moves through the maze and the accelerator room to ensure orderly flow. At the same time he can ensure that no one has intruded into the maze via the conveyor with the accelerator working. The option is provided for turning off the conveyor sections descending from the warehouse. The operator may then place a single package on the conveyor at the maze entrance, irradiate it, retrieve it, repack it or perhaps rotate it and irradiate it again. In these ways the facility can accommodate irradiation on both a small experimental scale and on a larger pilot scale for a wide variety of applications.

SAFETY CONSIDERATIONS

The consequences of a wide variety of accidents were considered prior to construction. A number of concerns regarding the safe operation of the facility were identified during the licensing stage. Protection against a variety of hazards has been built into the facility. Some of these were unusual in that they were related to the wedding of the relatively advanced accelerator technology to common or traditional industrial processes. Other concerns were related to perceived incompatibility in the wide range of applications of the facility. These concerns were in the realm of industrial hygiene as well as health physics. None were found to be so overwhelming as to unduly restrict the applications originally envisioned for the facility provided care and forethought are used in the preparation of experiments and product irradiations.

Industrial Hygiene

The industrial safety hazards considered included toxic gases (ozone and nitrogen oxides), high voltage electricity, electricity, biological pathogens, chemicals, pressurized systems, mechanical systems, noise, intense light (as from a pulsed radiolysis system), fire and flood. Many of these concerns, such as fire, electricity and pressurized systems are eliminated by choosing designs and operating procedures that comply with appropriate codes and standards. For some specialized uses, such as carcinogen detoxification and pathogen sterilization, it has been agreed that the industrial hygiene aspects will require review in advance by the appropriate panel of experts prior to installation of the experiment within the facility.

Radiation Protection

The two principal radiation protection concerns, which arose during safety review of the facility, are related to the use of accelerators as an industrial process device. The maze with conveyor and walkway was perceived by those charged with safety review as a potentially easy route for human intrusion to the accelerator room with the accelerator operating. The second concern was that the maze was wide and the expanses of bare concrete surfaces would provide ample opportunity for radiation scattering from the accelerator room into the control room.

The logical response to the first concern is to make access to the accelerator room via the conveyor as inconvenient as possible. We have achieved this by a combination of design features and administrative controls. The administrative controls consist of locking all access routes to the control room thus denying unattended access all to those not authorized to work in the facility. A locked hatchway cover has been supplied in the warehouse that fits tightly around the sloping conveyor sections when it is not in use. This hatchway is only unlocked and opened when an attendant is actually present loading packages onto the conveyor. Should administrative controls fail and someone gain entry from outside, the layout of the control room and maze requires that they pass the operator sitting at the control panel. Should the intruder manage to evade detection at this point, he would be observed by the operator on the closed circuit television used to monitor the movement of product through the maze.

The likelihood of undetected intrusion is further reduced by the inconvenience associated with crawling on the conveyor where it passes through the control room wall. The head-room above each conveyor section is only about [illegible] cm. The conveyor sections through the maze and at the maze entrance are independently driven roller conveyors that are difficult to crawl on, particularly when they are in motion. The chance of successful intrusion by this route during accelerator operation seems slight with the adopted accelerator facility design.

Our response to the second concern of radiation scattering through the maze has been to carry out a detailed Monté Carlo analysis for the specific geometry of the AARF to determine dose rates in the control room arising from radiation scatter. The results of these calculations follow.

SHIELDING

The principal penetrating radiations of concern in the AARF are bremsstrahlung and neutrons produced by the electron beam impinging on targets. The efficiency for bremsstrahlung production increases with atomic number, Z. Data given by Burrill [1] and reproduced by Swanson in Figure 17 of reference [2] enables us to estimate the intensity of the bremstrahlung radiation. The absorbed dose rate at 1 metre in the forward direction (0° to the beam) from a tungsten target ($Z = 74$) of optimum thickness is approximately 3×10^4 Gy·h^{-1} for a 10 kW, 10 MeV electron beam. The dose rate at 1 metre in the 90° direction is approximately one-thirtieth of this amount or 10^3 Gy·h^{-1}.

Burrill [1] also gives data that permit estimation of the neutron production in high Z materials. From this it is estimated that neutron production is 10^9 n·s^{-1}·µA^{-1} for 10 MeV electron beams impinging on thick targets of high atomic number. For a 10 kW beam the production is 10^{12} n·s^{-1}.

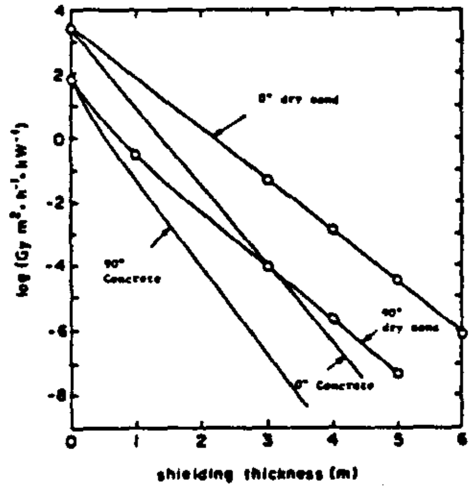

Figure 2: Shielding Factors for bremsstrahlung from 10 MeV electron beams.

Penetration of Radiation Through Shielding Material

The dose rate in the control room at the maze wall, and on top of the berm due to penetrating bremsstrahlung may be estimated from shielding curves shown in Figure 2. The curves for concrete have been taken from Brynjolfsson and Martin [3]. The curves for dry sand were derived from Equation 6 of Brynjolfsson and Martin assuming absorption and buildup factors for sand given by Clark [4]. It was assumed that dry sand of specific gravity 1.5 would be a reasonable representation of compacted clay.

With the accelerator operating normally, the beam may be bent downward via a magnet toward the conveyor or allowed to emerge horizontally onto a nearby target. The horizontal beam will be directed away from the control room. Therefore we have planned to shield against the 90° component of bremsstrahlung assuming that the backward (180°) component is no worse than this. The sources are assumed to be located 3300 mm from the north wall and 4100 mm from the west wall. This location is 14,300 mm from the control room. The bremsstrahlung source from the axial beam is closest to the top of the berm, which must be at least 4100 mm away. The radiation must penetrate at least 2400 mm of concrete (except in the conveyor openings) to reach the control room and 600 mm of concrete and 3500 mm of earth to reach the top of the berm. Using these values and the curves from Figure 2, the radiation fields on top of the berm and on contact with the maze wall in the control room are estimated to be 0.24 $\mu Sv \cdot h^{-1}$ and 0.36 $\mu Sv \cdot h^{-1}$, respectively. These values are approximately 2-3 times natural background. Continuous exposure at these rates over the period of one occupational year will result in doses which are a fraction of the annual public limit.

The spectrum of giant-resonance neutrons is similar to the neutron spectrum of an Am-Be source. Neutrons produced by an electron beam impinging on a high Z material are emitted very nearly isotropically. The Tenth Value Layers (TVL) for shielding neutrons from a giant-resonance source are 74 $g \cdot cm^{-2}$ and 96 $g \cdot cm^{-2}$ for sand (SiO_2) and ordinary concrete, respectively [2]. The berm and concrete over the accelerator room amounts to 8.5 TVLs. The concrete in the maze and 400 mm of concrete in the wall between the control room and the maze amounts to 6 TVLs. Assuming a dose conversion factor of 1.4 $\mu Sv \cdot h^{-1} \cdot n^{-1} \cdot cm^2 \cdot s$ as suggested by Swanson [2] and the same source locations as for bremsstrahlung we can estimate the dose rate from penetrating neutrons on top of the berm and at the maze wall in the control room to be 0.05 $\mu Sv \cdot h^{-1}$ and 0.002 $\mu Sv \cdot h^{-1}$, respectively. These values are small in comparison to the dose rate from penetration of bremsstrahlung. We see below, that neutrons scattered through the maze could be a more important contributor to dose rate in the control room.

Scattering Through the Maze

In order to study scattering through the maze using Monté Carlo, it was necessary to determine the spectral and directional distributions of the initial source particles.

For bremsstrahlung, it was assumed that the source could be modelled as an isotropic point source with the spectral distribution of the forward scattered bremsstrahlung from an optimum thickness tungsten target, but with the source strength corresponding to the radiation field in the 90° direction. A Monté Carlo generated bremsstrahlung spectral distribution for electrons of 9.6 MeV on a tungsten target 5.8 $gm \cdot cm^{-2}$ was used to model this source [5]. This spectrum is shown in Table 1. From this spectrum it is possible to deduce that 1.35 photons per electron per steradian are emitted into the forward direction.

TABLE 1

Spectrum of Bremsstralung Photons, Per Incident Electron, Emitted from a 5.8 $g \cdot cm^{-2}$ Tungsten Target [5]

Energy (MeV)	Photon Distribution (photons MeV^{-1} Sr^{-1})
0.1	0.15
0.3	0.45
0.5	1.20
0.7	0.90
1.5	0.28
2.5	0.12
3.5	0.082
4.4	0.060
5.5	0.050
7.0	0.023
9.0	0.008

assuming the fluence of photons in the 90° direction is about one-thirtieth the fluence of the forward direction and that a 10 kW beam corresponds to about 6.25 x 10^{15} electrons s^{-1}, the appropriate isotropic point source for the model would emit approximately 3.5 x 10^{15} photons$\cdot s^{-1}$.

The neutron source is very nearly an isotropic point source emitting 10^{12} $n\cdot s^{-1}$ with a Maxwellian energy distribution satisfying the equation

$$\frac{dN}{dE_n} = E_n \exp(-E_n/T)$$

where E_n = neutron energy (MeV)
dN = the number of neutrons having energy in the range E_n to $E_n + dE_n$
and T = the neutron temperature (MeV).

The neutron temperature used was 0.69 MeV.

The scattering was modelled with the three-dimensional Monté Carlo transport code MCNP [6]. Figures 3a and b show the details of the geometry, source location, the maze, and the opening in the 400 mm wall. The cross-hatching on Figure 3 indicates concrete; the interior was treated as void. The exterior was modelled as SiO_2. Note, that provision has been made for a thickness of

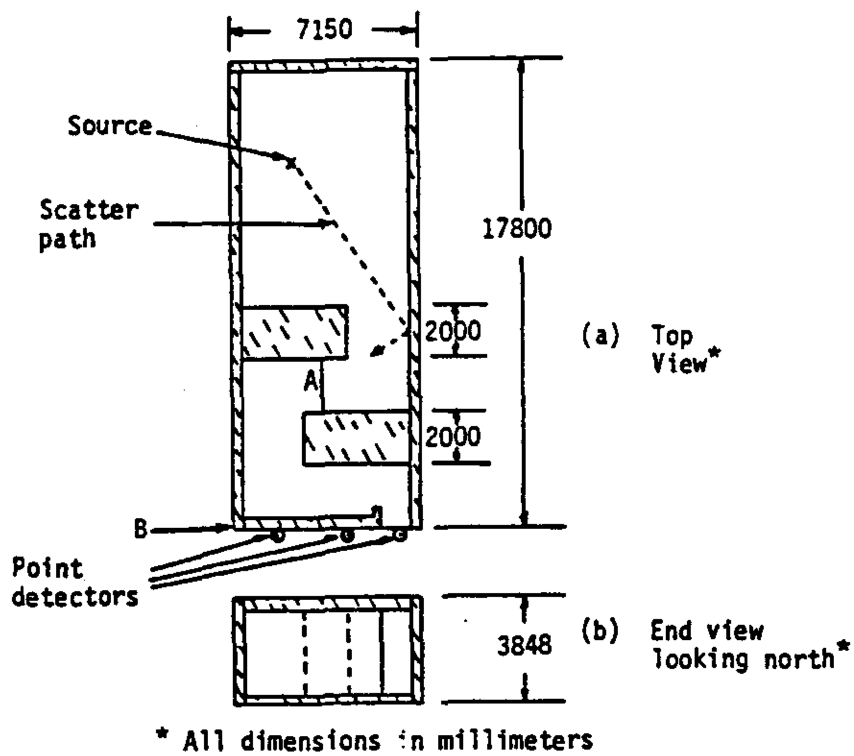

Figure 3: Geometry Used in MCNP.

steel in the maze access door equivalent to the 400 mm of concrete in the control room wall but for simplicity in running MCNP the whole wall has been modelled as concrete. This is recognized as a likely non-conservatism (dose underestimation) in the calculation of neutron doses in the control room. The source was positioned as previously except that in the MCNP model it has been located 1100 mm above the floor. The neutron discrete-energy cross-section library DRMCCS [7], derived from ENDF/B-V, and the photon cross-section library MCNPLIB [8] were used in MCNP.

A WNRE modification to the code was used to split the scattering problems into two parts as follows. Source particles were started from the target position and tracked throughout the accelerator room and around the first concrete block. Each time a particle reached the vertical surface, A, between the two blocks, shown in Figure 3, it was terminated and its position, direction of flight, energy and statistical weight at the point of termination were recorded. This information was then used as the source for the second part of the calculation which tracked the particles to the dose points on the control room side of the 400 mm concrete wall. This approach allowed separate processing of secondary gammas without having to re-run the entire calculation as well as a special procedure for bremsstrahlung described below.

The neutron scattering calculation was relatively straight forward. Dose rates were determined using surface tallies over the conveyor opening to the control room and over the east and west halves of the outer surface, B, of the 400 mm wall. The neutrons were transported as described above which yielded acceptable statistics without any variance reduction techniques. The results are reported in Table 2 for the higher of the two values at surface B and for the conveyor opening.

Secondary photons created in the first part of the neutron calculation were collected at surface A, scattered to surface B and tallied using point detectors as described below for the bremsstrahlung calculation. Secondary photons created in the second part of the neutron calculation were tallied using surfaces similar to the neutron tallies.

The photon scattering calculation presented a more difficult problem. Very poor statistics were obtained using the above method. Excessive amounts of computer time would have been required to obtain meaningful results. Therefore a different approach was taken, which made use of an MCNP facility called the DXTRAN sphere [6]. This feature increases the particle density in regions of the geometry that are difficult to sample adequately. This is accomplished by deterministically transporting "pseudoparticles" from real particle collisions in the rest of the geometry to the surface of the DXTRAN sphere centered at the point of interest. If $\mu = \cos\theta$, where θ is the half-angle subtended by points on the DXTRAN sphere surface at the collision point, the pseudoparticles are distributed on the sphere surface uniformly over two ranges of μ, with the inward range (higher μ values) given higher probability and the μ value separating the two ranges chosen by the user. The pseudoparticles, with weight and energy appropriately adjusted to reflect the probability of reaching the selected points on the sphere, are then banked for later transport into the sphere as real particles. Real particles that enter the sphere are killed to balance the artificially created pseudoparticles.

For the problem at hand the DXTRAN sphere was centered on surface A with a diameter the full width of the opening. The pseudoparticles, were tracked as normal particles to this surface where their weight, direction and energy were recorded. Approximately 6000 particles were collected on this surface. The DXTRAN sphere does not occupy the whole of the rectangular opening. Real particles crossing surface A without touching the DXTRAN sphere were collected and not killed.

This record of photons was then used as a source distribution for photon transport through the second leg of the maze. Dose in the control room was estimated using the point detector option in MCNP. Point detectors are similar to DXTRAN spheres in that the fluence through a vanishingly small sphere at the point of interest is calculated based on the probability of photons being scattered to that point from real collisions in all the other parts of the geometry. Three point detectors were used in estimating the scattered photon dose. These were located in the control room at the locations shown in Figure 3.

The results for photons scattered through the maze are also summarized in Table 2. The dose rate reported by the higher of the two detectors behind surface B has been used and the dose rate due to scattering in the conveyor openings has also been recorded. The second and third columns of Table 2 give the dose rates in the control room per source particle started in the accelerator room. Columns four and five give the dose rate in the control room from scattered radiation assuming a source of 10^{12} neutrons $\cdot$ s^{-1} and 3.5×10^{15} bremsstrahlung photons $\cdot$ s^{-1} from the 10 kW beam. The statistical errors in the scattered-neutron dose estimates are less than 10%. The photon statistics were much poorer. Statistical errors on scattered bremsstrahlung dose range from 10 to 50%.

We see from Table 2 that the dose rates in the control room behind the 400 mm wall from scattered bremsstrahlung are a small fraction of normal background (~ 0.10 $\mu Sv \cdot h^{-1}$ excluding internal dose from radon daughters and ^{40}K). The dose rate from scattered bremsstrahlung is appreciable in the conveyor openings but this area is not occupied by personnel. As well, this may be reduced further by additional local shielding just inside the maze access door.

The magnitude of the neutron dose rates in the control room leads us to conclude that care must be taken to control personal doses if high atomic number materials are to be used as targets or bremsstrahlung converters. This control might consist of reducing exposure time by limiting the workload factor or providing supplementary shielding. It must be remembered that the neutron dose rate in the control room may be worse than estimated with MCNP since the steel door offers little shielding against neutrons.

TABLE 2

Dose Rates in the Control Room From Radiation Scattered Through the Maze

	Dose Rate Per Source Particle $(\mu Sv \cdot h^{-1}) \cdot (\text{Source Particle} \cdot s^{-1})^{-1}$		Dose Rate $\mu Sv \cdot h^{-1}$	
Radiation Type	Conveyor Opening	Through 400 mm Wall	Conveyor Opening	Through 400 mm Wall
Neutrons	6.35 E-11	2.19 E-11	64	22
Neutron Induced Secondary Photons	1.70 E-11	2.97 E-11	17	30
Bremsstrahlung	1.03 E-14	2.06 E-18	36	0.007

To permit high-workload-factor operations with the accelerator, material controls will be required on accelerator components that may be brought into contact with the beam. In general, very few neutrons will be produced as long as materials of atomic number greater than 30, beryllium, or D_2O are not irradiated at energies of 10 MeV. With lower energy electron beams, material controls on high atomic number targets may be relaxed depending on energy and photoneutron threshold.

SUMMARY

An array of safety issues have been examined during the planning stages of this facility. Some of the issues examined are not normally encountered in the licensing of more familiar radiation facilities such as medical or research accelerators. In the case of the Accelerator Applications Research Facility, some questions of safety relate to the wide variety of uses proposed. The concern for scattered radiation in particular relates to the requirement that the facility must, at times, be operated as a production-line-oriented industrial irradiator with an open maze and conveyor.

We conclude that the individual operations proposed may be conducted safely provided adequate review is provided at every stage. The mechanism for this review is in place. The shielding provided is sufficient to protect against neutron and bremsstrahlung penetration and bremsstrahlung scattering, but may not be adequate for scattered neutrons if additional controls are not instituted to curb neutron production or reduce exposure time by limiting workload factors.

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