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CONTROL OF RADIATION

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1. General Considerations:

Radiation problems of the accelerator involve personnel protection, damage to materials, and control of background intensities for experiments. Personnel protection has two aspects: exposure to secondary radiations generated during accelerator operations, and exposure to residual radioactivity during essential maintenance and development activities. For the former, extensive shielding will be required around the accelerator housing, emergent beam runs and experimental targets.

Exposure to residual radioactivity (Raa) induced in accelerator components and the inside walls of enclosures is of primary concern, and will require some limitation of beam currents during initial operations. At the Brookhaven AGS the most serious problems of personnel exposure at present are those involving induced Raa in the "hot spots" around internal targets. At the NAL, where the design beam power will be 200 times that of the AGS, use of full beam current could soon lead to Raa levels which would forbid personnel access. To the extent that some personnel access to the hot spots at the NAL is required for essential maintenance and development activities, the Raa intensity should be kept below some practical limit, so as not to expend unwisely the acceptable tolerance to radiation of the maintenance and development staff.

The induced Raa comes from beam spills in localized regions such as the ejection straight section for the emergent beam, internal targets, etc. Around the rest of the ring the beam loss is expected to be small. It is at these localized hot spots where the problems of personnel exposure to Raa will be most acute. However, it is just at these locations where the problems of development will be most severe. The beam spill at an extraction area depends on percentage of beam loss; the beam current can be raised by

increasing extraction efficiency. At an internal target location the induced Raa depends on the effectiveness of local shielding around the target and the experiment. Accelerator components downstream from the spill or target will have the highest Raa intensities; for these, special quick-disconnect systems, local shielding and remote handling devices will be required to minimize exposure to personnel. If intensities due to such hot components can be controlled, the whole-body exposure of personnel depends on the ambient Raa from the rest of the accelerator and the walls of the enclosure. We take this ambient Raa intensity as the effective value for analysis of whole-body radiation exposure.

If Raa intensity rises to excessive values, the beam must be turned off for a cool-down period sufficient for intensity to decay to acceptable levels. After months of operation the very long-lived activities build up to be a relatively large fraction of the residual Raa, the decay rates are slow, and long cool-down periods are required for significant decreases in Raa intensity. The lengths of cool-down periods should be minimized to reduce off-time and increase beam on-time for experiments. The problem is to balance the loss of beam time for experiments against the desire for high beam currents which lead to excessive build-up of Raa.

Analysis of these factors, coupled with personnel exposure limitations, will provide an estimate of the maximum beam currents which should be permitted during initial operations when some personnel access is required for maintenance and development. The estimated beam spill intensities can then be used to calculate the external shielding required around hot areas, to reduce external radiation intensities to acceptable levels. In other "quiet" portions of the ring the Raa will probably be low enough to allow adequate personnel access, and the external shielding can be much less. However, in target areas, beam-dumps and other very hot areas, personnel must be denied access, all handling must be remote, and shielding must be provided for the maximum anticipated beam currents.

2. Personnel Radiation Dosages:

The maximum permissible dose (MPD) for radiation workers is based on recommendations by the International Commission for Radiological Protection which have been accepted and promulgated by the U.S. Department of Health and Welfare and the U.S. Atomic Energy Commission. Radiation workers of age N years are permitted an accumulated whole-body dose of 5(N - 18) rem, with a maximum exposure of 3 rem in any 3 months. This has customarily been interpreted as implying dose rates of 5 rem/yr, 0.1 rem/40-hr week, or 2.5 mrem/hr. However, the established limit is that accumulated in 3 months, which we use as the maximum allowed value: 1 MPD = 3.0 rem/3 months. The maximum dose permitted to the extremities (i.e., hands and forearms) is 25 rem/3 months. It is expected that local body shields will be used to reduce the whole-body dose to the MPD above.

Certain types of activities can be distinguished involving different personnel, for whom lengths and frequencies of exposure can differ. For maintenance staff on a weekly schedule, for example, the w.b. dose in a single weekly exposure should not exceed 0.23 rem. For development staff anticipating no more than 1 exposure per month the limitation should be 1.0 rem. The emergency maximum for any single exposure should never exceed 3.0 rem. The number of successive exposures is limited by the age of the individual. For a person of age 18 the yearly accumulation must not exceed 5.0 rem/yr; he would be restricted to 22 weekly doses of 0.23 rem in one year, with no more than 13 in any one 3-month period. A person of age 38 without previous radiation exposure would be allowed 12.0 rem/yr for 8 years, then reducing to 5.0 rem/year. The time scheduling of doses to stay within the permitted accumulated dose at age N years will be the responsibility of the Radiation Safety Division of the Laboratory.

The permissible dose levels given above determine the time duration of single exposures at a given Raa intensity level. When access by unshielded personnel is required (which we define as phase I), levels must be low to allow practical working times. A typical activity might be to remove a hot component (i.e. a magnet septum) and replace with an improved model. A sequence of operations might be involved, using different operators, such as disconnection of electrical, water and vacuum circuits, installation of pre-formed shielding and removal of hot components, placement of local body shielding, and a sequence of tool manipulations. The ambient Raa intensities at the working location of each operator will determine the exposure times. If the activity can be performed from within a shielded vehicle (phase II) the shielding factor will allow a higher external Raa intensity. In the LRL Design Study a shielded vehicle with 4.5-inch Pb walls is reported to give a shielding factor of 4.6×10^{-2}. With thicker Pb walls and further development we assume that a factor of 1.0×10^{-2} can be achieved. However, other limitations are involved, such as the longer times needed for manipulations from within a shielded vehicle.

In Table 1 we list typical personnel exposure times for phase I and phase II activities, for the 3 classes of workers described above, and for selected Raa intensity levels:

Table 1. Personnel Exposure Times

Raa Inten: (rem/hr)	Shielding Factor:	Weekly Mainten: (0.23 rem/week)	Monthly Develop: (1.0 rem/month)	Emerg. Max.: (3.0 rem/3 mo.)
	Phase 1: (unshielded)			
1.0 rem/hr	1.0	14. min	1.0 hr	3.0 hr
5.0 rem/hr	1.0	2.8 min	12. min	36. min
	Phase II: (shielded vehicle)			
50 rem/hr	1×10^{-2}	28 min	2.0 hr	6.0 hr
100 rem/hr	1×10^{-2}	14 min	1.0 hr	3.0 hr

3. Distribution of Raa Intensity:

In the main accelerator ring the hot spots will be localized in regions where beam spills occur, primarily at the ejection straight and around the internal target. Other hot spots may be associated with clean-up targets located in medium straights. And a less intense hot spot may develop at the injection straight due to spills of the 10-GeV injected beam. Losses can be expected to be very small (< 0.1% total) around the rest of the ring.

When high-energy protons are diverted out of the orbit by pulsed ejection fields and strike a deflecting magnet septum or other obstacle, they create a nuclear cascade or shower. The cascade builds up to maximum intensity (maximum number of ionizing secondaries) within a few interaction lengths of material (from a few inches to 6 inches of Fe, depending on energy), and then attenuates with a 1/e decay length of about 130 gm/cm^2 of matter. For example, forward intensity is reduced to 1% in about another 2.2 ft of iron or 7 ft of normal concrete. The highest energy particles, both primary and secondary, form a forward jet with small angular spread, typically within 10 mradian at 200 GeV. Lower energy secondaries spray out laterally from this jet with a broader angular distribution. The most penetrating of the secondaries ejected transversely are fast neutrons of $\lesssim$100-MeV energy; the intensity of these fast neutrons determines the thickness and type of shielding required around the hot area to reduce external intensity to acceptable levels during operations. A very great number of lower energy secondaries are produced in the material traversed by the shower, including slow neutrons. The Raa developed in accelerator components comes largely from Raa spallation produced by the very high energy particles. The Raa in the walls of the enclosure comes largely from slow neutrons in equilibrium with the lower energy secondaries. The total number of secondaries, and the

resultant total Raa intensity within the enclosure, are closely proportional to the total power in the beam spill.

The hot area downstream from a beam spill is limited in extent. If a cascade jet originates in and traverses solid material, the production of spallation Raa is primarily localized in the region of major attenuation of the jet, which is less than 10 ft in length. High energy secondaries which emerge transversely from the solid material, but have a forward direction, extend the Raa further downstream. At the Brookhaven AGS (30 GeV) the Raa drops to about half intensity at 15 ft. ~~from~~ beyond the target location. At 200 GeV the angular distribution will be more sharply forward, with the opening angle decreased by the ratio of energies or by a factor of about 1/7. Depending on the transverse shielding around the jet, the major deposition of Raa may extend downstream for a distance of about 100 ft. The fast neutrons which emerge transversely will be associated with this distribution of spallation Raa. The region requiring thick external shielding is limited to this relatively localized hot spot.

Another type of spill can occur with thin targets or septums when the scattered particles are projected downstream through the vacuum chamber or through air. Most of these can be caught on "clean-up" targets at the edges of the aperture, and their spills confined to local regions beyond these targets. Some may miss the clean-up targets and spray out against chamber walls, extending downstream for about $\frac{1}{4}$ betatron wavelength or about 250 ft. Again, the extent is limited and external shielding is needed only around the hot spot. If the accelerator is mistuned the location of spills can be observed by radiation monitors installed in the ring, and the orbits can be corrected from the control console. The infrequency and limited time duration of such off-resonance spills should make thick external shielding unnecessary around these normally "quiet" portions of the ring.

4. Beam Power and Raa Intensity:

Experience at several laboratories confirms the expectation that total Raa intensity developed beyond a spill or target is closely proportional to beam power in the spill, within the energy range where nucleonic showers are dominant in attenuation of the beam. The proportionality factor is affected by the chemical constitutents of material in the region where the shower develops, and on the amount and arrangement of transverse shielding around the region of the shower. Experimental evidence is available only for energies up to 30 GeV.

At the Brookhaven AGS, following long runs at energies up to 30 GeV, at an average beam current of 4×10^{11} protons/sec, with 90% of the beam striking an internal target (10% lost around the orbit), the ambient Raa intensity within the (concrete) enclosure, when hot spots were locally shielded, was observed to be about 1 rem/hr after a 48 hr cool-down. In local regions close to (tool distance) major hot spots and without local shielding, the Raa intensities were in the range 10 to 50 rem/hr. At these intensities the handling of essential maintenance activities by the AGS operations group without exceeding permissible exposures has been one of the major problems. The beam power spilled at the target was 1.9 kilowatt. The ambient Raa after 48 hrs cool-down, following long runs, can be expressed as:

<u>Raa Inten.(48 hr) = 0.52 rem/hr per kilowatt.</u>

In the AGS conversion program for higher intensity now in progress, the goal is for 2×10^{12} p/sec; at 33 GeV and with 90% on target, beam power will be 9.5 kw. The Raa intensity expected after 48 hrs is 5 rem/hr, in agreement with the value of Raa per kilowatt given above. It is expected that some minimal personnel access can be allowed, with maximum precautions, for essential tasks that cannot be handled by remote control.

Improvements can certainly be made in the Raa per kilowatt in the 200 GeV machine. Spallation products dominate the Raa in the dense metals used in accelerator components. The ambient Raa can be reduced by thick transverse shielding around the areas of shower development, or by more effective local shielding of exposed hot spots such as upstream faces of deflecting magnets or other components. It is unlikely that the chemical composition (i.e., Fe, Cu, stainless steel) can be modified to change the spallation Raa significantly. In enclosure walls the induced Raa due to slow neutrons is an important component. Addition of small amounts of boron to the concrete aggregate can reduced the slow neutron Raa; the factor by which this could reduce the ambient Raa level is difficult to estimate and probably small.

Another possible advantage at 200 GeV is the forward-folding of the angular distribution of high-energy secondaries, which might retain a larger fraction within the vacuum chamber or air beyond a septum, and so extend downstream the locations where showers in solid matter originate. The maximum factor by which the Raa could be longitudinally distributed along a straight section is the ratio of energies (7:1 from 30:200 GeV). However, this spatial extension can only be achieved with careful design. If the major part of the shower originates at one point and continues through solid material, the shower will be concentrated in a region not significantly longer than for 30 GeV.

The reduction of the Raa/kw factor will require continuous development, especially following the start of operations. In the absence of any provable improvement at the present stage of design, we will use the factor obtained from Brookhaven for estimating Raa intensities as a function of spill power.

5. Decay Rates and Cool-down Schedules:

The decay of induced Raa in a hot area depends on the materials being activated, their different activation cross-sections and decay rates, and ~~also~~ especially on the build-up of very long-lived activities. With the mixtures of materials used in accelerator components and enclosure walls, the observed decay rates from the several laboratories are highly variable and also change with time. The best experimental evidence at present is from the Brookhaven AGS. After months of operation at energies of 30 GeV with an average beam current of 2×10^{11} protons/sec, and a cool-down period of 48 hrs, the ambient Raa within the inside-target enclosure was observed to follow the relation: $I = I_o\, t^{-0.4}$ (t in hours). This relation is plotted in Fig. 1 on a log-log scale of relative intensity vs. time, extended backward and arbitrarily normalized at 1 hr and forward to 10^4 hrs. This result is consistent and reproducible only after very long runs at relatively constant beam current, and only following a relatively long cool-down period such as 48 hrs. The attenuation factor due to decay from 1 hr to 48 hr, coming from this extrapolation, is 0.21 ; at 48 hrs the further time to decay to half intensity (not the "half-life") is over 200 hrs. It is clear that long-lived activities have become very significant after several years of operation.

The 48-hr cool-down is now used as a minimum at both the Brookhaven AGS and CERN PS, associated with bi-weekly maintenance schedules. This long cool-down is found necessary due to the slow decay rate described above. And both laboratories are now severely restricted in further development work within hot areas by the high Raa levels even following a 48-hr cool-down. Years of development to minimize replacements and achieve high reliability have been required to allow such infrequent maintenance periods and long cool-downs.

Despite the best efforts in design and planning, it seems unlikely that the NAL accelerator can achieve equivalent reliability until some time after initial operations start. Shorter maintenance schedules and shorter cool-down periods will be necessary and, for a time, a significant fraction of both off-time and beam-time must be applied to development. During these development activities cool-down periods of 1 hr for short jobs are indicated; for jobs requiring longer personnel access, longer cool-down periods can be allowed. The Raa intensity in the hot areas should be maintained at levels such that practical personnel exposures can be scheduled after a 1 hr cool-down.

6. Maximum Raa Intensity and Beam Current Limitations:

The ambient Raa intensities which allow practical lengths of exposure time for the three classes of personnel described above, are listed in Table 1, for unshielded access (phase I) and access within a shielded vehicle (phase II). A general recommendation now follows based on the analysis of cool-down rates discussed above. For access by unshielded personnel after 1-hr cool-down, the Raa intensity should not exceed 5 rem/hr; which will decay to 1 rem/hr after 48-hr cool-down. Referring to Table I, this will allow unshielded access for the times listed for 5 rem/hr for the three classes of personnel; after 48-hr, with intensity decaying to 1 rem/hr, (the allowable exposures ~~are~~ will be 5-times longer. Similar limits can be set for phase II activities using a shielded vehicle. The Raa intensity should not exceed 100 rem/hr after 1 hr, which will decay to 20 rem/hr after 48 hrs. This allows the exposure times after 1 hr given in the last row in Table 1; after 48-hr cool-down the times will be 5-times longer.

Some criterion must be found to establish Raa intensity levels resulting in practical durations of personnel access for maintenance and development activities. Those described above and listed in Table 1 seem reasonable.

The design beam current at the NAL at 200 GeV is 1.5×10^{13} protons/sec; this represents a total beam power of 480 kilowatts. It can be compared with the past AGS output described earlier of 1.9 kw on an inside target. Plans at NAL include ejection of a single emergent beam, with switching magnets to direct the beam against 3 or more targets. The efficiency of the pulsed ejection magnets and the septum-type deflection magnets which produce and control the emergent beam, will determine the percentage of beam spill and the power in the spill in the ejection straight section.

A long extraction period is desired to extend the extend the time duration of extraction over 1 sec, or 25% duty cycle. The highest efficiency for long-pulse extraction achieved to date is about 80%, at the PS at CERN; an improved system aimed at less than 10% loss is being installed at the AGS. Conceptual designs of an ejection system for the NAL machine suggest a much higher efficiency, with less than 2% spill loss initially and 1% or lower with further development. In calculating the beam spill power in the ejection straight we will use spill fractions of 0.1, 0.02 and 0.01 to represent successive improvements during development. At an internal target the spill fraction is taken as 1.0 . In the absence of any conclusive evidence to the contrary, we assume the same Raa intensity per kilowatt of beam power observed in the AGS; Raa Inten(@48hr) = 0.52 rem/hr per kilowatt.

Table 2 lists the Raa intensities to be expected after 1 hr and 48 hrs, over the above range of spill fractions, at the design intensity:

Table 2: Raa Intensities at Design Beam Current:
(1.5×10^{13} p/sec at 200 GeV)

Spill Fraction:	Power: (kw)	Raa Inten.: (rem/hr)@1 hr	Raa Inten: (rem/hr) @ 48 hr
1.0 (int. beam)	480.	1200.	250.
0.1 (10% spill)	48.	120.	25.
0.02 (2% spill)	9.6	24.	5.0
0.01 (1% spill)	4.8	12.	2.5

We note from Table 2 that the ambient Raa intensities anticipated at design beam current and energy exceed those described above for phase I (unshielded) activities. Clearly some reduction in beam current is necessary as long as some unshielded personnel access is required. Many months of development can be anticipated to achieve lower Raa/kw and lower spill fractions. Until such developments are successful, the beam current in long runs should be limited. In Table 3 the maximum operating beam currents are listed which should result in the allowable Raa intensity limits described above for the two phases of activity:

Table 3. Maximum operating Beam Currents

Phase I:	Spill fraction:	Raa Inten: (rem/hr) @ 1 hr	Accelerator Beam power: (kw)	Beam current: (p/sec)	Fraction of design
Phase I:					
int. beam	1.0	5.0	2.0	6.2×10^{10}	0.004
emer. beam	0.1	5.0	20.	6.2×10^{11}	0.04
emer. beam	0.02	5.0	100.	3.1×10^{12}	0.21
emer. beam	0.01	5.0	200.	6.2×10^{12}	0.42
Phase II:					
int. beam	1.0	100.	40.0	1.2×10^{12}	0.08
emer. beam	0.1	100.	400.	1.2×10^{13}	0.83
emer. beam	0.02	24.	480.	1.5×10^{13}	1.0
emer. beam	0.01	12.	480.	1.5×10^{13}	1.0

From the above Table 3 we find that beam current must be limited for all levels of efficiency during phase I activties, and for low-efficiency extraction during phase II (shielded vehicle). The maximum allowable beam spill power for unshielded personnel access is 2.0 kilowatts, corresponding to a Raa intensity @ 1 hr of 5.0 rem/hr.

7. Shielding for Hot Areas and the Main Ring:

If the maximum beam-spill power is to be limited as indicated above, the intensity of fast neutrons and other secondary radiations generated in the spill will be reduced in direct proportion to the spill power. This means that the shielding required around the hot areas is also reduced below that needed if high-power spills were to be allowed.

The magnitude of this minimal shielding can be estimated from the observed radiation intensity outside the shield at the AGS during operations. In one measurement outside the standard overhead shielding of 1 ft of concrete and 10 ft of sand (density 1.9 g/cm^3), when the beam spill power on an internal target was 1.9 kilowatts as described above, the radiation intensity above the shielding was about 1.0 rem/hr. Now, if the beam spill power in a hot area at the NAL were limited to 2.0 kilowatt, in order to restrict the Raa intensity to 5.0 rem/hr after 1 hr, the same amount of shielding as used at the AGS would result in a radiation intensity outside the shield of 0.1 rem/hr. This is 1/30 of the MPD for radiation workers for 3 months; a person exposed to this radiation for 1 hr would receive a dose equivalent to 3 days at the MPD rate. If spill power were to be so limited, and only this amount of shielding were installed, the judicious use of fences to keep staff away from the hot area regions could make this intensity acceptable.

This is not intended to suggest that the AGS shielding is adequate for hot spots at the NAL. Actually, much higher beam spill powers can be and will be used temporarily at the NAL, particularly during early stages of operation before the long-lived Raa's have developed. The shield thickness to be installed should be determined from the maximum anticipated spills and from attenuation calculations.

Another situation deserving analysis is the radiation dose which would be given to a person outside the shielding resulting from an accidental spill of the entire beam at one point in the orbit. Again, assume the same shield thickness as at the AGS, of 1 ft concrete plus 10 ft of sand, for which a beam spill of 1.9 kilowatts gave a radiation intensity of 1.0 rem/hr outside the shield during operations. The maximum design beam power is 480 kilowatts. If one pulse at full intensity were accidentally spilled the energy in the pulse would be 4 times 480 or 1,900 kilojoules/pulse (at the cycling rate of 15 pulses/minute). The time-average radiation intensity outside the shield would be 480/1.9 or 250 rem/hr or 0.07 rem/sec. The external radiation dose due to one pulse would be 4 times 0.07 or 0.28 rem/pulse. This dose/pulse is less than 1/10 of the MPD for 3 months, equivalent to 8 days exposure at the MPD rate. Considering the low probability of such full-intensity accidental spills, this dose is not excessive. So the shield thickness at the AGS would be (barely) adequate for protection against single accidental spills at the NAL, if installed around the entire ring.

These calculations above based on the shield thickness at the AGS are not to be taken as a recommendation for the use of such thin shielding at the NAL. Rather, they are useful to illustrate the special conditions described above, in which spills are limited at all times to spill powers of 2.0 kilowatts, in order to avoid excessive build-up of Raa within the hot areas.

8. Radiation Policy Questions:

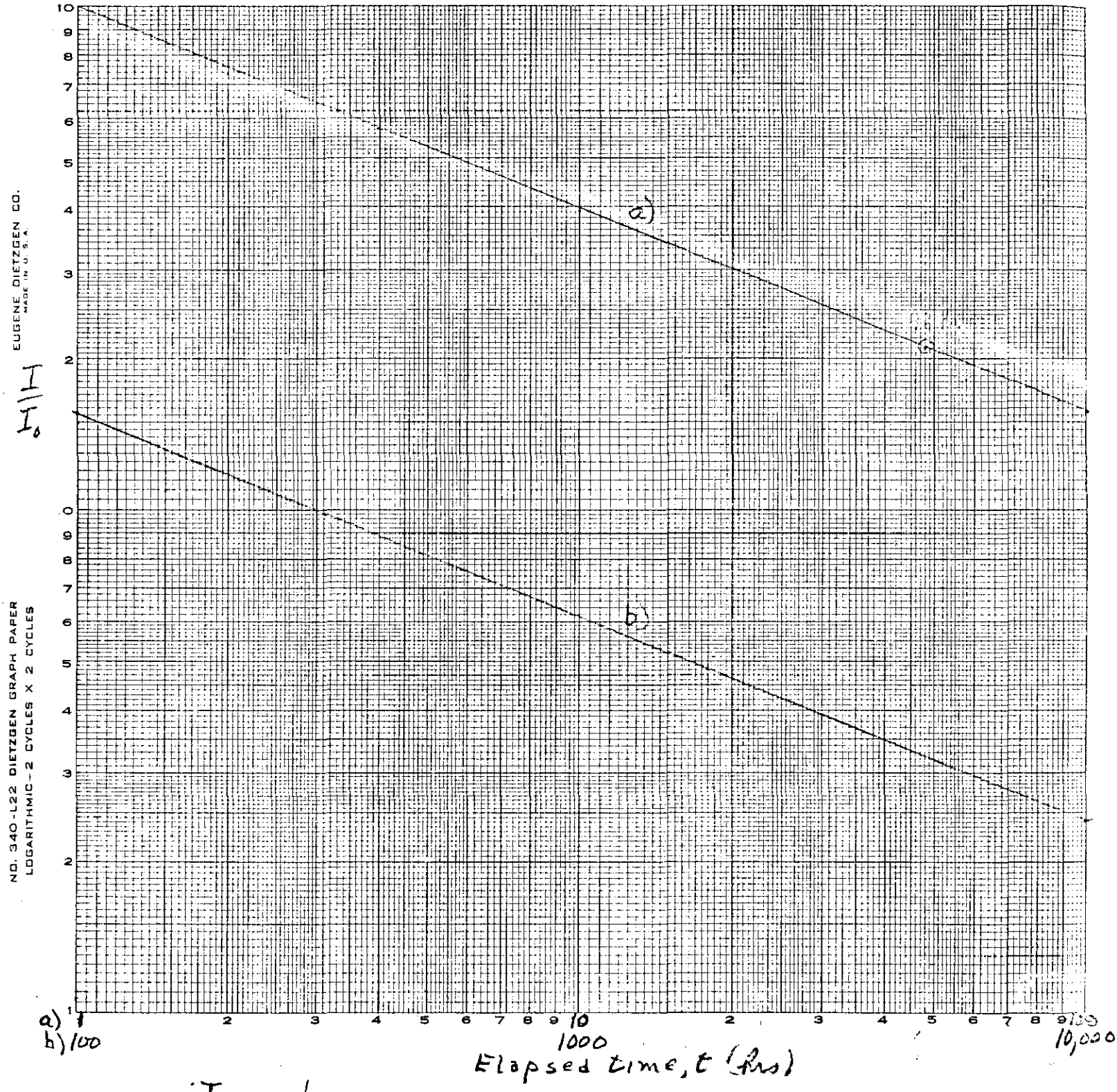
The most significant result of this analysis so far, is the concept it provides of a basic policy applying to radiation protection which differs markedly from past practice. With previous accelerators it has been customary to design for maximum possible beam current and to direct developments toward achieving this result at the earliest possible date; beam spills and Raa were considered necessary evils to be countered by installation of heavy shielding and special handling devices. The success of AG synchrotrons such as the AGS and PS in achieving beam currents far greater than their design values has been greatly appreciated by scientific users, but they have exceeded their designed shielding and have reached unsafe levels in the build-up of induced Raa, to the extent that further efforts to improve beam-handling efficiency are severely handicapped.

An alternate policy for the NAL accelerator would be to place first priority on the development of beam ejection and handling devices to increase efficiency and decrease spill losses, with beam currents meanwhile limited to allow safe personnel access for these continuing developments. Successful steps in this development would be followed immediately by raising the allowed beam current limits. This analysis suggests that ultimate success in this development can reasonably be anticipated, and that the design beam current can be achieved, without exceeding the Raa intensities required for practical periods of personnel access. Once this goal is achieved, the Raa intensities in the hot areas need never grow above the levels established for personnel safety and further developments will be expedited.

Following this alternate policy of control of radiation, a high priority will be given to the early development and testing of beam ejection and beam handling devices. Beam current will be limited during initial operations to values which will not produce Raa intensities greater than those specified to allow a practical amount of unshielded personnel access. Raa intensity will not be allowed to build up to the values listed under phase II activities until shielded vehicles and techniques for using them have been developed and tested.

The earth fill shielding installed during construction can be limited to that available as backfill from the earth excavated for the construction of the tunnel-shaped enclosure, redistributed to provide a uniform covering of the ring. Aside from factors such as strength of the enclosure structures, costs for the earth-fill shielding should not greatly exceed those for normal backfill. During early stages of operation at low beam currents, measurements of radiation intensity and of the induced Raa should identify unanticipated spills, where the earth fill can be increased as needed.

If this policy is accepted and carried out, it should lead ultimately to an accelerator with such excellent beam control and handling systems that spills around the ring will be minimal and the build-up of induced Raa will never become a serious threat to personnel access.



$$\frac{I}{I_0} = \frac{1}{t^{0.4}}$$

Fig. 1