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RADIOACTIVITY, SHIELDING, RADIATION DAMAGE, AND REMOTE HANDLING

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Summary

Proton beams of a few hundred million electron volts of energy are capable of inducing hundreds of curies of activity per microampere of beam intensity into the materials they intercept. This adds a new dimension to the parameters that must be considered when designing and operating a high-intensity accelerator facility. Large investments must be made in shielding. The shielding itself may become activated and require special considerations as to its composition, location, and method of handling. Equipment must be designed to withstand large radiation dosages. Items such as vacuum seals, water tubing, and electrical insulation must be fabricated from radiation-resistant materials. Methods of maintaining and replacing equipment are required that limit the radiation dosages to workers. The high-intensity facilities of LAMPF, SIN, and TRIUMF and the high-energy facility of FERMILAB have each evolved a philosophy of radiation handling that matches their particular machine and physical plant layouts. Special tooling, commercial manipulator systems, remote viewing, and other techniques of the hot cell and fission reactor realms are finding application within accelerator facilities.

Introduction

The recent past has seen the construction of accelerators whose energies and intensities are high enough that the problems associated with protecting men and equipment from the detrimental effects of radiation play a prominent role. Table I indicates the facilities that will be discussed.

Large amounts of shielding are required at these facilities, and its placement interacts with the design of everything from building structures to the individual components of the beam systems. The shielding itself may become activated and require special considerations, as to its composition, location, and method of handling. The beams can be expected to wander, to scatter from gas in the vacuum systems and from targets, and to grow halos--all of which can impinge upon adjacent equipment. Items such as vacuum seals, water tubing, and electrical insulation must be fabricated from radiation-resistant materials. Methods of maintaining and replacing equipment are required that limit the radiation dosages to workers. Each of the accelerator facilities listed in Table I have evolved a philosophy of radiation handling that matches their particular machine and physical plant layouts. Special tooling, commercial and home-made manipulator systems, remote viewing, and other techniques of the hot cell and fission reactor realms are finding application within accelerator facilities.

Table I. High-Power Proton Accelerators

Facility	Location	Energy (MeV)	Current (μA)	Power (kW)
LAMPF	Los Alamos, NM, USA	800	1000	800
SIN	Villigen, Switzerland	590	100	59
TRIUMF	Vancouver, B. C. Canada	500	100	50
		450	400	180
FERMILAB	Batavia, IL, USA	400 000	1.6	630

The Source

Energetic protons interacting with matter lead to the creation of many particles which are involved in additional interactions. Roeder[1] has looked at these secondary particles as a function of angle and energy for various target nuclei bombarded with protons, neutrons, and pions using the NMTC code.[2] Table II presents some of his results for the case of protons fired at a single copper nucleus.

Table II shows that a large number of particles are created in the process involving the collision of a proton. The prompt particles are liberated during the cascade process and tend to be energetic. The evaporation particles tend to have energies less than 10 MeV. These secondary particles travel until they too interact with other nuclei and create yet another batch of secondary particles. Through this process, the number of particles grows - although the energy of each particle decreases. The need to protect man and equipment from the effects of particle bombardment has led to a sizable effort to understand the physics of particle interaction and removal, as well as the effectiveness of various shielding materials. Patterson and Thomas[3] have discussed the history of this subject, and have described several experiments that were aimed at providing shielding parameters. Conferences dedicated to this subject have been held, in which participants have discussed calculational methods, dosimetry experiments and techniques, and actual radiation experience.[4,5] Sessions of other conferences have been devoted to the same subject.[6] Fortunately, the papers presented at these conferences have been published in their entirety. Efforts are constantly underway to improve the calculational codes to handle more complicated source terms and geometries, and to reduce

Table II. Secondary Particles emitted at all angles and energies when one proton interacts with a copper nucleus.

	Energy of Projectile Proton (MeV)				
	100	200	500	600	800
Prompt Particles					
Protons	0.867	1.246	1.819	1.976	2.245
Neutrons	0.774	1.108	1.508	1.798	2.126
Positive pions	0	0	0.080	0.120	0.185
Neutral pions	0	0	0.054	0.085	0.129
Negative pions	0	0	0.021	0.034	0.062
Evaporation Particles					
Protons	0.930	1.133	1.558	1.757	2.047
Neutrons	1.635	1.934	2.611	2.879	3.281
Deuterons	0.041	0.078	0.183	0.233	0.319
Tritons	0.005	0.011	0.032	0.038	0.059
Helium 3	0.002	0.006	0.018	0.026	0.039
Helium 4	0.094	0.106	0.148	0.173	0.212

problem setup and computer times, as evidenced by the work of Van Ginnekin and Awschalom.[7] The radiation levels that remain in materials that have undergone bombardment is the topic of a book by Barbier.[8] A comprehensive discussion of shielding is undertaken in Ref. 9.

A crude calculation can be made to estimate ball park activation levels. Consider a 1-mA, 800-MeV beam stopping in a material that produces 10 neutrons for each incident proton. Then,

$$6.28 \times 10^{15} \text{ protons/s-mA} \times 10 \text{ neutrons/proton}$$

$$= 6.28 \times 10^{16} \text{ neutrons/s}$$

are available to be captured by a nucleus; therefore, 6.28×10^{16} nuclei/s are being transmuted and, assuming that 10% of the new nuclei are radioactive and that equilibrium is attained,

$$\frac{6.28 \times 10^{15} \text{ disintegrations/s}}{3.7 \times 10^{10} \text{ disintegrations/s-Ci}} = 1.7 \times 10^{5} \text{ Ci}$$

of activity are present at the instant of beam turn off. If the radioactive nuclei could be separated from the surrounding material and packaged as a small source, the resulting radiation levels would be about 4.8×10^5 R/h at 1 m if the nuclei decayed by emitting an 0.5-MeV gamma ray. A person standing 100 m away from this source would be in a field of 48 R/h, and could remain there about 7 seconds per week.[10]

This exercise is perhaps useful only in pointing out the potential for isotope production and for its shock value--to impress one that he must consider the use of materials that do not activate, he must allow for decay times, and he must consider the maintainability of equipment.

The following section will discuss the various accelerator facilities, and mention will be made of the radiation levels experienced at each facility to date, as they begin their climb toward design intensity.

Accelerator Facilities

LAMPF - Los Alamos Clinton P. Anderson Meson Physics Facility, Los Alamos Scientific Laboratory, Los Alamos, New Mexico, USA, 87544

Most of the LAMPF accelerator is housed in a straight, reinforced-concrete, 770-m-long tunnel that is buried beneath the ground. An equipment aisle is located on the ground surface above the accelerator tunnel and communicates with it via ducts that are blocked with shielding where necessary. The equipment aisle is shielded from the accelerator by 70 cm of concrete plus 7 m of compacted backfill (volcanic tuff 1.6 g/cc). An average beam spill of 2 nA/m is the allowable limit for hands-on maintenance along the portion of the accelerator where energies are higher than 100 MeV.[11] Donald R. F. Cochran[12] has been responsible for shielding and activation calculations, and directed the construction and initial equipping of the switchyard and the experimental areas. The accelerator is capable of simultaneous acceleration of both H^- and proton beams. The H^- beam will be partially stripped to provide beam tailoring and additional beams. The proton beam passes into Experimental Area A, traverses through three pion production targets, and stops within isotope production targets and a beam stop.

The designs of the LAMPF Experimental Area A and Area A-East were based on a philosophy that permits completely remote maintenance where required.[13] The shielding is closely packed around the proton and the secondary beam lines. Shielding thicknesses in the vicinity of the first target are 4.3 m of steel plus 60 cm of concrete, and in the vicinity of the second target, 4.9 m of steel plus 60 cm of concrete. The top of the shielding is arranged to form a flat roadway whose surface is 5.5 m above the proton beam line. Horizontally opening shield doors, whose upper surfaces are part of the roadway and whose lower surfaces are 1.2 m above the beam line, are located over essentially all components that can be activated to the extent that they require remote handling.[14] The opening of these doors (which weigh hundreds of tons) expose either the component or the local shielding just above the component. When activity levels are too high to allow hands-on or long-tool maintenance, a portable hot cell can be used. This cell is a floorless steel room, 4.6 by 3.0 by 1.75 m inside and 5.5 by 4.0 by 2.4 m outside, with four lead-glass viewing windows mounted in the roof; the room weighs 240 tons. A PaR 3000 electromechanical manipulator and a 5-ton hoist are mounted inside the room. The room is hung on four ball screws from a steel framework mounted on the landing gear of a surplus B-52 bomber. A hydraulic system provides the power for driving and steering the gantry, lowering and raising the room, and opening and closing the shield doors. The room and gantry form a portable hot cell that is known as "Merrimac." When required, Merrimac is positioned astraddle the shield door over the component to be maintained. The door is opened, forming a shaft down to the component. The room is lowered partway into the shaft. Personnel on the roof of the room look down through the windows and use the hoist and manipulator to perform the necessary work. When a component requires replacement, it is disconnected with the manipulator and lifted up into the room, which is then used as a self-powered shielding cask. Merrimac drives over a hot cell that is located in Area A and lowers the component into the cell for transfer to a storage area or for maintenance, utilizing the master/slave manipulators that are available there.[15] Heavy components require lifting rods that pass through the roof of the room to high-capacity cranes. Most components were designed to fit within the room, and require only the simple motions of the PaR manipulator for disconnection. Unfortunately, none of the magnets were designed for remote maintainability, and must either be replaced with a spare component or stored until they decay sufficiently to permit hands-on maintenance. Special tools and shielding can be assembled to allow hands-on maintenance on components having high radiation levels. Spare main beam line quadrupole triplet magnets are available.

The beam line vacuum pipes are connected with V-clamps and utilize commercial metallic seals. The K-seal was chosen because of the low sealing force it required and its ability to conform to slightly warped or thermally cycled flanges. Target mechanisms extend through the main shielding mass; the first two handle radiantly cooled, rotating-wheel targets. These targets may be loaded and unloaded from outside the shielding. The third target is a water-cooled ladder, and requires mechanism removal and shielded transport to the hot cell for ladder replacement. The isotope production targets are attached to the ends of stringers which, when withdrawn, permit remote replacement within a small hot cell located adjacent to the shielding. All magnets located within sight of the proton beam are of radiation-resistant construction; either mineral-insulated[16] or concrete-insulated[17] coils are used.

The cooling-water systems are all closed loop, and dump their heat into one cooling tower water circuit. One system serves only those components that receive direct or scattered beam impingement, such as targets, target mechanisms, collimators, and the beam stop. Another system serves those magnets that transport the proton beams and the front-end magnets of the secondary beam lines. Other systems serve the magnets and jaws in areas with lower radiation levels. The water system has six subdivisions: pits, a valve gallery, transmission circuits, through-shield tubing, jumpers, and pump packages. Twelve concrete-lined pits are buried in the ground, flush with the ground surface. Supply and return cooling tower water pipes are stubbed off in each pit, as are vent lines and electrical services. Two stainless steel pipes are run from each pit to a valve gallery located in the switchyard. Seven transmission circuits are run from the valve gallery to valve caves tucked in the shielding at various locations throughout the experimental areas. Manifolds on the ends of the transmission lines are located in the valve caves from which tubes pass through the shielding to bulkheads mounted near the components. Remotely removable jumpers connect each component to a pair of through-shield tubes. Flow control valves, flow switches, and temperature gauges are located in the valve caves to control and monitor the water for each component. Flexible pipes in the valve gallery connect any one or more pits to any one or more transmission lines; system pressure control equipment is also located there. A pump package consists of one 100-hp pump, three 1-MW-capacity heat exchangers, and a cyclone air separator--all mounted on a steel frame. After a package is placed in a pit and connected, the top of the pit is sealed with molded concrete shield blocks. The pump motors are mounted above the shielding for maintenance access. In principle, any pump package can be dropped into any pit, and provide water to any component in the experimental areas. In practice, some of the pits are used for the make-up water systems; and to reduce congestion in the valve gallery, only certain pits are paired with particular transmission lines. The plug-in feature of the pump package provides accessibility for repair without closing down the entire facility for access, as would have been required had a conventional equipment room concept been used. This feature has proved its value as a considerable number of pump bearing and seal problems have been encountered with the vertical shaft turbine pumps. Pump outlet pressure is 20 atmospheres (300 psi). Each of the 7 transmission circuits is tapped to provide up to 10% bypass flow through demineralizer- and oxygen-removal resins and filters, located in the hot cell complex.

The radiation level in the filter cell adjacent to the resin tanks was observed to stabilize at approximately 6 R/h at a proton beam current of 10 μA. The growth and decay of this level closely follows the production and decay rates for ^{11}C and ^{7}Be.[18] The resins are remotely replaced by valving water flows. The old resins are flushed into the radioactive waste system, where they are trapped in a buried, 24-m-long, vertical sand trap. The trap capacity is large enough and so designed that it will retain resins for six months before they are carried on into the waste-system-holding tanks for receipt by the Liquid Waste Disposal Group of LASL. A tritium production of 100 Ci/year may occur in the most highly activated water systems.[12] Two methods of water disposal are under consideration if it should become necessary to drain any part of this system. One method involves making cement blocks with this water and burying the blocks in a radioactive waste repository. The other scheme involves evaporating the water in the 37-m-high exhaust stack and venting it; it appears to be practical to do this and maintain the stack emissions within acceptable limits.

The exhaust system draws air from the vicinity of each target and from the beam stop region. Since the shielding is rather tightly packed, there is very little volume of air exposed to secondary particles. It is expected that air activation will not be a problem; however, motorized dampers are located in each duct to restrict air flow if necessary. It is desirable to maintain some air flow to keep the pressure in the target region less than that in the adjacent occupied areas and to provide some cooling, since the inlet air must percolate through the stacked shielding. All the air passes through high-efficiency filters on its way to the exhaust stack. In normal operation, the air is stagnant in the accelerator and switchyard tunnels; it is allowed to decay, and numerous purges are made before personnel entry is permitted.

The shielding acquisition and placement have been under the direction of Paul R. Franke.[19] He estimates that LAMPF has almost 50 000 tons of portable shielding that represents an in-place expenditure of approximately $6 million. Fifteen thousand tons of concrete blocks in various sizes and shapes have been fabricated at a cost of from $42/ton (1970) to $63/ton (1974). Eleven thousand tons of surplus missile silo counterweights were obtained for only the $38/ton transportation cost; the counterweights are 1 m by 5.8 m by either 15 or 30 cm thick, and the two large faces were ground-flat and parallel within ±1 mm. Unfortunately, the 30-cm-thick counterweights are made of cast iron and are very difficult to cut and shape. Approximately 20 000 tons of off-chemistry, mill-reject steel have been purchased from U. S. Steel, at delivered prices of $80/ton (1968-1970), $100/ton (1973), and $260/ton (1974). Fortunately, only 1000 tons had to be purchased at the highest price. Most of the reject steel has been cut into rather small pieces and stacked into the three-dimensional jigsaw puzzle that comprises the main shielding in Area A. This effort has required rather large manpower expenditures for drafting, cutting, and placing. Franke has access to 8×10^6, 1-in-diam, Type 405 stainless steel balls. He is presently attempting to determine how best to use this 1000-ton gift of slightly magnetic and absolutely unstackable shielding material.

The secondary particles from a pion production target will deliver a considerable amount of power into adjacent hardware and shielding. At the second production target, it has been calculated that 240 kW is dissipated[20]; tens of kilowatts will be deposited in beam line components. Special cooling is being provided to prevent component damage.

Eighteen master/slave manipulators and 14 lead-glass shielding windows are used in the hot cells and Merrimac. These were all acquired from decommissioned facilities at a very low price.

LAMPF is presently off the air, to permit modifications and shielding completion prior to increasing the intensity in a climb toward the planned 1-mA capability. Three weeks after the beam was turned off, radiation levels of greater than 1000 R/h at contact were measured at the beam stop, and about 30 R/h in certain areas in the vicinity of the three pion production targets.[18] The average beam current that created this activity was less than 1% of the desired goal.

SIN - Schweizerisches Institut für Nuklearforschung
5234 Villigen, Switzerland

The SIN facility, described by Willax[21] produced its first beams during February 1974; by August 1974, their ring cyclotron had been in operation 510 h. During 200 h of this time, 590 MeV proton beams with intensities of between 0.2 and 6 μA were extracted from the accelerator.[22] A few weeks after beam shutdown, radiation levels of 1 R/h were observed in the pion target system vacuum chamber. The tantalum collimator, located downstream of the target, read 10 R/h.[23] The target systems are closely surrounded by 1.5 m of cast iron and steel, arranged so that disassembly can be done remotely if necessary. Two shielded target systems, the primary proton line, and the front ends of the secondary beam lines are located in a vault approximately 5 m wide and 3 m high, formed from shielding stacked on the experimental area floor. There is convenient personnel access to the line components for hands-on maintenance. The roof slabs are removable to permit crane access. Target changing is performed by lowering a shield cask into position adjacent to the target local shielding. The target mechanism is pulled into the cask and a door is closed to provide a shipping container. The target mechanism is transported to hot cells where the target wheels are replaced by using master/slave manipulators. It is intended to control the radiation levels within the vault by controlling the beam characteristics at the accelerator. Should some unforeseen event occur that creates radiation levels that preclude personnel entry, it is planned to remove the roof slabs and use long tools or a manipulator system.

The manipulator system, dubbed the "Minimac," consists of a PaR 3000 manipulator and bridge that is operated with television viewing.[24] The vault side shielding consists of 1 m of 5.7 g/cc density steel-shot-loaded concrete blocks, plus 1.5 m of steel, plus 0.5 m of ordinary concrete. The shielding behind the beam stop consists of 5 m of steel-shot-loaded concrete blocks, plus a 1.5-m core of steel. The shielding configuration and thickness are varied as needed to provide low-background areas for secondary beam line caves. The after-portions of the secondary beam lines penetrate the vault wall and are rail-mounted. The rail car also carries shielding that is placed tightly around the beam line components and forms a good fit with the vault wall.

Charles Perret[25] directed SIN radiation monitoring and control effort. His group has published several internal documents that pertain to shielding and activation; one of these documents, TM-10-01, is convenient to use for calculating residual radiation levels.[26-28] Examples of the levels expected after one year of full-power operation, with the beam on 50% of the time and with 2.5 h of cooling time since beam turn off, are: (a) 60 R/h around the extractor portion of the injector cyclotron, (b) 2×10^5 R/h at 1 cm from 2 beam-defining jaws (associated with the 590-MeV extractor on the main cyclotron), and (c) 8 R/h at the main cyclotron pole faces after the jaws and other components are removed.[25] The 2×10^5 R/h at 1 cm radiation level associated with the jaws was confirmed in another report that looked at the problem of removing these jaws.[29] The body of a workman removing the jaws would be in a 90 R/h field. Due to distance and intervening material, only 9 R/h of this field is from the jaws; the remainder is caused by the steel mounting plate, magnet, and aluminum vacuum chamber that had been activated by the secondary particles from the jaw.

A reduction of the radiation level by 1000 (90 R/h to 90 mr/h) means the difference between (1) receiving a one-quarter year dose in 2 min of work and (2) receiving a 1 wk dosage during 1 h of work. Three orders of magnitude attenuation of gamma rays is obtained with shield thicknesses of 9.5 cm of lead, 16 cm of iron, or 50 cm of concrete. However, if the local shielding is in place during accelerator operation, it, too, would become activated. In the case of a 9.5 cm lead shield, the radiation level due to the lead would be 1.1 R/h - or 13 times the contribution due to the source it was shielding. It would be more practical, therefore, to thin the local shielding until its contribution equaled that from the jaws. Thin local shielding can often be incorporated into the design of the component mounting system easier than thicker shielding; however, some materials (like marble or graphite) are activated only slightly, and make excellent--albeit bulky--shields. Another possibility is to have the local shielding reside in an area with a relatively low neutron flux and drive it into position prior to personnel entry. Eyke Wagner[24] is presently working on the best way to arrange shielding and modify components to minimize exposures.

The vacuum components of the proton beam lines are connected with chains that are wrapped around the flanges, latched, and tightened. The rollers of the chains are bobbin-shaped and, when forced down over the beveled rims of the flanges, provide sufficient clamping force to make a diamond-shaped aluminum gasket-seal vacuum tight.[30]

The air within the injector vault and within the main cyclotron vault is recirculated, and is vented only after machine shutdown and ^{41}Ar decay. It was anticipated that many fewer-energetic protons would go astray and have the opportunity to pass through air along the external proton beam line; therefore, the air in this area is continuously exhausted.

Aare River water is pumped through heat exchangers that remove the heat from closed-loop demineralized secondary systems that cool the injector, main cyclotron, and all components except those located in the vicinity of the targets or the beam stop. An all-stainless steel tertiary system, equipped with a shielded ion exchange resin tank, cools the components that are located close to the targets and the beam stop. The close-in magnets are MI-insulated and are indirectly cooled. All other magnets are epoxy insulated with organic hoses.

The Swiss are widely known for their artistry with concrete, and the SIN shielding blocks confirm this reputation. The concrete roof beams for the main cyclotron vault are 21 m long, 71 cm wide, and 150 cm high; the cost was 6500 SwF ($2200) each delivered. The injector vault roof beams are 21 m long, 136 cm wide, 75 cm high, and since they contain more reinforcing bars they cost 9000 SwF ($3000) each delivered. These long beams were cast with a curved shape that flattens when they are supported only on the ends. The beams were produced at the rate of two a week from one mold, and each of the long, vertical sides are flat and true within ±3 mm. Steel-shot-loaded concrete blocks of 5.7 g/cc density have tolerances of ±2 mm on all dimensions for blocks up to 2 m longest dimension. The block fabricator imported steel shot from England to load the concrete, and charged 700 SwF/ton ($230) delivered. Normal concrete blocks cost 83 SwF/ton ($28) delivered. All dimensions on normal concrete blocks are within ±1 mm tolerance for blocks up to 6 m longest dimension. The standard 2 by 2 by 1 m blocks were produced at the rate of two a day per mold with heating; the others at the rate of one a day without heating. The blocks were lifted from the molds by their own pickup inserts.[24] SIN has large numbers of hand-stackable size concrete blocks and cast steel bars that are flat and square within a few tenths of a millimeter; they stack so well that light does not pass between them. Work of this quality appears to be routine Swiss craftsmanship.

In Switzerland, corporations doing business in certain basic commodities are required to stockpile a fraction of their output for what could best be described as "war reserves." SIN arranged to have a portion of the steel stockpile stored within their shield walls. The steel is in the form of bars, 30 cm by 30 cm by 3 m, with slightly rounded edges. Stacks of these bars were tied together with steel strapping to form structurally stable units. These stacks are typically sandwiched between an inner row and an outer row of concrete blocks to form a shield wall. After a few years' use, any steel that activates to a level that is too high to allow it to be converted into concrete reinforcing rods for home construction must be purchased by SIN. It is expected that very few bars will be so activated.[25] The total cost of all shielding at SIN is approximately 8 000 000 SwF ($2.8 million).[23]

SIN utilizes the resources of the neighboring Swiss Federal Institute for Reactor Research for support in many areas, among which are radioactive waste disposal facilities and hot cells.

TRIUMF, University of British Columbia, Vancouver 8, British Columbia, Canada

A general discussion of the TRIUMF accelerator facility has been presented at these conferences by Warren,[31] Richardson,[32] and Burgerjon et al.[33] The facility is housed in a large, rectangular building with the cyclotron occupying roughly the central one-third. Cyclotron beams are directed into each of the end rooms that are named the Proton Hall and the Meson Hall. Ian Thorson was responsible for considering the shielding and activation problems, and in 1968 he published a comprehensive report on these topics.[34] He was concerned about a possible 10 kW of beam power that could be lost in the cyclotron by electromagnetic dissociation of the negative hydrogen ions. He estimated that these lost particles would create a residual radiation field in the cyclotron of the order of 1 R/h a few hours after shutdown following a long operating period. He calculated that approximately 9 m of concrete would be required around the cyclotron to reduce the radiation fields to 2.5 mR/h at full power; 4.9 m of this shielding made up the cyclotron vault walls and the remainder was tightly fitted around the perimeter of the cyclotron. The vault shield walls were poured in place, abutting the original structural walls. They were designed to be manageable sections through the use of plywood separators that will allow future removal of most of the wall without resorting to jackhammers or explosives. The cyclotron is encased in 380 shielding blocks - partly heavy concrete and partly standard concrete - that weigh 3.6 and 2.7 tons each. The on-site shielding block fabricating facility has also produced 400 standard concrete blocks and 230 heavy concrete blocks with the dimensions 0.6 by 0.9 by 1.8 m for use in the experimental areas.[35]

More recent estimates of the activity levels in the cyclotron predict that the lost beam particles, which impinge on a narrow band around the perimeter of the vacuum chamber, will produce 6 R/h fields. During the first year of operation, beam currents will be low and spill of the order of 0.5 kW will produce 300 mR/h. The calculations are based on infinite irradiation time and one day of cooling. The vacuum chamber is 18 m in diameter and 45 cm high. The cyclotron is constructed in a manner that permits the upper magnet halves and the vacuum chamber lid to be jacked upward 1.2 m for servicing. A service bridge is inserted into the opened vacuum tank with the inner end supported on the cyclotron center post and the outer end supported on wheels that ride on the cyclotron periphery. A drive system positions the bridge at any radial location desired. A variety of trolleys can be mounted on the service bridge to accomplish inspection and to perform maintenance functions.

The high-intensity meson beam line targets, the low-intensity proton beam line LD_2 target and associated collimators, and the beam blockers are serviced by removing overhead shielding. A support system is mounted on top of the remaining shielding and referenced to the target mechanism. A shielded cask is placed on the support system, directly over the target mechanism. The target mechanism is pulled up into the cask and the bottom doors are closed. The target mechanism is 3 m long, and consists of a ladder arrangement of water-cooled targets suspended below a shield plug and vacuum seal. The ladder can be moved vertically to place differing targets into the proton beam. Target ladders are exchanged and general maintenance performed by transporting the shield cask to the roof of a hot cell and lowering the target mechanism into the cell where it can be reached with master/slave manipulators. The first hot cell is a temporary structure formed with stacked concrete blocks and water-filled windows which can later be replaced by lead-glass windows. It is equipped with two Model D and one Model 7 CRL master/slave manipulators. This hot cell is adequate for servicing components with radiation levels of 1.2 R/h at 1 m, for example, a 9-g copper target that has received 1 μA at 500 MeV infinite irradiation.

The beam line seals and magnets located within 1.5 m of the targets are radiation hardened. The beam line pipes are 20 and 40 cm in diameter, and the seals are knife-edge, spring loaded into a band of indium. Lead screw driven tapered pins inserted into the flanges provide a spring load of about 9 kg/cm of seal circumferential length. The lead screws can be manually operated from a position above the shielding.[36]

FERMILAB - Fermi National Accelerator Laboratory P. O. Box 500, Batavia, Illinois, USA 60510

The target systems at FERMILAB are expected to dominate that laboratory's considerations of induced activity and remote handling. The stiffness of the high-energy proton beam can be appreciated by the fact that two targeting systems, consisting of magnets, collimators, and targets, are 61 and 24 m long. A comprehensive description of the target-handling system has been given by Grimson et al.[37] The target systems are mounted on bedplates and carried into a target box by a railroad transporter. When lowered into place in the target box, the bedplates dependably position the components within a few tenths of a millimeter. The transporter can then be removed. The longer of the target systems is used in Area I to produce a muon beam and a neutrino beam. Spare systems allow a target to be used for 6 wk and then to cool for 3 months. The radiation levels have been found to be 100-200 R/h immediately after beam off, and levels above 10 R/h at 30 cm are regularly encountered. Dennis Theriot, leader of the mechanical support group of the neutrino department, reports that manual repair is still used but expects that as beam intensity increases and activity levels grow remote handling will take over.[38]

The remote-handling philosophy utilizes a target laboratory that is essentially a shielded room, 9 by 26 by 7 m high, into which the railroad transporter can bring a target system. The target laboratory is equipped with remote servomanipulators that can cover the entire floor area. The manipulator operators use television viewing to repair or replace components. The most radioactive of the components can be remotely removed to reduce radiation to levels that allow hands-on maintenance or rebuilding.

Radiation Damage

Energetic particles traversing through matter cause disruptions that alter their chemical makeup and stress patterns. Organic molecules are broken with the result that plastic insulations tend to lose their flexibility and strength. Often, however, a multiple conductor cable can remain in use with severely damaged insulation as long as it is not flexed. The properties of most structural metals and ceramics are not altered until they have received many times the dosage that would ruin any organic material. Metallic nuclei can be ejected from their lattice positions by a projectile. The resulting lattice void and interstitial atom represent local lattice strains. Table II, above, indicates that each 800-MeV proton will create 0.2 helium atoms when striking copper. The helium atoms can conglomerate and create rather large voids in the metal. A loss of ductility is experienced in irradiated metals. The fluxes of particles available at high-intensity accelerators permit the study of this phenomenon to provide guidance in the tailoring of materials for use in high radiation fields for fast-breeder reactors and controlled fusion reactors. Such an irradiation facility is being commissioned at the LAMPF beam stop.

Of interest to the accerator facility builder is the consequence of component failure caused by radiation damage. Of particular concern are magnet insulation failure, water hose failure, vacuum seal leakage, and electrical cable shorting.

Epoxy has been a traditional and convenient material for use as a magnet coil insulation and binder. Investigations have been made to compare the radiation resistance of various epoxies, additives, moldable materials, and spacer materials.[39,40] Essentially every accelerator facility has a few magnets insulated with "radiation-resistant" epoxy. For those cases where the predicted radiation doses are clearly beyond the capability of epoxy insulations, MI, concrete, and anodized aluminum coils are used. MI (mineral-insulated) magnets utilize a coil wound from a copper conductor that is surrounded by a layer of compacted magnesium oxide powder held in place by an outer jacket of copper. The conductor is swaged to have a square cross section, and is wound on a form to the proper coil configuration. It may be cooled directly by passing water through the center conductor[16] or indirectly by soldering the conductors together with external cooling tubes.[41] Metal-to-ceramic-to-metal seals must be used between the inner conductor and the outer jacket to prevent moisture from reaching the magnesium oxide insulation. Similar seals are used to duct cooling water into the inner conductor. MI magnets are used at LAMPF, SIN, and TRIUMF. The conductor for these magnets was manufactured by Pyrotenax of Canada Ltd., Trenton, Ontario, Canada.

A few magnets at LAMPF have been insulated with alumina-loaded concrete.[17] Ceramic seals similar to those used on MI cable are used to channel cooling water into and out of the conductors.

Columbia University's Nevis Laboratory has fabricated magnet coils from hard anodized aluminum conductor.[42] The coil is first wound and then anodized. Since the anodic coating is inflexible, care is taken to prevent further bending. Thin anodized aluminum sheet is sandwiched between layers of windings to reduce the chance of layer-to-layer shorts.

MI wire is in general use in the electrical wiring industry for heat-resistant wiring, and in the nuclear industry as electrical leads into reactor cores for thermocouples and flux detectors. Thousands of meters of fine MI wire are used at LAMPF to transmit beam position monitor signals.

Soft nonmetallic materials have found considerable usage as vacuum seals. Tests have been run on some of these materials to determine their behavior after heating and exposure to radiation.[43] Nonmetallic vacuum sealing materials are used in all accelerators. However in high radiation areas at LAMPF aluminum wire and K-seals are used; at SIN diamond-shaped soft-aluminum rings are used; TRIUMF and SLAC[44] use indium.

A last comment concerns the corrosive nature of cooling water. Penner[45] expressed concern because of his experience at the NBS electron linac. The SC group at CERN investigated the advantages of additives.[46] LAMPF and SIN people expressed anxiety and took what precautions they could. Penner's concern appears to be valid in the LAMPF experience, where an MI target-cell-triplet magnet sprung leaks in the metal portion of many of its metal-to-ceramic-to-metal water seals. That magnet was on a water circuit whose conductivity was not maintained at a low level.[47]

Remote Handling

The general topic of remote handling covers a tremendous realm and degree of complexity, from driving an automobile to adjusting a camera aboard a space probe. The popular concept of remote handling grew up with the development of fission reactors. There exists a quarter of a century of experience dealing with the handling of radioactive materials. An organized group of people that deal with all aspects of remote handling make up the membership of the Remote Systems Technology Division of the American Nuclear Society (ANS). Their yearly publication, "Proceedings of the Conference on Remote Systems Technology," published by the ANS, is perhaps the best reference in this field. The first 14 volumes of these proceedings have been indexed.[48] The 23rd volume will be published this year. An industry has been created to provide the specialized equipment used by the remote-handling community. The ANS publishes an annual buyer's guide that lists hundreds of companies that cater to the nuclear industry.

Remote-handling concepts in the accelerator world did not originate with the accelerators mentioned in this report; the neophyte designer would do well to visit the personnel and facilities at Stanford, Berkeley, Nevis, Brookhaven, Argonne, National Bureau of Standards, Saclay, and CERN.

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