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RESIDUAL RADIATION OF THE LRL 184-INCH CYCLOTRON

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ABSTRACT

Residual radioactivity at the Lawrence Radiation Laboratory 184-Inch Cyclotron was measured during November 1960 in connection with similar problems which may be encountered with a high-intensity, 850-Mev accelerator. The five-day study was conducted along three principal lines: (1) general survey of radiation levels in the cyclotron vault, (2) activation of foils placed near the cyclotron, and (3) gamma-ray spectra of the cyclotron gap region, including dee structure. Initial radiation levels were less than 8 r/hr, and these dropped to about 10 mr/hr after 48 hr. The observed activities induced in copper foils were Cu^{64} and Co^{58}; in iron foils, Mn^{52}, Mn^{54}, and Mn^{56}; in aluminum foils, Na^{24}. The gamma-ray spectra from the gap region included two intense long-lived peaks, at 510 and 810 kev, due principally to Co^{58}. It is concluded that a 100-μa, 850-Mev cyclotron will be highly radioactive, but at a level which can be handled with fairly straightforward techniques.

INTRODUCTION

The problem of residual radiation in high-energy accelerators becomes increasingly serious as the beam intensity of the machines increases. The Oak Ridge National Laboratory is investigating the possibility of constructing an 850-Mev proton cyclotron with beams of the order of 100 μa. It is obvious that this accelerator will present serious residual radiation problems. Its components will be highly radioactive and will have to be handled remotely, and the cyclotron vault itself may be so active as to require limited access to it for adjustments and maintenance.

There are at least three approaches which may render this problem manageable: (1) beam selection, steering, and control, which will carefully define the beam in the initial orbits and will then minimize losses of high-energy particles, (2) choice of construction materials to minimize reactions leading to long-lived gamma emitters, and (3) design of the cyclotron in a way to permit remote maintenance and incorporation of gamma-ray shielding.

To study these problems firsthand a group from ORNL investigated the residual radioactivity of the Lawrence Radiation Laboratory 184-Inch Cyclotron during a five-day shutdown in November 1960. The 184-in. cyclotron is used to produce a beam of 730-Mev protons about 70% of the operation time; deuterons or alpha particles are also accelerated in the machine. The beam current averages about 1 μa. The cyclotron is operated three shifts per day, seven days per week. Thus a factor of 100 in residual activity may be expected between the 184-in. and the 850-Mev cyclotrons if none of the preventive measures prove efficacious.

The study of radioactivity was conducted in three ways:

1. A radiation monitor was used to measure background radiation from various parts of the 184-in. cyclotron and in the vault area. A decay curve for the radiation was obtained.

2. A 3 × 3 in. NaI crystal was placed in a large lead collimator and pointed at the cyclotron magnet gap near the probe position. The dee, dee support, liner, and magnet pole pieces all contributed to the spectra obtained. A 256-channel pulse-height analyzer was used to obtain the spectra. The gamma-ray spectra were followed for five days.

3. Foils of iron, stainless steel, copper, and aluminum were affixed to the cyclotron vacuum tank for a few days before shutdown. The gamma-ray spectra from these foils were measured with a 2 × 4 in. NaI crystal, and the induced activities were identified from the gamma-ray energies and half-lives. The gamma-ray spectrum of an iron screw which had been in the cyclotron for many years was also measured, and its decay is still being followed.

From these data, conclusions were drawn regarding the induced-radioactivity problem in an 850-Mev cyclotron, and some suggestions are made concerning construction materials.

Since the experimental techniques of radiation dosimetry and gamma-ray scintillation spectroscopy are very well known, we dwell little on the details of the measurements and confine ourselves principally to giving results.

RESULTS

Dose Measurements

The instrument used for dose measurements was a calibrated Geiger counter supplied by G. S. Hurst and E. B. Wagner of the Health Physics Division. Measurements made with it started about 30 min after shutdown and continued for five days. The positions at which the measurements were made are marked A–F in Fig. 1. Table 1 lists the initial radiation level at each position, its approximate half-life, and the residual level reached at about 48 hr after shutdown. The residual level did not show any appreciable decay over the remaining three days. The dose measurements were hampered by the fact that the cyclotron vacuum system was blown

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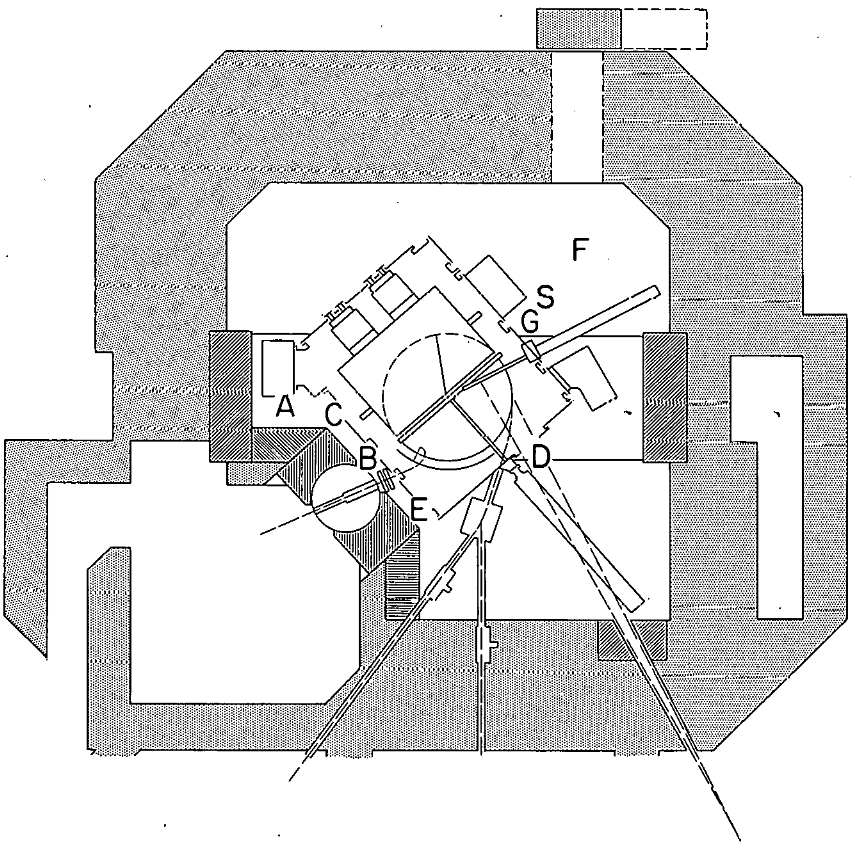

Fig. 1. Schematic Representation of the 184-in. Cyclotron Vault. The points marked A–F are positions where dosimeter readings were taken; the point S is the position of the gamma-ray spectrometer.

Table 1. Radiation Levels at Various Positions in the Cyclotron Vault (see Fig. 1)

Location	Initial Radiation Level	Level After 48 hr	Approximate Half-Life
A	70 mr/hr	10 mr/hr	Indeterminate
B	2.5 r/hr	15 mr/hr	3 hr and long
C	80 mr/hr	9 mr/hr	Indeterminate
D	150 mr/hr	10 mr/hr	12 hr and long
E	1.5 r/hr	11 mr/hr	3 hr and long
F	18 mr/hr	10 mr/hr	Indeterminate
G	110 mr/hr	10 mr/hr	12 hr and long

Note: Fluctuations in readings, possibly due to construction activity and/or Geiger counter performance, make long-half-life determinations impossible.

out under pressure about 9 hr after shutdown; the radiation levels increased at all positions at this time. Similarly, when the compressor was shut down the radiation levels dropped. The residual radiation levels reported here were corroborated by measurements made with several Lawrence Radiation Laboratory survey instruments. Some difficulties with the Geiger counter were experienced in the course of the measurements, and the results in Table 1 are probably good only to a factor of 2.

The integrated dose as recorded on two sets of film badges worn in the cyclotron vault also substantiates the results of the Geiger counter dosimeter measurements.

Gamma-Ray Spectra

The gamma-ray spectra* taken with the 3 × 3 in. NaI crystal at the cyclotron gap started about 8 hr after shutdown. One or two spectra were taken earlier, but difficulties with the 256-channel analyzer made systematic measurements possible only after 8 hr. Thus, much of the short-lived activity was missed, but then the longer lived activities are of greater interest.

*The spectrometer was supplied by C. C. Harris and J. E. Francis, Jr., of the Thermonuclear Research Division.

Measurements were taken at position S in Fig. 1. The NaI crystal was completely shielded with 2 in. of lead except for a 1-in.-diam hole 8 in. deep, aimed at the median plane of the cyclotron. A lead plug could be inserted in the hole to provide for background measurement. When the counter was pointed away from the median plane, say at the pole base, the spectra were identical in shape and intensity to the background spectra. From this it is concluded that the important source of radiation in the cyclotron comes from the gap and the structures in it, rather than from neutron-induced activities in the magnet yoke or other peripheral equipment.

Each measurement of a gamma spectrum was followed by a background count taken for the same analyzer live time. The background was subtracted from the gross count to obtain a net gamma-ray spectrum. Altogether, 11 such measurements were taken; Fig. 2 shows one of the net spectra. This run was 96 hr after shutdown; only the activities longer than 10 hr were measured. An energy calibration was taken immediately before or after each run; an Na^{22} source was used.

The spectrum in Fig. 2 was unfolded by taking into account the spectrometer resolution, NaI crystal stopping efficiency, fraction of gammas

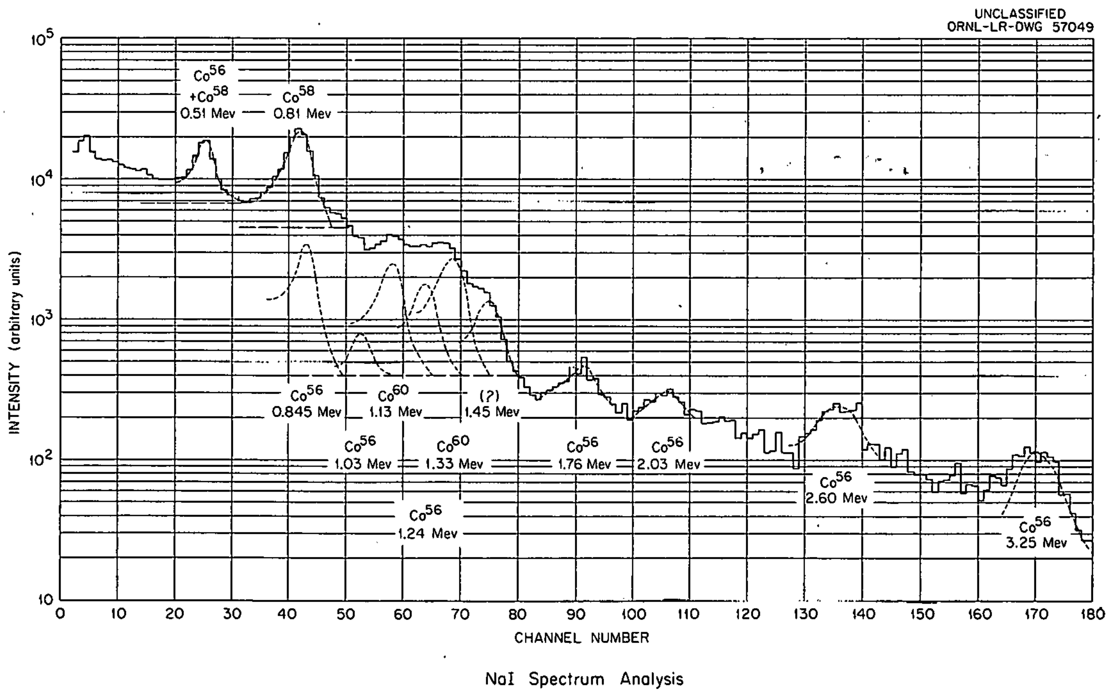

Fig. 2. A Net Gamma-Ray Spectrum, Looking into the Cyclotron Magnet Gap. This spectrum was obtained 96 hr after the cyclotron shutdown.

in the photopeak, and the filtering effect through an Al faceplate on the cyclotron vacuum tank immediately opposite the spectrometer. A 12-hr positron emitter was identified as Cu^{64}. The Co^{56} activity was identified from the high-energy lines present in the spectrum. The Co^{56} gamma-ray intensities calculated from the unfolding procedure agree very well with published transition probabilities,[1] as shown in Table 2. After the proper subtractions were made, Co^{60} was also found in the long-lived spectrum. There remained the 810-kev line and additional positron annihilation at 510 kev. The 810-kev line could be due to Co^{58} or, with a small

Table 2. Comparison of Observed Gamma-Ray Intensities with Published Values Listed in the "Table of Isotopes," D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. 30, 585 (1958)

Isotope	Gamma-Ray Energy (Mev)	Relative Gamma-Ray Intensity	
		Observed	Predicted
Co^{56}	3.26	13	12
	2.60	15	16
	2.03	13	12
	1.76	16	17
	1.24*	70	70
	1.03*	16	16
	0.84*	100	100
	0.98**		1.8
	1.35**		5.7
	2.98**		1.9
Co^{58}	0.81	100	100
	1.62**		0.5
	0.51*	32	30
Co^{60}	1.33*	100	100
	1.13*	83	100

*Peak unfolded from complex spectrum.
**Not found.

shift in energy, to Mn^{54}. The positron annihilation did not show any observable decay over a three-day period. Many combinations of activities were tried, including various amounts of Mn^{52} and Mn^{54}, and the best fit was obtained if all the 810-kev radiation was assigned to Co^{58}. In this way the remainder of the 510-kev peak could be accounted for as being due to Co^{58}. The 510-kev peak was approximately constant and did not show any decay in five days; it could thus not be due to Mn^{52}.

The magnet gap of the cyclotron at which the spectrometer was pointed contains a variety of materials; these include steel (pole pieces), copper (dee and liner structure), and stainless steel (support structure). Part of this stainless steel support structure, a member 1 in. thick, 10 in. wide, and 10 ft long, was closest to the crystal; thus, the spectra present a picture in which the importance of stainless steel is greater than it would be for the average radiation from the gap region.

The radiation hazard, as indicated in Fig. 2, is due to the 510- and 810-kev lines. These are due to Co^{58}, although as much as 20% of the 810-kev peak may be due to the 830-kev radiation from Mn^{54}, and some of the 510-kev peak is from Co^{56}. Some of the 510-kev peak may also be from Mn^{52} decay. The source of the Co^{58} can be spallation of Cu (bombardment of Cu with 340-Mev protons showed the yield of Co^{58} to be greater than that of any other radioactive product[2]), or (n,p) reactions in the nickel content of the stainless steel. These two possibilities could not be distinguished on the basis of present measurements.

A peculiar result of this measurement is the absence of a large amount of Mn^{54} activity. This is interpreted to indicate that materials in the median plane, such as the stainless steel support structure or the copper dees themselves, are a greater source of radioactivity than the magnet pole pieces. It will be seen in the next section that Mn^{54} is by far the main long-lived activity induced in iron.

The results of this gamma-ray survey are limited for two reasons. One was the inability, because of construction during the cyclotron shutdown, to move the spectrometer about the vault to obtain spectra at different positions. The spectra obtained are, therefore, not characteristic of the entire machine. It is known, for instance, that the region of the meson port and the deflector are much more radioactive than the part of the gap seen by the NaI crystal. Furthermore, during the five days of the shutdown no reliable decay curves could be obtained for any activity with a half-life longer than a few days. In fact the changes in the radiation pattern resulting from construction work permit the identification of only one half-life: that of the 12-hr Cu^{64} annihilation radiation. All the other activities shown in Fig. 2 do not seem to decay and are thus considered simply as having half-lives longer than a week.

Activities Induced in Metal Foils

A few days before the shutdown, foils of aluminum, copper, iron, and stainless steel were affixed at various positions on the walls of the cyclotron vault and on the cyclotron vacuum tank. Starting 30 min after shutdown, gamma-ray spectra of the activities induced in these foils were investigated with a 2 × 4 in. NaI crystal connected to a 100-channel pulse analyzer. Activities were identified by means of their gamma-ray energies and half-lives.

The main activity found in aluminum was Na^{24} (15.0-hr). The first gamma-ray spectrum taken of one of the aluminum foils showed the presence of Mg^{27} (9.5-min), but this isotope had essentially decayed by the time counting was initiated. A positron annihilation peak possessing a 2-hr half-life was also observed; this would seem to indicate the presence of F^{18}. Aluminum foils counted two weeks after shutdown showed no activity.

The chief activity induced in copper was found to be Cu^{64} (12.8-hr). One of the copper samples was wrapped in cadmium prior to irradiation to eliminate reactions due to slow neutrons. The cadmium-wrapped sample was then left very near a copper sample of approximately equal size but not wrapped in cadmium. After irradiation it was determined that the ratio of Cu^{64} activity in the cadmium-wrapped sample (due only to fast particles) to that in the uncovered foil was ~1/1.6. Two weeks after shutdown the copper samples displayed two prominent gamma-ray peaks at 510 and 820 kev. When the samples were counted again, three months after the shutdown, the counting rate of each of the two peaks was found to have decreased by a factor of 2. It was then concluded that the two peaks belong to Co^{58} (71-day) which is produced with a large cross section from spallation of copper.

Initially, the iron and stainless steel samples showed two main activities, Mn^{56} (2.6-hr) and Mn^{52} (5.7-day). Samples placed in the median plane showed larger amounts of Mn^{52} than those placed above the median plane, as expected, because Mn^{52} should be produced in reactions induced by fast particles. Two weeks after shutdown the samples all showed Mn^{52} to be the dominating activity. The samples were counted once again, three months after shutdown. At this time the foils displayed gamma-ray spectra with three prominent peaks: 320, 510, and 820 kev. The three peaks varied in intensity relative to one another, depending on whether the foils were stainless steel or iron. The stainless steel foils were known to contain 10% nickel and 20% chromium. Indeed, the 320- and 510-kev peaks were much more intense, relative to the 820-kev, in the stainless steel than in the iron foils. The 320-kev gamma ray is due presumably to Cr^{51} (27-day) and can be produced by means of spallation of iron. In the stainless steel samples the Cr^{51} can also be produced by reactions on chromium. The 510-kev peak in iron samples is probably due to either Co^{56} (77-day) and/or Co^{58} (71-day). The two isotopes may be produced by (p,xn) reactions on iron. In the stainless steel, Co^{58} can also be produced by an (n,p) reaction on Ni^{58}. The presence of the 510-kev peak in a particular spectrum accounted for part of the 820-kev peak. The remainder of the latter peak is presumably due to Mn^{54} (300-day) produced by various reactions on iron. In this connection, an iron screw taken out of the cyclotron vacuum tank at the time of the shutdown contained, three months later, only one intense gamma ray, the 830-kev Mn^{54} gamma ray. Only suggestions of peaks at 320 and 510 kev were visible. Figure 3 shows this gamma-ray spectrum. Since the screw had been irradiated for a considerably longer amount of time than any of the other samples, it is not surprising that it should contain more of the longer-lived Mn^{54}. The peaks at 1120 and 1300 kev (Fig. 3) probably belong to Fe^{59} decay, though the half-life of these peaks has not been determined.

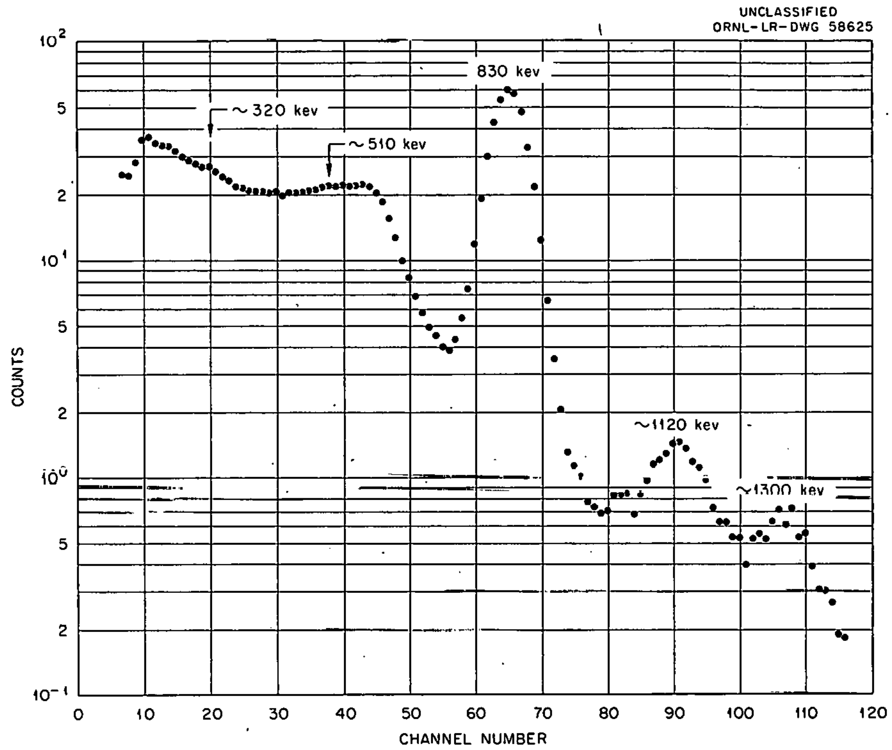

Fig. 3. Gamma-Ray Spectrum of an Iron Screw Taken Out of the Cyclotron Vacuum Tank. The spectrum was obtained approximately three months after the cyclotron shutdown with the use of a 1-1/2 × 1-1/2 in. NaI crystal detector.

CONCLUSIONS

The radiation level in the 184-in. cyclotron is just about tolerable. It is possible to go into the vault immediately after the beam is turned off to make quick changes or emergency repairs. After cooling for about a day, the radiation level in the cyclotron vault is such that a person can safely spend an 8-hr day in it, provided he stays a few feet away from the one or two most active spots. External radiation sources, such as meson ports, are quite radioactive, but could be handled either by very fast work or with tools which allow the person to be about 3 ft away. The dees and other structures in the magnetic gap are, on the other hand, highly radioactive. Since no measurements were made on them, we can not evaluate just how dangerous they would be. Still, a few inches of steel and a few feet of distance make the radioactivity of the dees quite harmless.

The 850-Mev cyclotron would, however, present much more serious radiation problems if it is assumed that its residual radioactivity is 100 times that of the 184-in. cyclotron. Levels of several hundred r/hr would probably prevail immediately after the beam is turned off, and they would decay to background dose rates of about 0.5 r/hr. This means that no quick adjustments or repairs could be made after the machine is shut down, and even after cooling down, a person could only spend an hour or so in the cyclotron vault.

These estimates apply to a cyclotron constructed in a conventional way, with no special provisions for handling the residual radioactivity problem. The situation, however, is not nearly so bleak. Present-day techniques allow a great deal of work to be done in radiation fields between 1 and 100 r/hr. Furthermore, a careful choice of materials of construction, for example, using as much aluminum as possible and very little stainless steel, should reduce the radiation problem significantly. Aluminum yields no long-lived activities, while Co^{58} is produced from copper. In addition, the ratio of Na^{24} yield from aluminum to that of Cu^{64} from copper was found to be: $Cu^{64}/Na^{24} \approx 50/1$, this ratio being good to within a factor of 2. Stainless steel produces two long-lived isotopes, Co^{58} and Mn^{54}, while only Mn^{54} is induced in iron. Good control of the beam both during acceleration and during deflection should also help in reducing the radiation problem. Altogether, it is not improbable that by these two methods one might reduce the residual activity by as much as an order of magnitude from the 0.5 to 100 r/hr estimate, at least in some parts of the cyclotron vault.

Shielding against this radiation is also not very difficult. Most of the activity is evidently in the 510- and 810-kev peaks, and the half-thickness in lead for gamma rays of this energy is 0.6 cm. To reduce the radiation by an order of magnitude one needs only 2 cm of lead — an amount that can readily be made into a portable shield. Shadow shields of 6 cm of lead would reduce even the 100 r/hr radiation field to a quite tolerable 100 mr/hr. The same radiation has a half-thickness of 4 cm for concrete. One might, therefore, have permanent shadow shielding in the cyclotron vault to allow entry soon after beam turnoff and achieve safe access to certain key parts such as valves, the ion source, and rf components.

Finally, considerable attention will have to be paid to remote handling of highly radioactive parts of the accelerator, such as dee structures and ports. Shielded aging pits will have to be provided for cooling, as well as hot cells for repairs of highly radioactive cyclotron components.

Our conclusion is that an 850-Mev cyclotron producing 100 μa of protons will be highly radioactive, but at a level that can be handled by using fairly straightforward techniques and precautions. Care will have to be taken in selecting construction materials and in designing the layout in the vault, so that the machine can be maintained and repaired safely and most simply.

ACKNOWLEDGMENTS

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