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HEALTH PHYSICS FOLLOWING A NUCLEAR EXCURSION: THE LRL INCIDENT OF 26 MARCH 1963

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Abstract—On 26 March 1963 at 0000 hours a nuclear excursion occurred in a shielded vault designed for critical assembly experiments. The excursion was estimated at 4×10^{17} fissions, and was followed by oxidation of the enriched uranium metal in the assembly. The fire was observed via closed circuit TV; later entry established that burning was limited to the assembly. Nearby combustibles did not burn or scorch.

Disaster plans were immediately implemented to determine: (1) radiation exposures to personnel directly involved, (2) the possibility of recurring critcality, and (3) the extent of release of radioactive materials to the Laboratory and to the off-site environment.

Air and surface contamination levels were determined in the building housing the vault and at other points within the Laboratory perimeter. Air, vegetation, and soil samples, obtained within hours following the excursion, were analyzed for fission product and alpha activity fallout. Results indicated the release of small amounts of short-lived, high-yield gaseous fission products and their daughters. No detectable alpha activity was released to the environment.

The maximum exposure to any of the four persons in the building at the time was 120 mrem penetrating gamma radiation. All neutron exposures were less than detectable limits, i.e., 50 mrem fast neutrons and 1 mrem thermal neutrons. Urinalyses, nasal swipes, and thyroid scans were all negative, indicating no internal exposure.

An air sample taken from within the vault 57 hours after the excursion showed levels of $\sim 2 \times 10^{-6}$ μc/cc of short-lived fission products. Radioactive decay and changing the vault air reduced these levels to below MPC values. The air exhausted from the vault was filtered and scrubbed with caustic before release to the atmosphere.

The initial vault entry was made to size up and — if necessary — to eliminate the possibility of a further excursion. The gross amounts of all fissile material were removed before decontamination operations were begun. The building, exclusive of the vault, was reoccupied six days after the incident.

This incident reaffirms for us the value of carefully designed vault facilities for critical assembly work.

INTRODUCTION

On 26 March 1963 at 0000 hours, a nuclear excursion occurred in a shielded vault at the Lawrence Radiation Laboratory, Livermore. The experiment in progress was the stepwise measurement of neutron multiplication in a critical assembly.

The vault, designed for critical assembly experiments, is part of a building housing office spaces, a machine shop, and other experimental areas

Fig. 1). Two of the vault walls are poured concrete and two are made of large concrete blocks set in mortar; all walls are 5 feet thick. The insides of the walls were painted with two coats of polyvinyl paint. The roof is made from interlocking concrete beams 30 inches thick with all cracks taped to form a complete seal. A 6 foot water window and a closed-circuit television permit direct observation from the control room into the vault. A slight negative pressure (~0.015 inch water) can be maintained in the vault by an exhaust ventilation system independent of the rest of the building. Air withdrawn from the vault is passed through a double bank of filters before being released to the environment.

THE INCIDENT

The experimental critical assembly consisted of concentric cylinders of enriched uranium, surrounded by a beryllium reflector. When fitted together, the uranium formed a single hollow right cylinder. The approach to criticality was to be achieved by moving an enriched uranium ram up into the open portion of the cylinder. This was to be accomplished in a stepwise fashion to determine neutron multiplication at several levels of the ram. A maximum neutron multiplication of 100 was set for this experiment. The total quantity of uranium in the assembly was 47 kilograms.

On the eve of the excursion, two safety check assemblies had been tested satisfactorily; the experiment was then begun with the actual assembly. Neutron multiplication measurements were made at the first seven stepwise positions of the ram (Fig. 2). After each measurement, the ram was lowered away from the rest of the assembly and a polyethylene safety ring removed. Removal of the ring permitted the ram to be raised to the next higher step. The ram was raised to the eighth stepwise position and a measurement begun. Neutron multiplication rose to the expected level for a few seconds, and then without warning the assembly went prompt critical (Fig. 2).

This sudden rise in reactivity was accompanied by an explosive sound heard in the control room over the intercom system to the vault. Scram and criticality alarms were actuated, the vault vent valve automatically closed, and the ventilation system shut down. For a few seconds, the television monitor was blank, then the observers in the control room could see flames and what apparently were portions of the assembly melting and breaking apart. The emergency call was sounded and the four occupants of the building quickly left.

The prompt gamma radiation from the burst was detected by continuous air monitors located in the building (Figs. 3, 4), and by continuous air monitors in each of two other buildings about 350 meters distant (Fig. 5). Hand and foot counters in these buildings alarmed. The burst was not detectable elsewhere on the Laboratory site.

Fire and monitoring units responded to the emergency call independently and arrived on the scene about three minutes after the burst. Radiation levels outside the building were less than 1 mr/hour. An entry was made into the building approximately nine minutes after the criticality by emergency personnel wearing full protective clothing and air-supplied respirators. Radiation levels were low, varying from 10 mr/hour in the control room to a maximum of 90 mr/hour near the vault door. No entry was made into the vault, but gamma radiation was about 10 r/hour as indicated by three remote area monitors on different interior walls of the vault (Fig. 1). Later readings showed that these levels closely followed the $t^{-1.2}$ decay estimate for fission products.

CAUSE AND MAGNITUDE OF THE EXCURSION

The cause of the excursion is believed to be directly attributable to mechanical failure. The ram may have been slightly off center with respect to the remainder of the assembly (Fig. 6A), and, as it was raised, the ram carried the innermost cylinder upwards (Fig. 6B). A small disturbance realigned the cylinder, and it slipped down over the ram, changing the geometry sufficiently to allow a prompt criticality to occur. The excursion was halted by a change in geometry caused by the melting uranium, and by the activated scram system. The explosive noise probably resulted from portions of the assembly being forced against the top plate of the assembly carriage.

The magnitude of the excursion was estimated by radiochemical analysis for Mo^{99} at 8×10^{12} fissions/gram. For a 47-kg assembly this results in 3.76×10^{17} fissions. Table 1 presents some comparative data on the energy release of the criticality.

Table 1. Comparative energy release data.

Number of fissions	3.76×10^{17}
Heat generated	3.07×10^{6} calories
Power produced	1.28×10^{7} Watt-seconds
Quantity of U^{235} fissioned	2.0×10^{-4} gram
Radioactivity produced	3.84×10^{7} curies
I^{131} produced	0.280 curie
Sr^{90} produced	0.590 curie
Yield (TNT equivalent)	5.76 pounds

The Mo^{99} estimate of the extent of the excursion is not inconsistent with those made by other means, including a nuclear accident dosimeter located in the vault. A similar dosimeter in the control room indicated no detectable thermal or fast neutron exposure, based on gold and sulfur activation analysis (limits of detection: thermal neutrons, 1 mrad; fast neutrons, 1 rad).

Exposure to personnel in or near the building at the time of the excursion was low, in no case more than 120 mrem. These data were obtained from film badges and are presented in Table 2.

Table 2. Personnel exposures from criticality burst.

(Limits of detectability: Gamma, 10 mrem; fast neutrons, 50 mrem)

Initial	Location (Fig. 1)	Gamma (mrem)	Fast Neutrons (mrem)
AR	Control Room	120	0
HB	Washroom (opposite control room)	100	-
HR	Kiosk (outside NE corner of bldg.)	0	-
MR	Hallway	0	-
RR	Control Room	70	0

In all cases, the films had been worn by the individuals for several days prior to the excursion; hence, some or all of the gamma exposure may have actually occurred before the excursion. Nasal wipes, thyroid scans, and urinalyses on the individuals in the building were negative, indicating no internal exposure. Theoretical internal dose estimates can be made using the equations derived in the Appendix.

Physical damage was confined to the assembly and associated equipment (Figs. 7 through 9). About 15 kg of uranium and some polyethylene were burned. Other combustibles in the vault were not consumed. The vault floor was highly contaminated with gross quantities of melted and oxidized uranium (Fig. 10); the walls, overhead, and other apparatus in the vault were contaminated to a lesser degree. About 10 kg of uranium had melted and was spread over the floor.

RELEASE OF RADIOACTIVITY

Shortly after the incident, efforts were begun to determine the amount of radioactive material released from the vault, and to determine if any had escaped off-site. It had already been determined by the emergency response team that a direct radiation hazard did not exist outside the vault. However, the possibility of air contamination and recurrence of criticality suggested the evacuation of the emergency crew to a control point away from the building. From this point entries were made to the building to collect air samples and wipes and to view conditions in the vault via the television monitor in the control room. Estimates of possible excursion cloud movements were made and a perimeter survey team dispatched to make radiation surveys and to collect air samples. Vegetation and soil samples were collected a few hours later. A summary of the data from both on- and off-site contamination is shown in Table 3.

The overpressure generated by the excursion released a small fraction of the radioactivity from the vault; most of this was confined to the building. Contamination was found along the cracks between shielding blocks on top of the vault and about 1.2×10^{-8} μcuries/cc of particulate beta activity was

Table 3. Summary of post-incident contamination.

Location	Time – date sample taken	Air Samples: Beta-gamma activity	Air Samples: Alpha activity	Air Samples: Isotope (s)
Vault stack (downstream from filters)	0000-0500, 3/26	1.2×10^{-8} μcuries/cc	4×10^{-10} μcuries/cc	MFP[a] and U^{235}
Ambient air in building	0000-0100, 3/26	2.8×10^{-7} μcuries/cc	----	Short-lived fission gases and daughters
Work area just outside vault	0045-0305, 3/26	$\sim 8 \times 10^{-7}$ μcuries/cc	7×10^{-10} μcuries/cc	MFP and U^{235}
On-site, 350 meters north of building	0100, 3/26	1.3×10^{-9} μcuries/cc	----	
On-site, 1000 meters southwest of building	0200, 3/26	1.6×10^{-8} μcuries/cc (by pulse-height analysis and total gamma counting)	----	I^{135}
Site perimeter	0200, 3/26	$\leq 3.7 \times 10^{-8}$ μcuries/cc (by pulse-height analysis and total gamma counting)	----	I^{135}
Vault	0500-0504, 3/26	25 rad/hour (direct reading on filter with open window Juno) estimated to be $\sim 10^{-3}$ μcurie/cc		MFP and uranium
Vault	0900, 3/28	2.0×10^{-6} μcuries/cc		MFP and uranium

Table 3. (Continued)

Wipes

Location	Time – date sample taken	Beta activity (d/m/100 cm^2)	Alpha activity (d/m/100 cm^2)	Time – date counted
Work area just outside vault	0800, 3/26	93,000	6	1400, 3/26
		1,000	6	1345, 4/10
Downtown Livermore	0900, 3/26	NDA[b]	NDA	1600, 4/2
Work area mezzanine	1200, 3/27	57,000	5	1701, 3/27
		8,800	5	1135, 4/10
Floors and desk tops in building offices	Morning, 3/29	≤ 800	≤5	Afternoon 3/29
Vault floor	1500, 3/29	15 mrad/hour (by open window Juno)	----	1500, 3/29
		500,000	42,000	5/17

Vegetation

Sampling location	Date taken	Sample preparation	Results (μcuries/gram of sample) High	Average
Samples taken from the Livermore-Pleasanton area	3/26	Total digestion	1.1×10^{-4}	6.9×10^{-5}
		Iodine extraction	$7.4 \pm 1 \times 10^{-7}$	$2.7 \pm 1 \times 10^{-7}$

Table 3. (Continued)

Soil

Sampling location	Date taken	Sample preparation	Results (μcuries/gram of sample)	
			High	Average
Livermore Valley	4/2	Soil dissolved and plated	12.9×10^{-5}	4.3×10^{-5}
Livermore Valley	1962	Soil dissolved and plated	25×10^{-5}	4.2×10^{-5}

[a]MFP – mixed fission products.

[b]NDA – no detectable activity.

ound in the air that had passed through the vault stack filter bank. Particulate radioactivity in the cloud was observed to have a short half-life Fig. 4). A peak concentration of 2.8×10^{-7} μcuries/cc was recorded on an air monitor used to sample ambient air in another part of the building.

A few hundred meters to the north of the building the particulate beta radioactivity was 1.3×10^{-9} μcuries/cc. These levels did not indicate any serious problems, since the activity was due mostly to daughters of the high-yield, short-lived gaseous fission products. Furthermore, cloud movement and dilution tended to reduce the average concentration in the cloud rapidly. Actually no visible "cloud" existed; this word is used merely for convenience.

During early entries to the building, an effort was made to determine whether significant amounts of uranium had escaped from the vault. Air samples (Table 3) recovered from the building did indicate that some alpha activity had escaped. Wipes taken throughout the building showed slight alpha contamination (Table 3) when counted in the laboratory. However, no detectable alpha surface contamination was found at the same locations with portable survey instruments, underscoring the need for laboratory counting techniques. Portable survey instruments were useful for finding "hot spots" ($\leq$20,000 dpm/100 cm^2) along the cracks between the vault-roof shielding blocks. No alpha activity – other than that of natural radon and thoron daughters – was found in any air samples or wipes taken outside the building or in the off-site environment.

A PoBe neutron source was included in the experiment at the time of the excursion. Because of the radiotoxicity of Po^{210}, alpha pulse-height analyses were made of samples showing alpha activity with a solid state detector. A typical energy spectrum is shown in Fig. 11, indicating no alpha activity from Po^{210}.

A few hours after the incident, an air sample (Table 3) was pulled from .e vault through an existing sampling line designed for routine vault air ıonitoring. This and subsequent air samples obtained during the week were ıken using Whatman ACG-B charcoal filter paper. By using these filters in ɜries with HV-70 or Whatman 41 filter paper, a collection efficiency of greater ıan 90% was obtained for iodines and particulate mixed fission products. amma pulse-height analysis substantiated earlier assumption that most of the irborne radioactivity collected was from radioiodines. To provide ultracon- ervative health physics estimates, all activity collected on the charcoal filters ɣas assumed to be I^{131}, the most hazardous of the radioiodines. Airborne radio- .ctivity, as determined by this method, was for the most part at or below the ;0-hour MPC for I^{131} in work areas adjacent to the vault.

The extent of release of radioactive materials to the off-site environ- nent was difficult to determine since the quantities were small enough to be nasked by background. External beta-gamma levels were nominally back- ground. No removable alpha or beta activity was found on wipes taken at several locations in the Livermore area. Vegetation samples may have con- ained small amounts of beta contamination, but lack of previous data from similar samples prevented accurate evaluation of such low levels. Since the nost hazardous probable nuclides were the radioiodines, iodine extraction was performed on vegetation samples. Results of these analyses are pre- sented in Table 3 and confirm that the off-site environment had not been com- promised as a result of the incident.

Soil samples, collected a week after the incident, showed no significant rise in activity (Table 3) when compared with samples collected at the same locations during the past year. Milk samples, obtained from local dairies

over the two-week period following the burst, were analyzed by the California State Department of Public Health for radioiodine. Iodine was not detected in any of the samples.

VAULT RE-ENTRY AND CLEANUP

During the first several hours following the excursion, attempts were made to establish what might have caused the burst and to determine what configuration the material took after the excursion. It was decided that this information could best be determined by entry into the vault.

In the afternoon, the vault ventilation system was sealed and operated on "recirculate" in an attempt to reduce airborne radioactivity by passing the vault air through the filter bank. The vault pressure increased to about 0.015 inch of water positive, forcing airborne radioactivity from the vault. The recirculating attempt was halted after about two minutes of operation.

A caustic scrubber (Fig. 12) was installed on the afternoon of 28 March as a further attempt to reduce air concentrations in the vault. The scrubber system effectively maintained the vault at a negative pressure, ≥0.01 inch of water. Several changes of the vault air were accomplished during the 1-day scrubber operation. The unit pulled about 400 cfm from the vault through three absolute filters and a caustic scrubbing solution, and then released this air directly into the building work area adjacent to the vault. This air contained about 10^{-8} μcuries/cc (Table 4), essentially radioiodines as indicated by gamma pulse-height analysis (Fig. 13).

The first vault re-entry was accomplished on the morning of 29 March to size up the situation and, if necessary, to eliminate the possibility of a further criticality. The entry party noted levels of 10 rad/hour β - γ near

the assembly and 2 rad/hour β - γ at 1 meter. General levels in the vault were 50 mrad/hour β - γ. Based on information gathered at this time, plans were made to remove the large pieces of fissile material from the assembly and surrounding floor (Figs. 7-10).

Table 4. Air concentrations from vault scrubber exhaust.

Date	Sampling Time (on-off)	Total beta μcuries/cc	Estimated I^{131} μcuries/cc
3/28	1645-1710	3×10^{-8}	6×10^{-9}
	1710-1755	2.1×10^{-8}	4.2×10^{-9}
	1755-2005	6×10^{-9}	1.2×10^{-9}
	2005-2237	9.8×10^{-9}	2×10^{-9}
	2237-2316	1.2×10^{-8}	2.4×10^{-9}
3/29	0852-0957	6.5×10^{-9}	1.3×10^{-9}

No further vault entries were attempted until Monday morning, 1 April, at which time the PoBe neutron source was located and removed. On the following afternoon, approximately 15 kg of uranium were recovered from the structural members of the assembly machine.

A lifting device was built to facilitate remote removal of the upper portion of the assembly, which still contained a large amount of fissionable material surrounded by a beryllium reflector. Figures 14 and 15 show the device used to raise this large chunk of beryllium and uranium from the floor. A holding tray with a boral bottom plate was used to support the beryllium and uranium chunk while loose oxidized material was removed. By the afternoon of 4 April, approximately 90% of the fissionable material had been

ıysically removed from the vault. This reduced the general background ıdiation in the vault to 10 mr/hour and about 25 mr/hour near the partially smantled assembly. The balance of operations was reduced to routine, but fficult, decontamination of the vault. The large chunk of beryllium and ranium was still a potential criticality hazard and plans were made to dissemble it remotely.

Although levels of contamination throughout the building were very low, 'et wiping was done as an additional precautionary measure. The office areas 'ere reoccupied one week after the excursion.

CONCLUSIONS

The data presented in this report lead to the following conclusions:

1. No uncontrolled external radiation hazard was present on- or off-;ite at any time.

2. Although some gaseous fission products were released to the en-/ironment, no internal hazard resulted. This was due to the small total volume of the cloud, the short potential exposure time, and the short half-life of most of the radionuclides, as well as the small total quanity released.

3. No measurable alpha activity was released to the outside environment. Very small amounts of surface and air alpha contamination were noted inside the building in the immediate vicinity of the vault.

4. Scrubbing with caustic proved to be effective in cleaning the vault air and permitted early re-entry into the vault.

5. Well-designed valult facilities for critical assembly experiments are valuable for containment and personnel safety.

6. The off-site environment was in no way compromised by the excursion.

ACKNOWLEDGMENTS

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APPENDIX

THEORETICAL ESTIMATES OF INTERNAL RADIATION EXPOSURE

Many attempts have been made to characterize the internal exposure of an individual located downwind from a single instantaneous release of radioactivity. Most of these are either quite similar to, or based on, Sutton's well-known solution of the Fickian diffusion equation for a "puff" case.

Fitzgerald, Hurwitz, and Tonks[1] have developed an expression that is well suited for describing the amount of activity deposited in a critical organ of a downwind observer. Their equation takes into account the variation of cloud size as a function of distance from the point of origin as well as atmospheric stability and diffusion parameters. This expression, adapted to the release of U^{235}, is given by Eq. (1):

$$q = \frac{kfJQ}{s\pi d^2} \qquad (1)$$

where

- q is the activity retained in the critical organ, in μcuries,
- k is a constant numerically equal to 1.17×10^{-6} curie minutes/g-sec,
- f is the fraction of inhaled activity retained in the critical organ, and is numerically equal to 0.083 (Ref. 2),
- J is the breathing rate, taken as 17 liters per minute,
- Q is the quantity of U^{235} released, in grams,
- s is the wind velocity, in meters/sec,
- d is the distance from the point of release to the observer.

Substituting the constants, Eq. (1) becomes:

$$q = \frac{1.6 \times 10^{-5} Q}{s\pi d^2} . \qquad (2)$$

Since $\pi d^2 = V^{2/3}$ where V is the cloud volume, Eq. (2) becomes:

$$q = \frac{1.6 \times 10^{-5} Q}{s V^{2/3}} . \qquad (3)$$

The cloud volume, V, can be conveniently obtained from the nomographs of Fitzgerald and Chappell[3] if the distance from the point of release to the observer, the stability parameter, and the diffusion coefficient are known.

In our case, the distance selected was 3200 meters, about the distance from the point of release to the city of Livermore. At the time of release, an inversion was present and the stability parameter was taken as 0.5, a conservative estimate. The wind velocity was approximately 1 meter per second, and the diffusion coefficient was taken as 0.08, based on measurements made by Holland[4] at Oak Ridge. Hence, V was found to be 5×10^4 cubic meters. If a 1% release of activity (470 g) is assumed, then the amount of U^{235} retained in the critical organ of the hypothetical observer in the city of Livermore would be

$$\frac{1.6 \times 10^{-5} \times 470}{1 \times (5 \times 10^4)^{2/3}} = 5.7 \times 10^{-6} \ \mu\text{curies}.$$

This quantity, based on extremely conservative assumptions, is several orders of magnitude less than the maximum permissible body burden.[5]

The dose rate, dR/dt, to the critical organ, can be obtained from Eq. (4), which is based on the body burden equations put forth by the International Committee on Radiation Protection[2]:

$$\frac{dR}{dt} = \frac{k_1 k_2 q E}{k_3 m} e^{-\lambda t} \qquad (4)$$

where

k_1 is a constant equal to 1.32×10^8 disintegrations per hour per μcurie

k_2 is a constant equal to 1.6×10^{-6} ergs/MeV

q is the quantity retained in the critical organ, in μcurie

E is the effective absorbed energy per disintegration in MeV

m is the mass of the critical organ, in grams

k_3 is a constant equal to 100 ergs/gram

λ is the effective decay constant, in reciprocal hours

t is the time, in hours, after deposition.

Since $\lambda << 1$, $e^{-\lambda t} \rightarrow 1$, and, by putting in the constants, Eq. (4) becomes

$$\frac{dR}{dt} = \frac{2.1\ qE}{m} . \qquad (5)$$

Substituting in Eq. (5) q from Eq. (3), and E = 230 MeV and $m = 7 \times 10^3$ g, the dose rate to the critical organ is

$$\frac{2.1 \times 5.7 \times 10^{-6} \times 230}{7 \times 10^3} = 4 \times 10^{-7} \text{ rad/hour}$$

or about 3.5 millirad per year.

Internal exposures from other nuclides can be computed in an analogous fashion. For nuclides with relatively large λ (i.e., coming to equilibrium in the body within 50 years), the total exposure to the critical organ, R, at any time t after deposition, can be obtained by integration of Eq. (4):

$$R = \int_0^t \frac{k_1 k_2 qE}{k_3 m} e^{-\lambda t}\, dt ,$$

$$R = \frac{k_1 k_2 qE}{k_3 m} (1 - e^{-\lambda t})$$

or, as $t \rightarrow \infty$,

$$R = \frac{k_1 k_2 qE}{k_3 m\lambda}$$

which reduces to

$$R = \frac{2.1\ qE}{m\lambda} \qquad (6)$$

when the numerical values of the constants are substituted.

For example, Eq. (6) can be used to obtain the infinite exposure to the thyroid from I^{131} released by the incident. If the release of I^{131} is assumed to be 2.75 millicuries, q for the observer 3200 meters from the point of release is 5.8×10^{-5} μcuries and the infinite exposure to the thyroid is

$$R = \frac{2.1 \times 5.8 \times 10^{-5} \times 0.23}{20 \times 3.8 \times 10^{-3}} = 3.7 \times 10^{-4} \text{ rad.}$$

REFERENCES

1. J. J. Fitzgerald, H. Hurwitz, Jr., and L. Tonks, "Method for Evaluating Radiation Hazards from a Nuclear Incident," KAPL-1045 (1954).

2. "Report of ICRP Committee II on Permissible Dose for Internal Radiation 1959," Health Physics 3, 1 (1960).

3. J. J. Fitzgerald and D. G. Chappell, "Graphic Aids to Estimate Nuclear Radiation Hazards," KAPL-1178 (1954).

4. J. Z. Holland, "A Meteorological Survey of the Oak Ridge Area," ORO-99 (1953).

5. "Maximum Permissible Body Burdens and Maximum Permissible Concentrations in Air and Water for Occupational Exposure," National Bureau of Standards Handbook 69, (1960).

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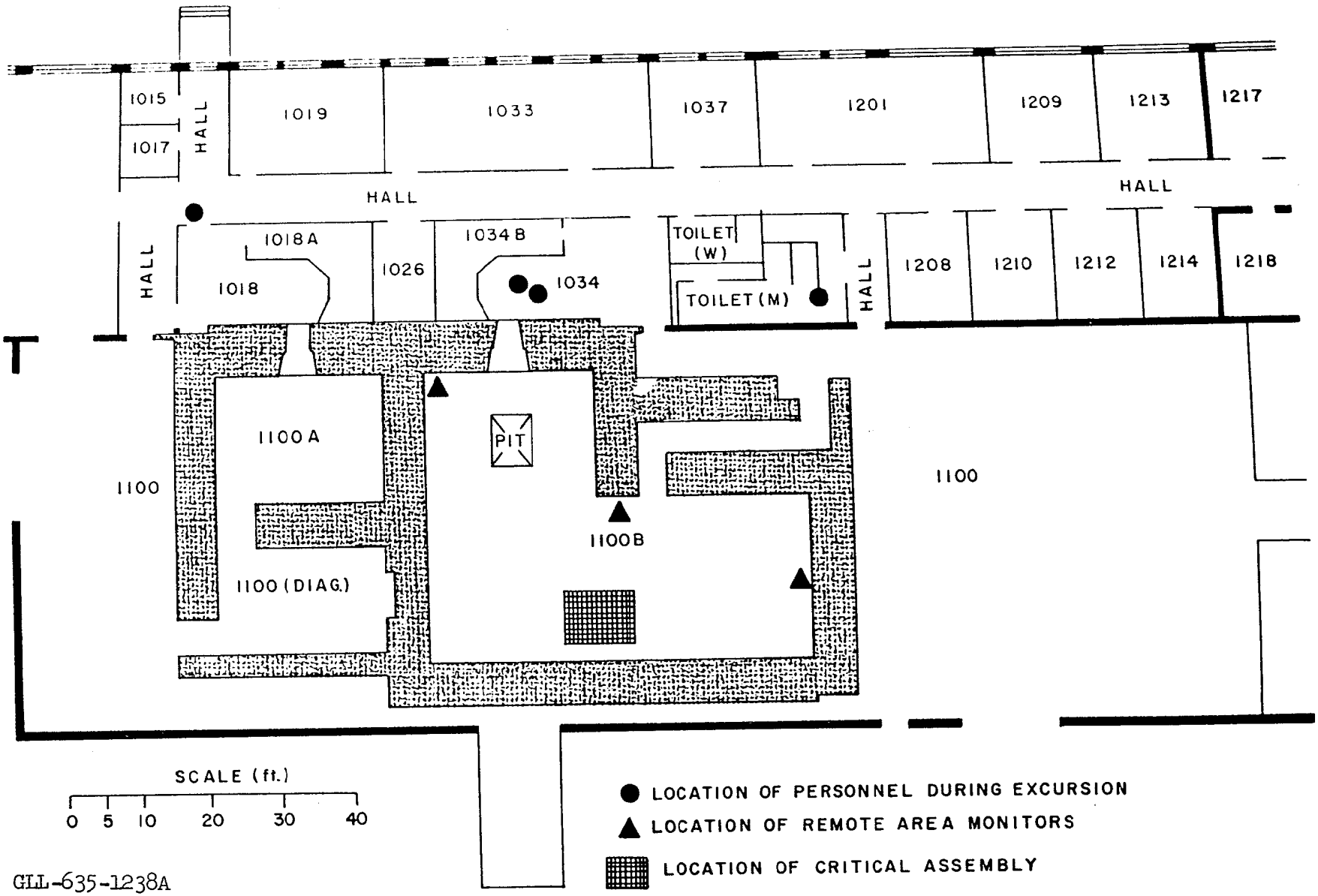

Fig. 1. Building layout.

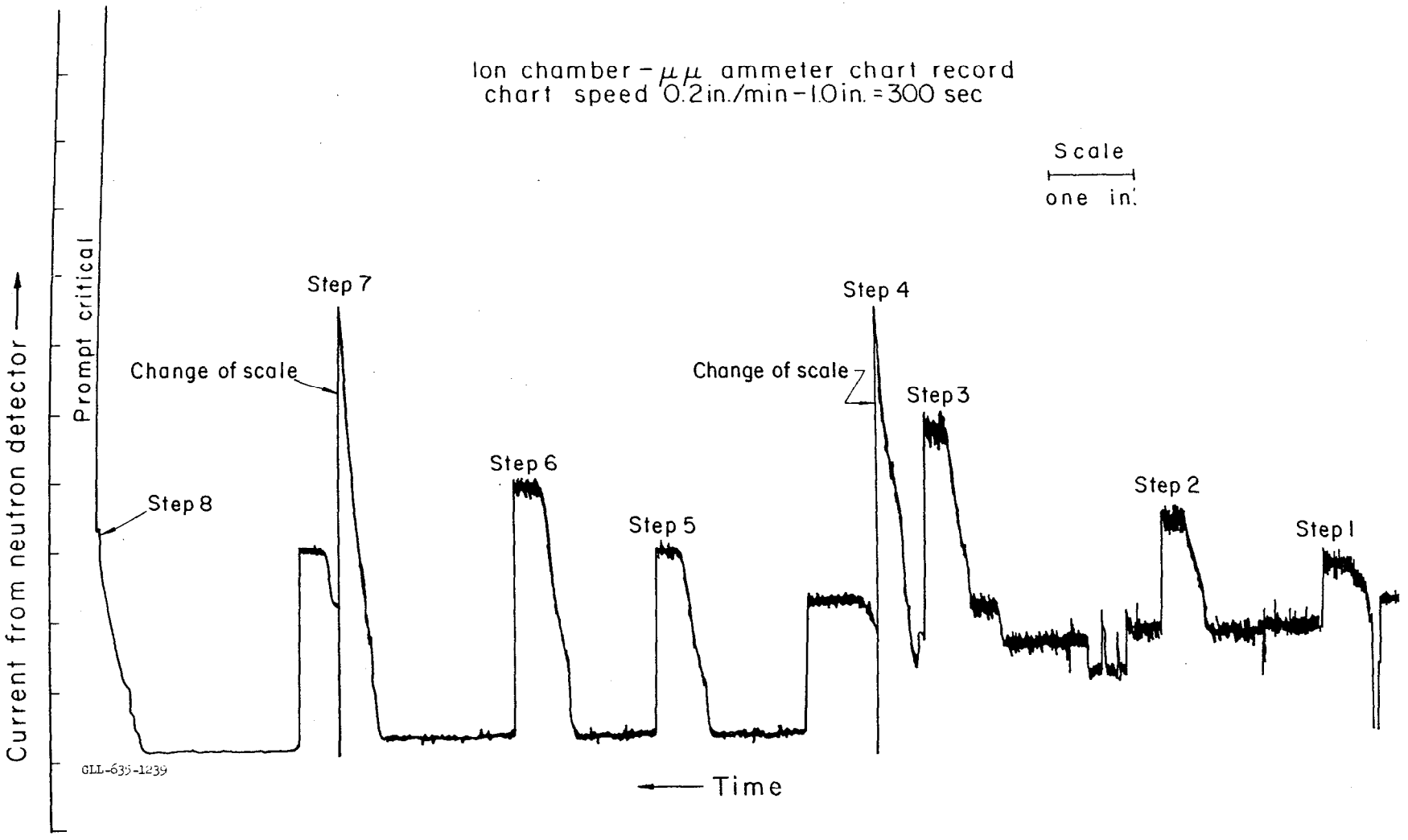

Fig. 2. Neutron levels during experiment.

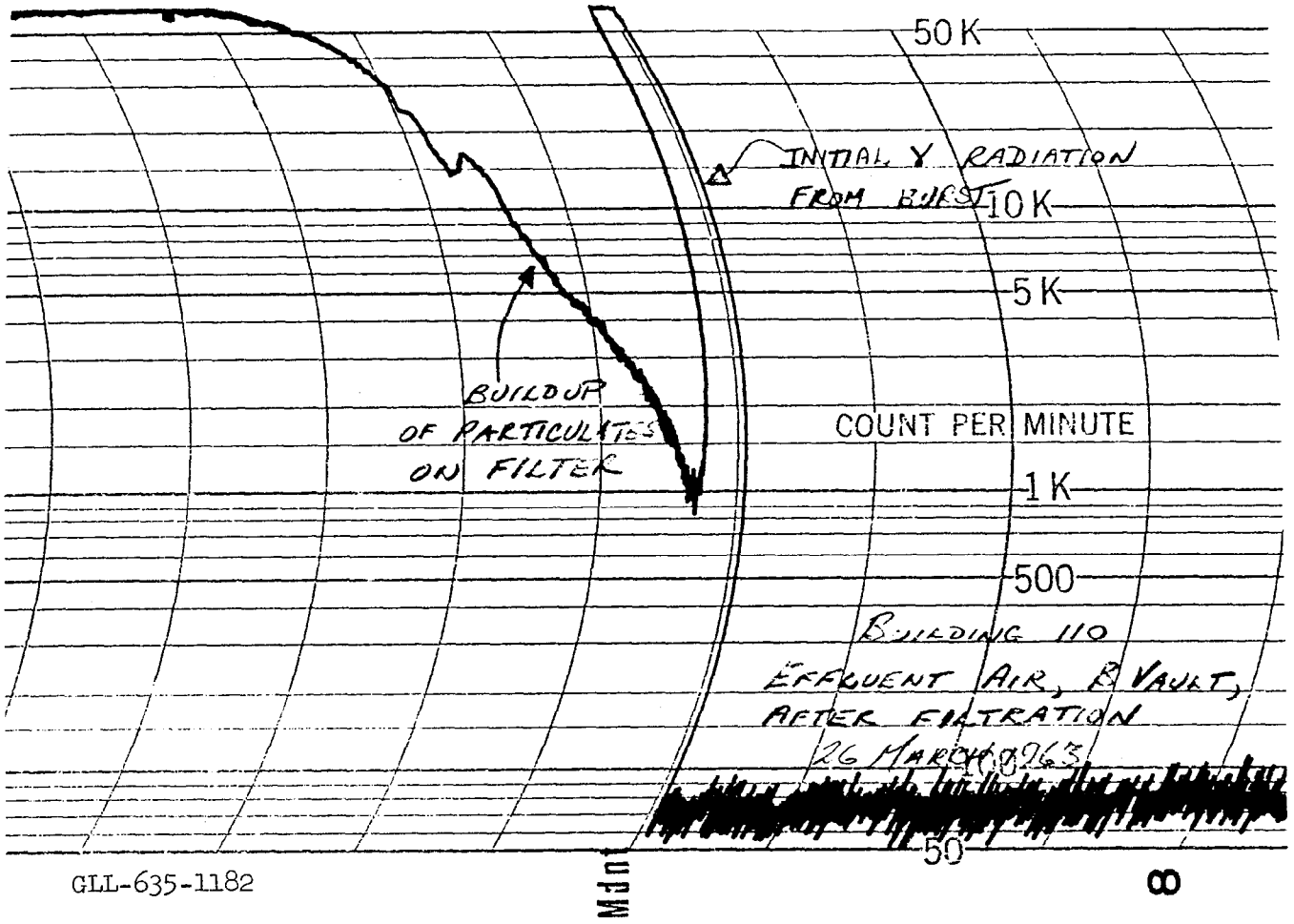

Fig. 3. Constant air monitor chart record from unit located outside of vault near wall and sampling vault stack effluent.

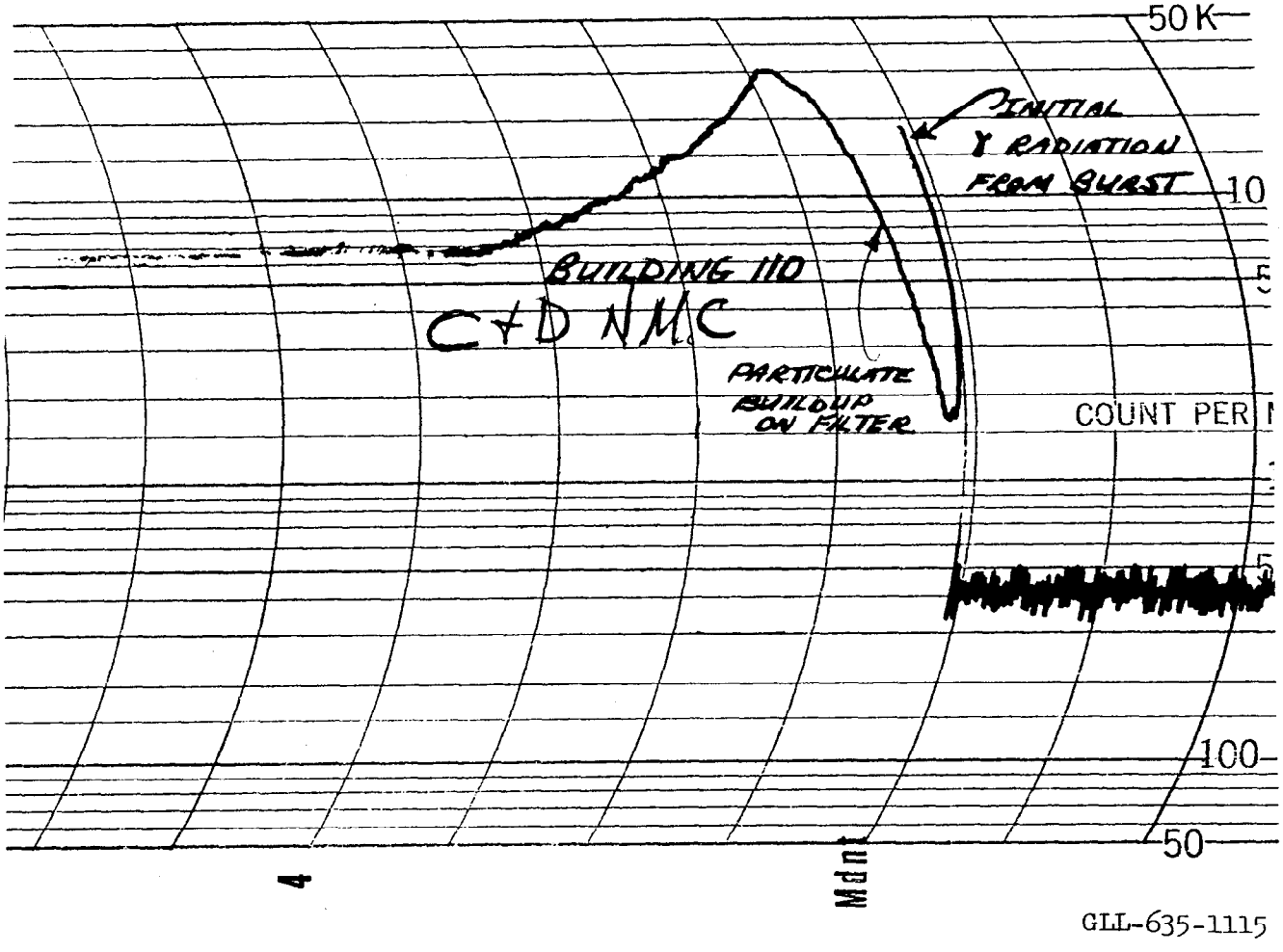

Fig. 4. Constant air monitor chart record from units located 35 meters from assembly and sampling building air.

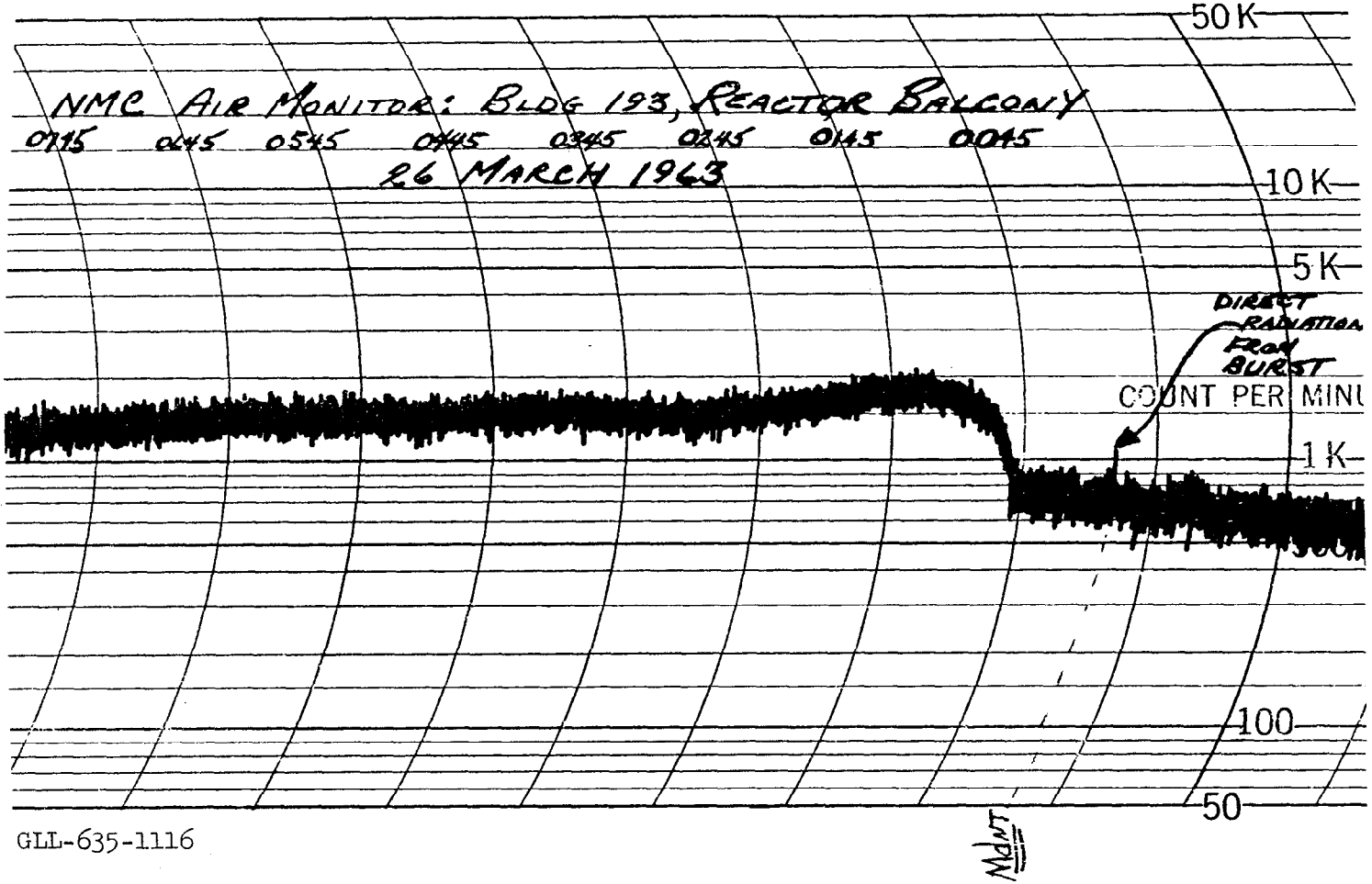

Fig. 5. Constant air monitor chart record from another building located 350 meters north.

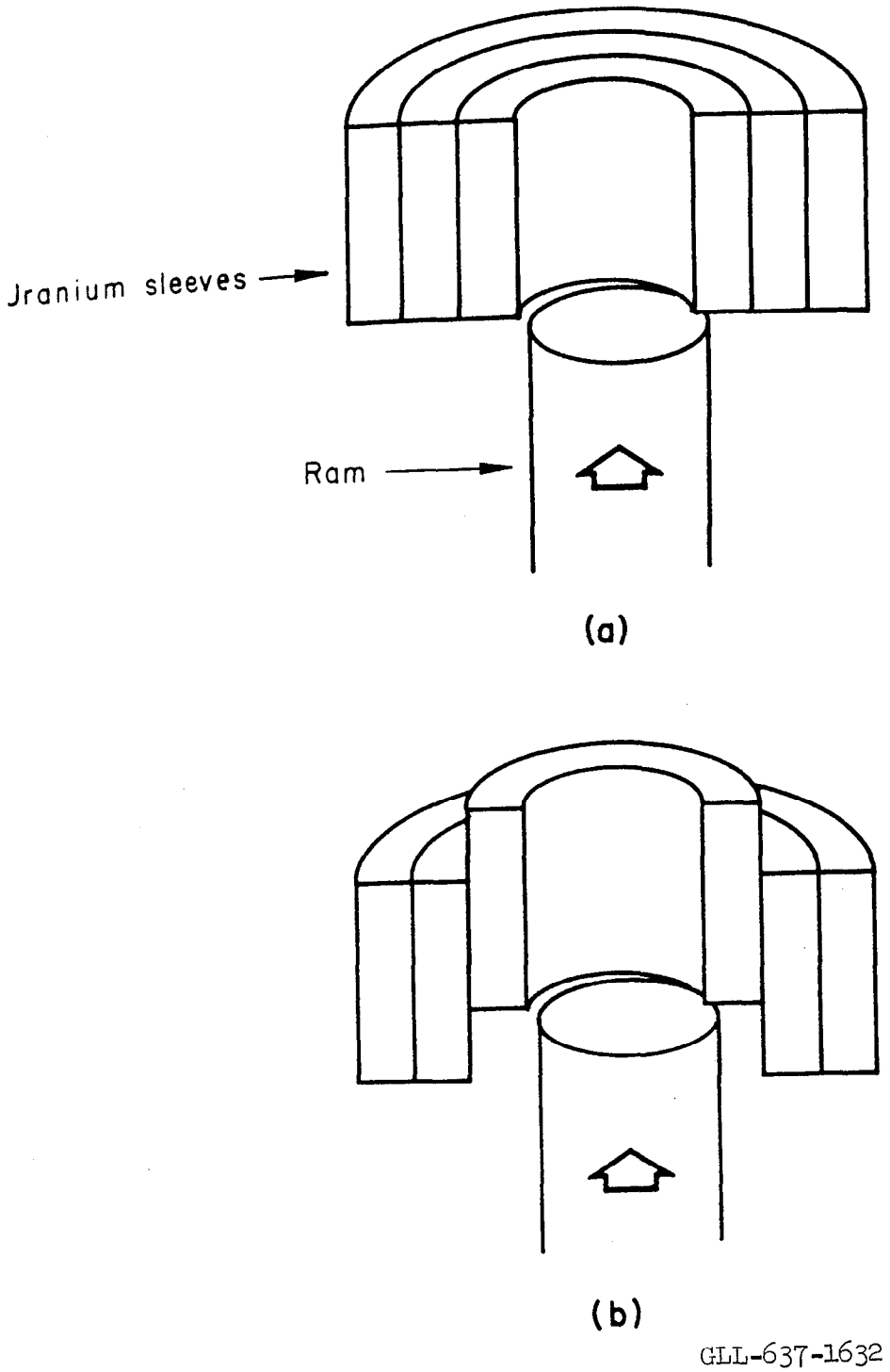

Fig. 6. Schematic representation of criticality mechanism. (a) Ram positioned slightly off center below the uranium cylinders. (b) Ram off center in raised position forcing innermost uranium cylinder upward.

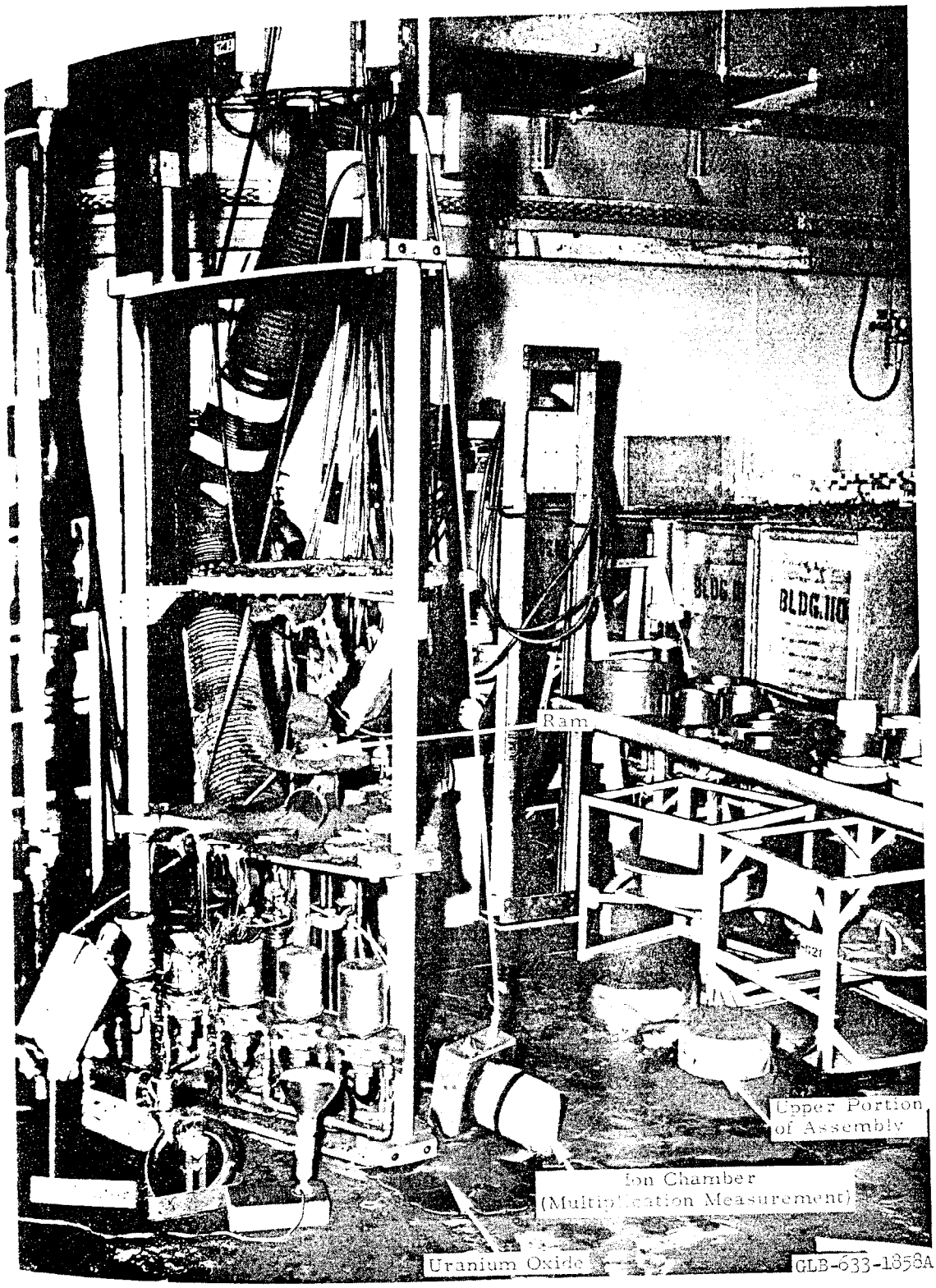

Fig. 7. Overall view of assembly after excursion showing extent of damage.

...a of assembly following excursion. Note oxidized uranium.

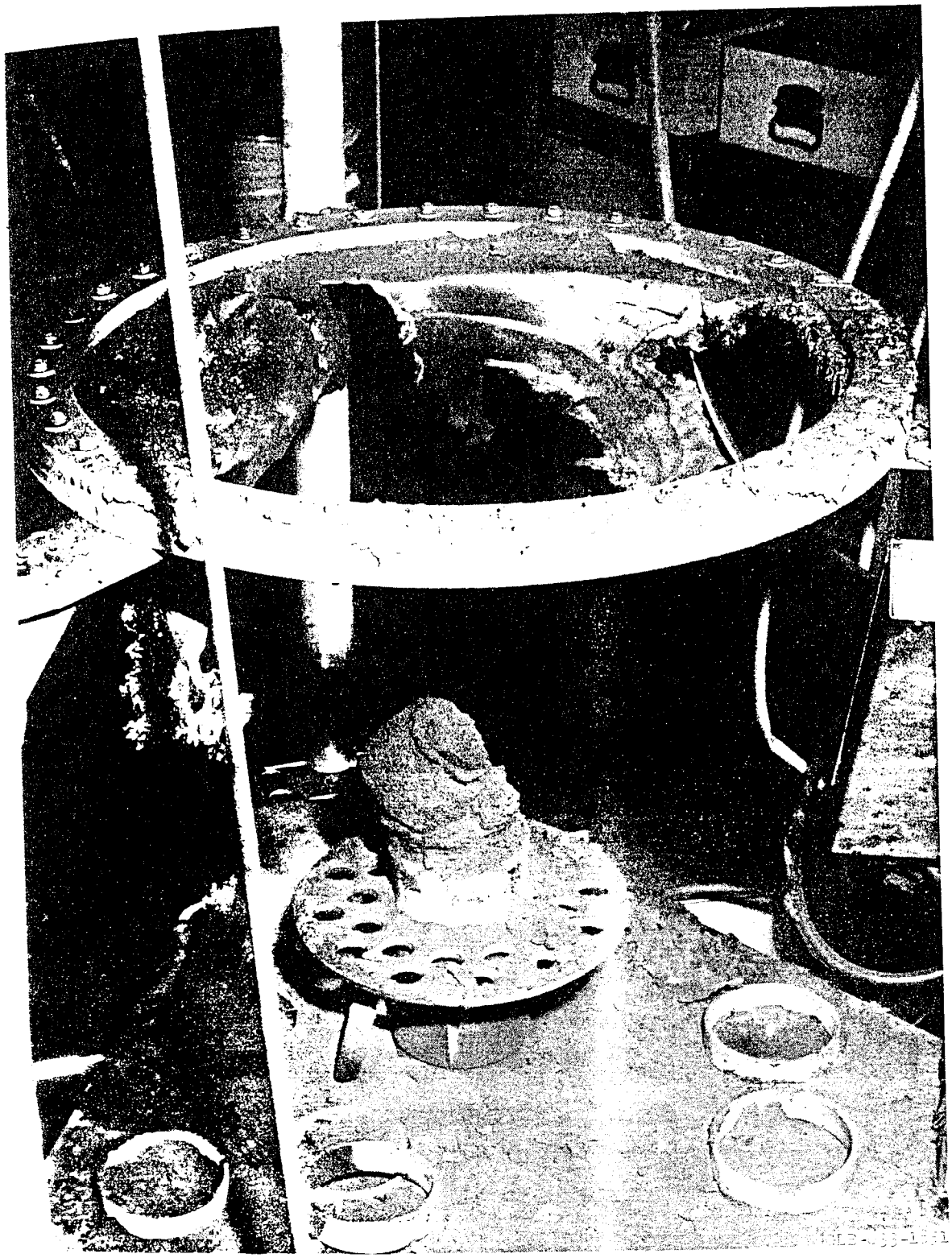

Fig. 4. Close-up of assembly following excursion. Note oxidized uranium.

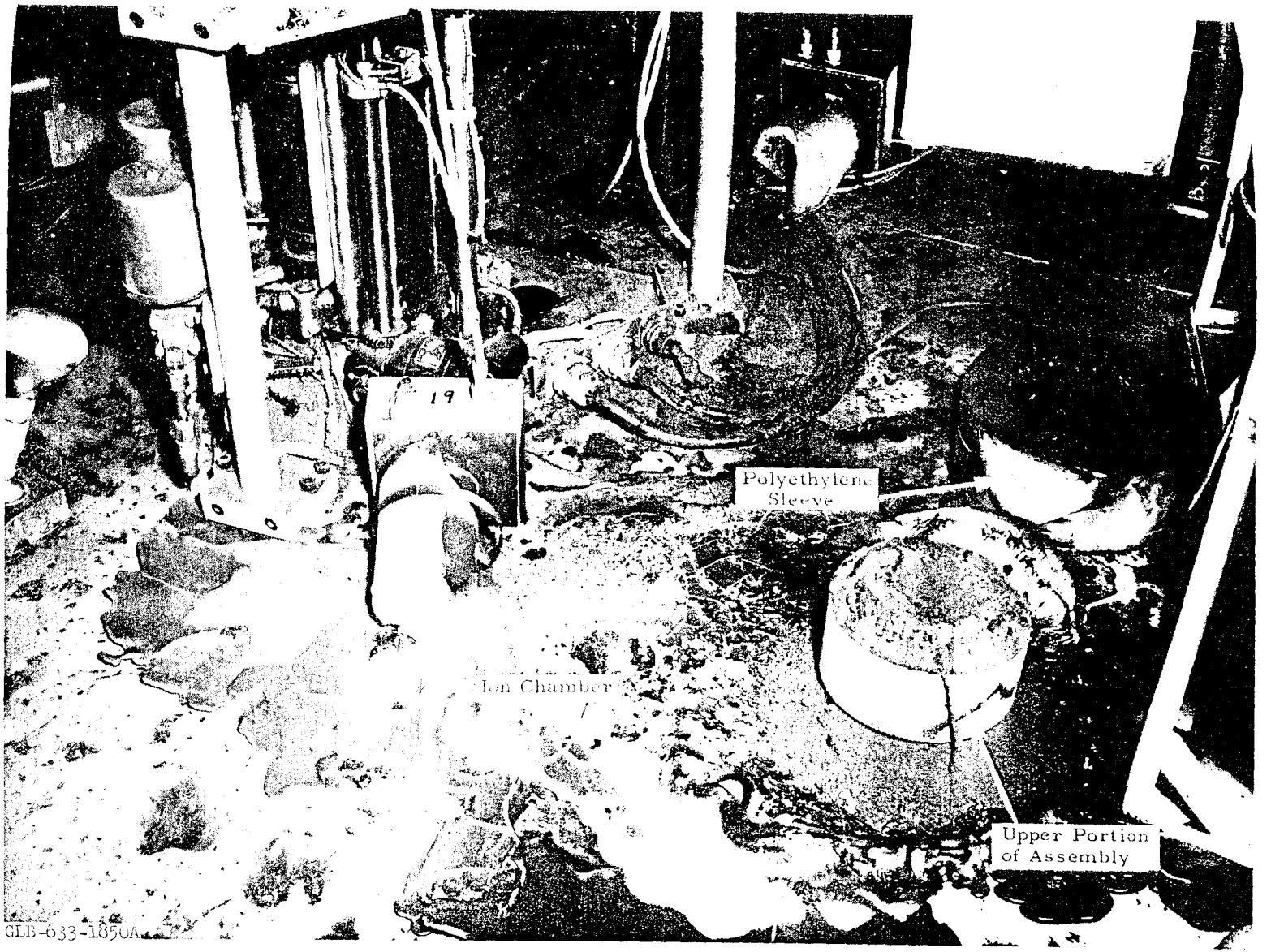

Fig. 10. Floor contamination near assembly.

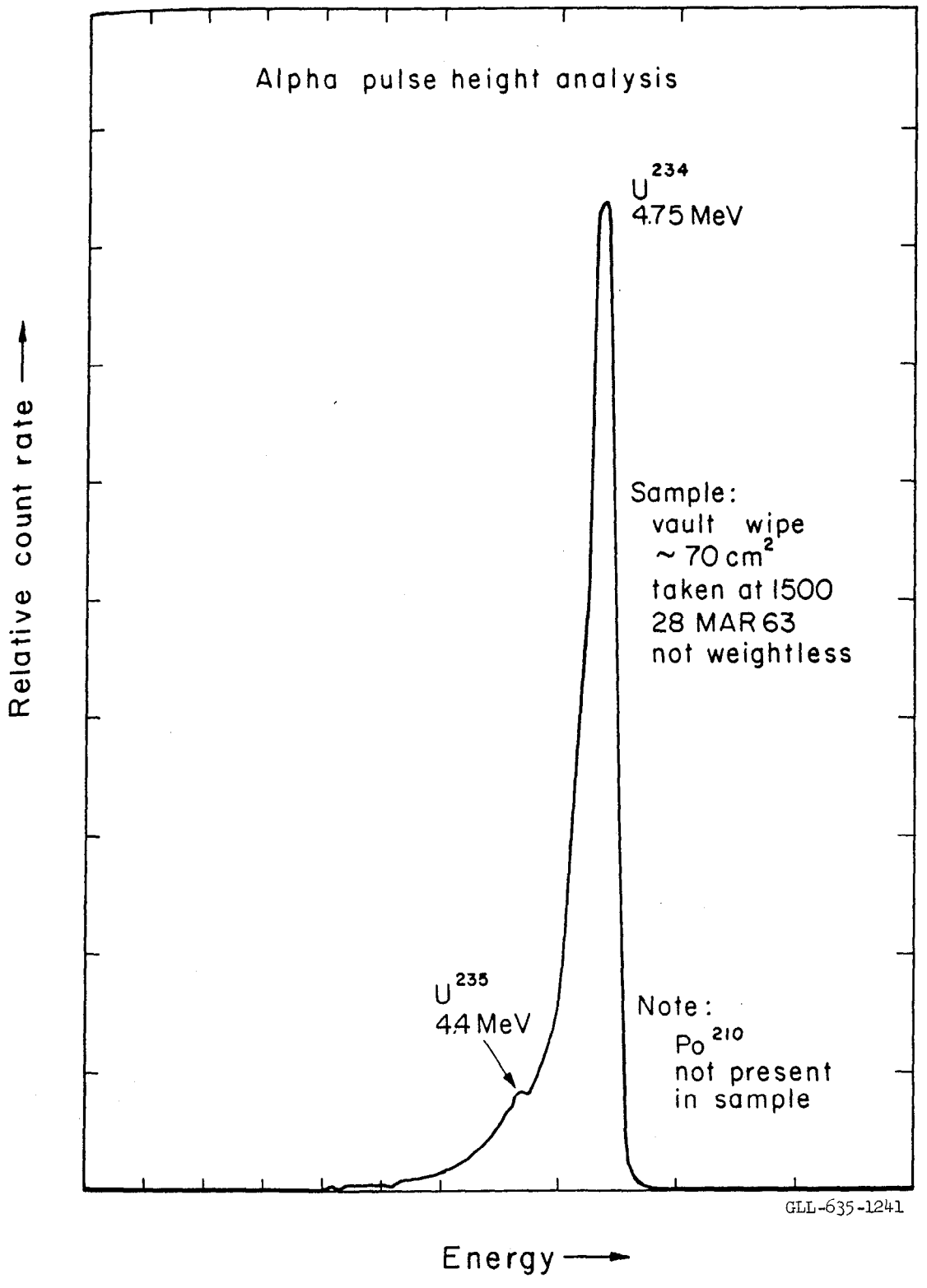

Fig. 11. Alpha pulse-height spectrum of vault floor contamination showing absence of Po^{210}.

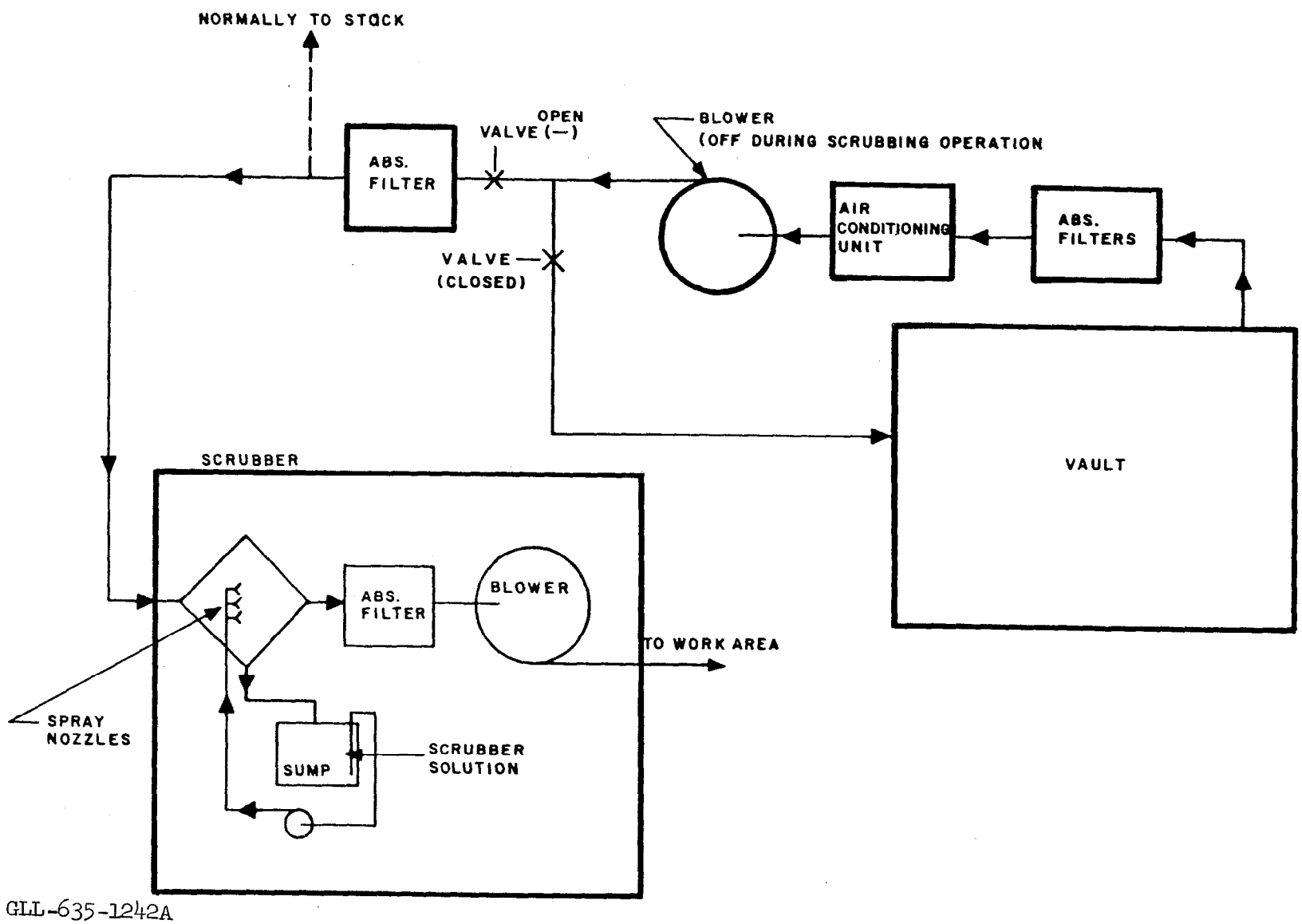

Fig. 12. Scrubber flow diagram.

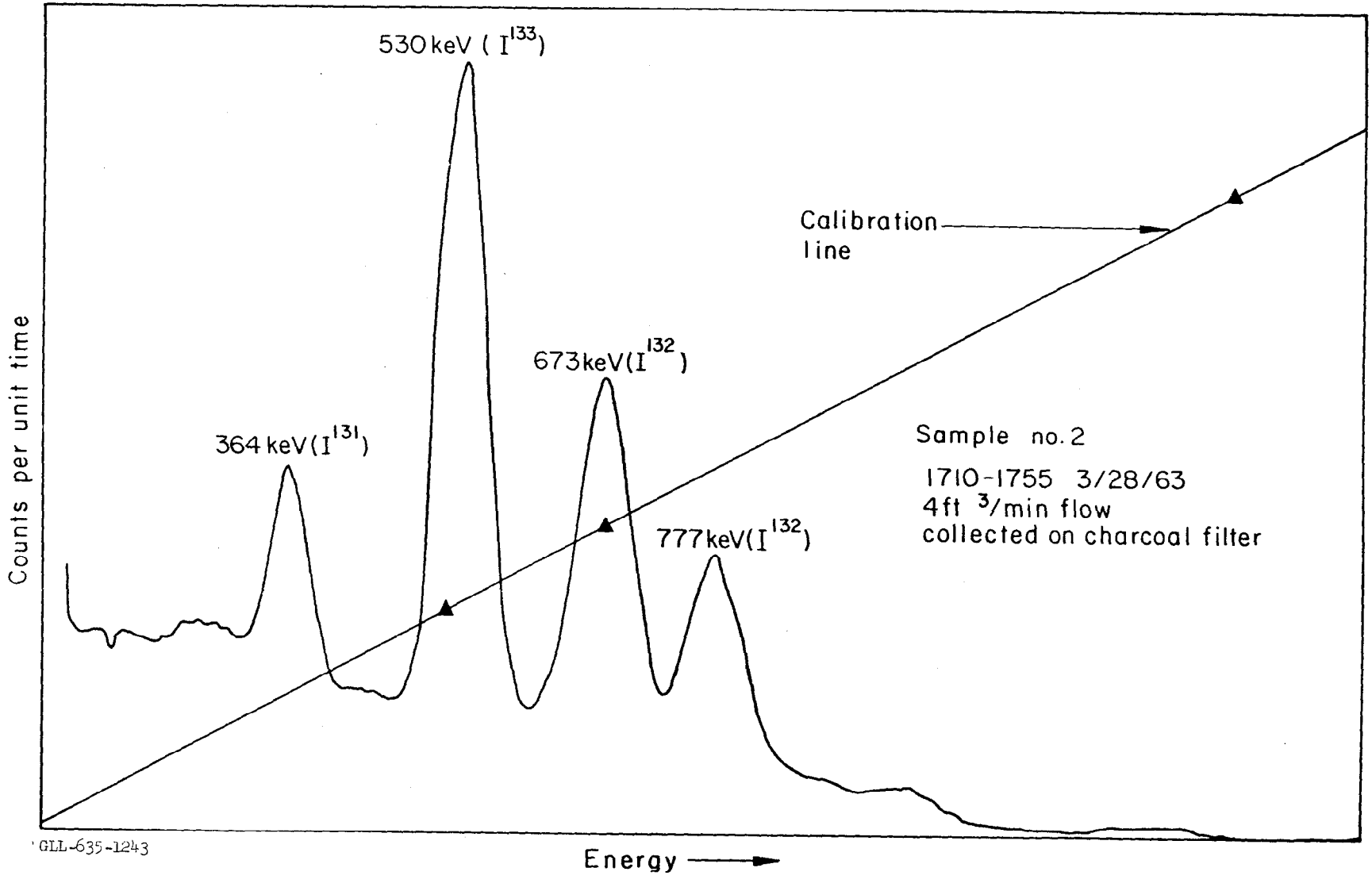

Fig. 13. Gamma pulse-height analysis of scrubber effluent air.

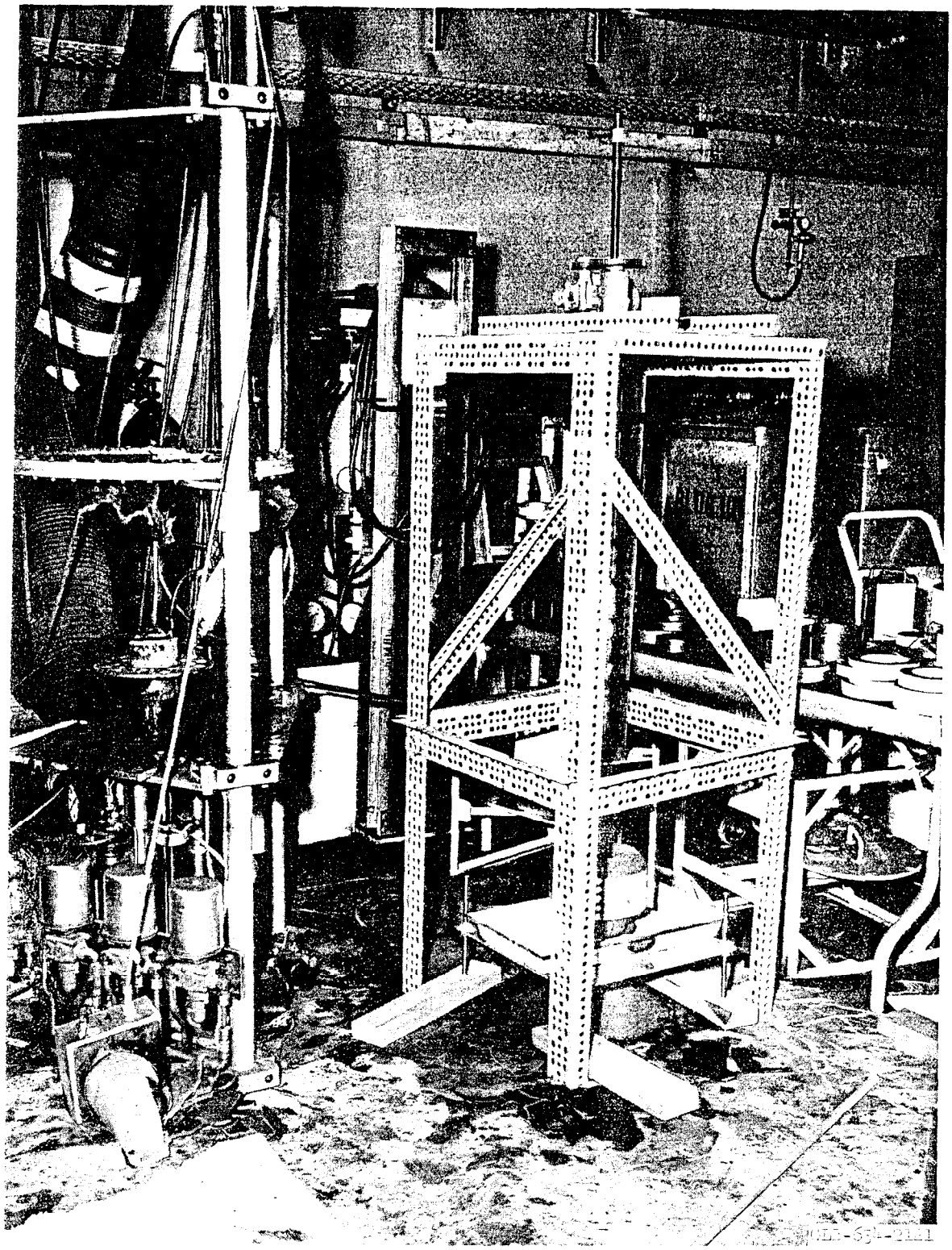

Fig. 14. Lifting device for raising large chunk of uranium and beryllium (remains of upper portion of assembly).

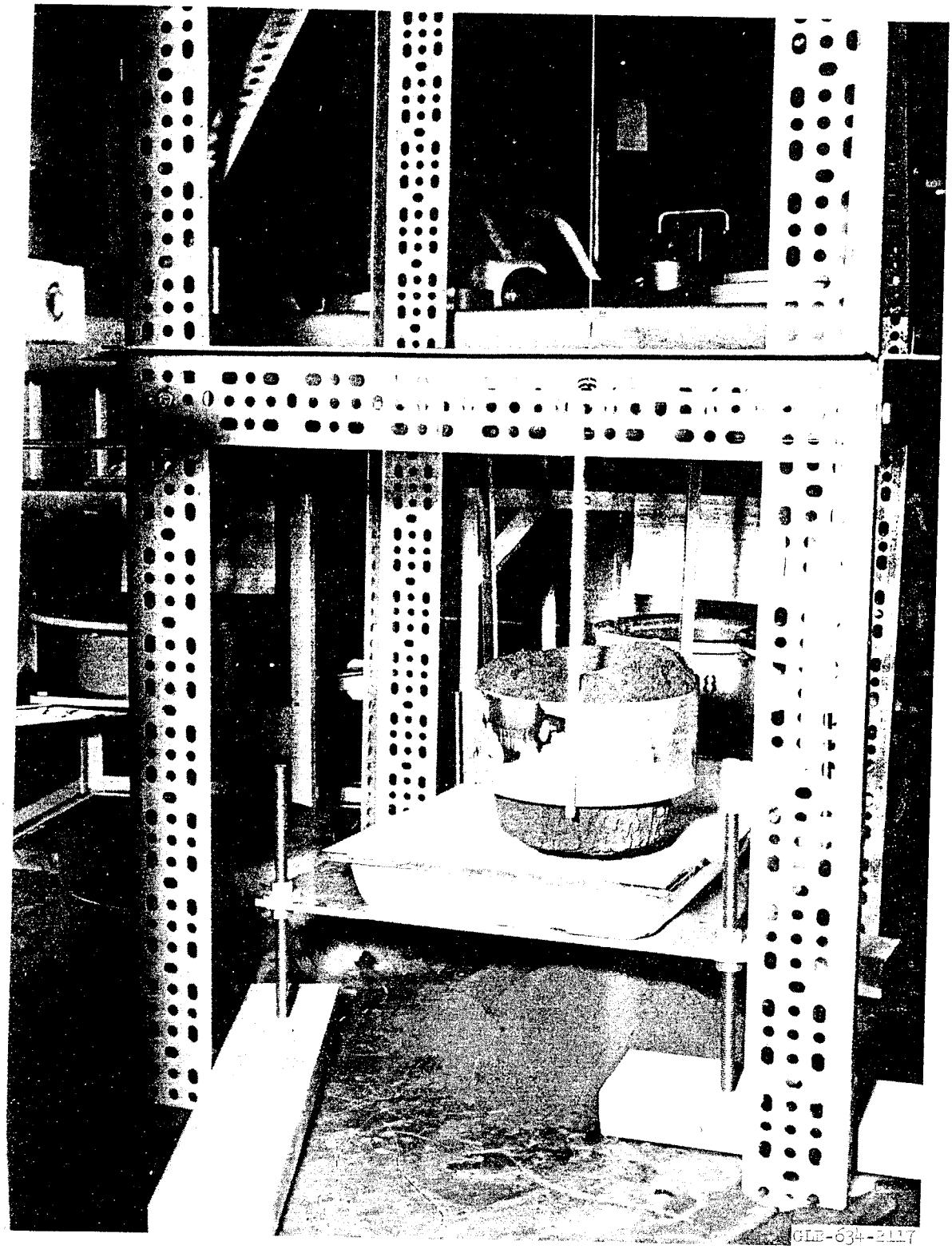

Fig. 15. Closeup of lifting device for raising large chunk of uranium and beryllium.