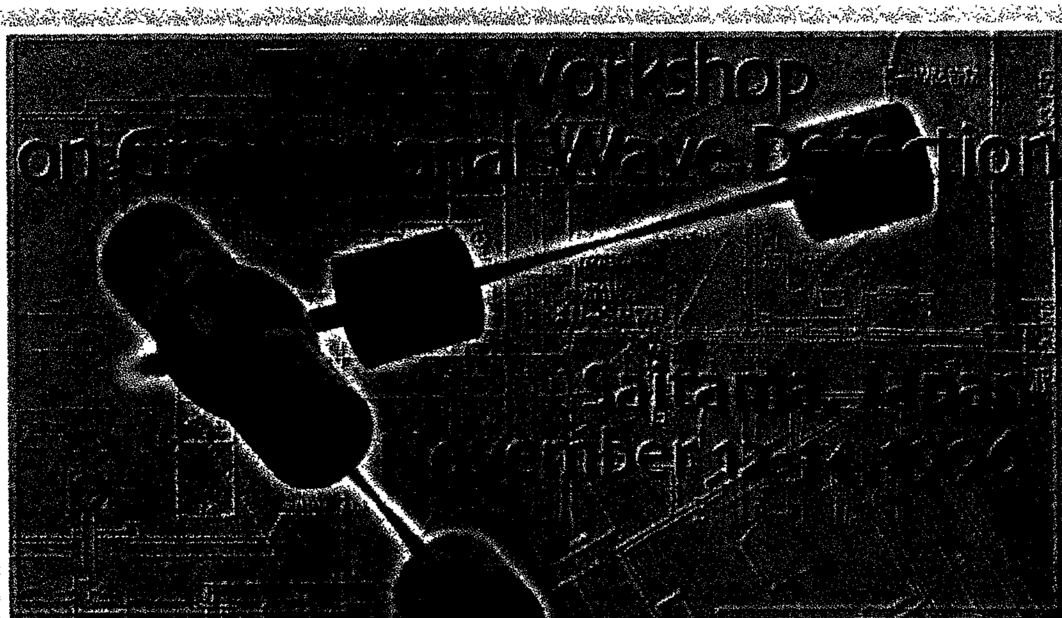
Status & Plans for LIGO

Barry Barish

TAMA Workshop

Nov 13, 1996

LIGO-G960237-00-M



OBJECTIVES:
Detecting gravitational waves has been a dream for a long time in the fields of astrophysics and astronomy, and recent developments make us very confident of it becoming a reality. We wish to establish the field of "gravitational wave astronomy" which will afford new knowledge of supernova explosions and coalescences of binary neutron stars that cannot be obtained from other more traditional sources such as optical and radio astronomy. A few projects have already started throughout the world for the construction of large-scale laser interferometric gravitational wave detectors, such as those of LIGO and VIRGO. We in Japan have begun to develop a medium-scale laser interferometer, with a baseline of 300 m. This three day workshop is devoted to discussions and to communication among researchers in the field.

PROGRAM:
Speakers working in LIGO, VIRGO, GEO, AIGO and TAMA will be invited to give talks about their projects, and related topics will be discussed. More than half the talks will be given by invited speakers and talks on contributed papers will be quite short.

CONFERENCE SITE:
The National Women's Education Center in the west of Tokyo. A map and detailed instructions for travel by train or car can be accessed at
http://www.icrr.u-tokyo.ac.jp/gr/TAMA96/access.html.

For further information please contact:

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Tel: +81-422-34-3622
Fax +81-422-34-3793

URL for information:
http://www.icrr.u-tokyo.ac.jp/gr/TAMA96/main.html

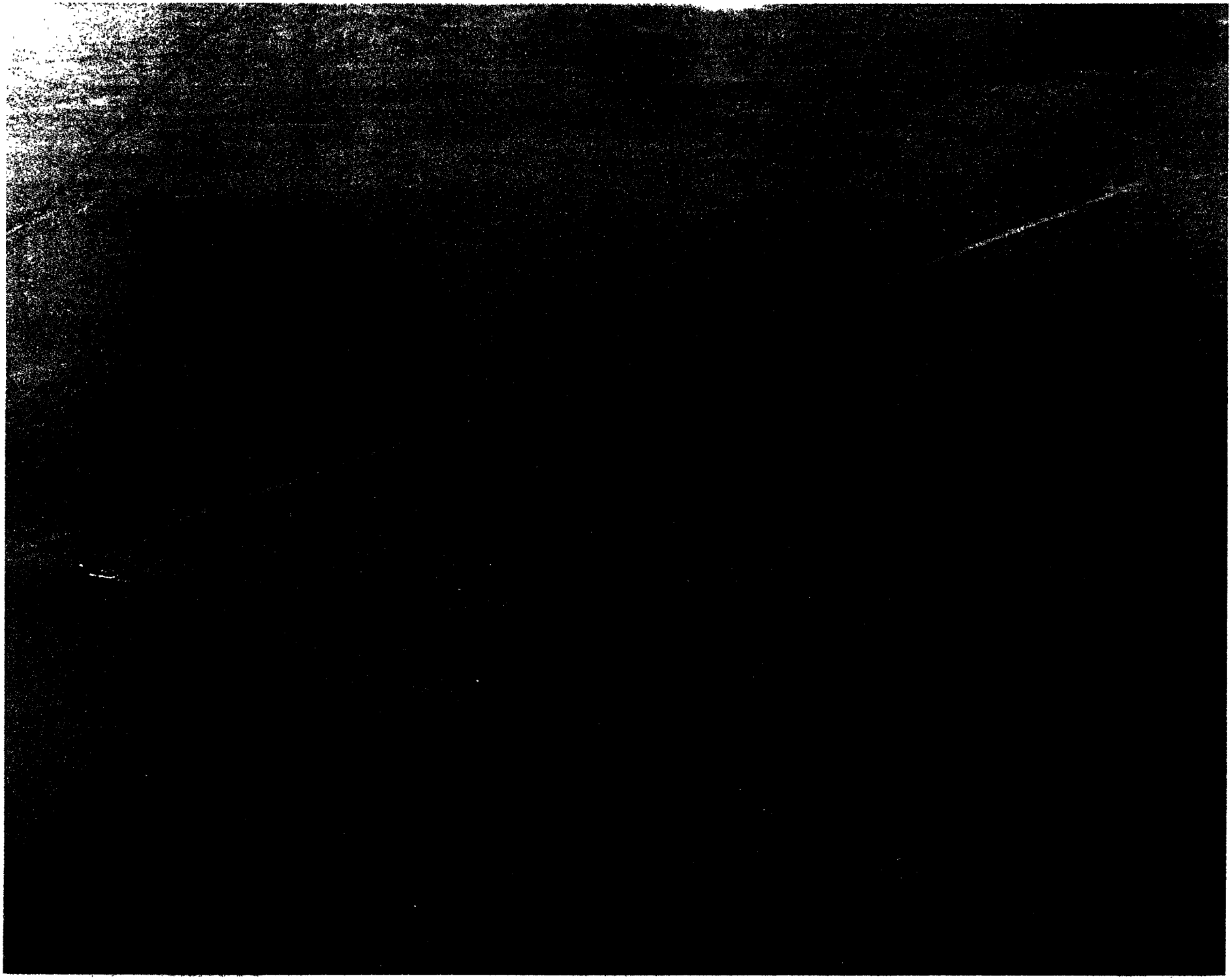
An International Workshop on Experiments and Developments for Gravitational Wave Detection

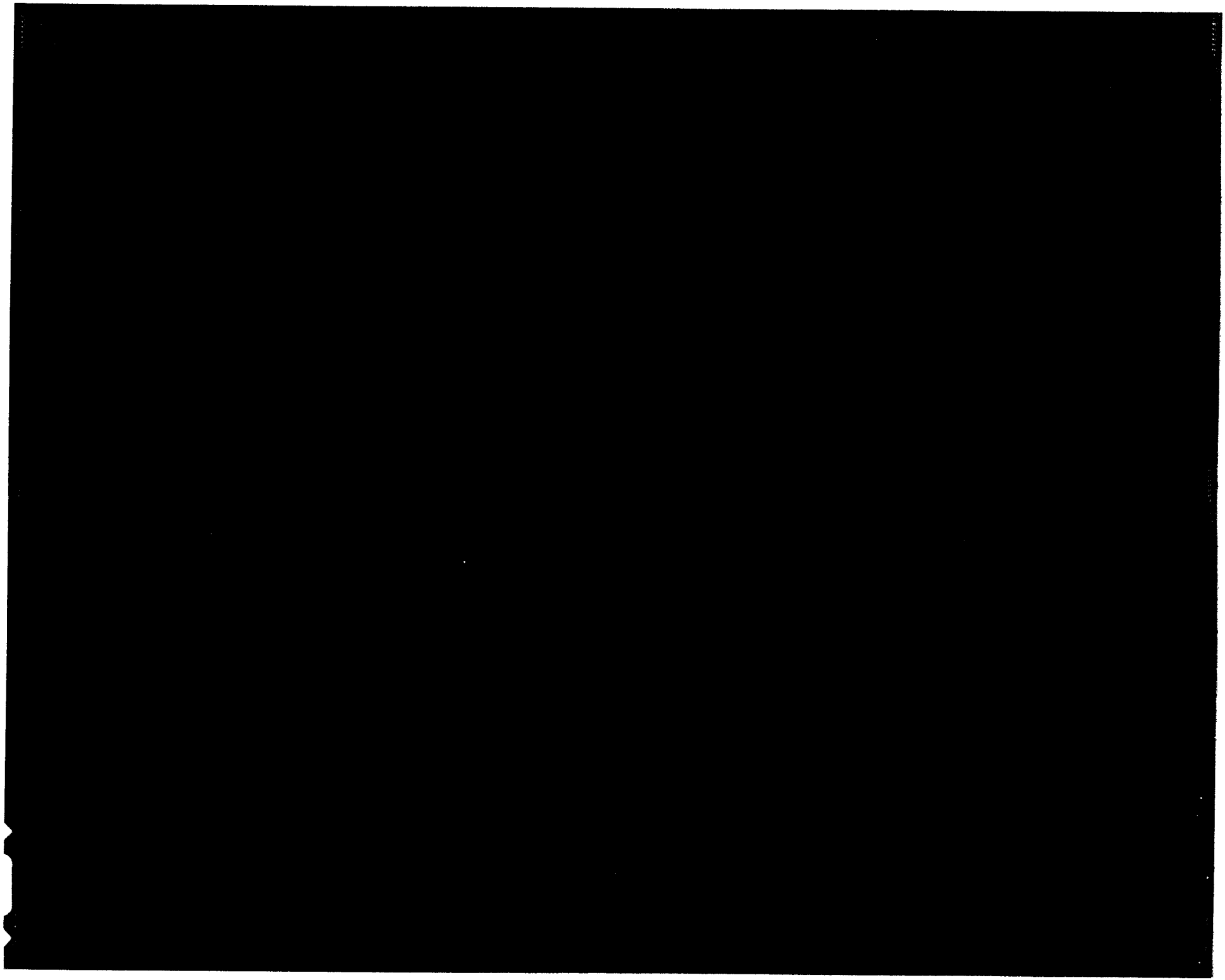
SCIENTIFIC COMMITTEE: *Chairman* Yoshihide Kozai, the leader of TAMA project
T.Kaifu and M.-K.Fujimoto (National Astronomical Observatory), J.Arafune and K.Kuroda (ICRR of the University of Tokyo)
Y.Saito (National Labotratory for High Energy Physics), K.Tsubono (Faculty of Science of the University of Tokyo)
N.Mio (Faculty of Engineering of the University of Tokyo), K.Ueda (ILS of the University of Electro-Communications)
N.Kawashima (the Institute of Space and Astronautical Science), T.Nakamura (YITP of the Kyoto University)

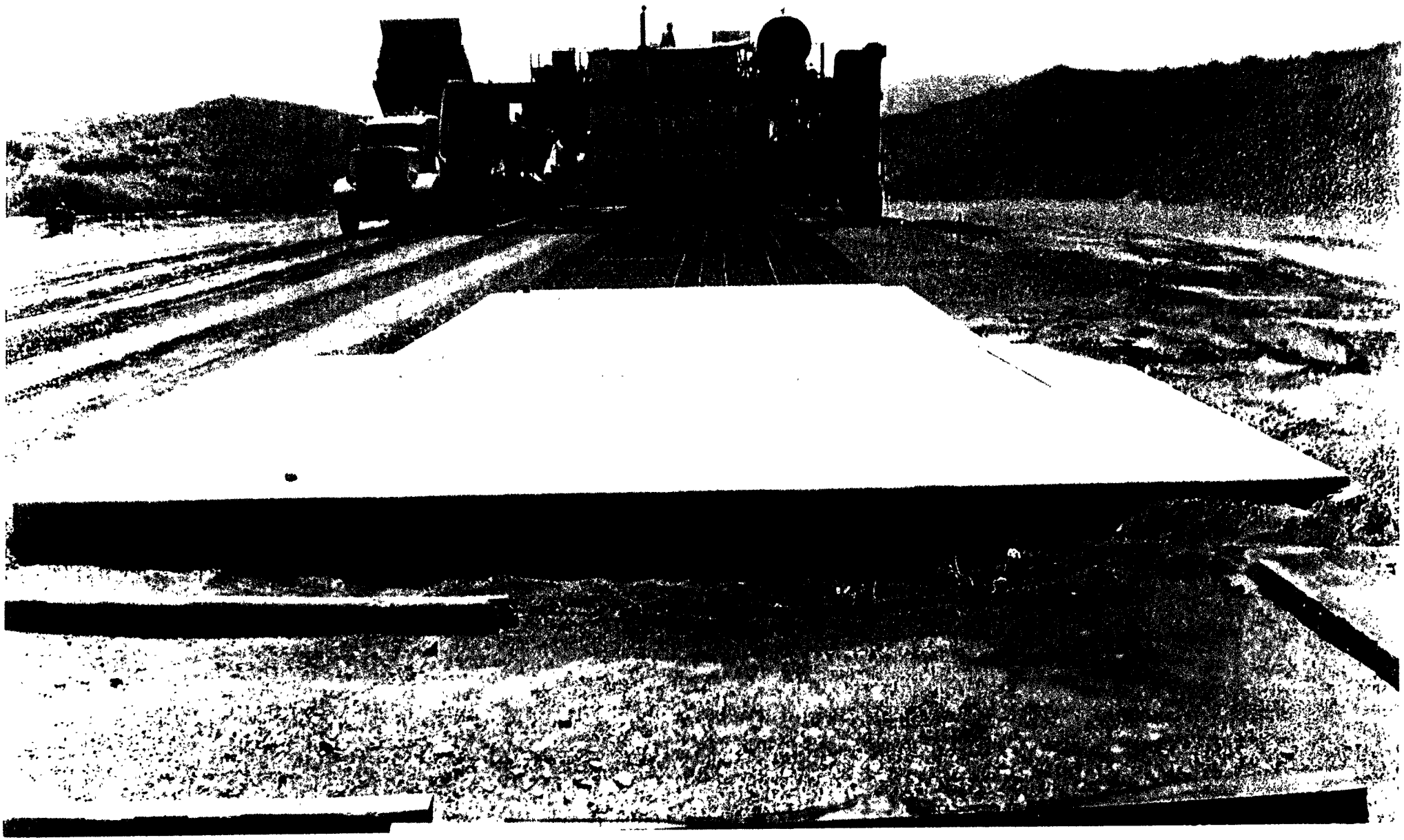
TAMA is funded by Grant-in-Aid for Creative Basic Research of the Ministry of Education and this conference is supported by the National Astronomical Observatory of Japan.
TAMAは文部省科学研究費補助金[illegible]プログラム方式による研究「[illegible]レーザー干渉計を用いた重力波天文学の研究」のプロジェクトです。

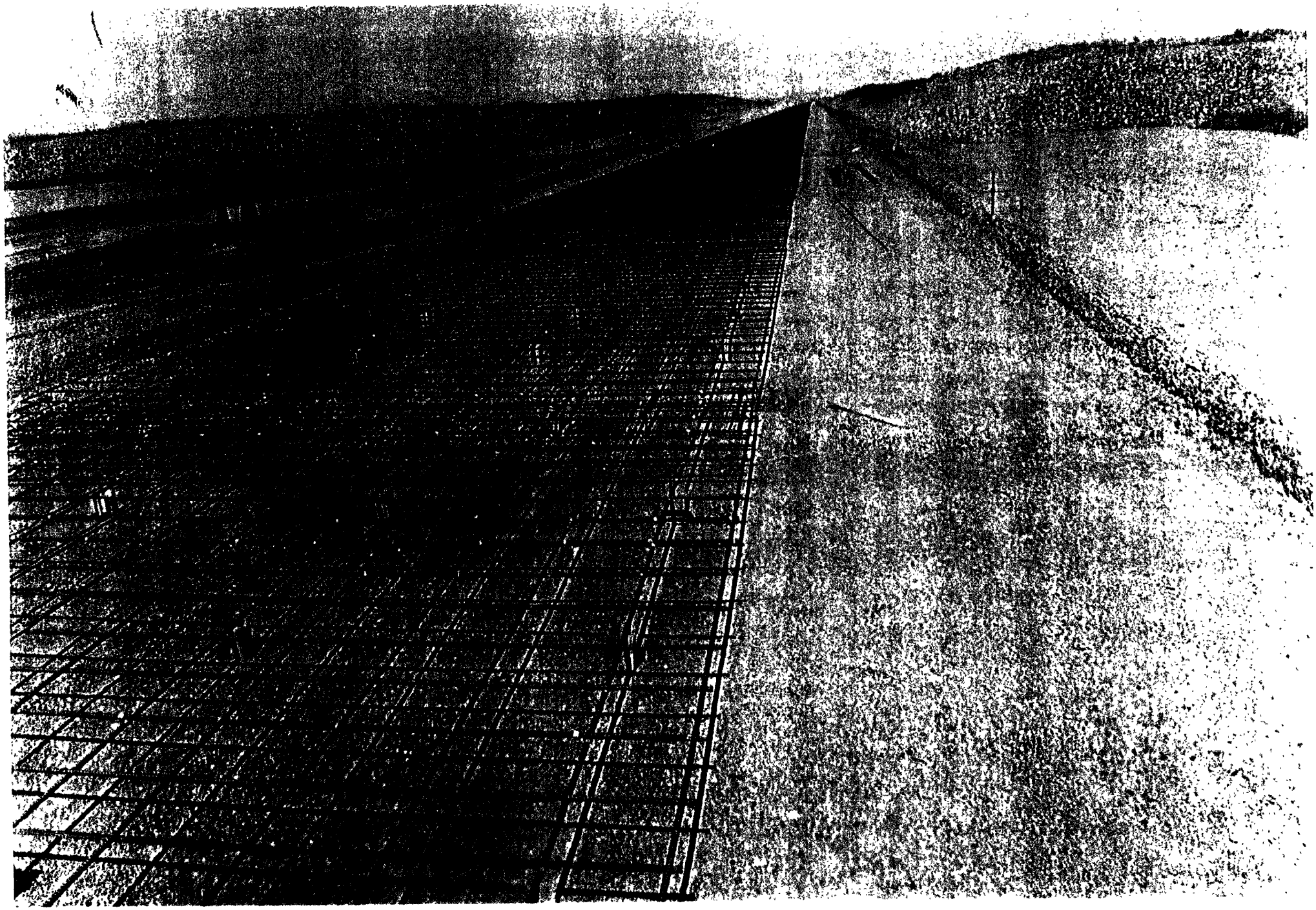
Civil Construction

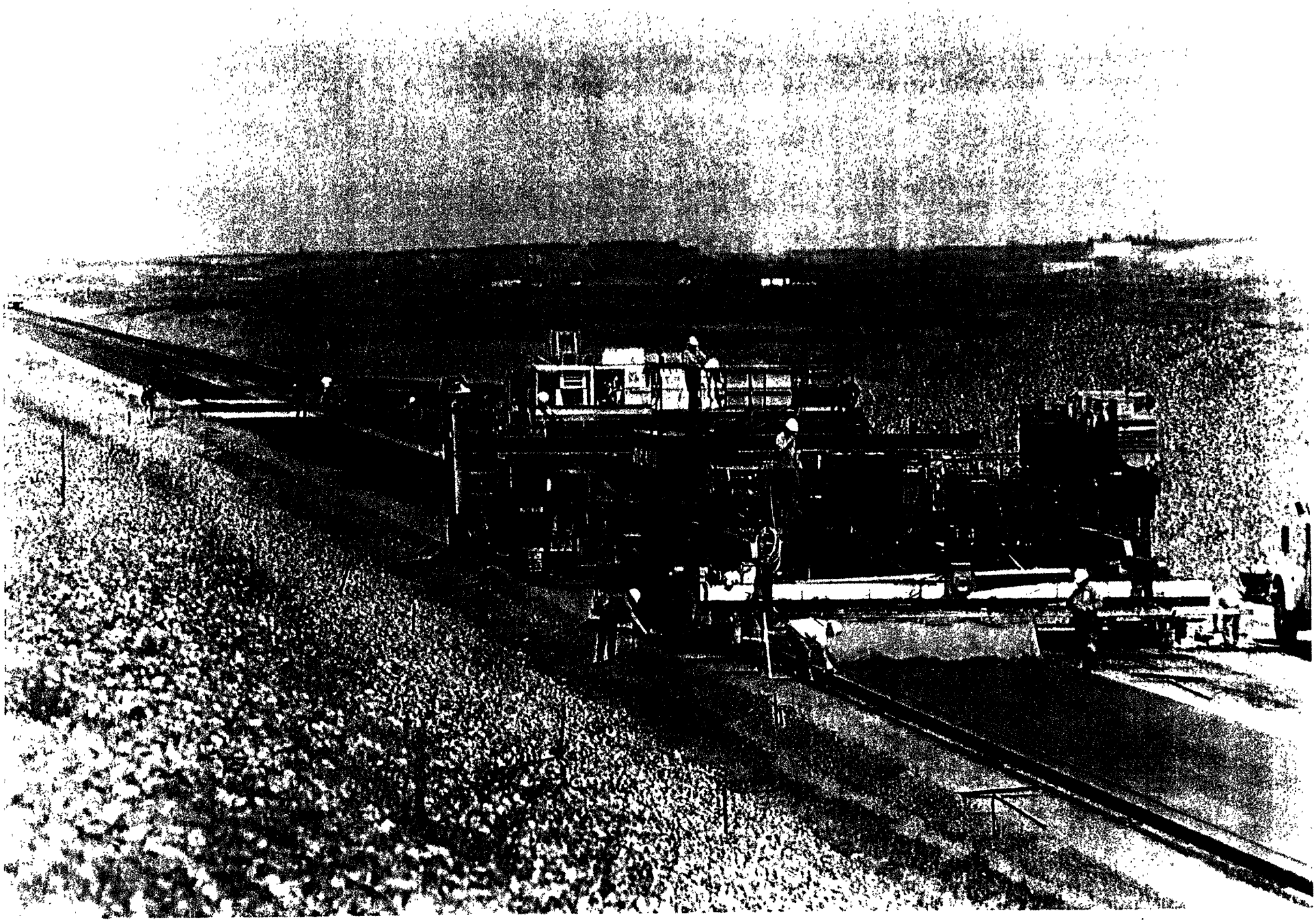
- WA site
  - completed finish grade and slip form of slab
  - completed service road and distributed electric power along arms
  - Completed precast approx 1500 BT enclosure segments
  - demo'd installation technique
  - completed final design and initiated construction of WA bldgs
  - awarded BT enclosure installation contract

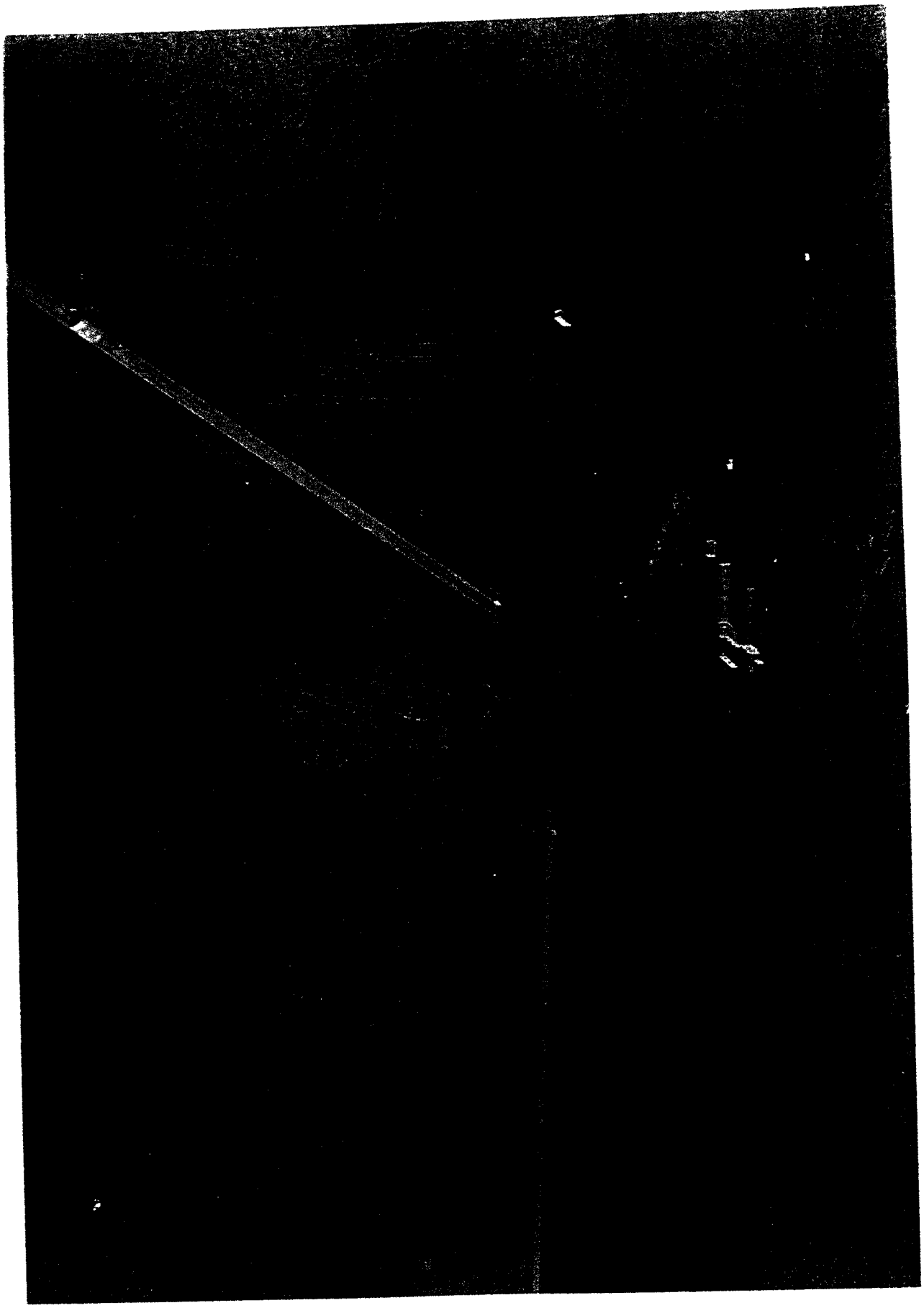








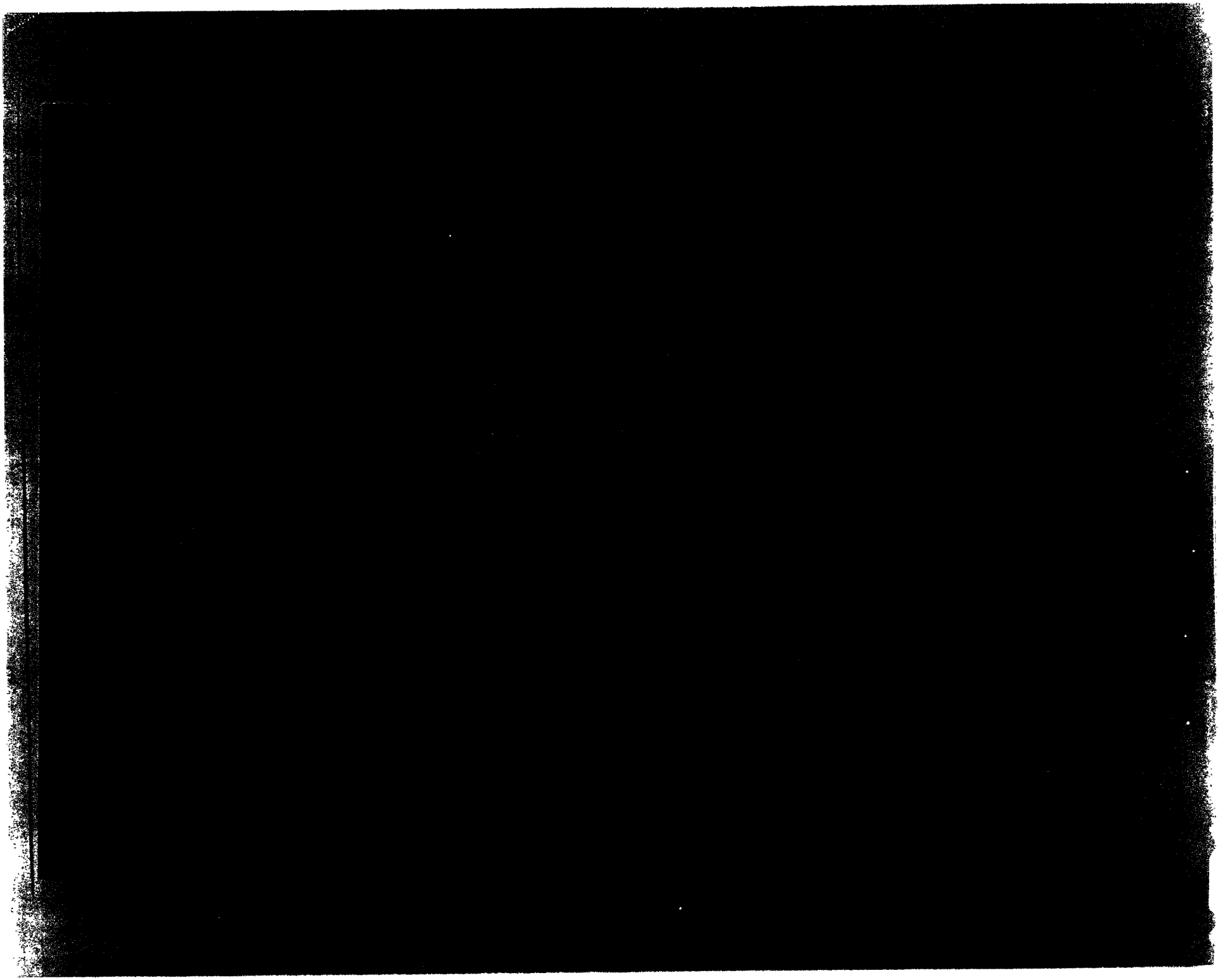


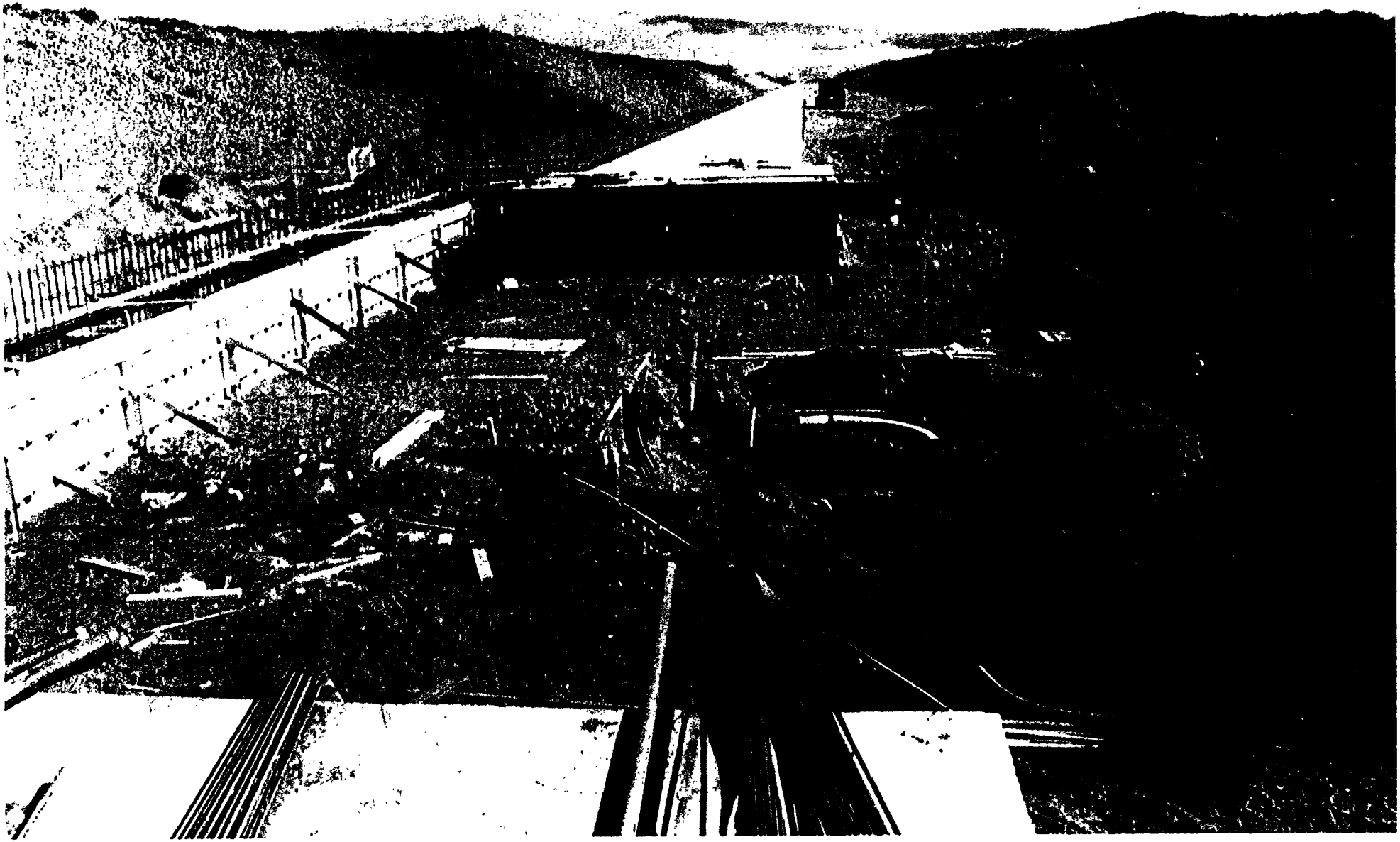


WA bldg status

Otto Matherny

- Bldg construction status
  - mid and end station footers installed
  - conduit for power and data acquisition and control installed
  - vaults and power for bakeout and site power installed
  - conduits to chiller yards from mid and stations placed.

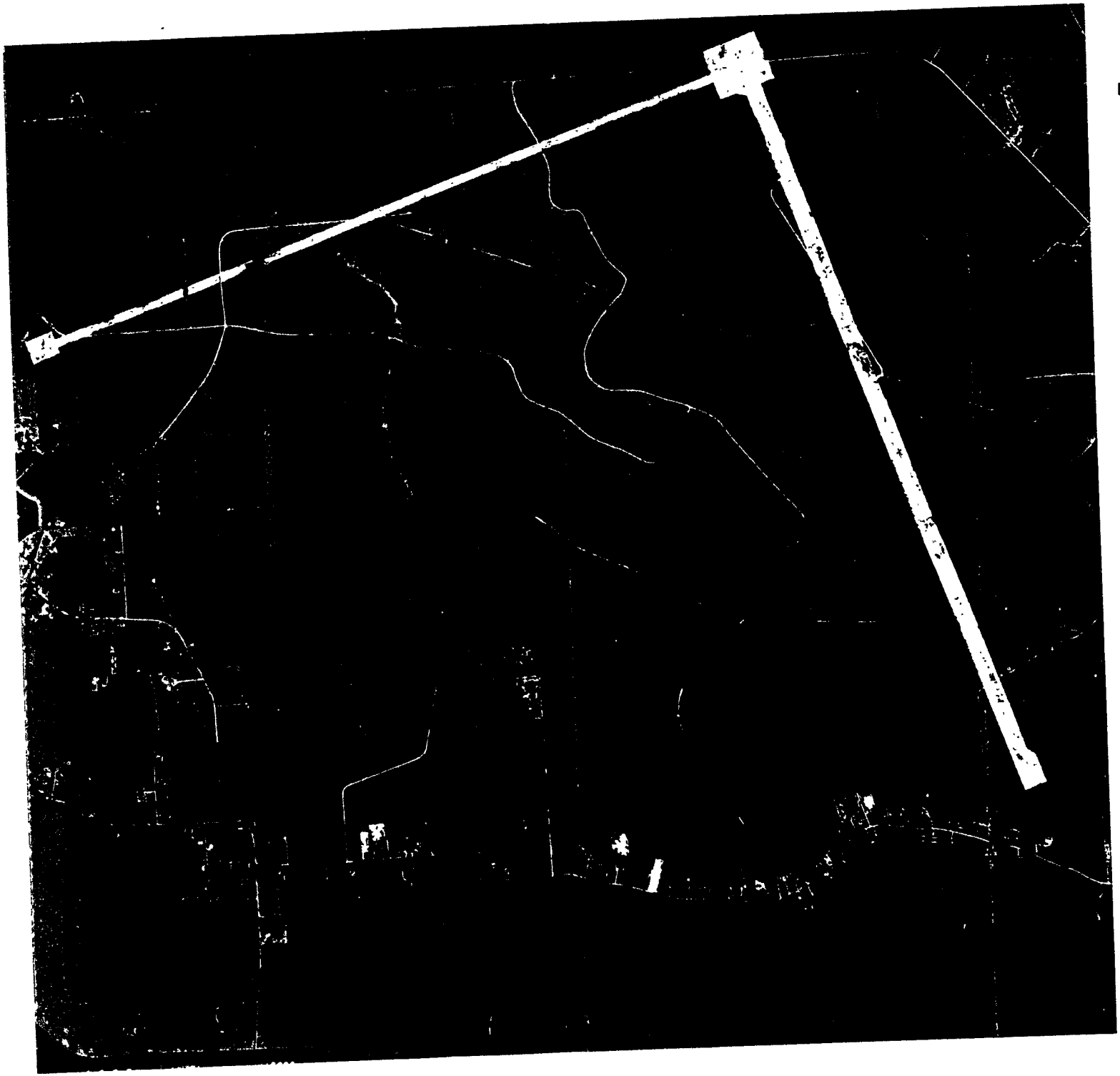




LA Civil Construction Status

Otto Matherny, Fred Asiri

- Bids opened for slabs, enclosures, roads, buildings
  - apparent low bidders within budget.
- Rough grading:
  - It rains a lot in LA
  - approximately 150 days lost to weather delay
  - arms at full height since July
    - » should allow sufficient time for settlement for Feb 97 slab installation
    - » monitoring of settlement plates to look at creep rate.



LIGO

LIVINGSTON PARISH

LOUISIANA

1A

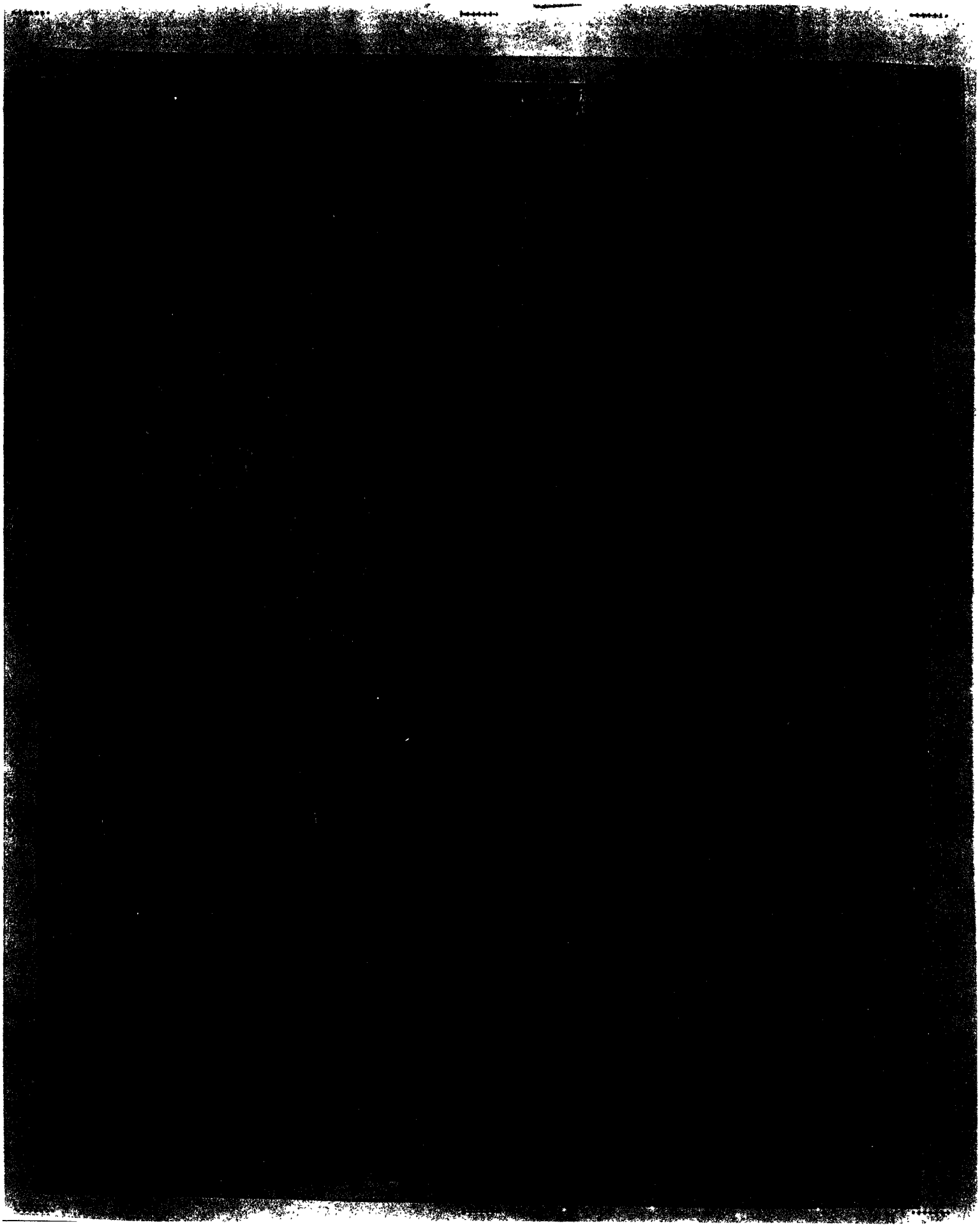
AERIAL PHOTO BY:

GULF COAST AERIAL MAPPING

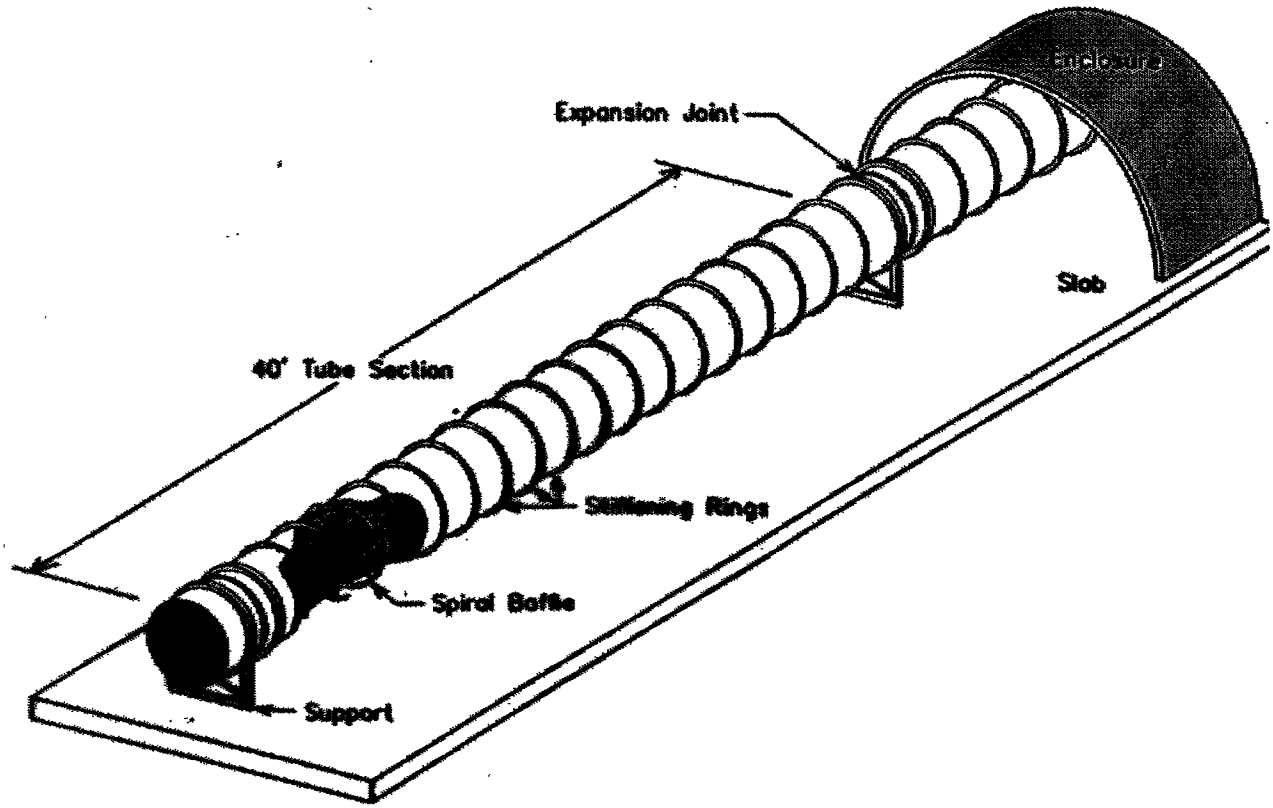
FLOWN: AUGUST 25, 1995

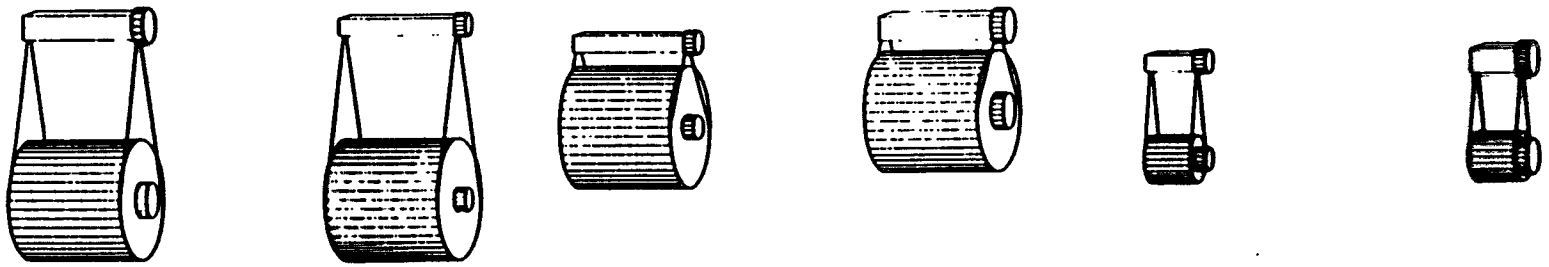
ALTITUDE: 12,000 FEET

G960028-17-O-V

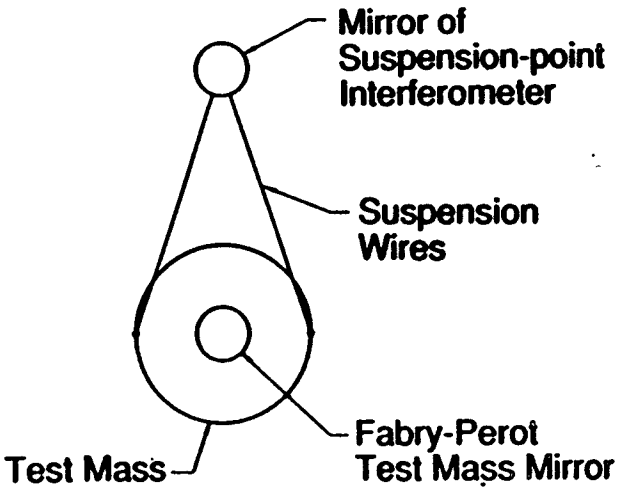


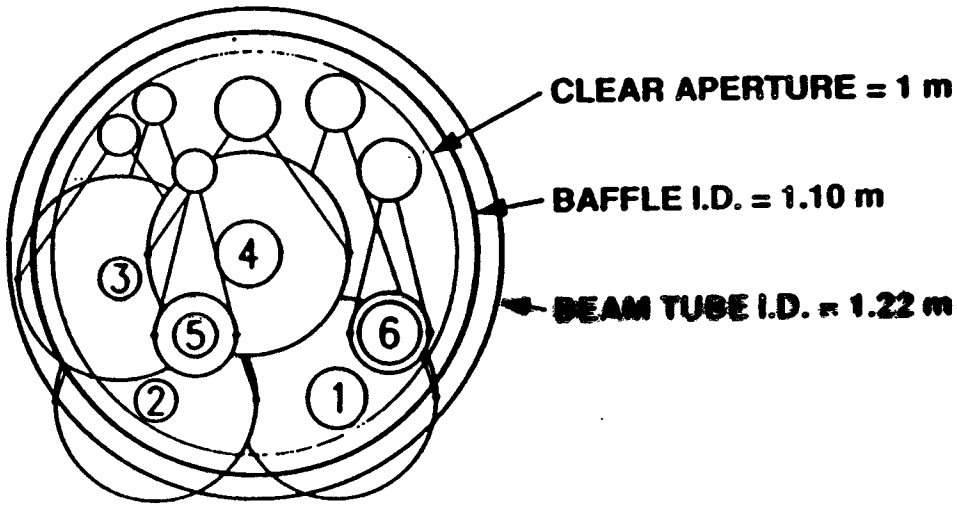
Beam Tube


Enclosure
Expansion Joint
Slab
40' Tube Section
Stiffening Rings
Spiral Baffle
Support



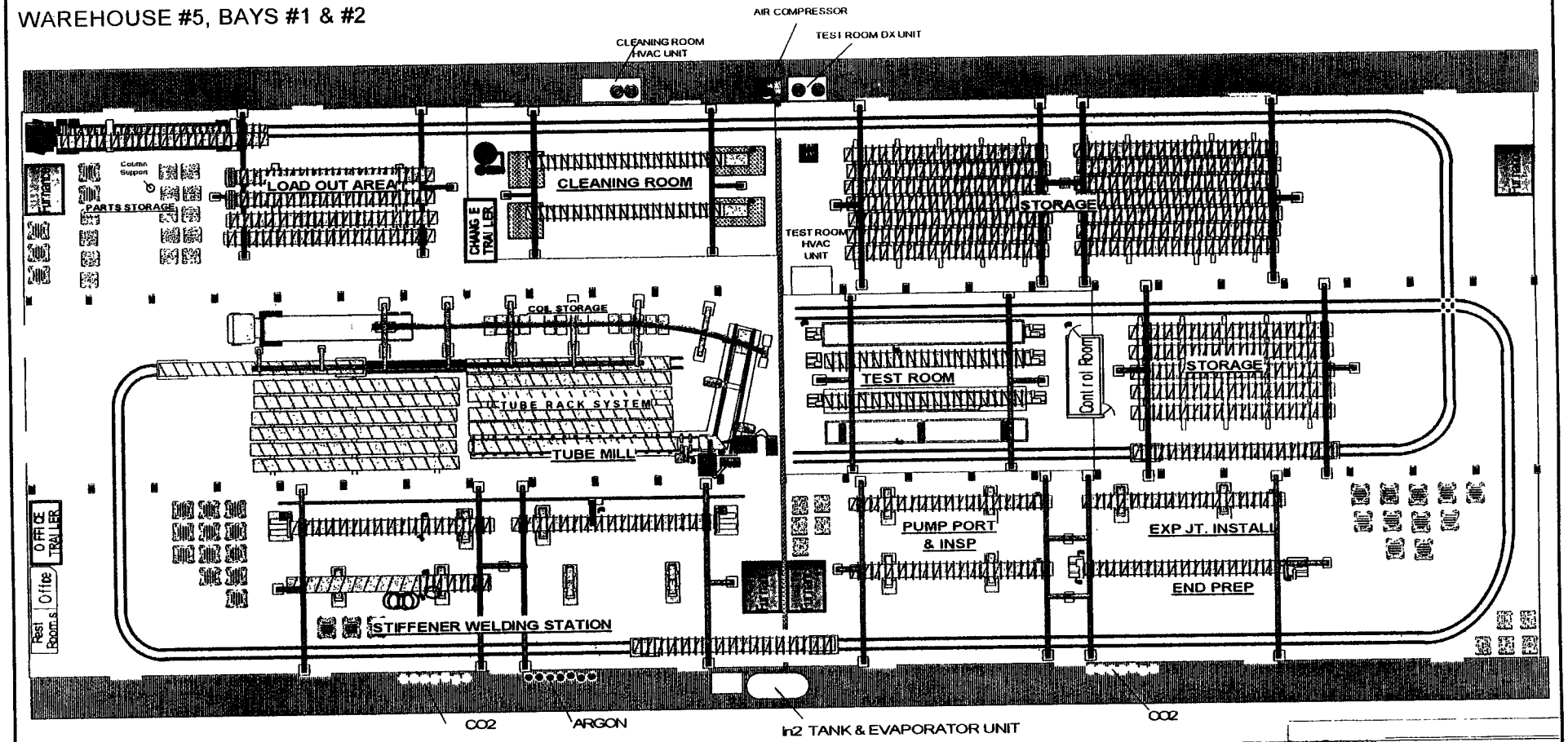
1 2 3 4 5 6


Mirror of
Suspension-point
Interferometer
Suspension
Wires
Fabry-Perot
Test Mass Mirror
Test Mass


CLEAR APERTURE = 1 m
BAFFLE I.D. = 1.10 m
BEAM TUBE I.D. = 1.22 m
1
2
3
4
5
6

BIG PASCO

WAREHOUSE #5, BAYS #1 & #2



LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

HANFORD LOCATION

FABRICATION FACILITY

BIG PASCO WHSE #5, BAYS 1 & 2

PC181520

95-0574

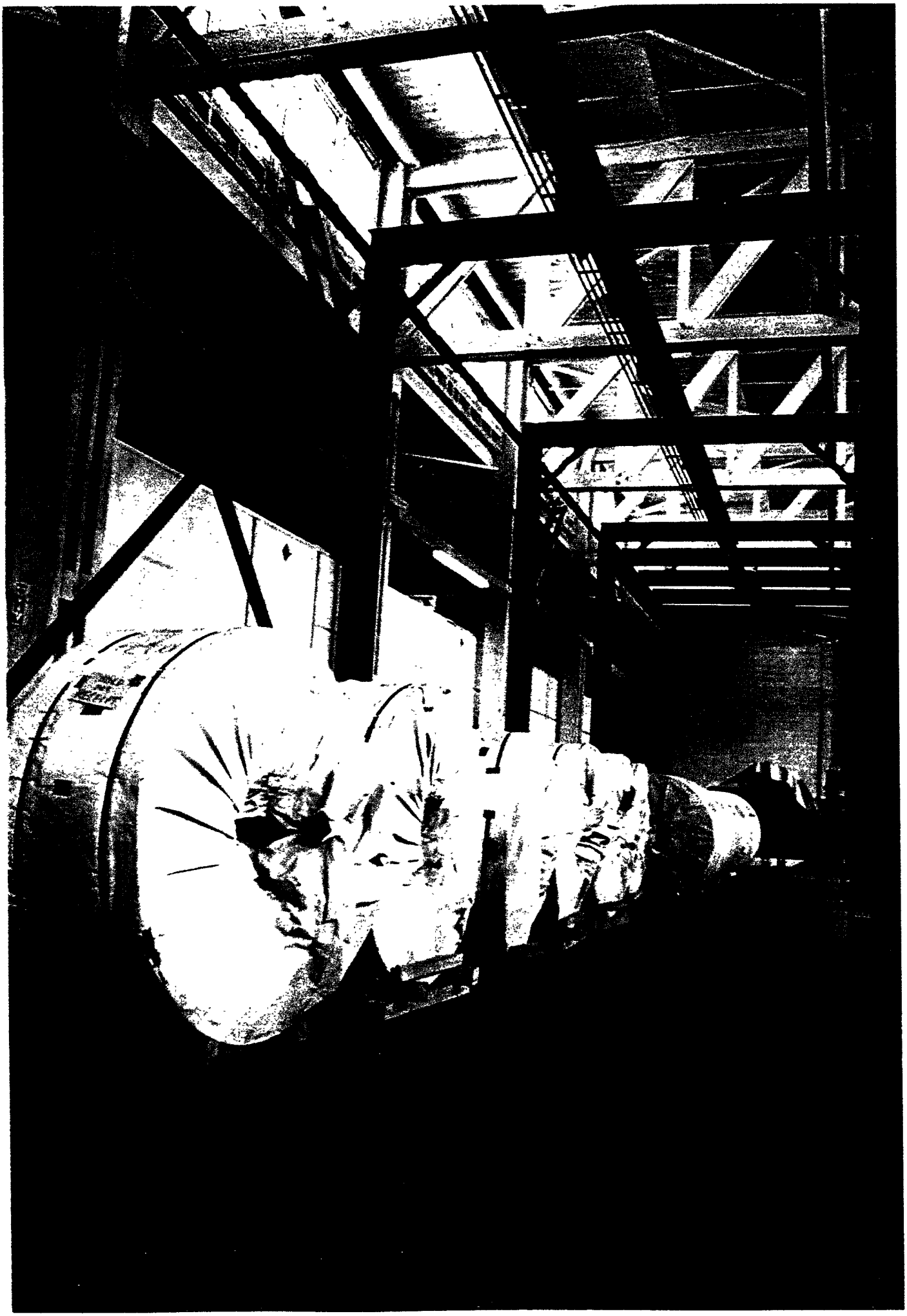
Engineering Supervisor

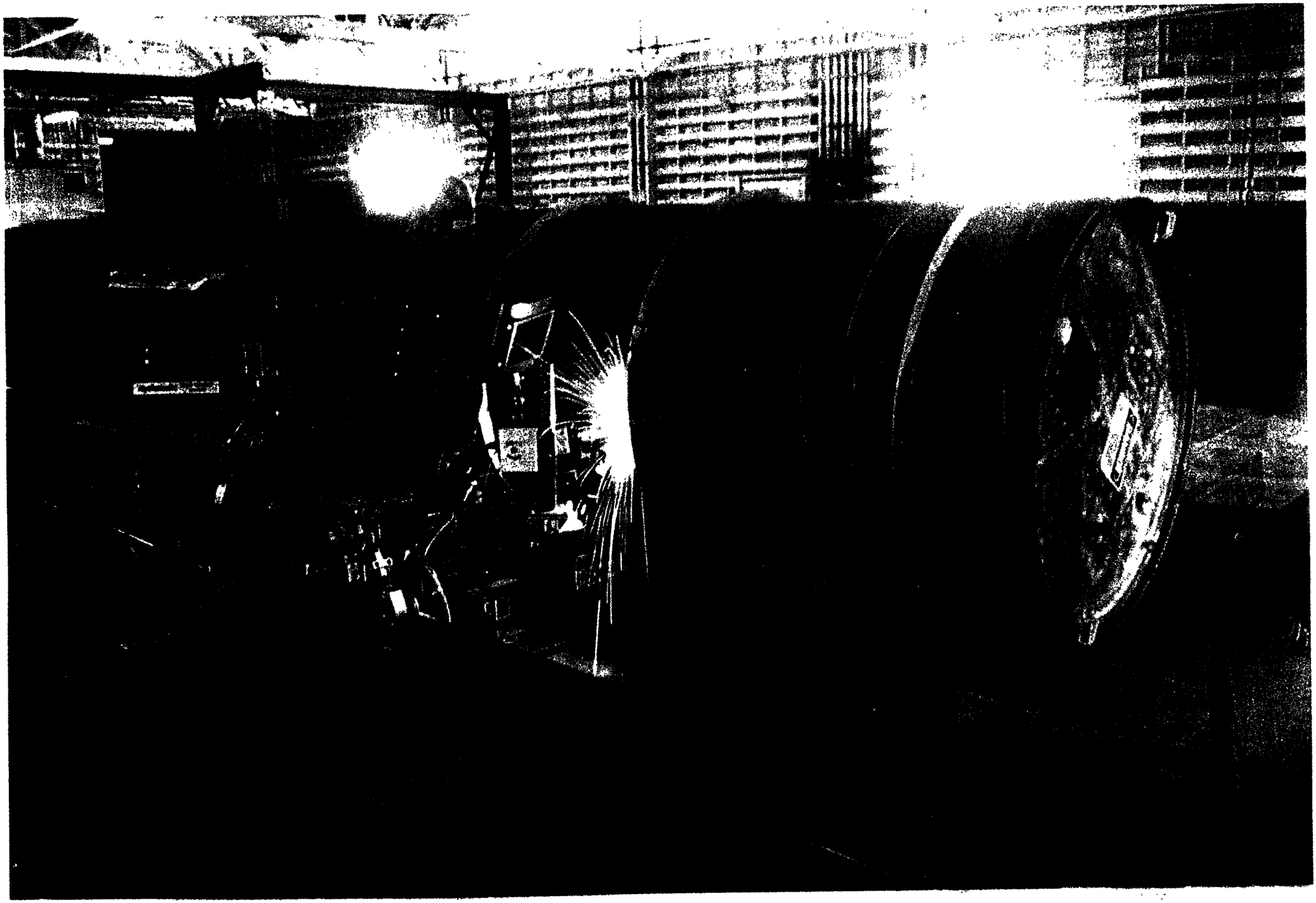
Dwg

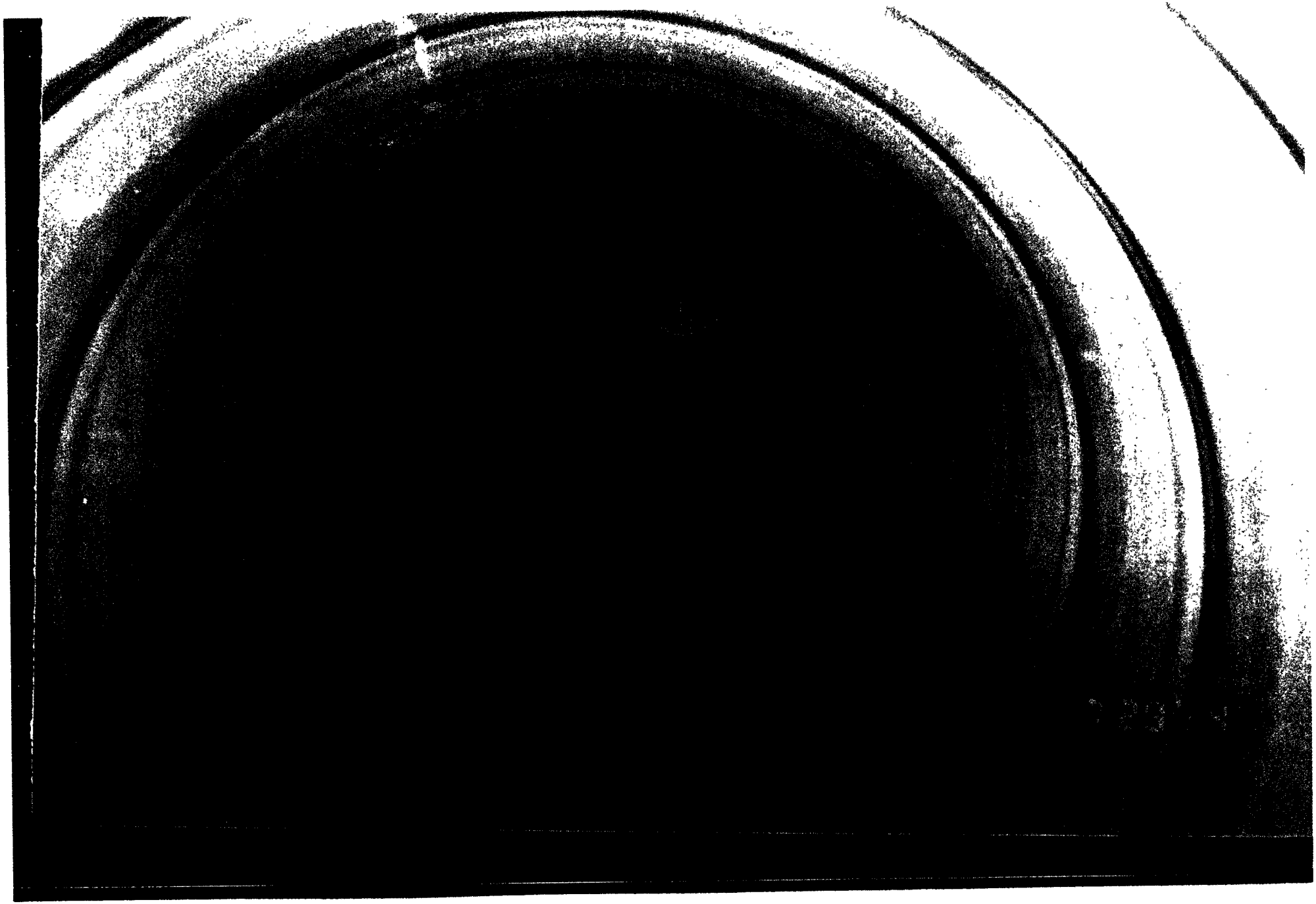
Sheet

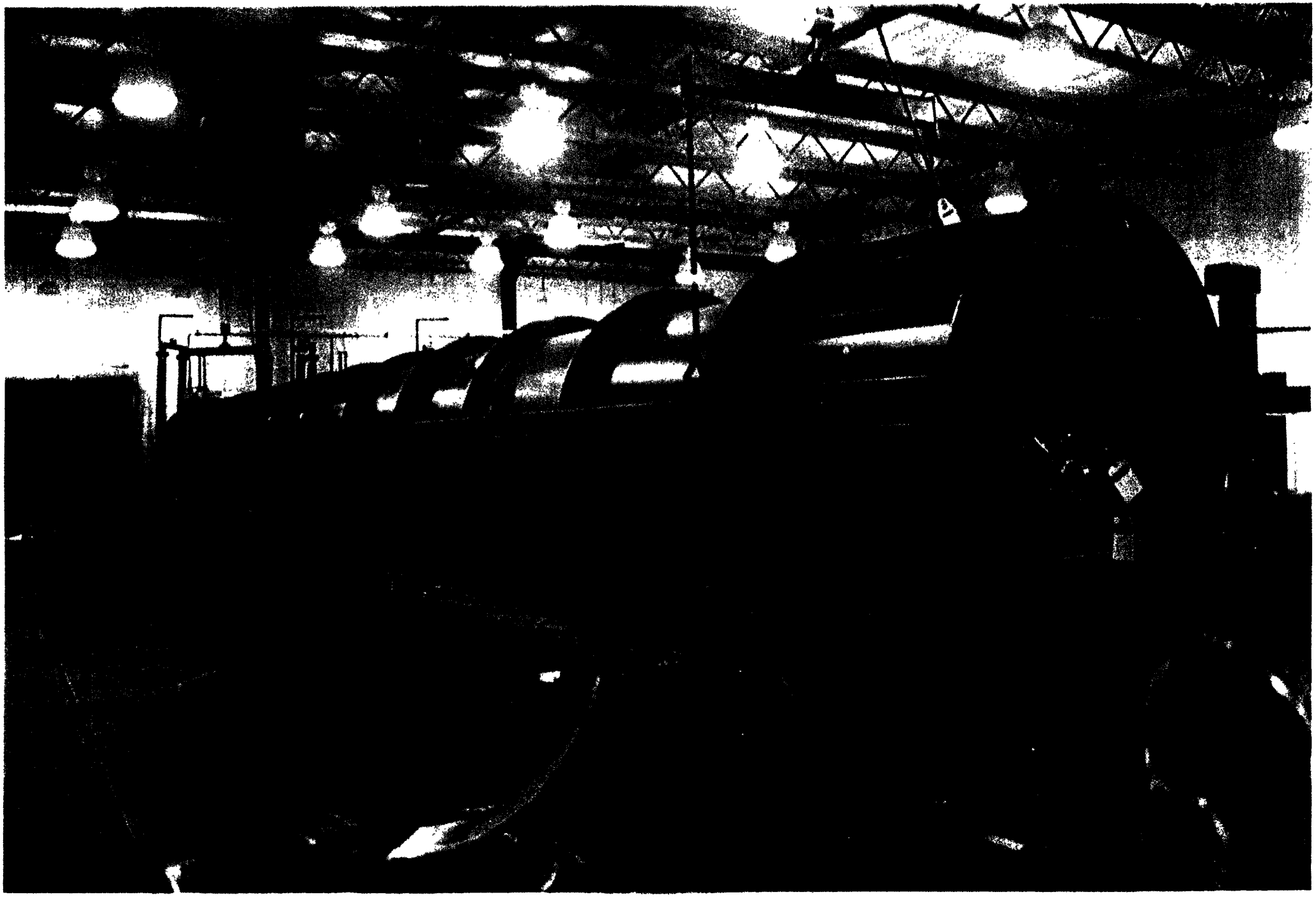
Rev

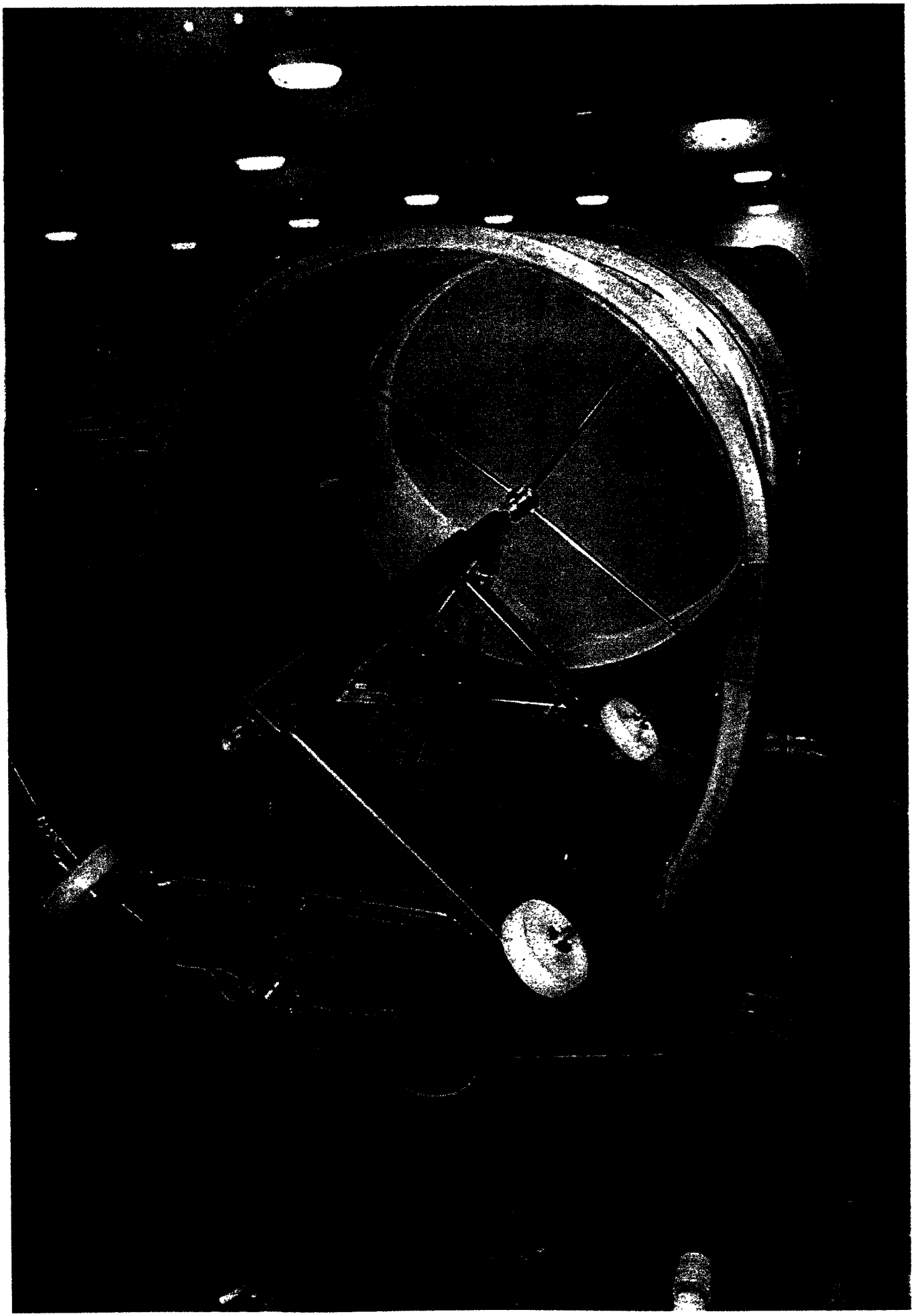
BIGPASO1.CVS

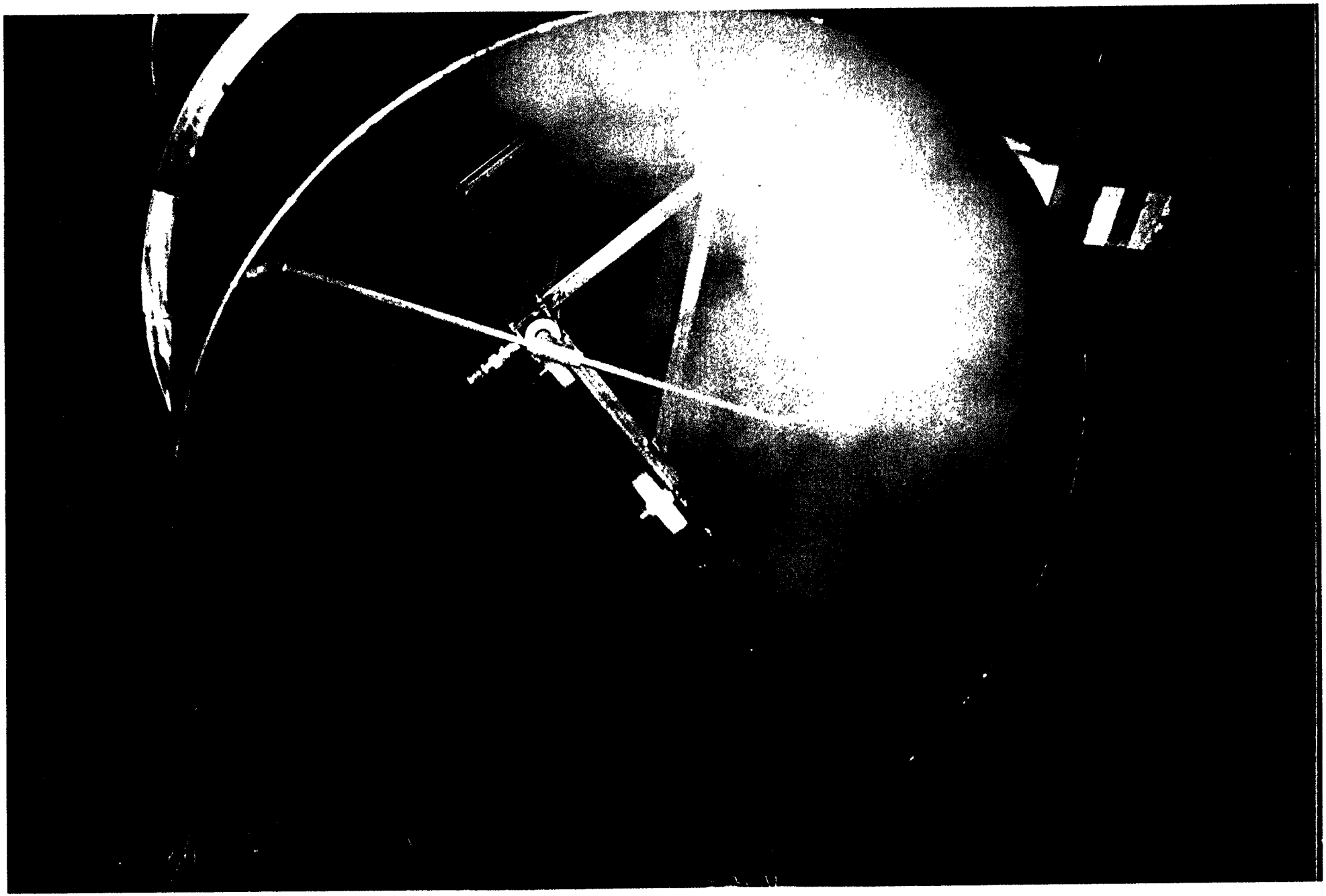


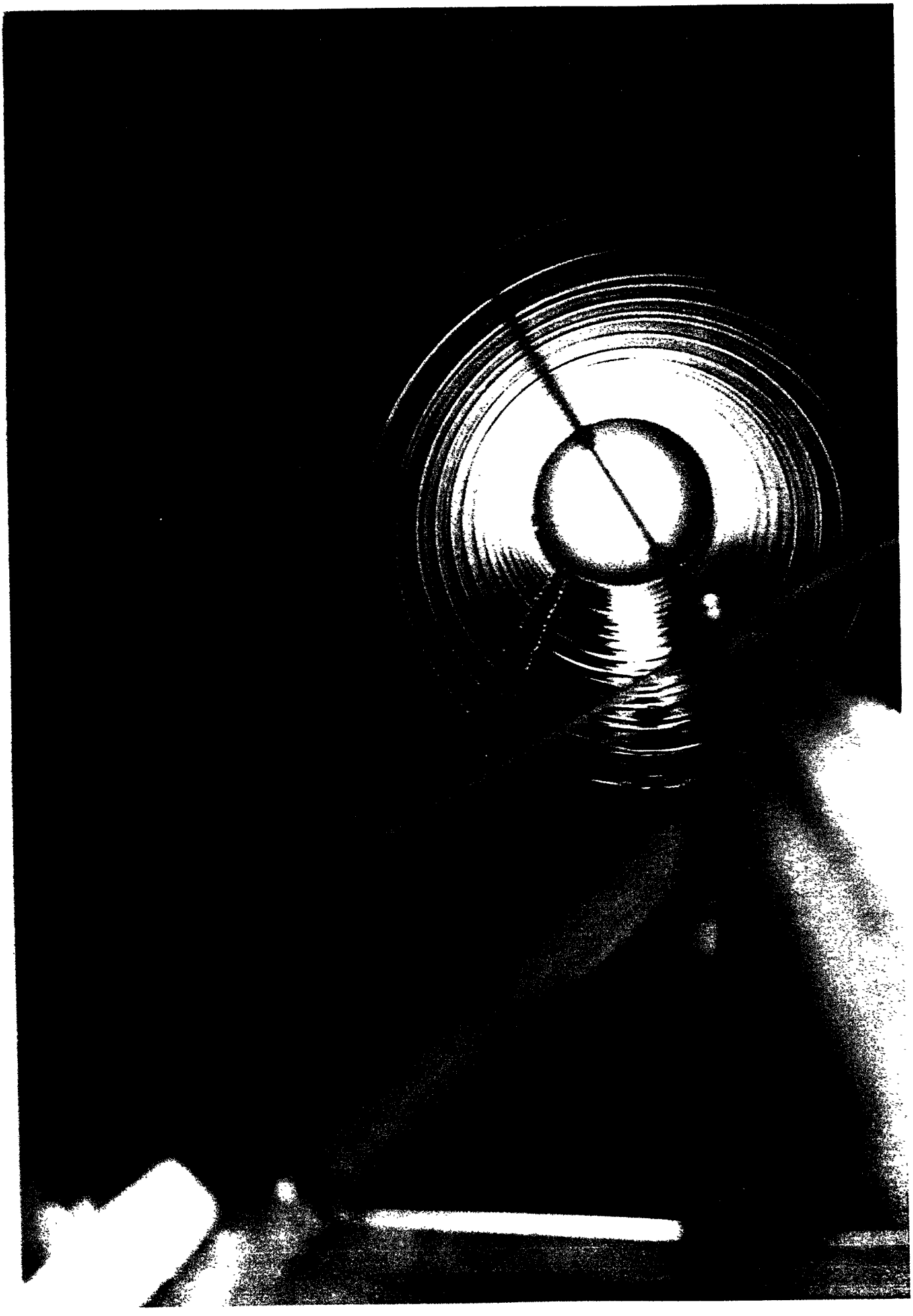












Beam Tube Enclosure

- Objective:
  - 700 pre-cast BTE's on site by 9/1
  - Installation contract placed to have BTE installer work approx 3-5 sections behind CBI.
- Status:
  - ACME manufacturing 17 enclosures/day
  - Lavernier and ACME agreement to provide "just in time" delivery

LIGO Facilities

Beam Tube Enclosure

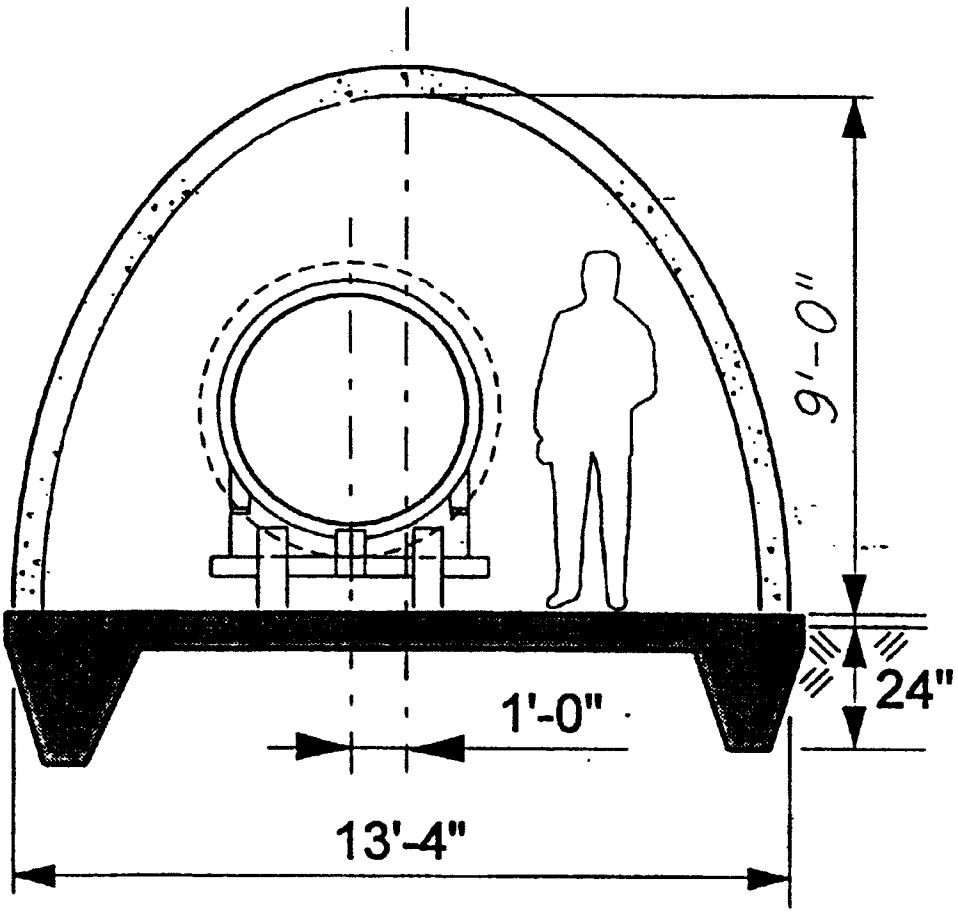
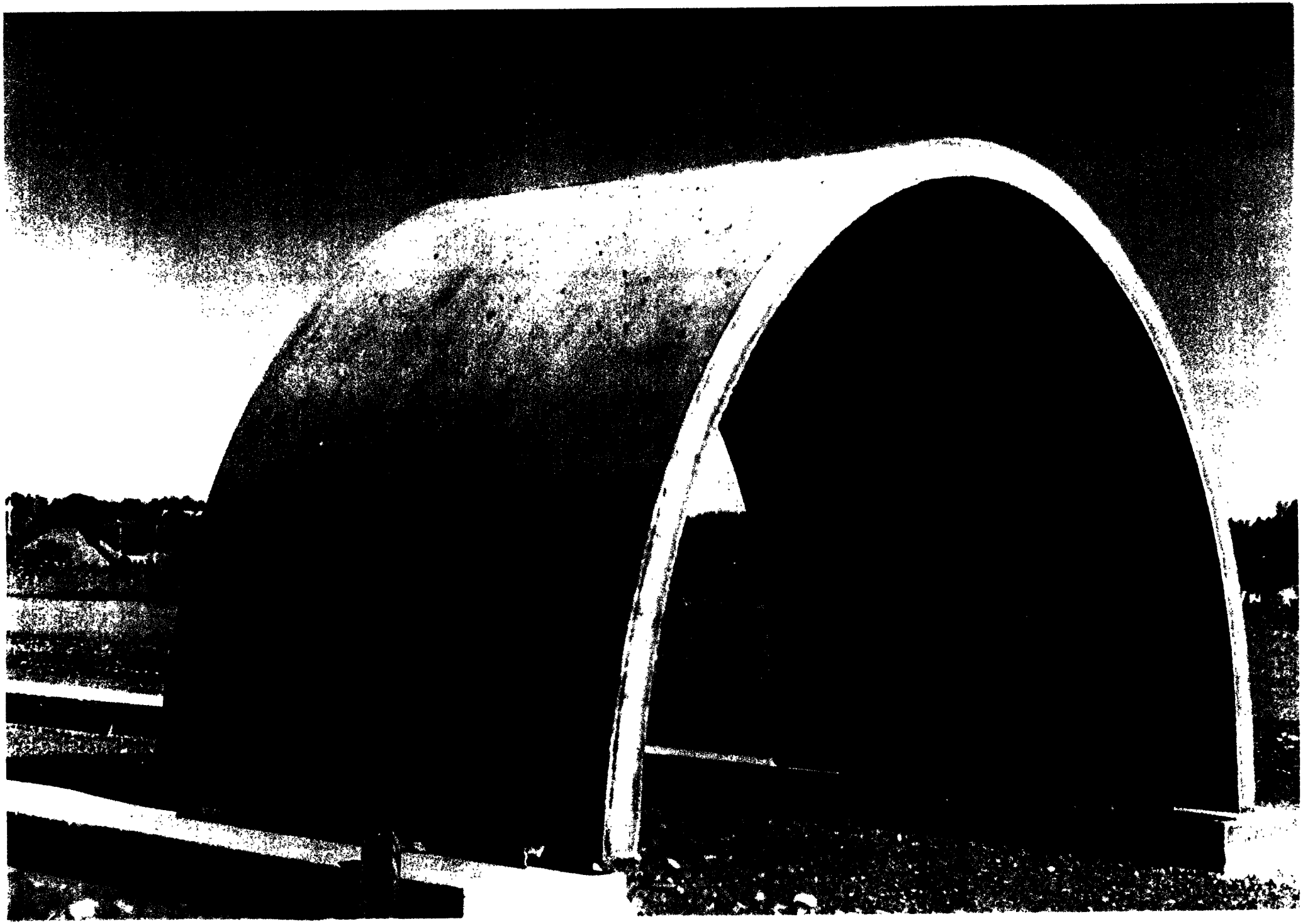
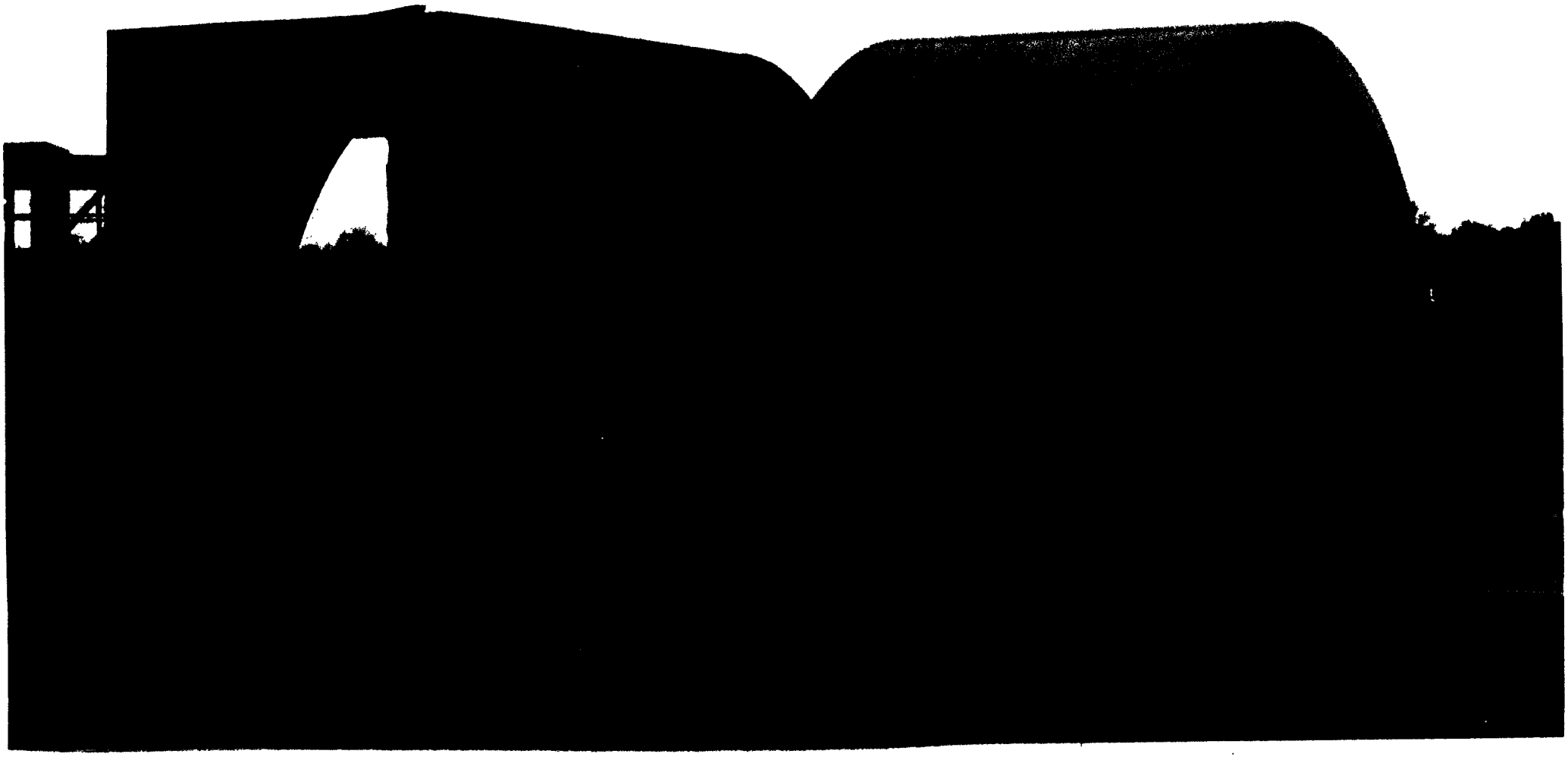
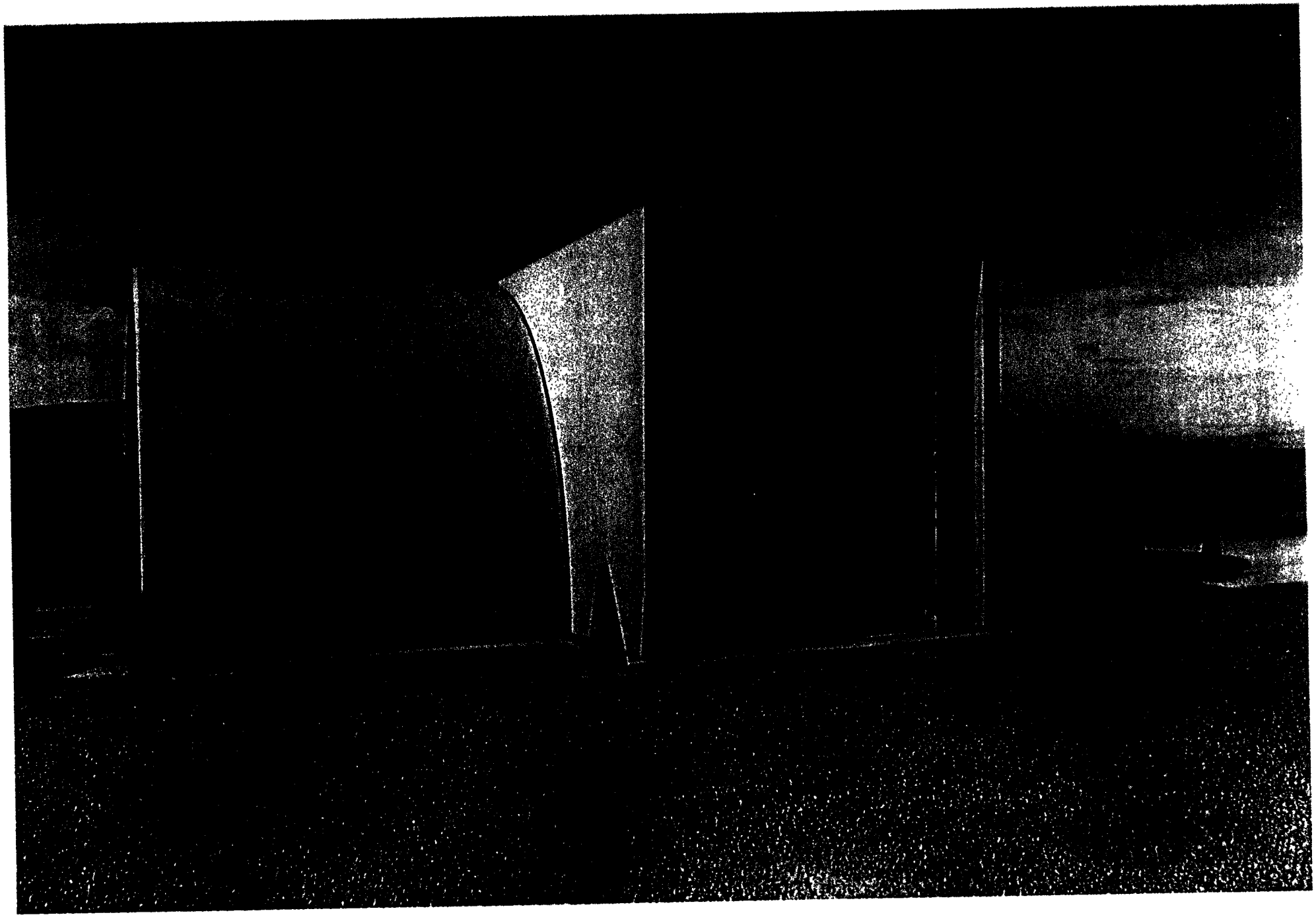
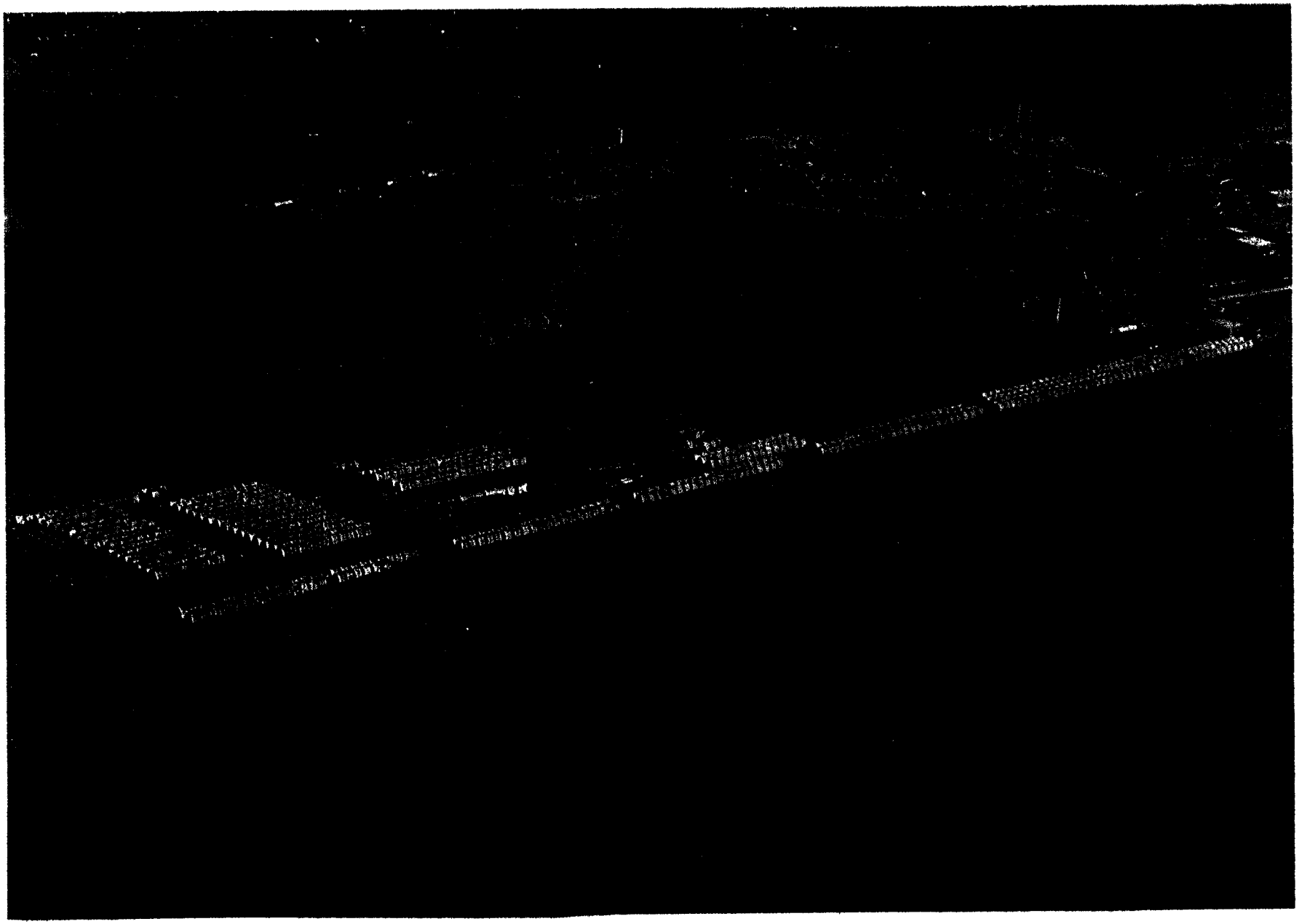


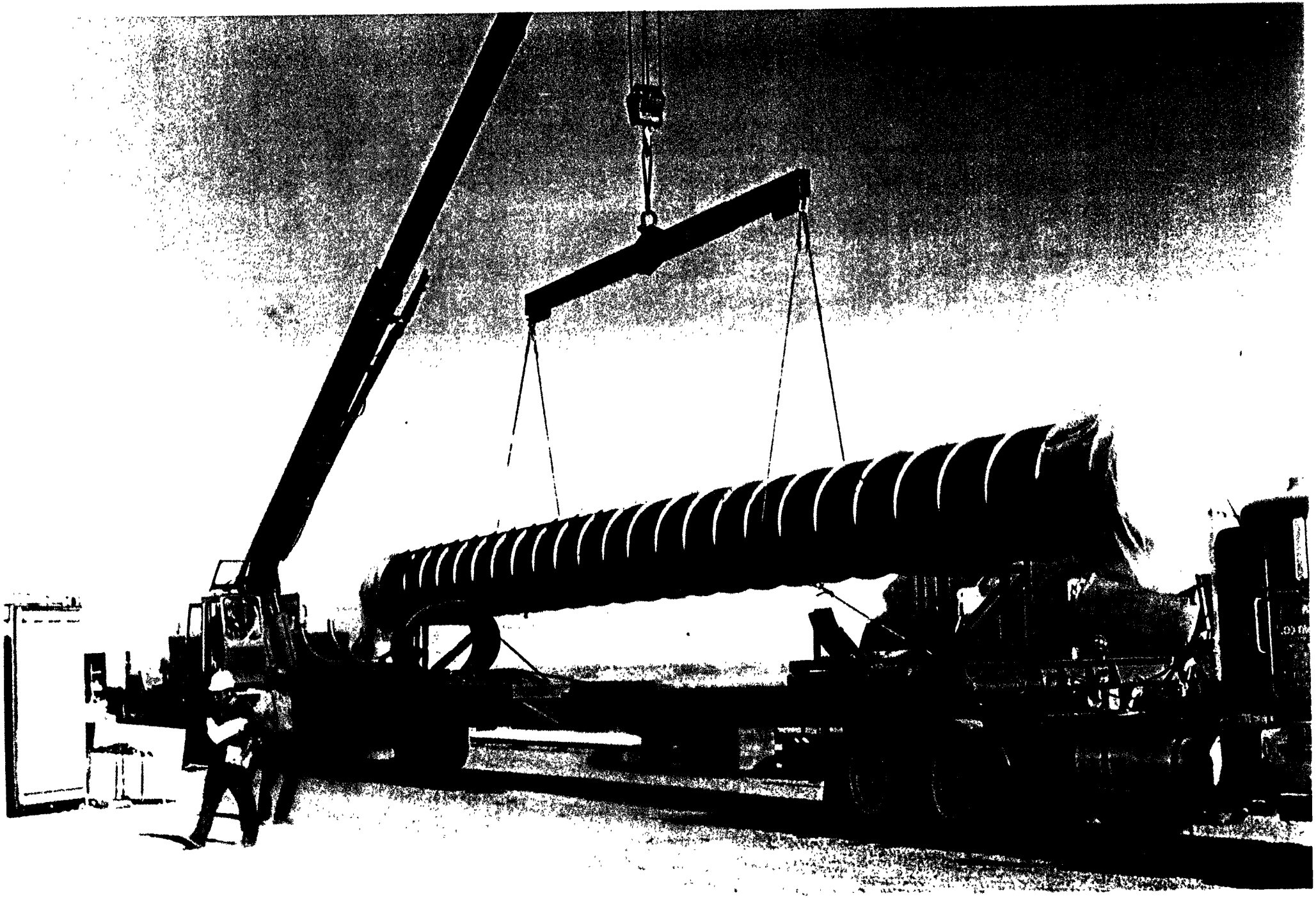
Figure 2.1-1 -- Cross Section of Design Baseline at Hanford





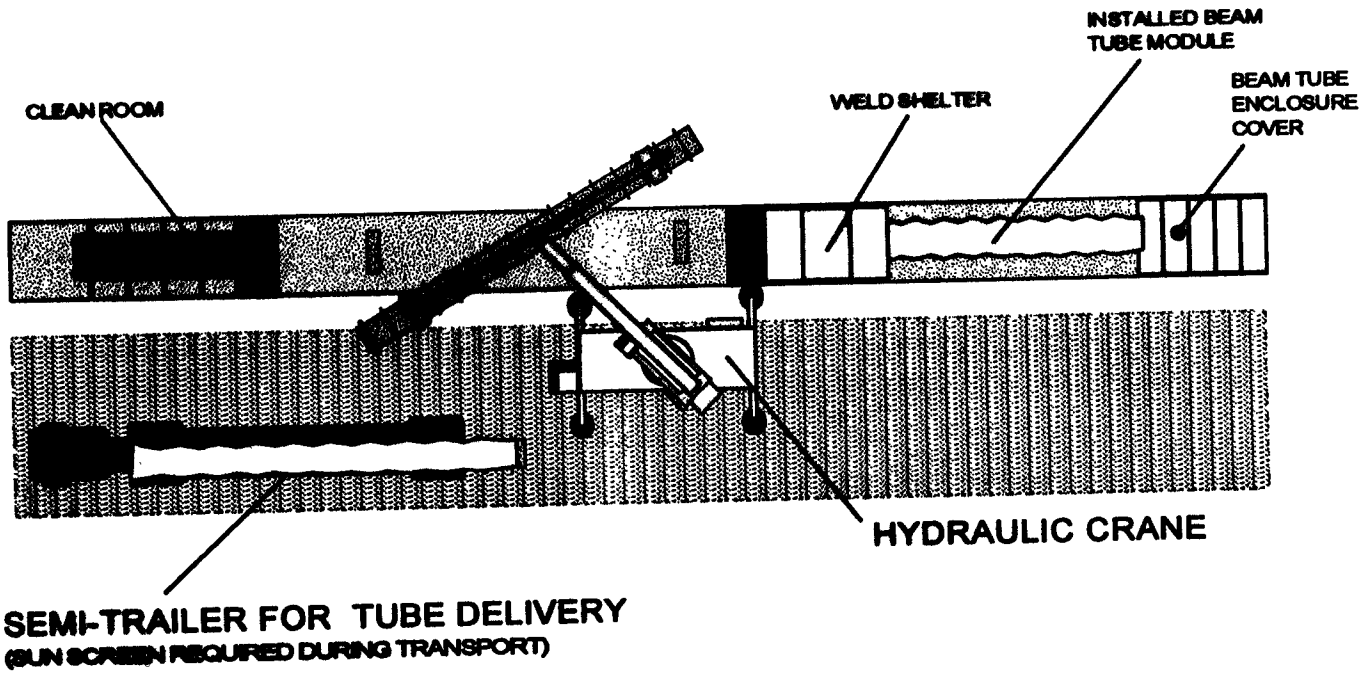






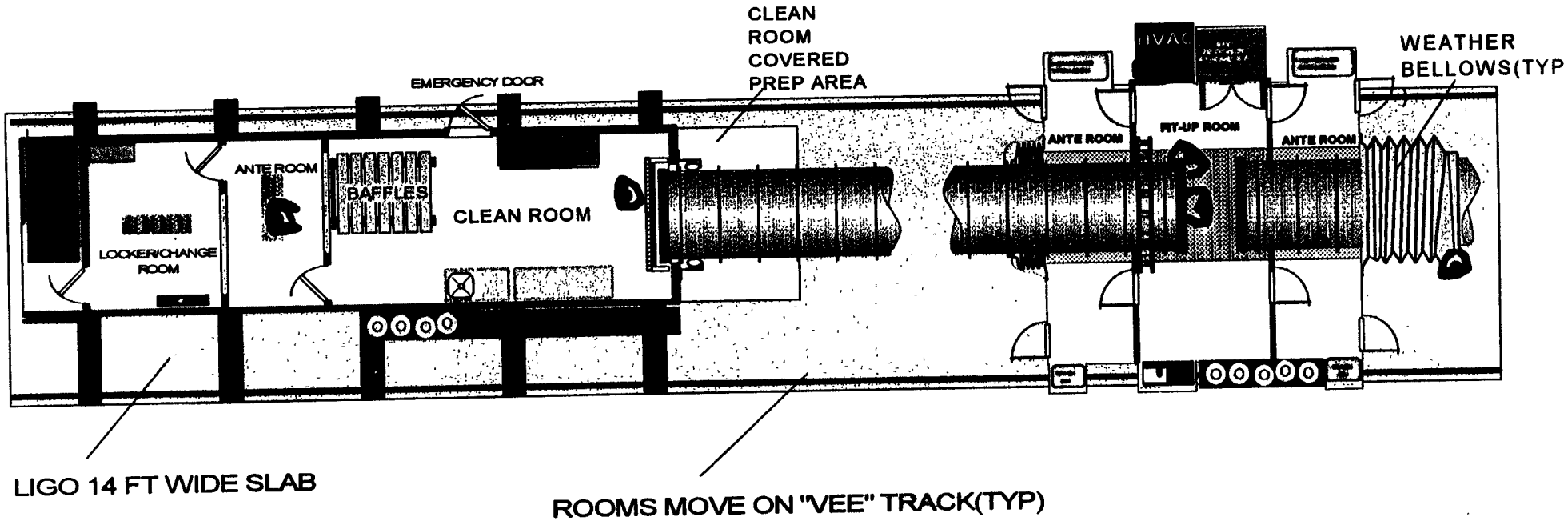
INSTALLATION WORK AREA - INSTALLING TUBES

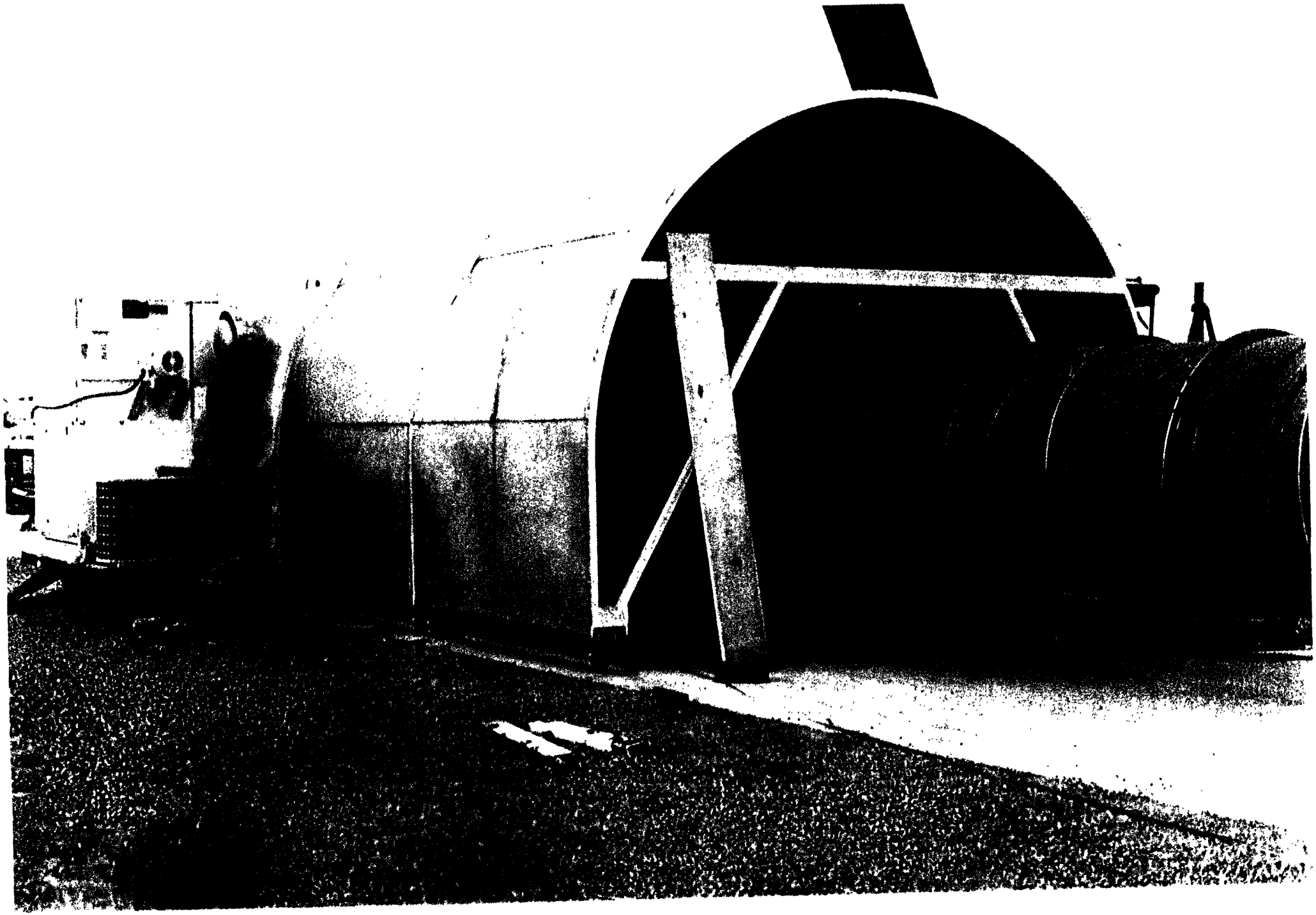
ATTACHEMENT ""D""



PLAN VIEW AT TYPICAL TUBE LOCATION

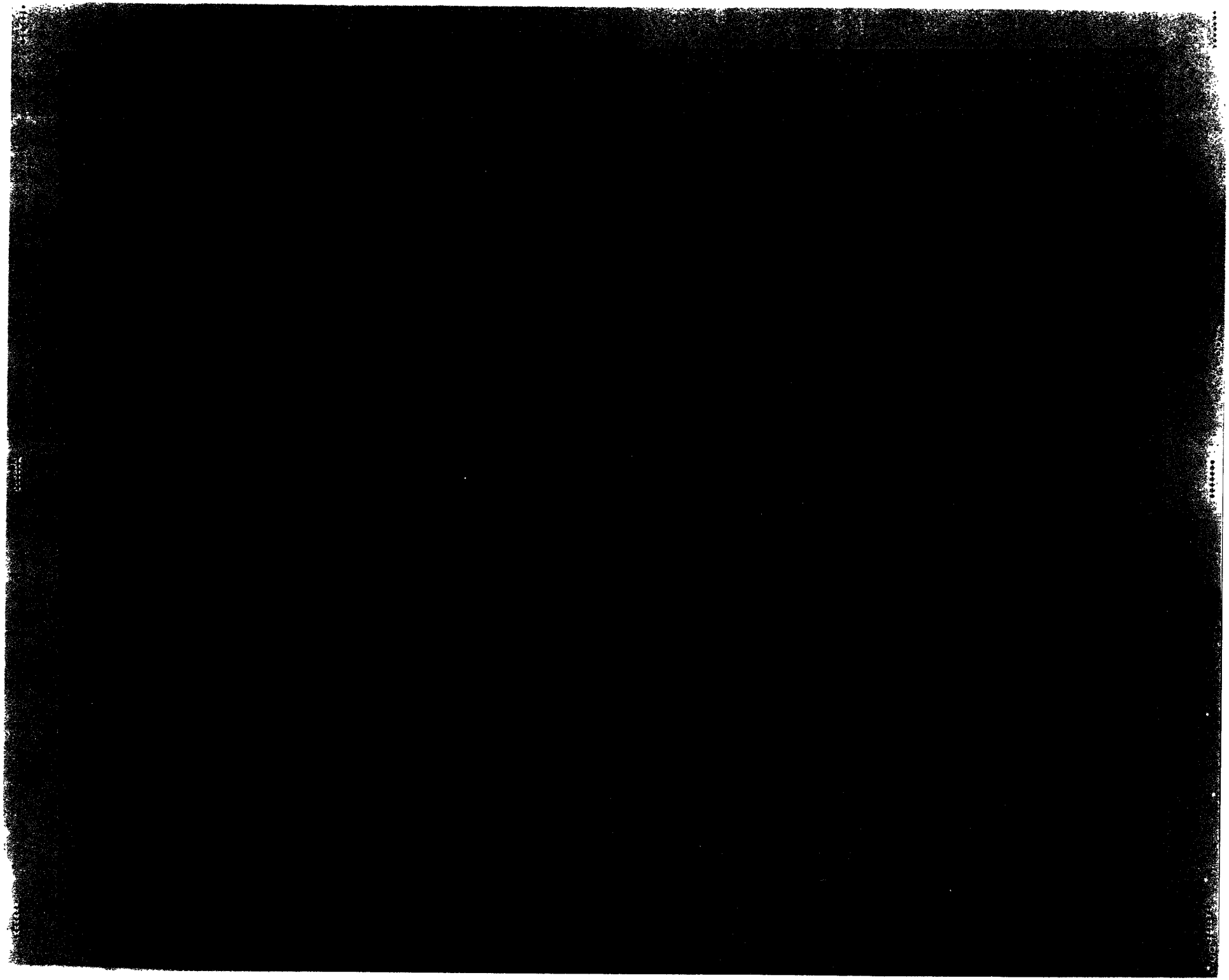
INSTALLATION PLAN

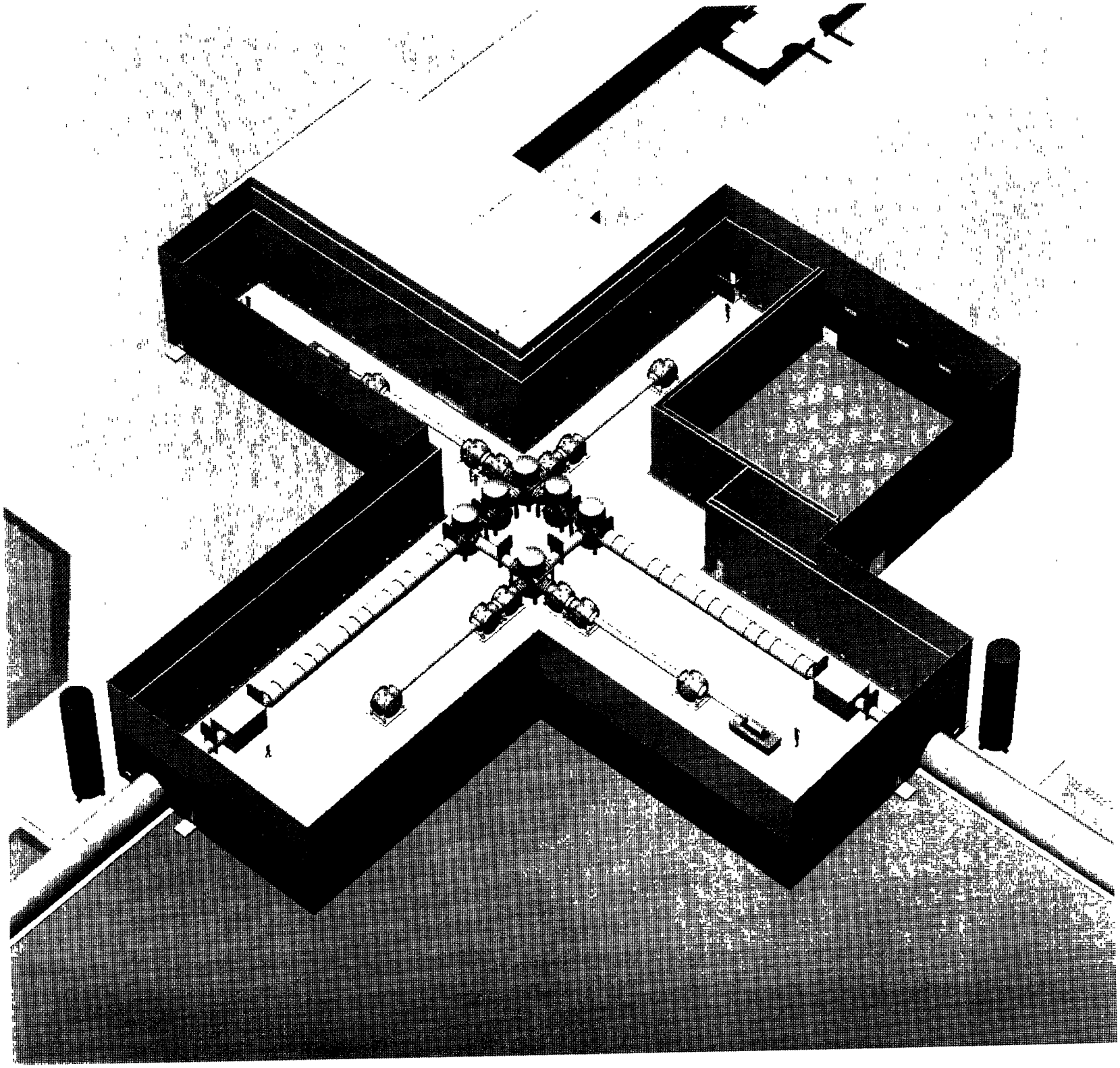


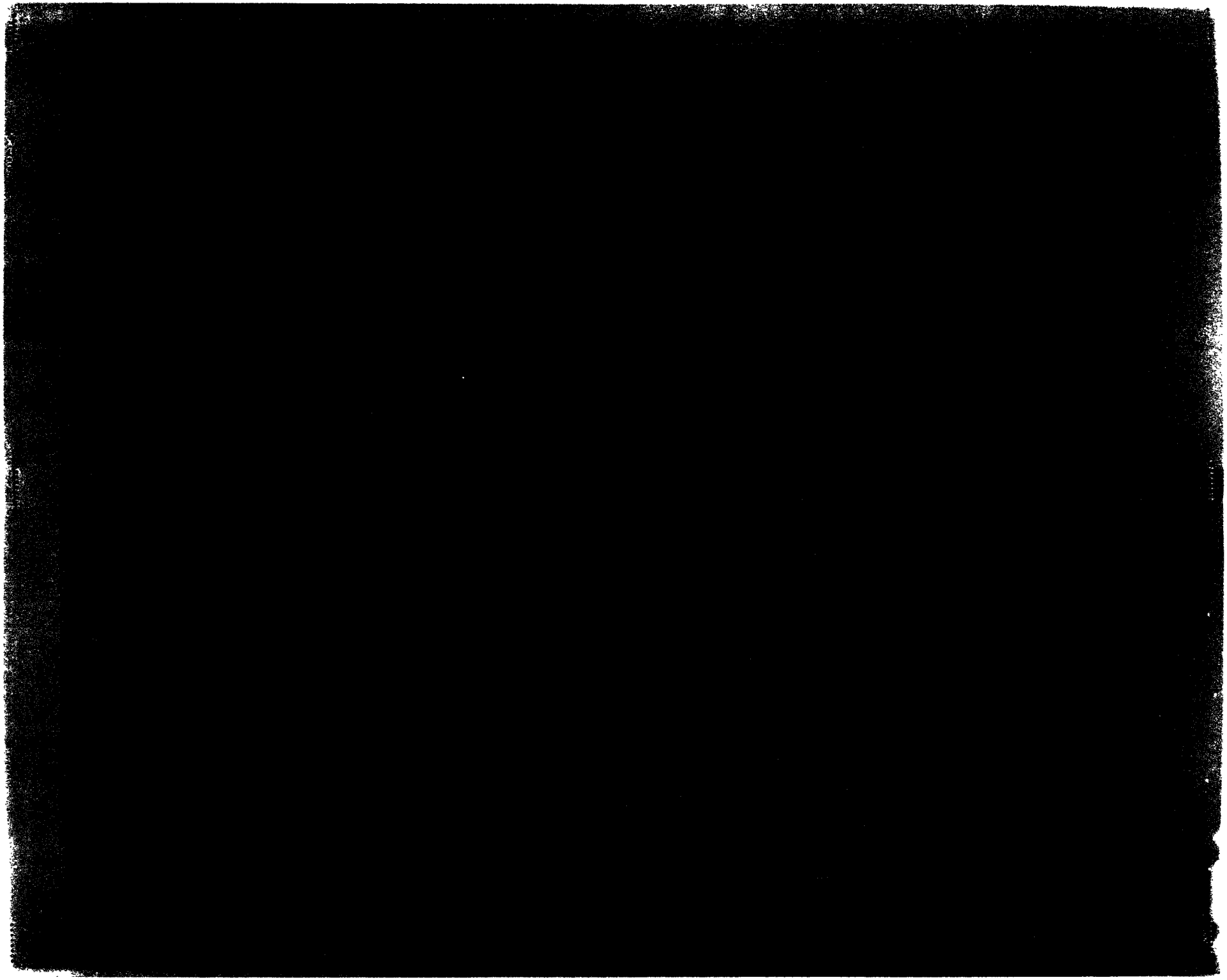


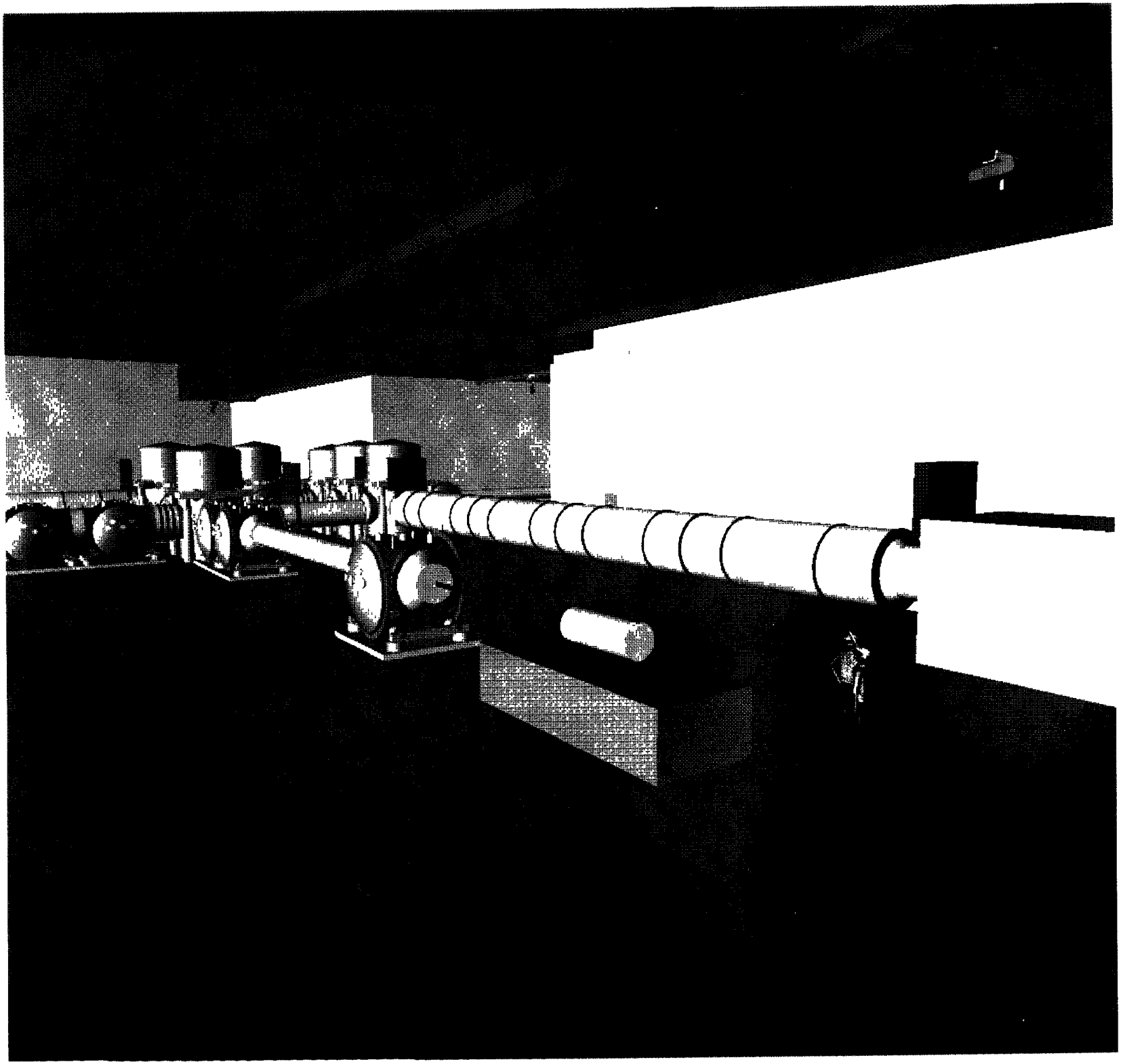
BT installation

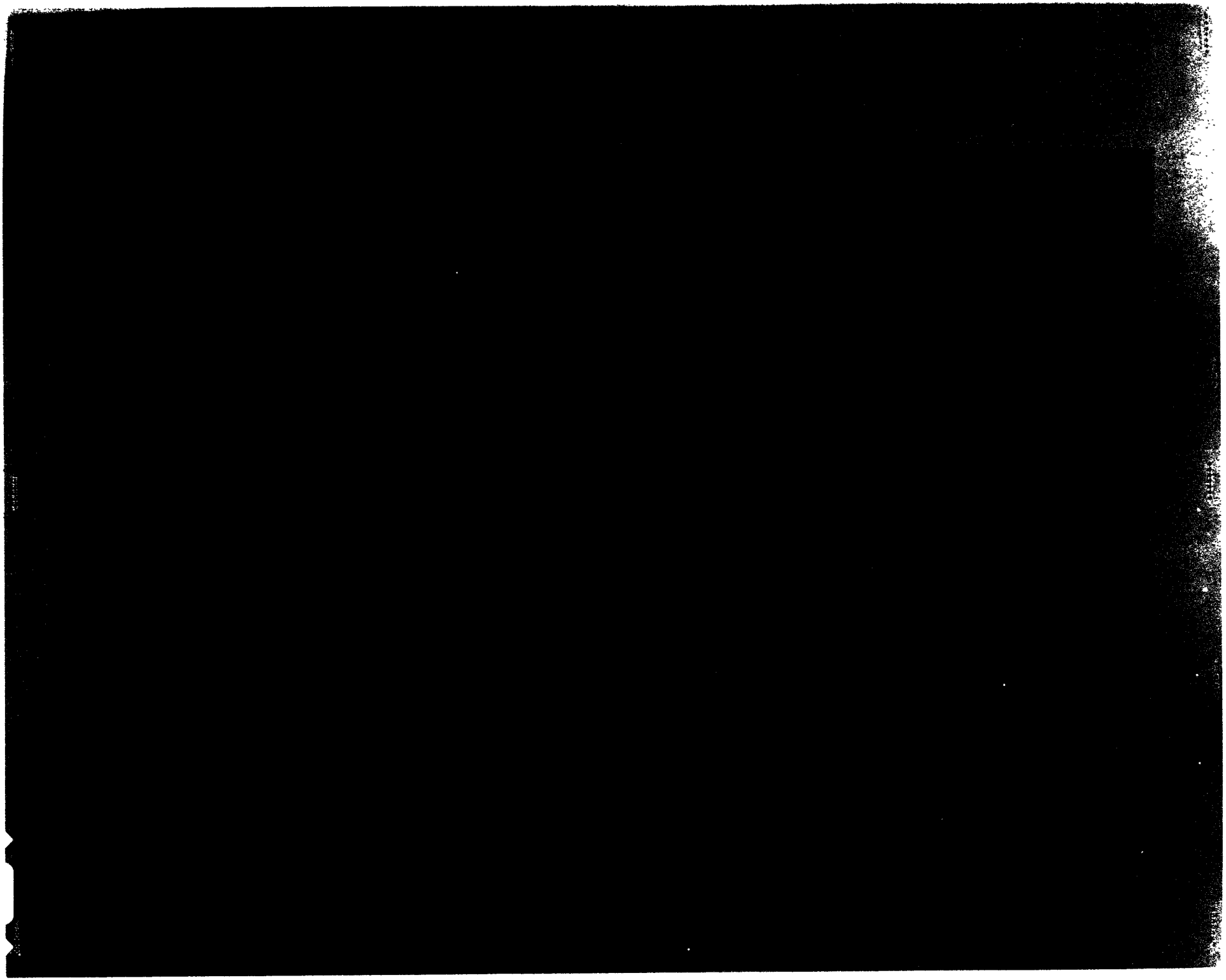
- Installation:
  - » weld enclosures, air filtration system delivered to site
  - » first gate valve installed
  - » high precision site survey completed to provide reference locations for BT installation
  - » installation readiness review completed

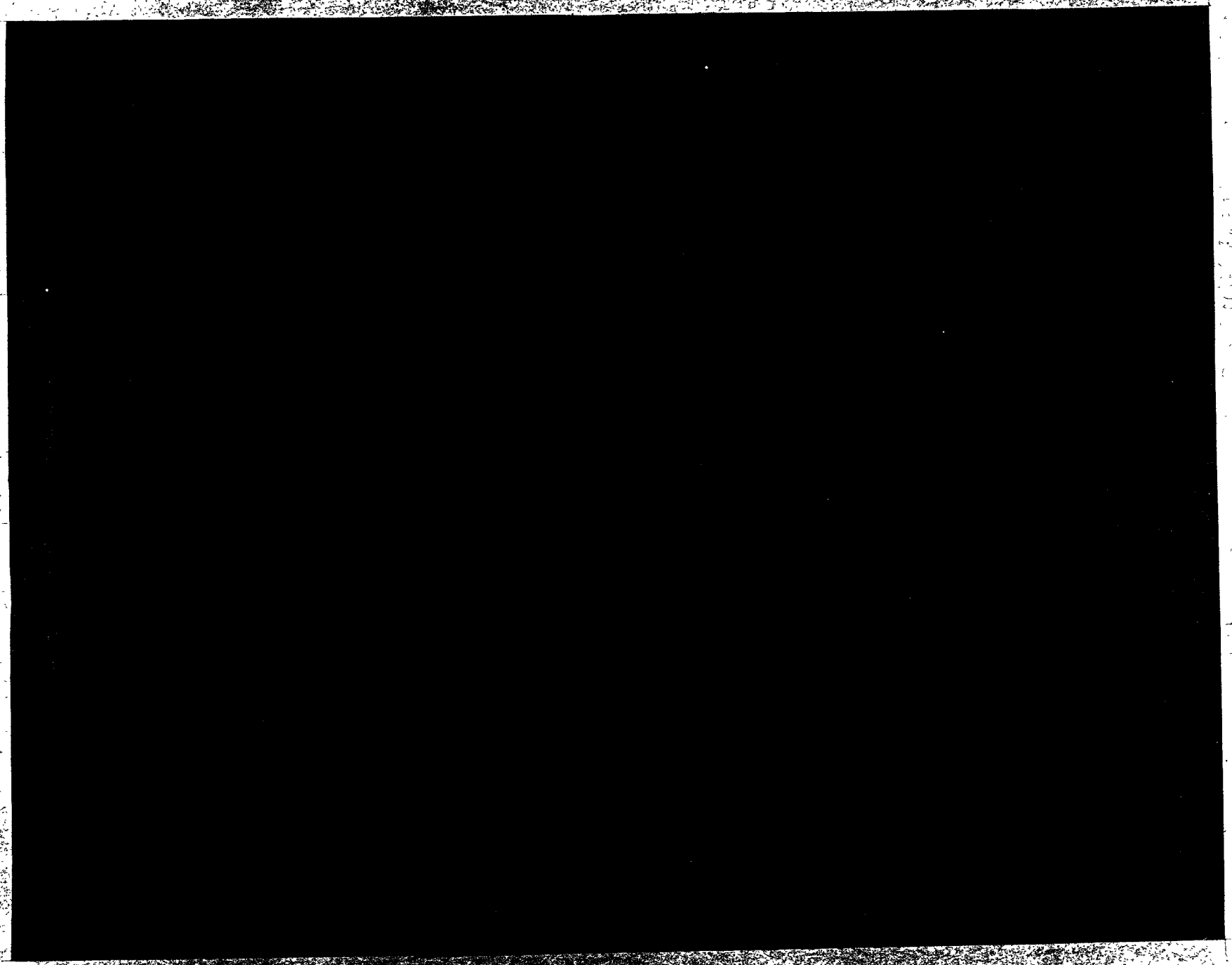


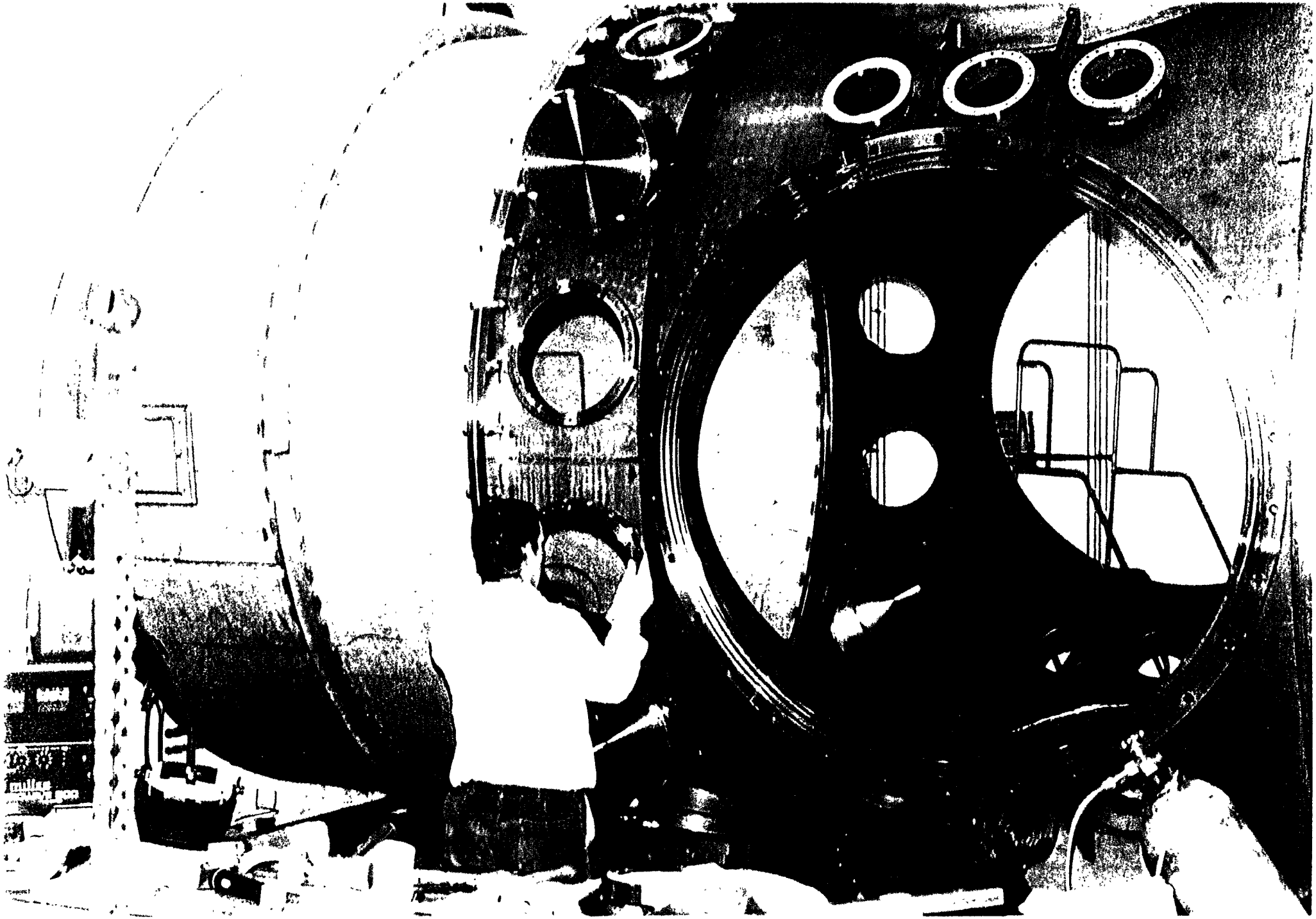


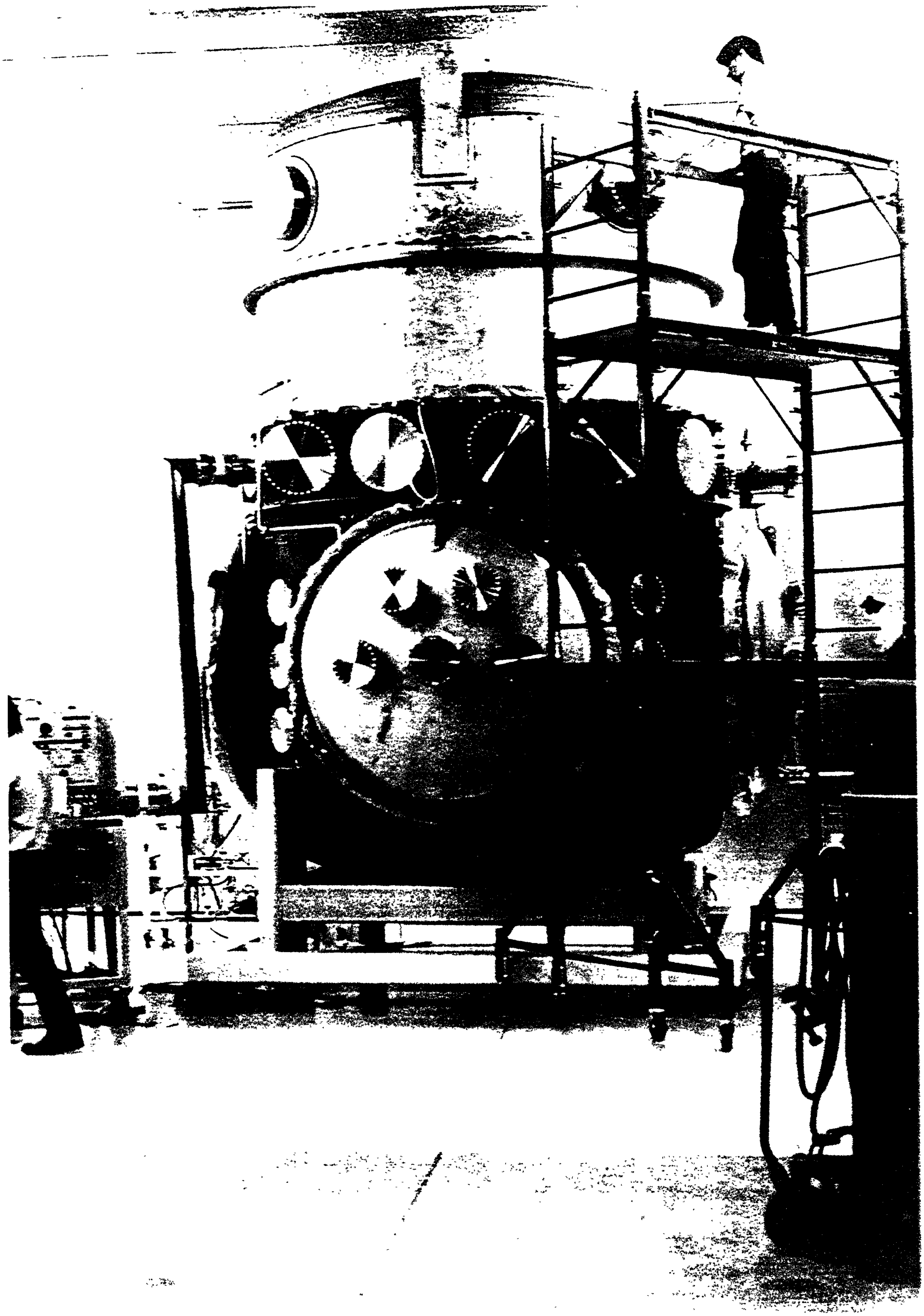












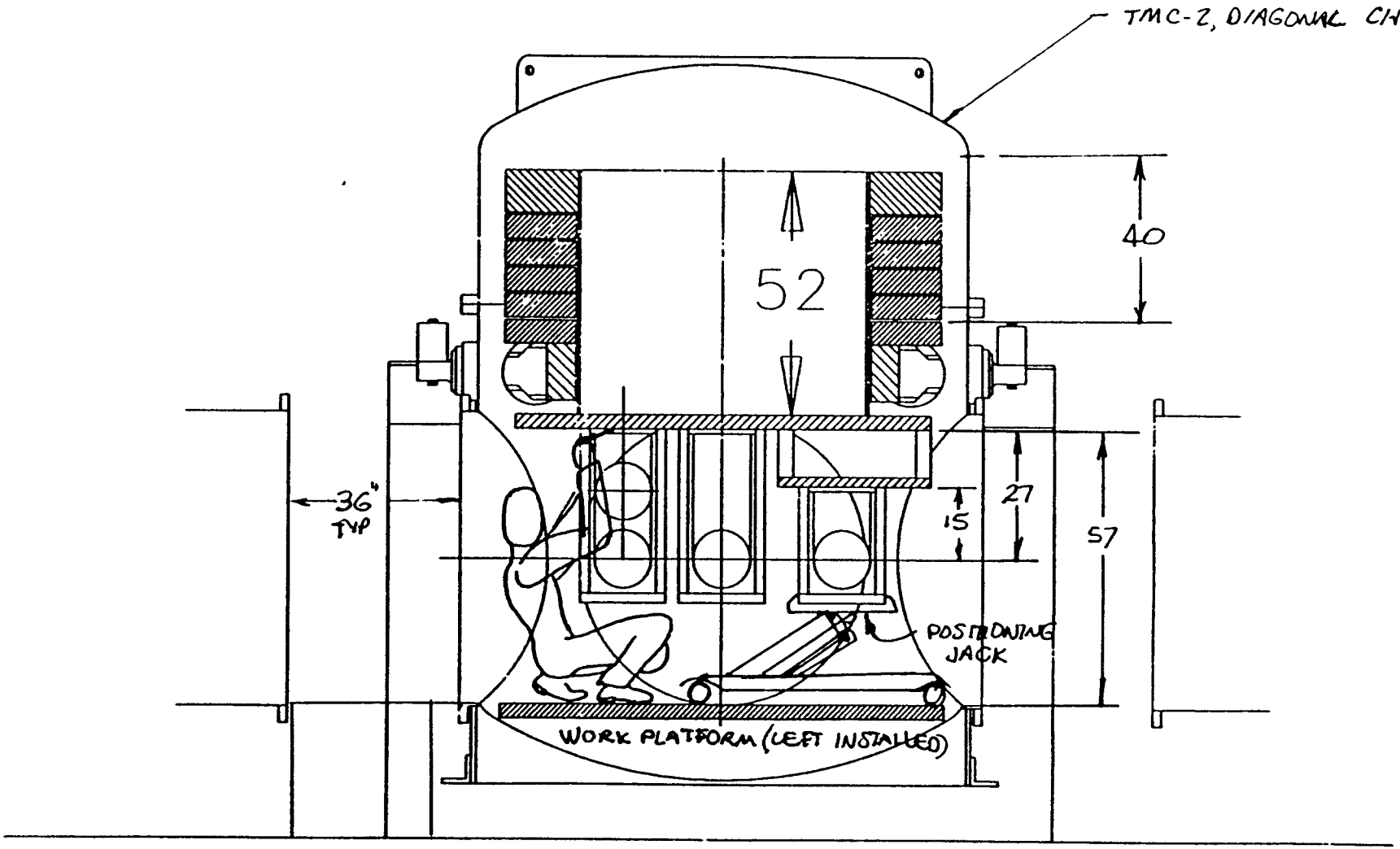
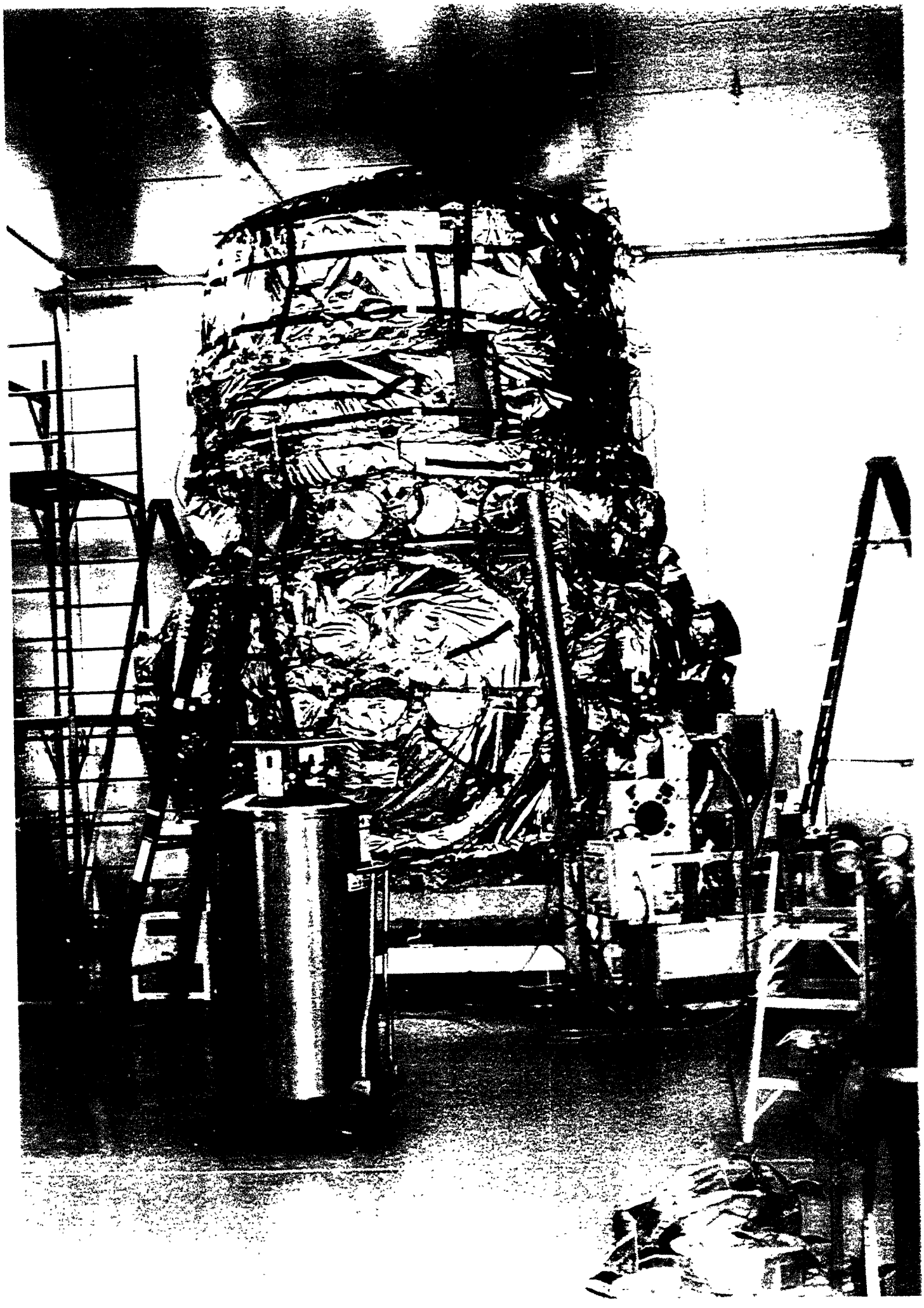
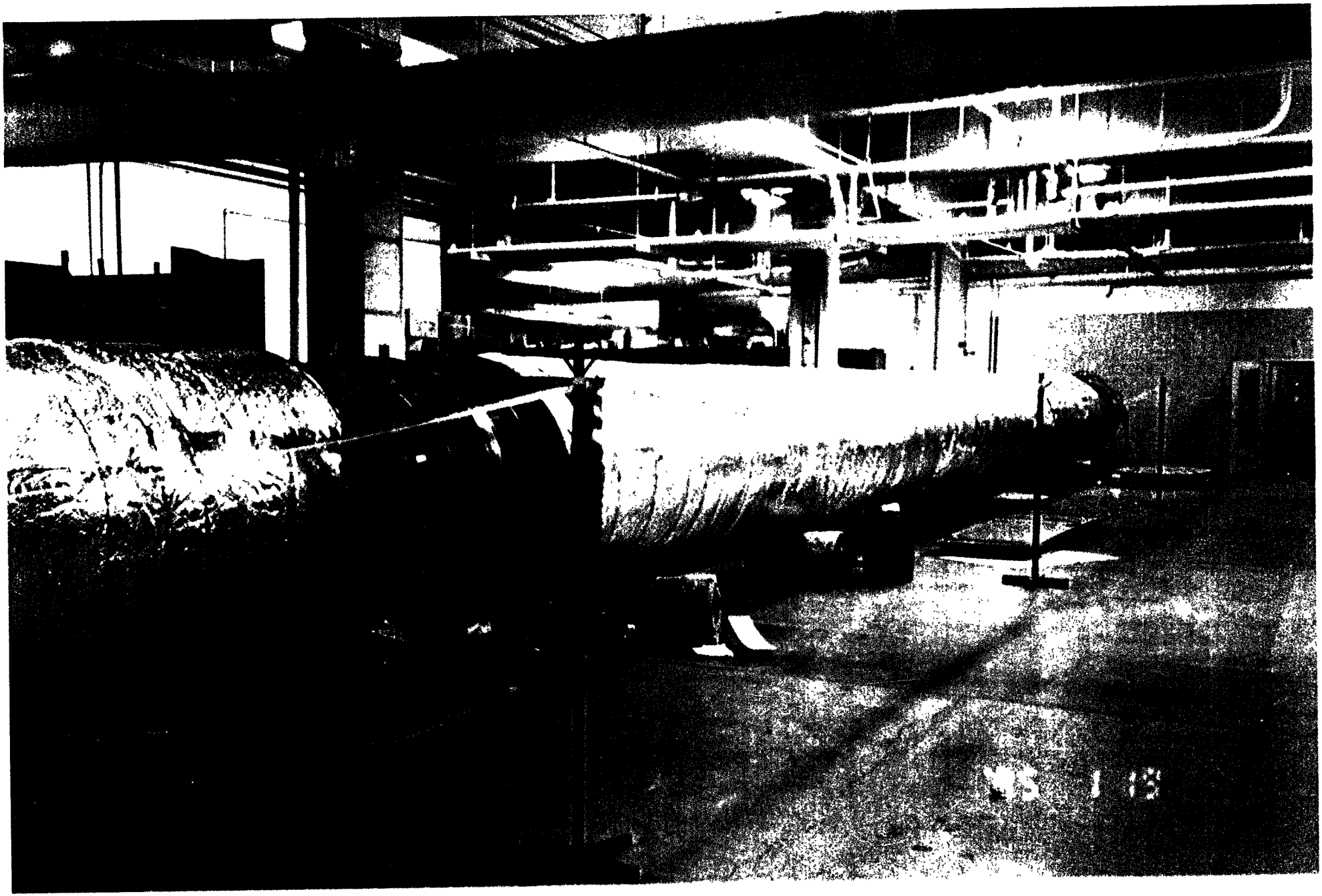


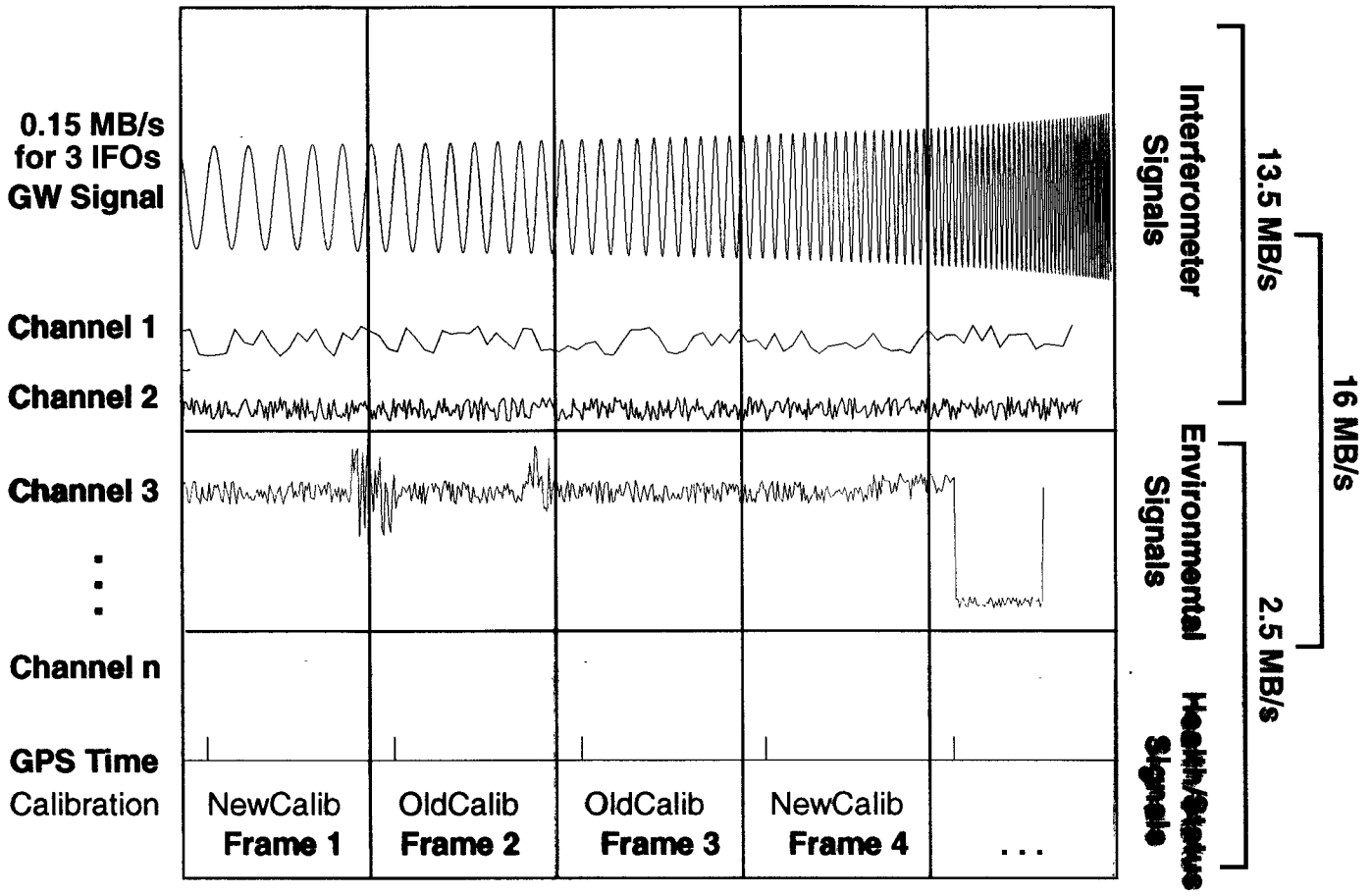
FIG. 3 INTERNAL ACCESS

9-2-92



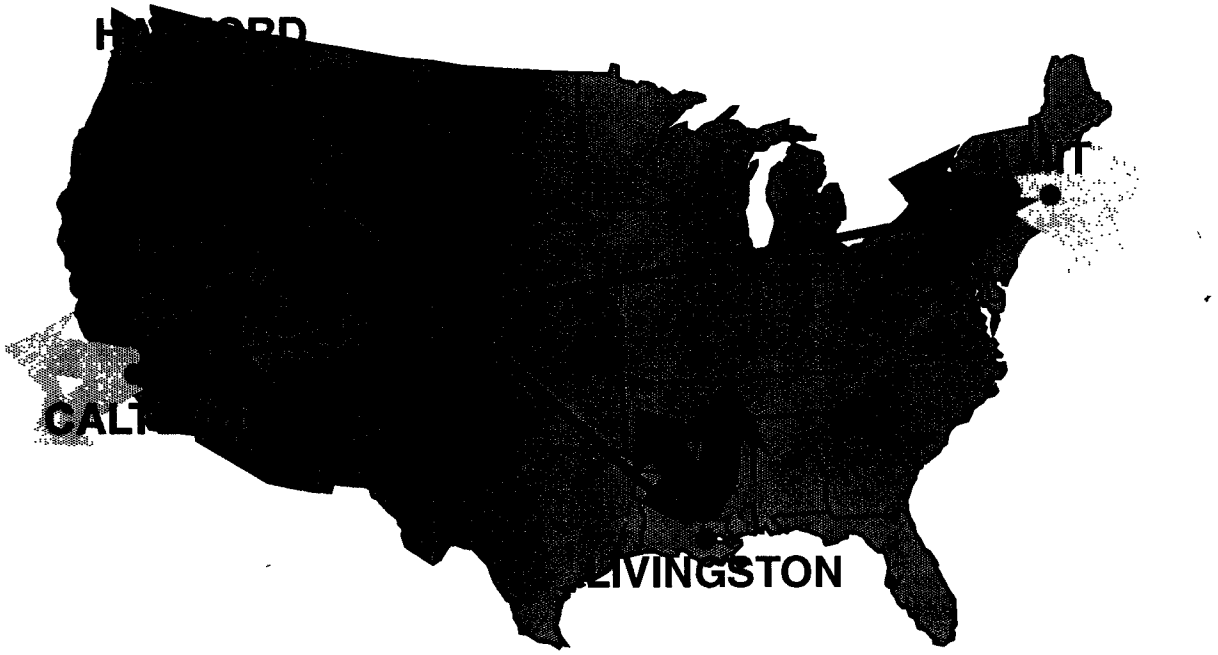


LIGO Data Stream and Data Frame Design



- Frame is (structured) self-contained snapshot of data for a period of time
  - GW channel & ancillary IFO channels
  - Environmental monitoring (veto) channels
  - Facilities/Vacuum health & status

LIGO Site-to-site Communications



- Hanford-Livingston link permits real-time cross-correlations among instruments
- Caltech-MIT link provides high speed link to data archives; data tapes to be archived at university.
- Site-University links provides site scientific staff access to archived data
- University gateways provide broader access to database
- Data tapes transported to University repository

Data Analysis Requirements

Science & Computational Requirements

Initial LIGO Sources and Estimated Analysis Capability Requirements

	Sources	Initial LIGO Performance Estimate	Data Analysis Requirements		
			CPU	Storage	Comments
Burst Signals $\Delta T < 1s$	Supernovae	$\Re_0 \sim 2-3/$ yr @ 15 Mpc If sufficiently asymmetric	Minimal for straightforward correlation; *if optimal filters are discovered, problem may increase in complexity.*	Minimal **Need PEM/houskeeping data for veto**	• *On-line analysis* desirable for correlation with other astrophysics: **Electroweak** • visible/radio/γ (HETE, GRO) • ν (Super-K/SNO) **Gravity** • VIRGO/GEO • Resonant bars • Waveforms unknown • 2x/3x IFO correlation • Off-line analysis to enhance SNR
	BH/BH Collisions	$\Re_0 \sim 1/$ yr(?) @ 500 Mpc; $M_{BH} \sim 30 - 200 M_{SUN}$			
Chirped Waveform $10s < \Delta T < 1000s$	NS/NS Inspirals	$\Re_0 \sim 3/$ yr @ 23 Mpc; $\Delta T \sim 4 \times 60$ s $M_{NS} \sim M_{SUN}$ $\Delta T \sim 4 \times 500$ s $M_{NS} \sim 0.3 M_{SUN}$	Templates/Data ~ 2 GFLOPS ~ 50 GFLOPS	~20 GB /~1 GB ~500 GB /~10 GB	• *On-line analysis* for $M_{NS} > M_{SUN}$ can be done; appears feasible down to ~ 0.3 M_{SUN} • 2x/3x correlations feasible depending on SNR. • Coalescence event may generate correlated (EW) signals as above. • PEM/housekeeping needed for vetoing • Template matching (Wiener filtering) or wavelet analysis in f-t domain. • Off-line analysis to enhance SNR
	BH/BH Inspirals	$\Re_0 \sim 1/$ yr @ 150 Mpc; $\Delta T \sim 4 \times 10$ s $M_{NS} \sim 10 M_{SUN}$;	~ 2 GFLOPS	~20 GB /~1 GB	

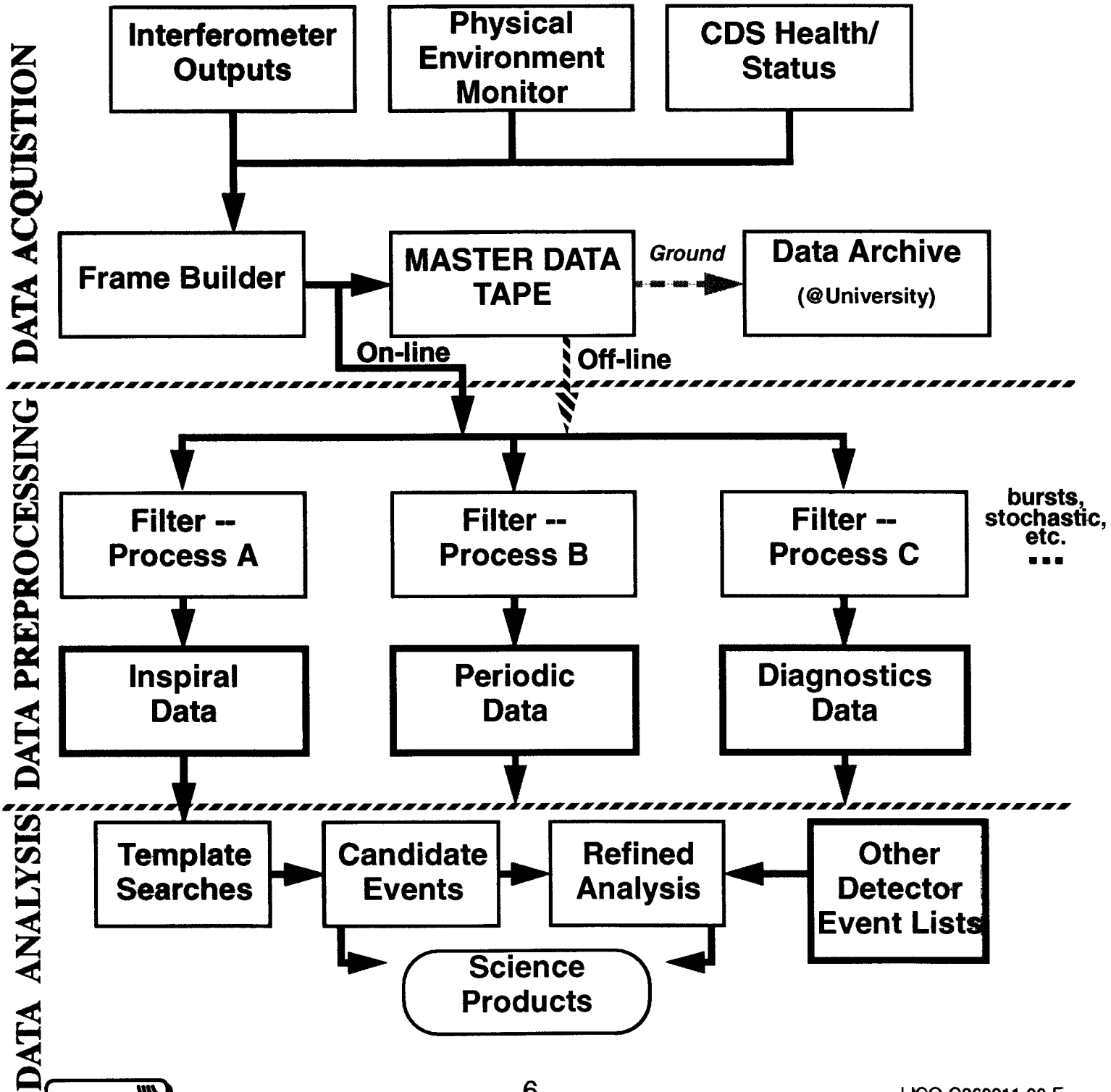
Data Analysis Requirements

Science & Computational Requirements

Initial LIGO Sources and Estimated Analysis Capability Requirements

	Sources	Initial LIGO Performance Estimate	Data Analysis Requirements		
			CPU	Storage	Comments
Periodic Signal $\Delta T \sim 10^6 - 10^7$ s	Pulsars with mass asymmetry $h \propto \left(\frac{\varepsilon}{10^{-6}}\right)\left(\frac{10\text{kpc}}{r}\right)\left(\frac{1\text{ms}}{P}\right)^2$	$\varepsilon = 3\times10^{-5}$; r=10kpc ; P=1ms $T_{int} = 10^6$s SNR ≈ 5	Directed searches (e.g., galactic center, known pulsars) require minimal resources All-sky searches require tens of TFLOPS -- beyond anticipated capabilities	10 GB for 10^6s (GW waveform)	• *Off-line analysis* • Detection less sensitive to non-Gaussian noise; more sensitive to calibration drifts&drop-outs • Detection techniques as for pulsars -- narrow line sources with modulated frequency. • Correlations among interferometers may be performed (if needed) after detection. • All-sky search requires decomposition of 4π sr into $>10^{10}$ pixels, each region requiring a different spectral transformation of same dataset.
Broadband Signals $\Delta T \sim 10^6 - 10^7$ s	Stochastic Background $\Omega \equiv \frac{\Omega_g}{\Omega_0}$	$\Omega \geq 3\times10^{-6}$ Δf, f ≈ 100Hz $T_{int} = 10^7$sec	Minimal requirements -- analysis maybe done on single workstations		• *Off-line analysis* • Requires multiple interferometers to be correlated; may use PEM to imprive SNR.

LIGO Data Analysis Flow -- Baseline



LIGO-G960211-00-E

Data Analysis for Initial LIGO
On-line Processing Computing Resources & Distribution

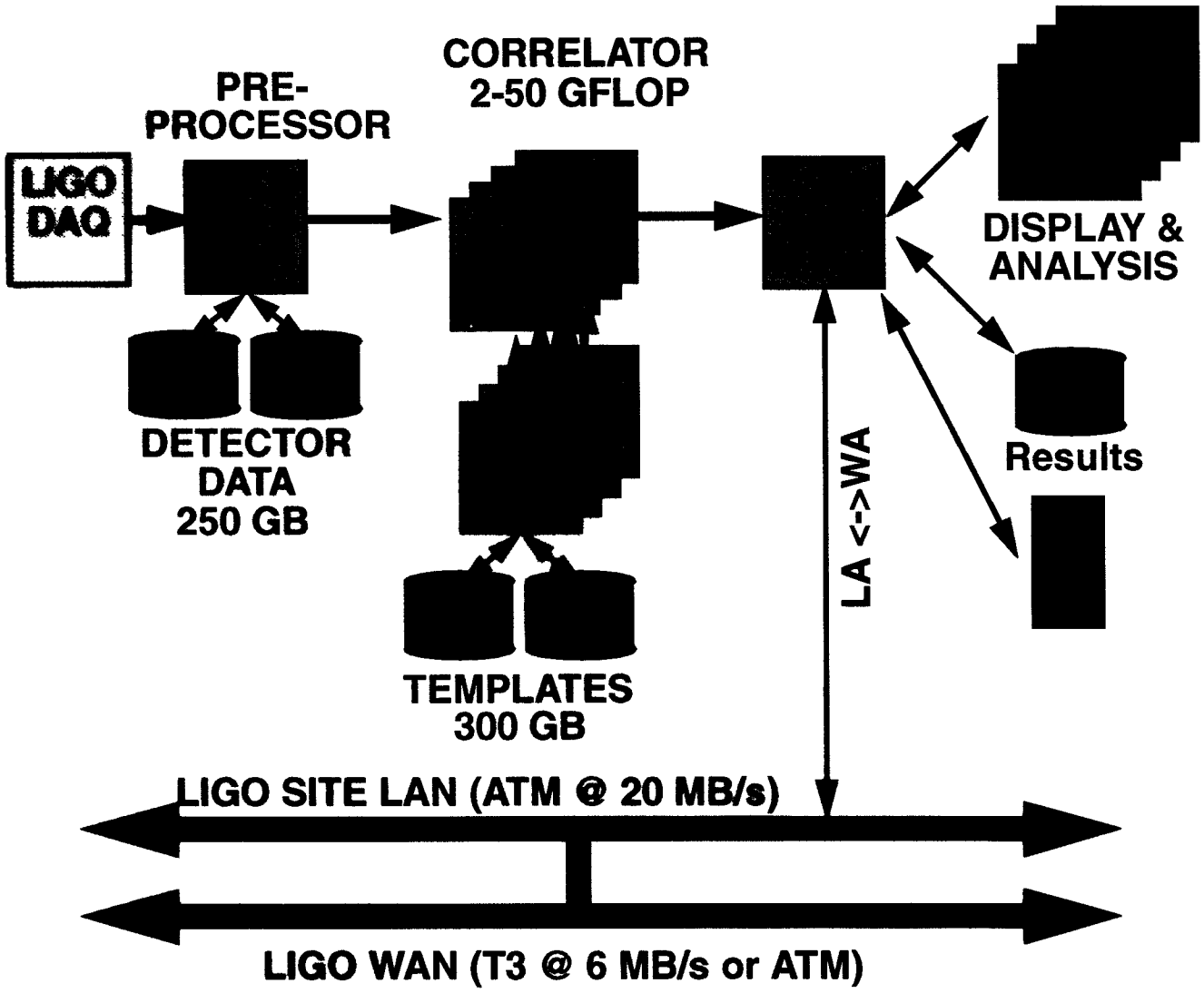
- Redundant systems at LA & WA Observatories
- Support for 1x, 2x, 3x operations independently
  - Diagnostics -- especially during commissioning
  - 2x/3x operations between sites feasible with reduced datastreams
    - Transient/burst signals ($\Delta T < 1s$) -- GW + superveto/QA
    - Inspiral & coalescence waveforms ($10s < \Delta T < 1000s$) -- events
- System configuration (target: $M_{NS} > 0.3\ M_{SUN}$)
  - Volatile data storage for 3 hours of data + 3 hours of analysis (FIFO) for 2 IFOs (WA) @ 100% data stream: 125GB+125GB
  - Template storage for:300 GB
  - ~ 2-50 GFLOP CPU system -- intrinsically parallel computational requirements:
    - Parallel processor(s) -- *monolithic/efficient/more expensive*
    - Workstation cluster -- *versatile/less efficient/less expensive*
    - Specialized (DSP) system -- *less versatile/efficient/least expensive/upgrade difficult*

Data Analysis for Initial LIGO
On-line Processing Computing Resources & Distribution

- System configuration (cont.)
  - ›› Site-to-site communication link to provide 2x and 3x real-time cross-correlation
    - Selected (pre-processed) data subsets (GW + super-veto; event lists)
    - Two way: WA->LA & LA->WA
      - Can support independent algorithms
    - T1: 0.2 MB/s is barely sufficient for GW WA->LA
    - T3 (6 MB/s) or ATM (20 MB/s) will be available by time needed

Data Analysis for Initial LIGO

On-line Processing Computing Resources & Distribution



Data Analysis for Initial LIGO

Off-line Processing Computing Resources & Distribution

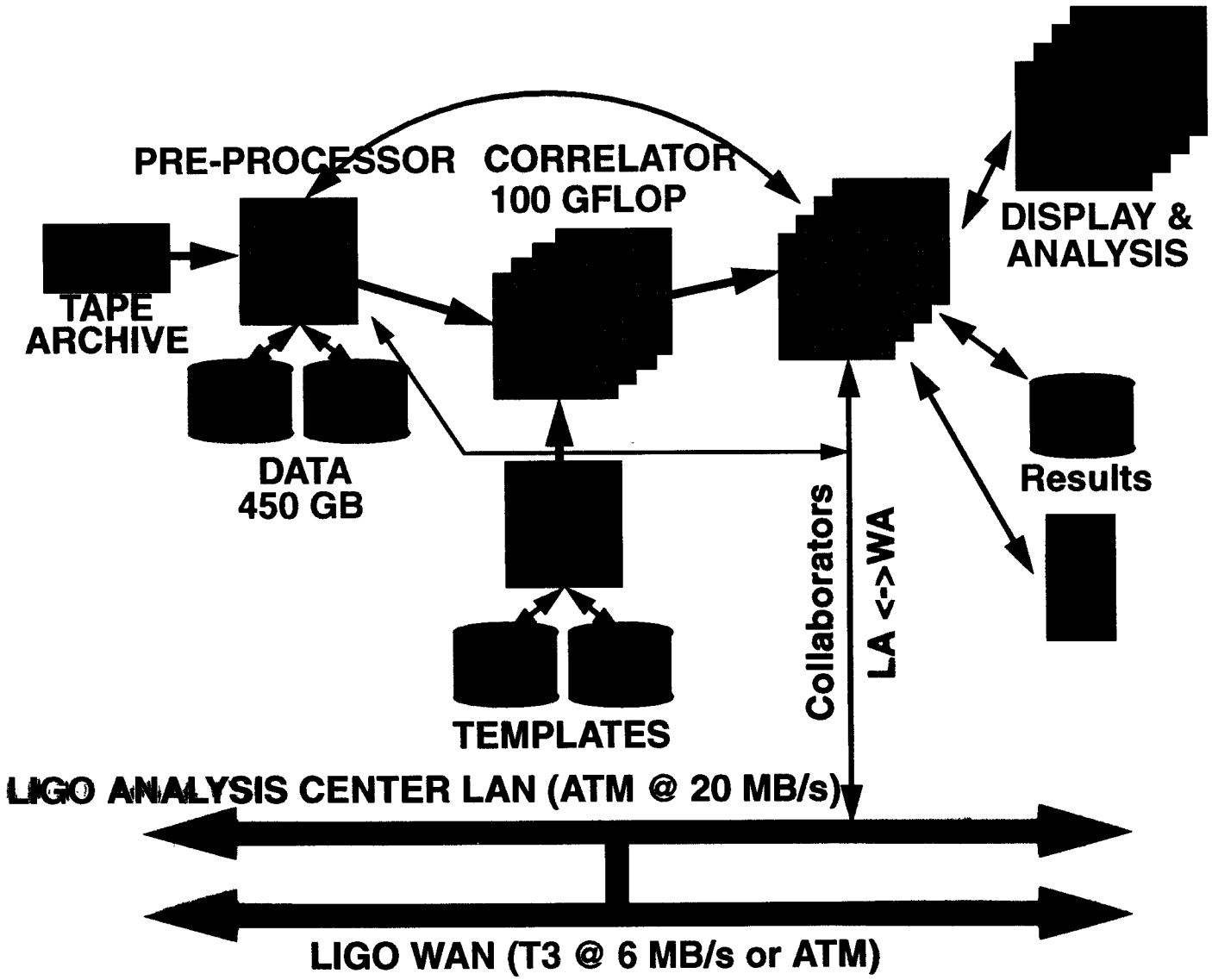
- Single system at a LIGO Laboratory University*
- Supports analyses either not feasible or not required on-line.
  - Stochastic background
  - Pulsar searches (directed/partial sky)
  - Inspiral with combined IFOs (vector data for max. SNR)
  - Research on algorithm development & signal processing
  - Refined analyses
  - Novel searches
- Provides/manipulates data archive.
- Data access via WAN to other LIGO sites and users.
- Utilizes and is designed around existing University resources for maintenance, availability, communications & support.

Data Analysis for Initial LIGO
Off-line Processing Computing Resources & Distribution

- System configuration (target: max. capability for multiple users)
  - Large data archive
    (~ 500 TB/yr => 10k tapes/yr @ 50 GB/tape => $0.5M/yr @ $50/tape)
  - Robotic tape access -- size TBD
  - Disc cache system capable of storing 450GB of data
    - 8 hours of 100% data ~ 450 GB
    - ~ 5 weeks of GW data (suitably filtered to not require ancillary channels)
  - Processors for computationally intense analyses (100+ GFLOPS)
    - Support multiple, independent analyses (4 - 6)
    - Parallel processor(s) -- *monolithic/efficient/more expensive*
    - Workstation cluster -- *versatile/less efficient/less expensive*
    - Distinctions will fade with time
  - High bandwidth communication to other LIGO sites & collaborating institutions
    - T3 (6 MB/s) or ATM (20 MB/s)

Data Analysis for Initial LIGO

Off-line Processing Computing Resources & Distribution



LIGO
R&D Program

- Sensitivity
  - » main features of 40 m spectrum understood
  - » monolithic test masses improve sensitivity
- Demonstration Experiments
  - » optical recombination demonstrated on 40 m
  - » acquisition locking with LIGO controls
  - » MIT phase noise experiments
- Pre- [detector design freeze][<1998]
  - » Program testing directed at tasks that could effect design over the next two years
- Post- [detector design freeze][>1998]
  - » Advanced R&D program on techniques for improved sensitivity;
  - » understand performance - initial interferometer
  - » gain experience running an interferometer facility (perform search)

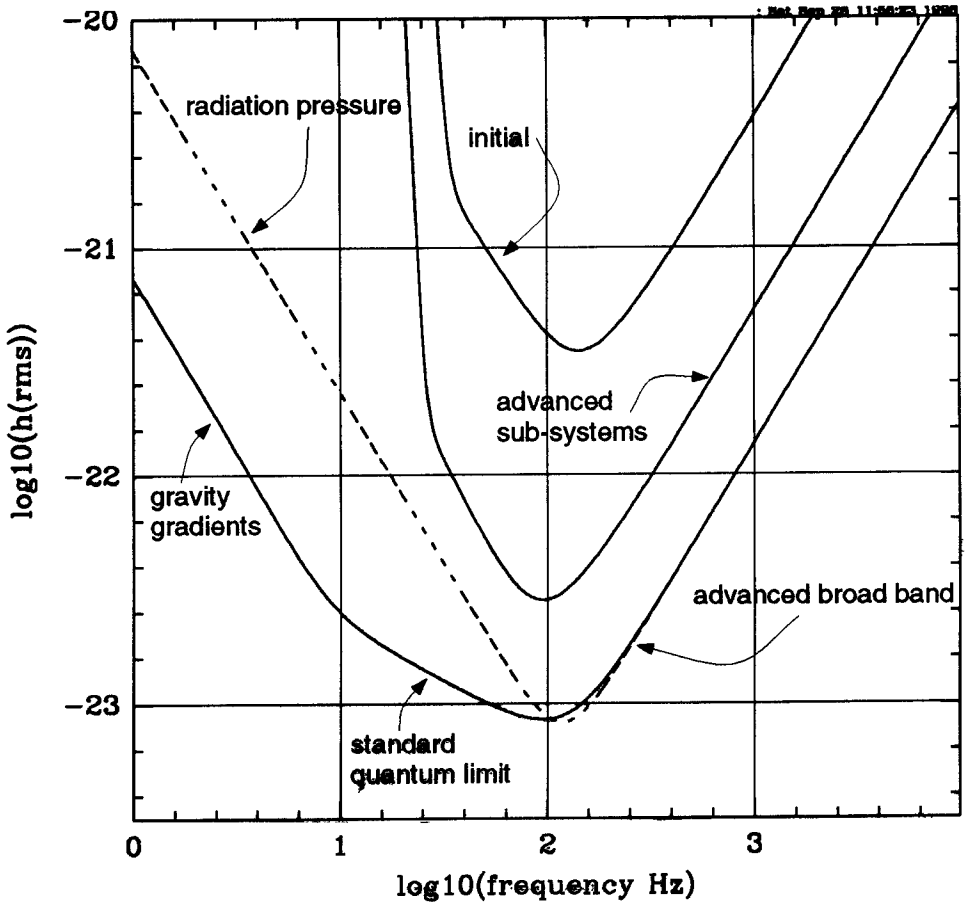
LIGO Funding by NSF Task and by Year

Fiscal Year	*Construction*	*R&D*	*Operations*	*Proposed*	*Total*
Thru 1994	35.9	11.2			47.1
1995	85.0	4.0			89.0
1996	70.0	2.4			72.4
1997	55.0	1.6	0.3		58.6
1998	27.1		7.3		37.1
1999			20.9		23.6
2000			21.1		23.8
2001		10 months >	19.1		21.7
All funds shown in 'then'-year $M					

Advanced Subsystems R&D

- Double Pendulum Suspension
- Reduced Thermal Noise
- Reduced Internal Test Mass Thermal Noise: Sapphire
- Higher Laser Power and Core Optics for Higher Power
- Increased Mass (Sapphire)

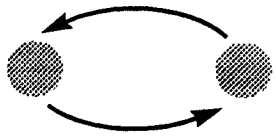
h_{rms} Noise Envelopes for Initial LIGO and Advanced Subsystems/Detectors



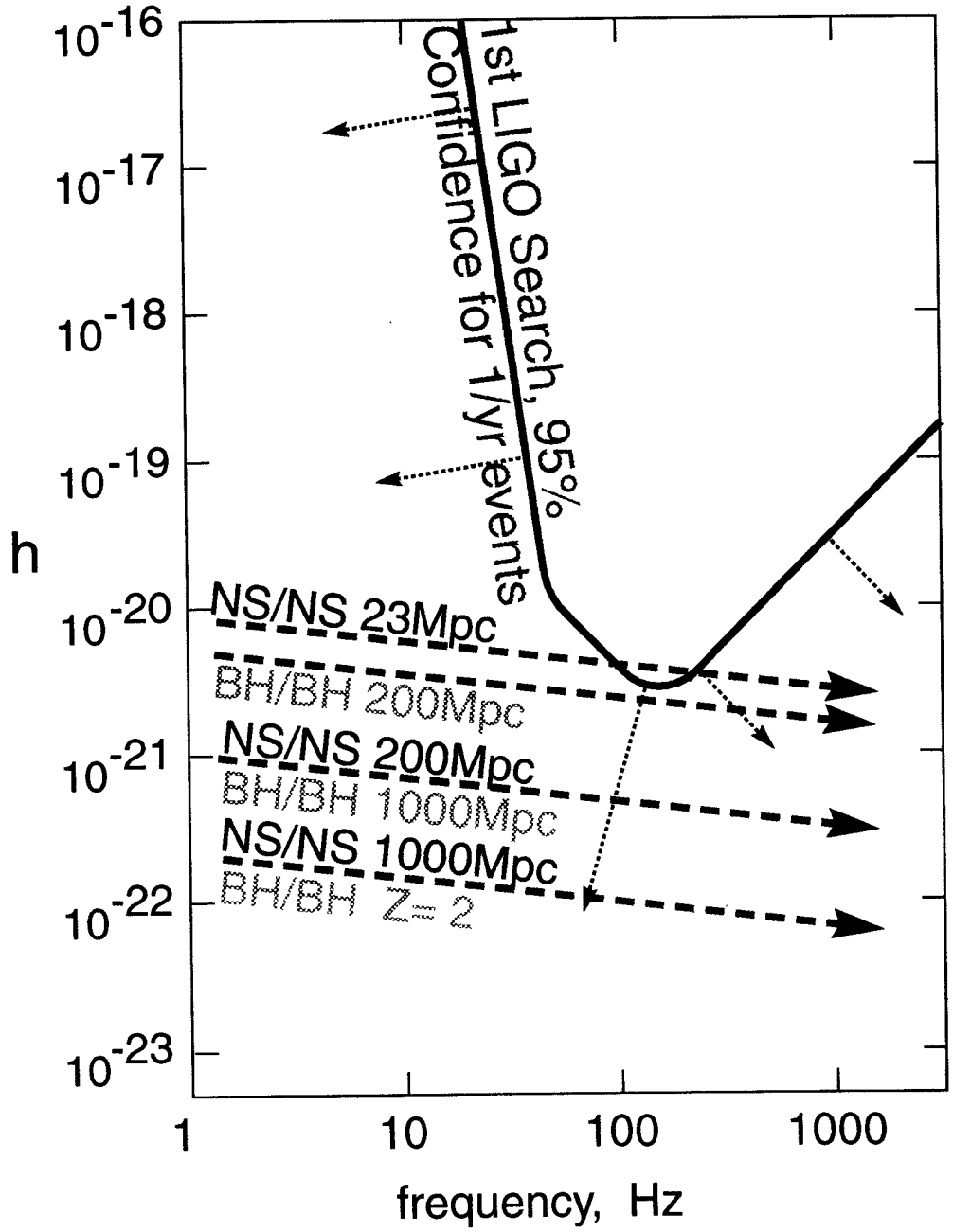
What We Propose

- A program of research to define advanced subsystems intended to be enhancements to the initial LIGO interferometers
- A program of research to define new advanced detectors
- A five year program in each thrust
  - ›› Some areas of research will enable implementation proposals
  - ›› Some research areas will not be completed and will become part of a following R&D proposal
- A program based upon the benchmark gravitational wave sources, but intended to be flexible if the course of physics research dictates a different evolution of LIGO capabilities

NEUTRON STAR BINARIES



["Near-Guaranteed" source]



- *15 minutes & 10,000 orbits in LIGO band*
- *Rich information in waveforms:*
  masses, spins, distance, direction, nuclear equation of state