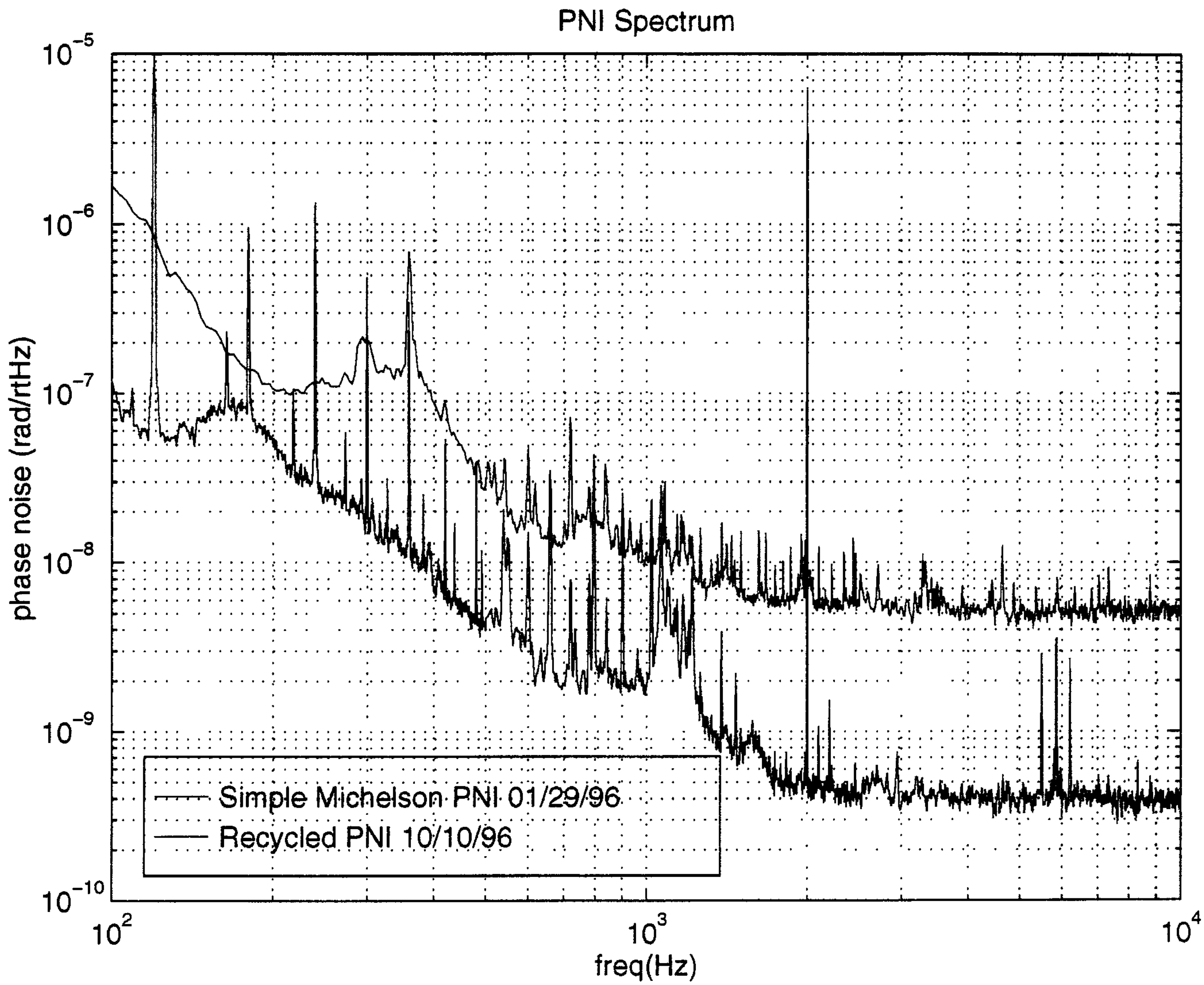
LIGO PROJECT

California Institute of Technology / Massachusetts Institute of Technology



National Science Foundation Technical Review
October 22-24, 1996 - California Institute of Technology-Pasadena, California 91125
LIGO G960215-00-M

Laser Interferometer Gravitational Wave Observatory

National Science Foundation Technical Review of the LIGO Project
October 22-24, 1996
112-114 East Bridge

Agenda
Tuesday October 22, 1996:

8:30 am - 9:00 am: Review Committee Executive Session

9:00 am - 10:00 am: Project Status/Overview - Sanders

10:00 am - 12:00 pm: Detector/ R&D Technical Status - Whitcomb/Zucker

12:00 pm - 1:00 pm: Lunch Break

1:00 pm - 2:00 pm: Advanced Detector R&D Proposal - Sanders/Thorne

2:00 pm - 3:30 pm: Facilities Technical Status - Coles

3:30 pm - 3:45 pm: Break

3:45 pm - 4:45 pm: Data Format/Analysis/Modeling - Lazzarini

6:30 pm - 8:00 pm: Dinner at Clearwater Cafe

LIGO PROJECT

California Institute of Technology / Massachusetts Institute of Technology

NSF Technical Review - October 22-24, 1996

Second Day of Review-Possible Topics for Discussion

Detector:

• Seismic Isolation Design	F. Raab, R. Vogt, HYTEC
• Suspension Design/Prototype Status	S. Kawamura, J. Hazel
• Pathfinder Polishing Results	B. Kells
• Core Optics Polishing Plan	G. Billingsley
• Coating Uniformity Testing	D. Jungwirth, H. Yamamoto, B. Kells
• 10 W Laser Status and Plans	S. Whitcomb, R. Savage
• Alignment Sensing & Control Conceptual Design	P. Fritschel, M. Zucker
• Length Sensing & Control Conceptual Design	J. Camp
• Control & Data System Global Design Data Acquisition Vacuum Controls	R. Bork, J. Heefner

R & D:

• Recycling Status & Plans	J. Logan
• PNI Status & Plans	P. Fritschel
• Alignment Status & Plans	M. Zucker
• Double Suspensions	R. Weiss
• Advanced Interferometer Configurations	S. Kawamura
• Thermal Noise Studies	R. Weiss

- Other Topics from Advanced R & D Proposal, as requested

Data Format/Analysis/Modeling:

• Data Formats for LIGO Archives	K. Blackburn
• Data Analysis Concept	A. Lazzarini/K. Blackburn
• Modeling and Simulation	H. Yamamoto

Civil Construction (WA): (O. Matherny)

- BT Slab
- Enclosures
- Buildings
- Surveying

Civil Construction (LA): (F. Asiri)

- Rough Grading
- Access Road
- Building and BT Slab Contract

Beam Tube: (L. Jones)

- Fabrication
- Installation
- LIGO Audit

Baffles: (A. Sibley)

Vacuum Equipment: (J. Worden)

- Fabrication
- Prototype First Article

Glossary of Acronyms and Abbreviations

1x/2x/3x	notation for single, double, and three-fold coincidence operational modes of the LIGO detector comprised of 3 IFOs
10BaseT	telephone type Ethernet cable
ADC	Analog-to-Digital Converter
AMU	Atomic Mass Unit
API	Application Programmer Interface
AS	Alignment System
ASC	Alignment Sensing and Control
ATM	Asynchronous Transfer Mode (inter-processor communications pr
BAC	Budget At Completion
BCU	Beam Control Unit
BNWL	Battelle Northwest Laboratories
BSC	Beam Splitter Chamber
BT	Beam Tube
BTD	Beam Tube Demonstration
BUDG	Budget
CA/NS	Control Area and Networking System
CACR	Center for Advanced Computing Research (Caltech)
CAM	Control Account Manager
CAP	Control Account Plan
CBI	Chicago Bridge & Iron
CCB	Change Control Board
CCD	Charge Coupled Device
CDF/HDF	Common/Hierarchical Data Format
CDR	Conceptual Design Review
CDRL	Contract Data Requirements List
CDS	Control and Data System
CDS/DAQ	Computer & Data Systems Data Acquisition System
CNTR	beam Centering Alignment System
COC	Core Optics Components
COS	Core Optics Support
COTS	Commercial Off-The-Shelf software
CPU	Central Processing Unit
CSIRO	Commonwealth Scientific & Industrial Research Organization
CSR	Center for Space Research (MIT)
DAC	Digital-to-Analog Converter
DCC	Document Control Center
DCCD	Design Configuration Control Document
DEC/SUN	Computer Manufacturers: Digital Equip.Corp/SUN Microsystems,
DMA	Direct Memory Access
DOE/ESNET	Dept. of Energy/Energy Sciences Network
DOF	Degree of Freedom
DRD	Data Requirement Description
DRR	Design Requirements Review
DSP	Digital Signal Processor
EAC	Estimate At Completion
EFINISH	Early Finish
EPICS	Experimental Physics and Industrial Control System
ESTART	Early Start
ETC	Estimate to Complete
FAB	Fabrication
FDR	Final Design Review
FFT	Fast (Discrete) Fourier Transform
Fiber Channel	255 Mbit per second communications network
FIFO	First In, First Out Method of reading data written to dynamic
FMI	Fixed Mass Interferometer
FSSC	Frequency-Shifted Subcarrier generator
GCDS	Global CDS Functions
GO	General Optics (Company Name)
GPIB	General Purpose Interface Bus

GPIB	General Purpose Interface Bus
GPS	Global Positioning System
GUI	Graphical User Interface
GW	Gravitational Wave
HAM	Horizontal Access Module
HDOS	Hughes Danbury Optical Systems (Company Name)
HEP	High Energy Physics
HNR	Hanford Nuclear Reservation (LIGO Site)
HYTEC	Company Name
I/O	Input/Output
IAS	Initial Alignment System
IFO	Interferometer
IFODAQ	Interferometer Data Acquisition
IOC	Input/Output Controller
IOO	Input/Output Optics
IPAC	Image Processing & Analysis Center (Caltech)
IPS	Integration Project Schedule
IR	Infrared
ISC/ASC/LSC	Interferometer/Alignment/Length Sensing & Control Systems
JPL	Jet Propulsion Laboratory
kB/MB/GB/TB	kilo-/mega-/giga-/terabyte: 10^3/10^6/10^9/10^12 bytes
kFLOP/MFLOP/GFLOPS	kilo/Mega/Giga Floating Point Operations per second
kpc	3 x 3^3 lightyear (kiloparsec)
LA	Louisiana
LAN	Local Area Network
LIGO	Laser Interferometer Gravitational-Wave Observatory
LN2	Liquid Nitrogen
LNT2	Liquid Nitrogen Trap No. 2
LOS	Large Optic Suspension
LRC	LIGO Research Community
LSC	Length Sensing and Control
LSU	Louisiana State University
LVDT	Linear Variable Differential Transducer
LVEA	Laser/Vacuum Equipment Area
MIMO	Multiple Input, Multiple Output
MOPA	Master Oscillator, Power Amplifier
NPRO	Nonplanar Ring Oscillator
NIST	National Institute of Standards and Technology
NS	Neutron Star
NSB	National Science Board
NSF	National Science Foundation
OPI	Operator Interface
OptLev	Optical Lever Alignment System
OSEM	Integrated Optical Position Sensor/ElectroMagnetic driver
PAC	(LIGO) Program Advisory Committee
PDR	Preliminary Design Review
PDRR	Preliminary Design Requirements Review
PEM	Physical Environment Monitoring System
PERF	Performance
PLC	Programmable Logic Controller
PM	Project Manager
PMB	Performance Measurement Baseline
PMCS	Project Management Control System
PMDAQ	Physical Environment Monitor Data Acquisition
PNI	Phase Noise Interferometer
POSIX	established industry standard for software/hardware interface
PSI	Process Systems International
PSL	Prestabilized Laser
PZT	Piezo-electric Transducer
QT	Qualification Test
QTR	Qualification Test Review
RAID	Redundant Array of Inexpensive Disks
RAM	Responsibility Assignment Matrix
RDIAG	Remote Diagnostics
REO	Research Electro-Optics (Company Name)

RF	Radio Frequency
RFP	Request for Proposal
RGA	Residual Gas Analyzer
s	Second
SC	Supercomputer(ing) Center(s)
SEI	Seismic Isolation
SI	Seismic Isolation
SNR	Signal-to-Noise Ratio
SOS	Small Optic Suspension
SPARC	Scaled Processor Architecture
SS20	SunSparc 20 workstation
SUR	IBM's Sponsored University Research Grants Program
SQL	Standard Quantum Limit
SQRT	Square Root
STACIS	(Product Name)
SUP	Support Equipment
SUS	Suspension System
SYS	Systems Engineering
T	Time
TAMA	Japanese Interferometric Gravitational-Wave Detector Project
TCP/IP	Transmission Control Protocol/Internet Protocol
TF	Total Float
TLA	Three-letter Acronym
TMC	Test Mass Chamber
TWIDDLE	name of a particular modelling code within LIGO
UTC	Universal Time Code
VAC	Vacuum System Controls
VBNS	NSF counterpart to DOE's ESNET
VE	Vacuum Equipment
VEA	Vacuum Equipment Area
VFC	Vacuum Feedthroughs and Cabling
VIRGO	Italian-French Laser Interferometer Collaboration
VME	Versa Modular Eurocard (IEEE 1014)
VXI	VME eXtensions for Instrumentation
VxWorks	a real time operating system for VME based systems
WA	Washington
WAN/LAN	Wide/Local Area (Computer) Network
WBS	Work Breakdown Structure
WFS	Wavefront Sensing
WP	Work Package
WVFNT	Wavefront Alignment System
XCVR	Transmitter/Receiver

LIGO Project Status

Gary Sanders

NSF Technical Review

October 22-24, 1996

This Talk

- Technical Status
- Cost/Schedule Status
  - ››covered mainly in this talk as emphasis in this review is technical
- Evolution of LIGO Organization
  - ››LIGO Collaboration and LIGO Laboratory
  - ››LIGO Program Advisory Committee

LIGO Construction is 34% complete!

Technical Highlights - Vacuum Equipment

- Vacuum Chambers
  - ›› First BSC article built and tested, outgassing data available
  - ››PSI has placed full BSC chamber contracts and is fabricating HAM chambers in-house
- Gate Valves
  - ›› First two large valves are on site
    - – One is installed on slab
  - ›› Much learned during first article testing of operation and shock
- Pump sets, bellows, bakeout equipment, etc. now being fabricated
  - ›› Deliverables for Hanford Beam Tube installation are nearly complete

Vacuum Equipment System Cartoon

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Beam Splitter Chamber

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48" Gate Valve Body

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Technical Highlights - Beam Tube

- Beam Tube Fabrication is qualified and underway in the field
  - materials conformance, spiral welding, other welding, leak checking, and cleaning have been qualified, verifying major technical risks are under control
  - ~50 tubes fabricated and no leaks in 28 checked
- Installation is ready to proceed
  - Installation Readiness Review successfully completed last Thursday
- 300 baffles ready for installation at Hanford
- CB&I team performing very well and LIGO team witnessing all operations .

Big Pasco CB&I Fabrication Plan View

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Stainless Steel Delivery

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Spiral Mill

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Stiffening Ring Welding

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Segment Vacuum Testing Cask

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Expansion Joint at Fab. Readiness Review

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Weiss Lecturing to CB&I Boilermakers

Installation Cartoon Plan View

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Installation Cartoon Detail

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Technical Highlights - Hanford Civil Construction

- Hanford beam tube enclosures construction very far along
  - ~1400 enclosures fabricated, rejection rate ~1%
- Hanford site concrete work nearly done
- Hanford buildings construction 7% complete

Beam Tube Enclosures at Fab. Site - Aerial View

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Enclosure Segment Installation

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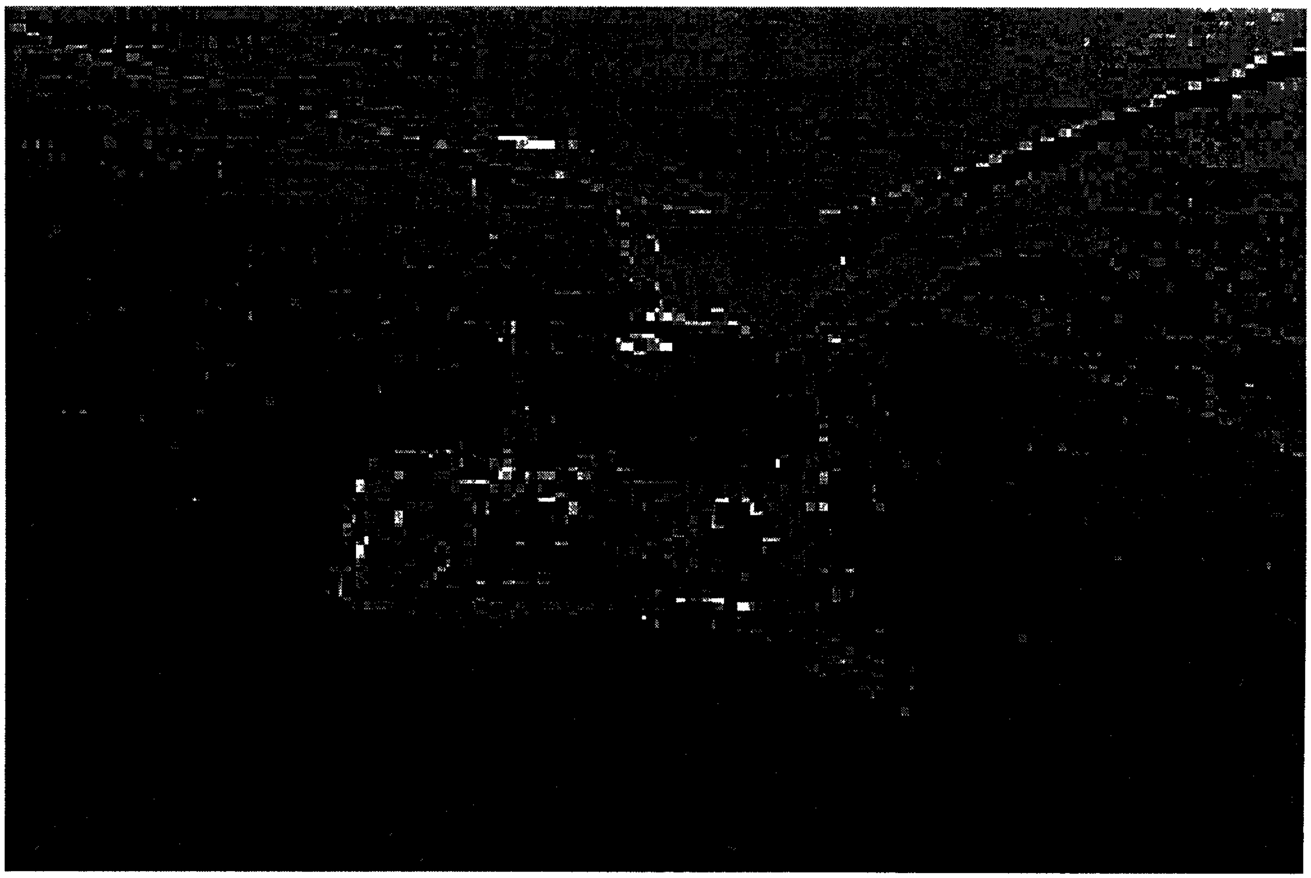
LVEA Aerial View



Technical Highlights - Livingston Construction

- Livingston rough grading essentially complete (The rain is not mainly in Spain!)
- Livingston concrete and building packages bids opened on October 15

Contract	LIGO Cost Book	Bid Price
Slab, Enclosures, Roads, Enc. Inst.	$9.2 million	$8.8 million
Buildings	$13.39 million	$13.46

- These contracts are the last of the very large LIGO contracts, marking LIGO passage beyond major bid jeopardy
  - »we must now manage these fixed price contracts to the contract cost

Livingston Site View 1

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Livingston Site View 2

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Technical Highlights - R&D

- MIT Phase Noise Interferometer

  ››Demonstration of phase sensitivity *3.5×10^{-10} rad/√Hz,* to the best of our knowledge the highest optical phase sensitivity ever, and only a factor of 3 less than the LIGO goal

- CIT 40 Meter Interferometer

  ››Successful test of single loop suspension

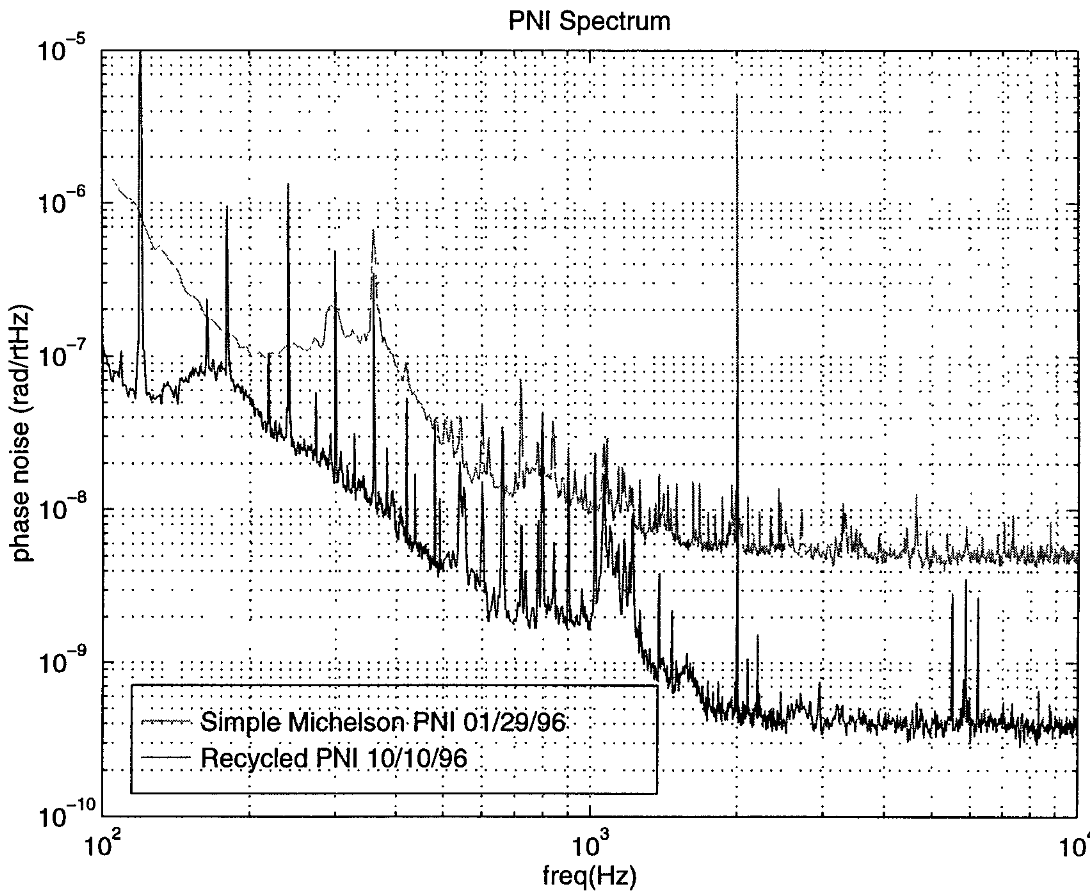
  ››Completion of optical recombination

  ››Power recycling experiment in early stages

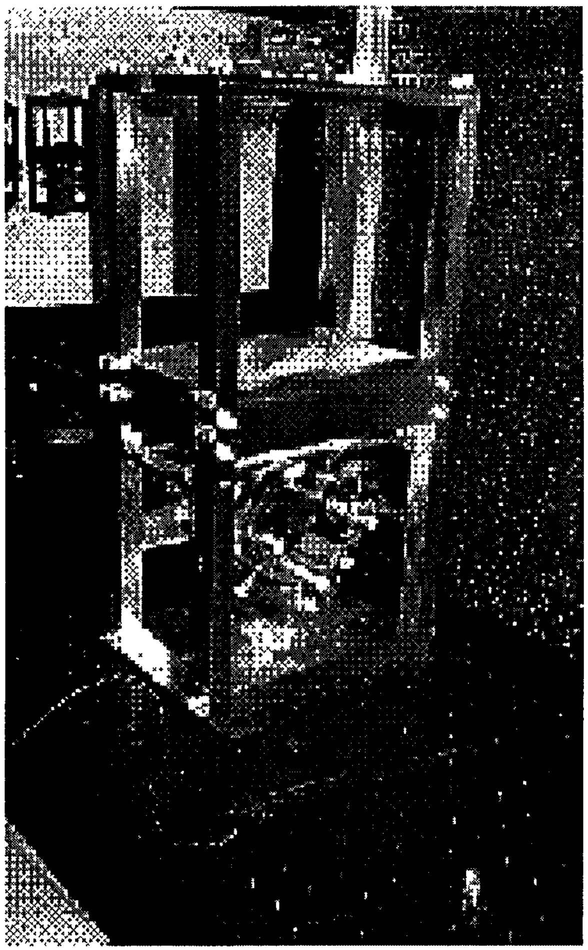
  - higher transmission vertex mirrors installed
  - vacuum, beam splitter, recycling mirror changes this winter and spring

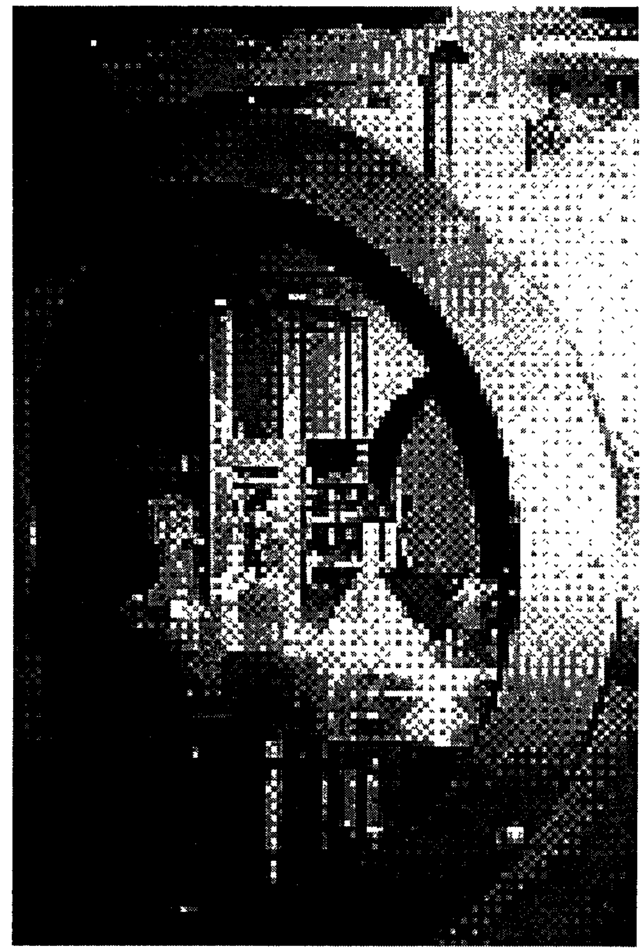
- MIT Fixed Mirror Interferometer experiment ~ complete

Phase Noise Sensitivity From MIT Interferometer



New Single Loop 40 Meter East Vertex Suspension





Technical Highlights - Detector

- 10 W laser contract started with Lightwave Electronics; breadboard unit being assembled
- Placed order for fused silica blanks for all Core Optics
- Placed order for polishing primary lot of End Test Masses
- Proposals for polishing remaining Core Optics being evaluated now

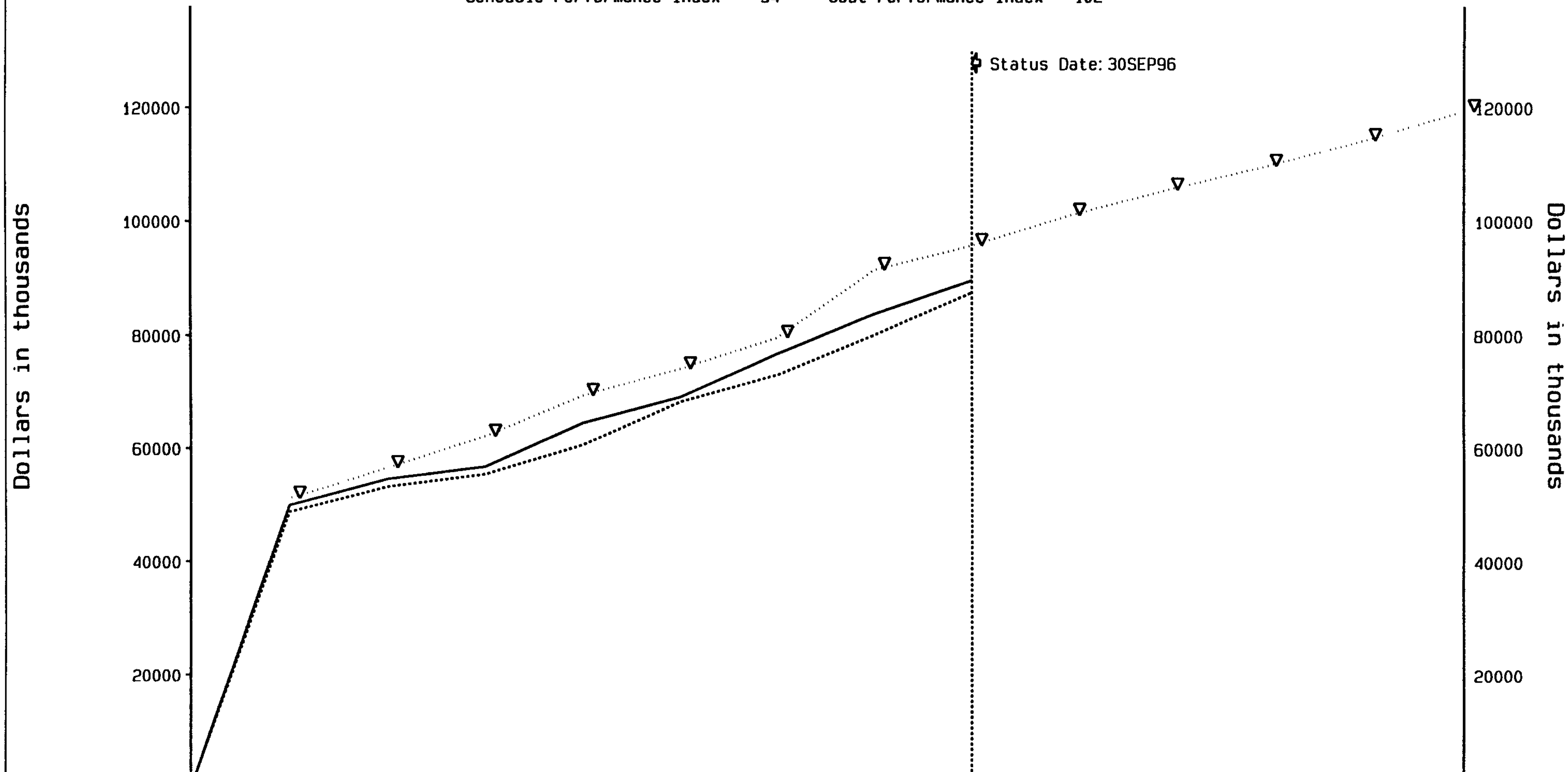
Technical Highlights - Detector

- Preliminary designs for Length and Alignment Sensing and Control Systems underway
- Preliminary mechanical design for suspensions completed and prototypes in fabrication/test
  - ››SOS prototype in test now
- Seismic Isolation Stack requirements defined and preliminary design started at HYTEC
- Preliminary design of Control and Data System global achitecture completed
- Preliminary design of Vacuum Control and Monitoring System complete and awaiting review

LEGEND	LIGO PROJECT	Date: 17OCT96
Bud ▽ / Per / Act	1 LIGO Construction	Program: PMB_0996 Report: LIGOSPA COBRA (R)

Budget vs Performance vs Actual

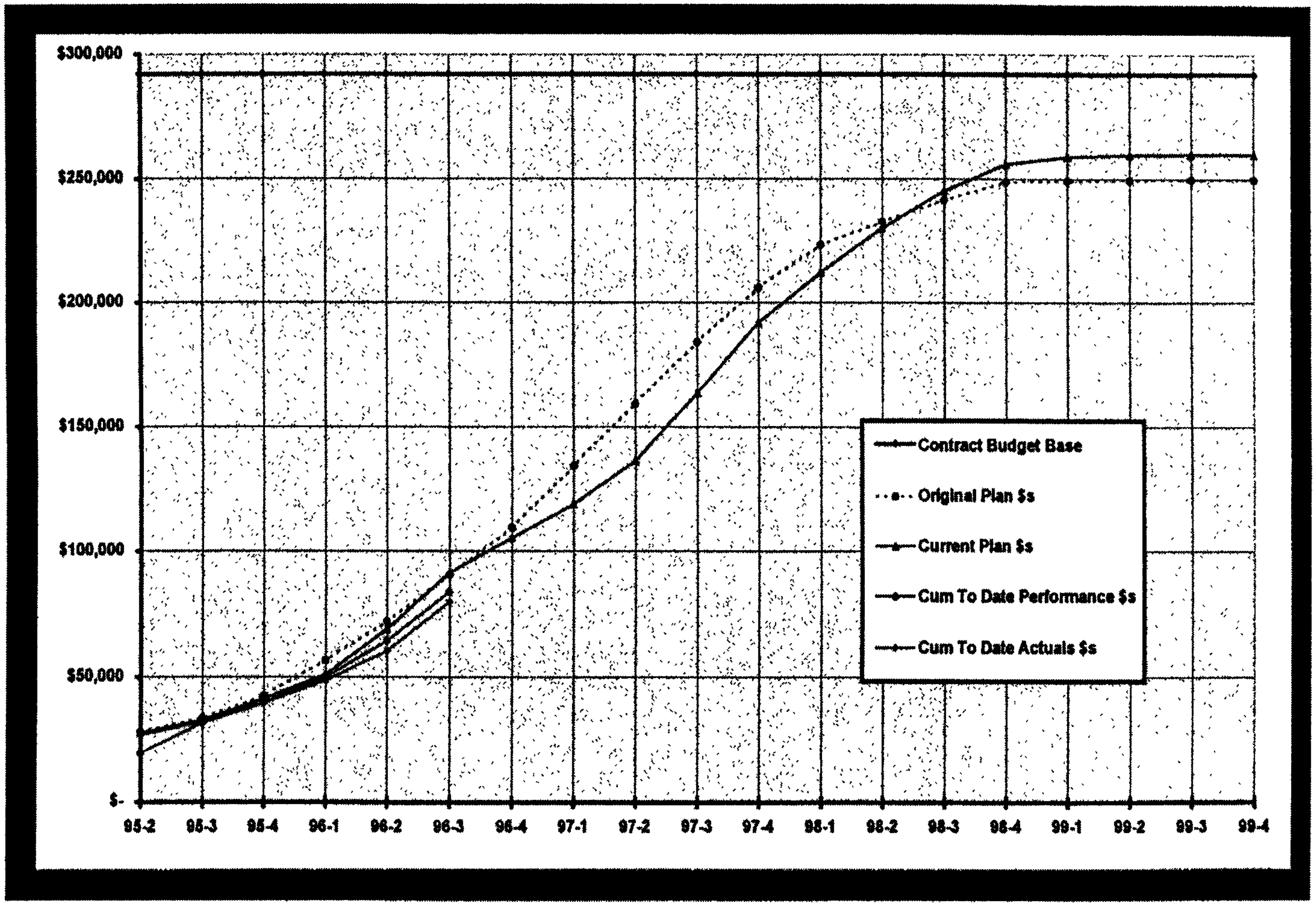
Schedule Performance Index = 94 Cost Performance Index = 102



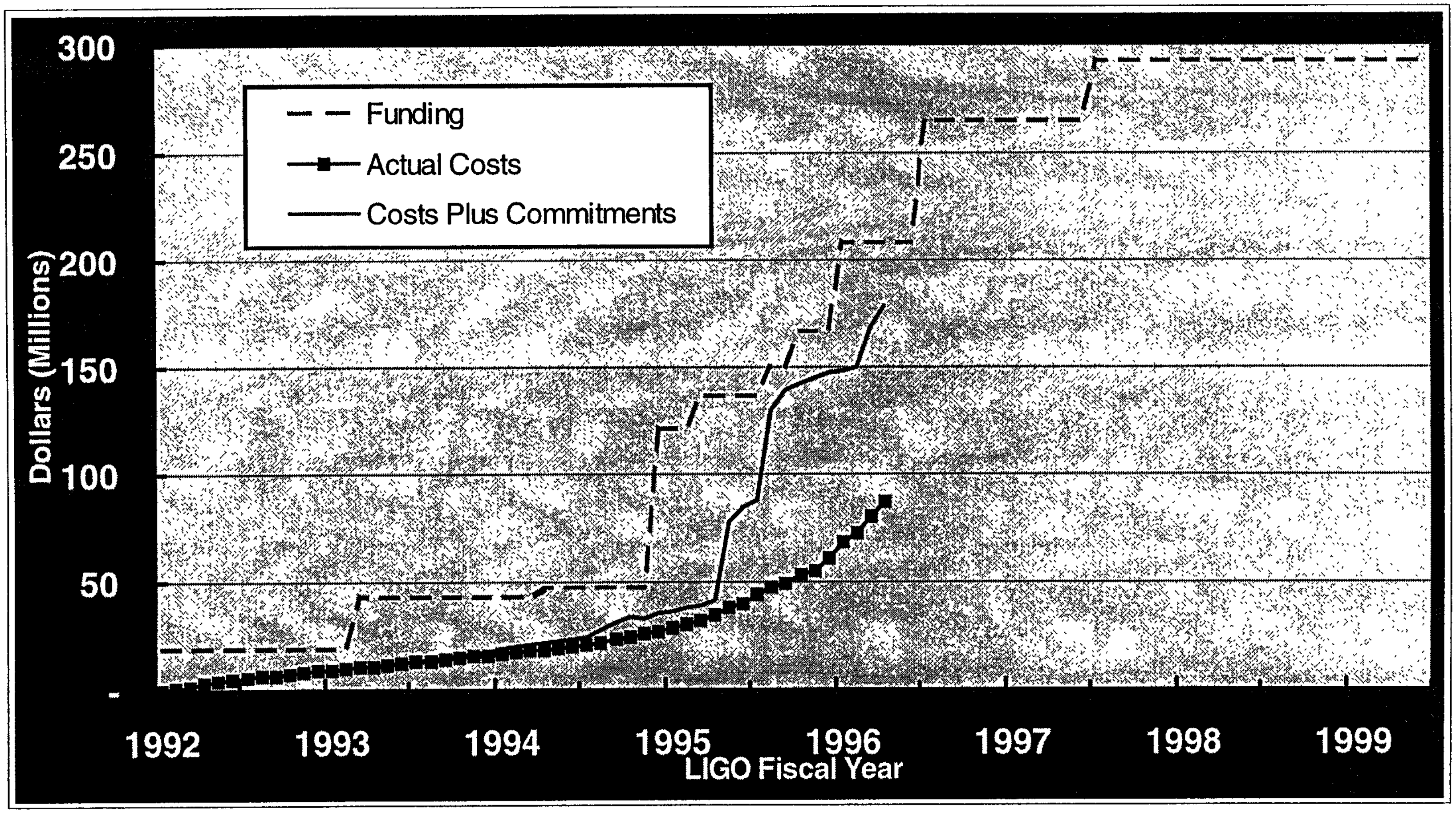
	FEB96	MAR96	APR96	MAY96	JUN96	JUL96	AUG96	SEP96	OCT96	NOV96	DEC96	JAN97	FEB97	SCALE
Planned Budget	51,168	56,547	62,162	69,351	74,102	79,650	91,525	95,667	101,052	105,543	109,719	114,256	119,309	K$
Performance	49,962	54,586	56,741	64,526	69,091	76,784	83,782	89,671						K$
Actuals	48,777	53,219	55,432	60,656	68,220	73,037	80,104	87,570						K$
Schedule Variance	-1,206	-1,961	-5,421	-4,825	-5,011	-2,866	-7,743	-5,996						K$
Cost Variance	1,185	1,367	1,309	3,870	871	3,747	3,678	2,101						K$

Schedule Variance = Perf-Budg Cost Variance = Perf-Actual Schedule Performance Index = Perf/Budg Cost Performance Index = Perf/Actual

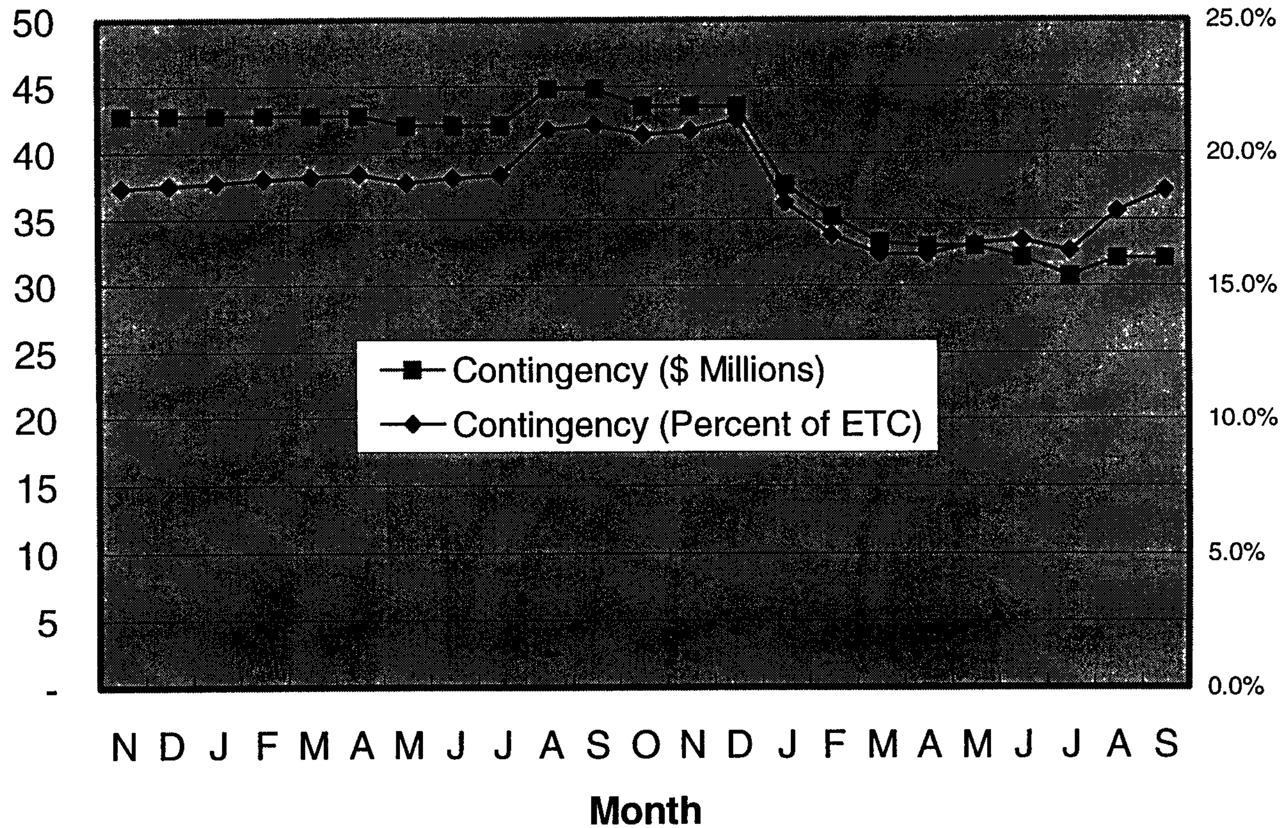
Cost Schedule Status as of End of August 1996



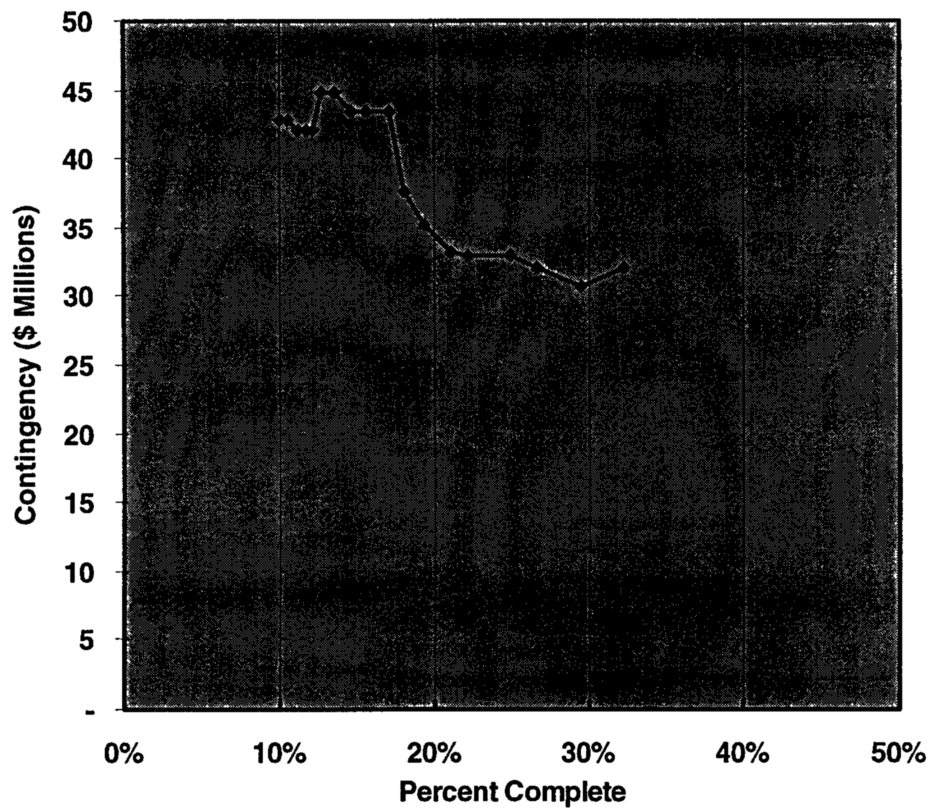
Funds, Commitments, Costs



Contingency vs. Estimate to Complete



Contingency vs. Percent Complete (through August 1996)



LIGO Funding by NSF Task and by Year

Fiscal Year	Construction	R&D	Operations	*Proposed* Advanced R&D	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	1.7	58.6
1998	27.1		7.3	2.7	37.1
1999			20.9	2.7	23.6
2000			21.1	2.7	23.8
2001		10 months >	19.1	2.6	21.7

All funds shown in 'then'-year $M

Costs and Commitments through September 1996

(All Entries are $ Thousands)

WBS	Costs Thru Nov 1995	Three Quarters LFY 1996	Sep-96	Oct-96	Nov-96	Cumulative Costs	Open Commitments	Total Cost Plus Commitments
1.1.1VacEquip	4,081	14,425	415			18,921	22,749	41,670
1.1.2 BmTube	2,736	6,822	3,862			13,420	36,575	49,995
1.1.3 BTEncl	468	3,924	947			5,339	3,568	8,907
1.1.4 Civil	6,677	4,981	1,377			13,035	19,622	32,657
1.2 R&D	2,430	2,620	258			5,308	5,529	10,837
1.3 Detector	13,321	2,963	152			16,436	1,185	17,621
1.4 ProjOffice	10,152	4,544	455			15,151	1,782	16,933
Unassigned	79	(122)	(1)			(44)	74	30
TOTAL	39,943	40,157	7,465	-	-	87,565	91,084	178,649
Cumulative Actual Costs	39,943	80,100	87,565					
Open Commitments	44,993	88,814	91,084					
Total Costs Plus Commitments	84,935	168,914	178,649					
NSF Funding	*138,089*	*208,468*	*208,468*					

Note: Unassigned costs have not been assigned to a LIGO WBS, but are continually reviewed to assure proper allocation.

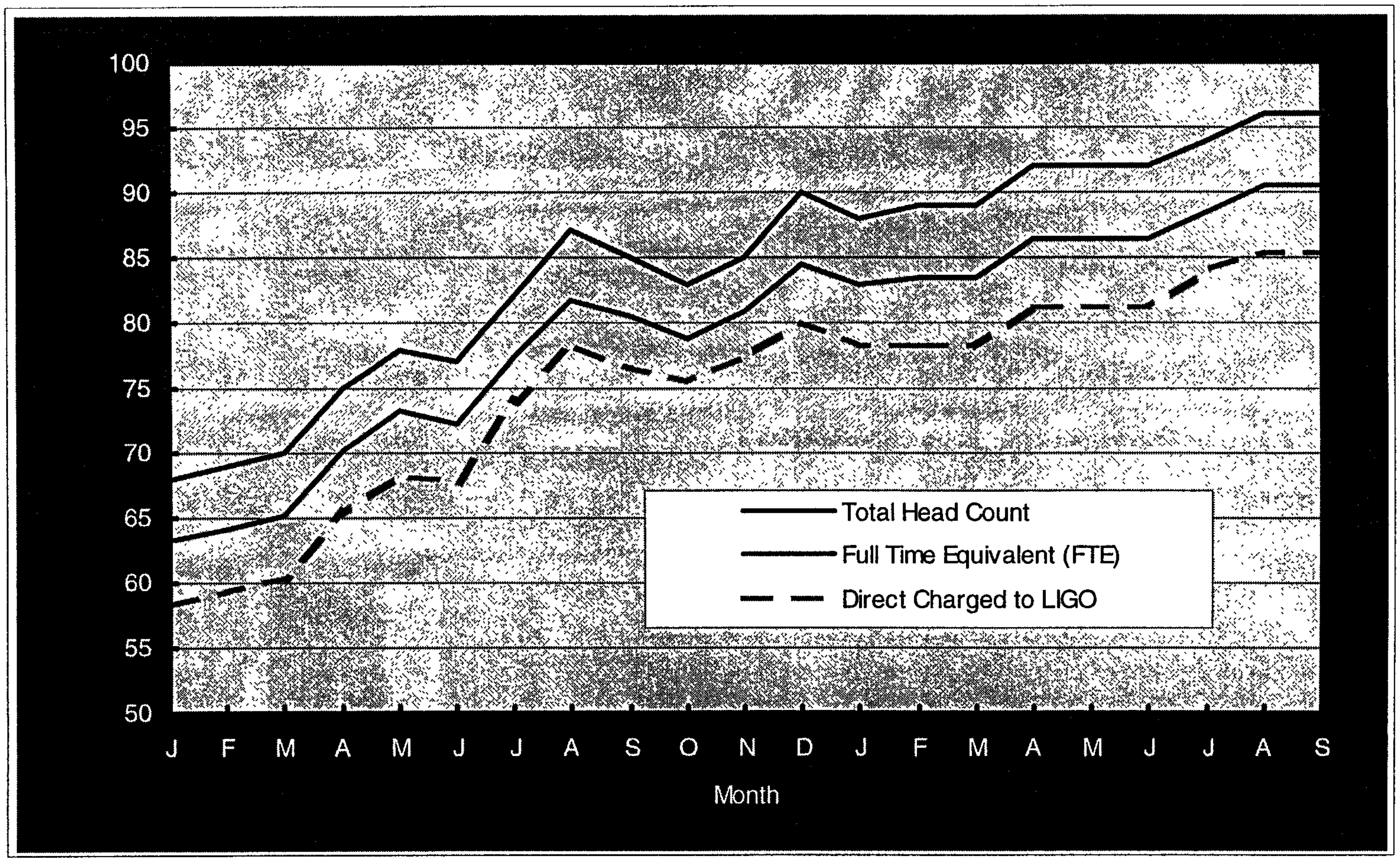
Major Subcontracts Awarded Since the Last Semi-Annual Review

Subcontract	Award Date	Award Amount	Selection Basis
Baffle Coating - West Coast Porcelain	April 1996	$163K	Competitive
Civil Construction (WA) - Levernier Construction	July 1996	$15,651	Competitive
Installation of Beam Tube Enclosures (WA) - Levernier Construction	September 1996	$1600K	Competitive
Nd3+ Lasers - Lightwave Electronics	May 1996	$735K	Competitive
Fused Silica Mirror Blanks - Heraeus Amersil (17 pieces)	August 1996	$1230K	Competitive
Fused Silica Mirror Blanks - Corning, Inc. (21 pieces)	August 1996	$360K	Competitive
Seismic Isolation Stack Development - Hytec	August 1996	$1865K	CO to Existing Contract
MIT Contract Change Orders 19 and 20	Waiting NSF Approval	$1023K	CO to Existing Contract

Major Subcontracts Planned in FY 1997 (and the remainder of this year)

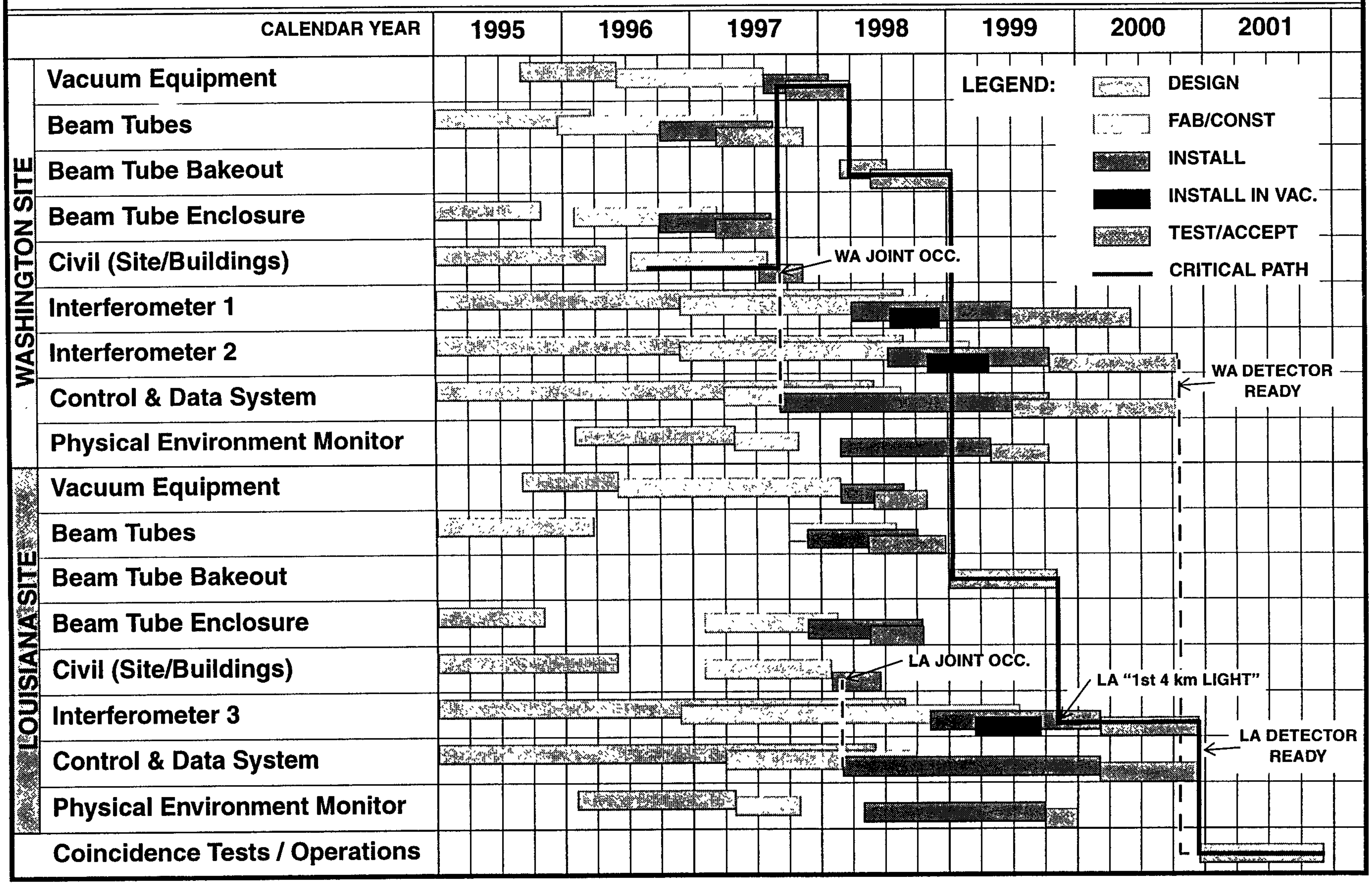
Subcontract	Award Date	Award Estimate	Selection Basis
Civil Construction (LA)	November 1996	$13,500K	Competitive
Slab, Beam Tube Enclosures, Installation of Beam Tube Enclosures (LA)	November 1996	$8820K	Competitive
Optics Polishing	October 1996	$65K	Sole Source FFP
Full Service Polishing	December 1996		Competitive FFP
Optics Coating	Spring 1997		Change Order
Detector Stack Fabrication (multiple contracts)	Winter 1997		Competitive FFP
Suspension System Fabrication	Winter 1997		Competitive FFP
IOO R&D (University of Florida)	November 1996	$300K	Sole Source Collab
Optical Modeling	Winter 1996	$200K	Change Order NTE
Metrology (NIST)	Winter 1996	$200K	Change Order NTE

LIGO Project Staffing History

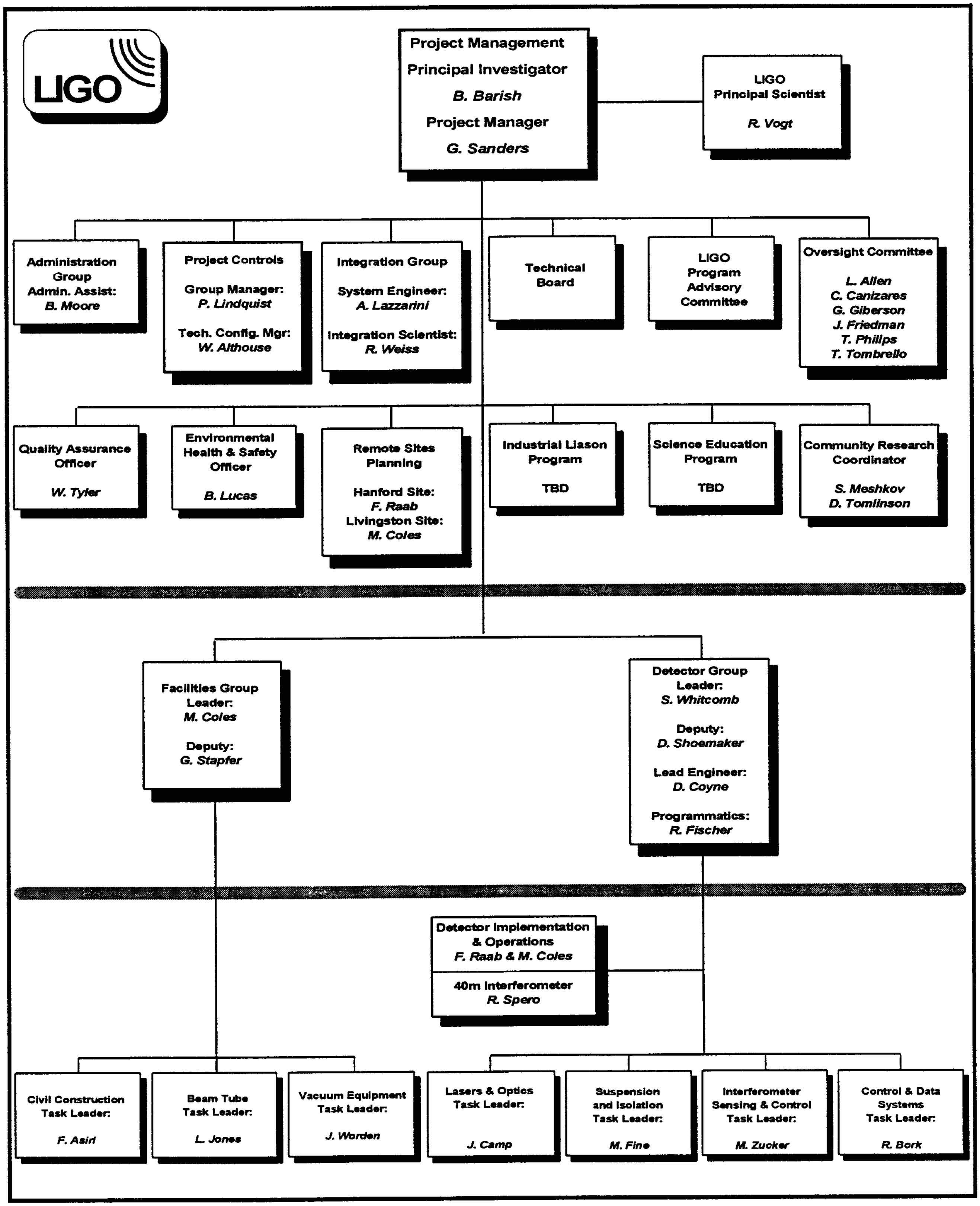


OCTOBER 1996

SUMMARY INTEGRATED SCHEDULE



LIGO Project Construction Phase Organization



Evolution of LIGO Personnel

- Since last review, remaining management positions have been filled
  - ››Jordan Camp is the Laser and Optics Task Leader
  - ››Mike Fine is the Isolation Task Leader
  - ››Dennis Coyne has assumed new role as Lead Engineer in the Detector Group
- Two new faculty members at Caltech have joined LIGO
  - ››Professor Tom Prince
  - ››Professor Ken Libbrecht

Evolution of Organization

- Hanford Site Head Fred Raab moves to Hanford mid-1997
- Otto Matherney, John Worden, Cecil Franklin, Rich Riesen currently resident in Hanford
- Rolf Bork from CDS Group moves to Hanford early in 1997
- Livingston Site Head Mark Coles moves approx. one year later
- Gerry Stapfer, Allan Sibley locate in Livingston in 1997
- Other members of LIGO are currently planning relocation to the sites
- LIGO organization and reporting will become site-based

Evolution of Organization

- Organization will evolve to reflect this
- Beam Tube bakeout predominantly executed during site-based construction period, when integration of the system is at peak
- Beam Tube bakeout planning and execution will be coordinated by Bill Althouse, in collaboration with the Integration Group, and reporting to the respective site heads during execution

››LIGO Project is proceeding to plan the beam tube bakeout and execution, but commitment is made only to execute the first module bake. Commitment to remaining three module bakeouts will be made at a point close to execution.

LIGO Collaboration / Laboratory

- NSF McDaniel Report presented a vision of a Laboratory and a Collaboration after construction
- McDaniel Report urged definition of an appropriate R&D program and of adequate computation capability

  ››Our Advanced Detector R&D Proposal is consistent with R&D recommendation

  ››Albert Lazzarini will report later in this review on LIGO efforts in modeling, data format standards, and data analysis, and our view of the future. This will introduce the LIGO study to be considered at the next NSF review in spring 1997.

Program Advisory Committee

- LIGO Program Advisory Committee (being formed now) will be the principal review/advice mechanism used in guiding LIGO's program on
  - proposals for scientific use of LIGO
  - R&D proposals
  - McDaniel Report guidance
- First meeting will be held this year, several meetings by summer

Program Advisory Committee

- Members
  - ››Bill Fraser, Chair
  - ››Paul Avery
  - ››Alain Brillet
  - ››Sam Finn (LRC)
  - ››Bill Hamilton
  - ››Peter Michelson
  - ››Peter Saulson
  - ››Robbie Vogt
  - ››and others that round out the committee, currently considering our invitation

Summary of Technical Status

- Vacuum Equipment contractor is underway, all materials ordered, first article fabrication successful, designs validated, contract about 50% complete. Major technical issues resolved. ✔
- All major beam tube fabrication processes now qualified. Fabrication in progress. ✔
- All major beam tube installation processes have been successfully reviewed for readiness. Installation begins this week. ✔
- Beam tube baffle design, performance, fabrication processes qualified and in production. ✔

Summary of Technical Status

- Hanford slab construction complete and meets LIGO requirements. ✔
- Hanford beam tube enclosure proceeding on schedule and enclosures and installation have been qualified. ✔
- Hanford building construction 7% complete and no significant issues developed. ✔
- Livingston rough grading nearing completion and first surveys appear to meet our requirements. ✔
- Livingston early soil settlement appears very slow and very slight. ✔

Summary of Technical Status

- All facility design, integration and interface issues appear to be well within design envelope. ✔
- Phase Noise measurement has set a record. ✔
- New suspension design successfully tested at 40 Meter. ✔
- Fixed Mirror Experiment nearing completion. ✔
- Laser breadboard unit in fabrication. ✔
- Industry ready to produce blanks, polishing, coating meeting LIGO requirements. ✔
- SOS prototype successfully tested. ✔

Summary of Technical Status

- Seismic stack baseline and superior alternate designs progressing. ✔
- Preliminary design processes complete for suspensions, CDS global, Vacuum Control System. ✔

LIGO Construction is 34% complete!

NSF Review -

Detector and R&D

S. Whitcomb

22 October 1996

Outline

- Overview (detector organization update)
- R&D progress and accomplishments (Mike Zucker)
- Detector progress and status
- Response to committee recommendations

LIGO Detector Organization

Detector Group Leader: *S. Whitcomb*

Deputy: *D. Shoemaker*

Lead Engineer: *D. Coyne*

Programmatics: *R. Fischer*

Implementation / Operations *F. Raab & M. Coles*

40m Interferometer *R. Spero*

Lasers & Optics Task Leader: *J. Camp*

Suspension and Isolation Task Leader: *M. Fine*

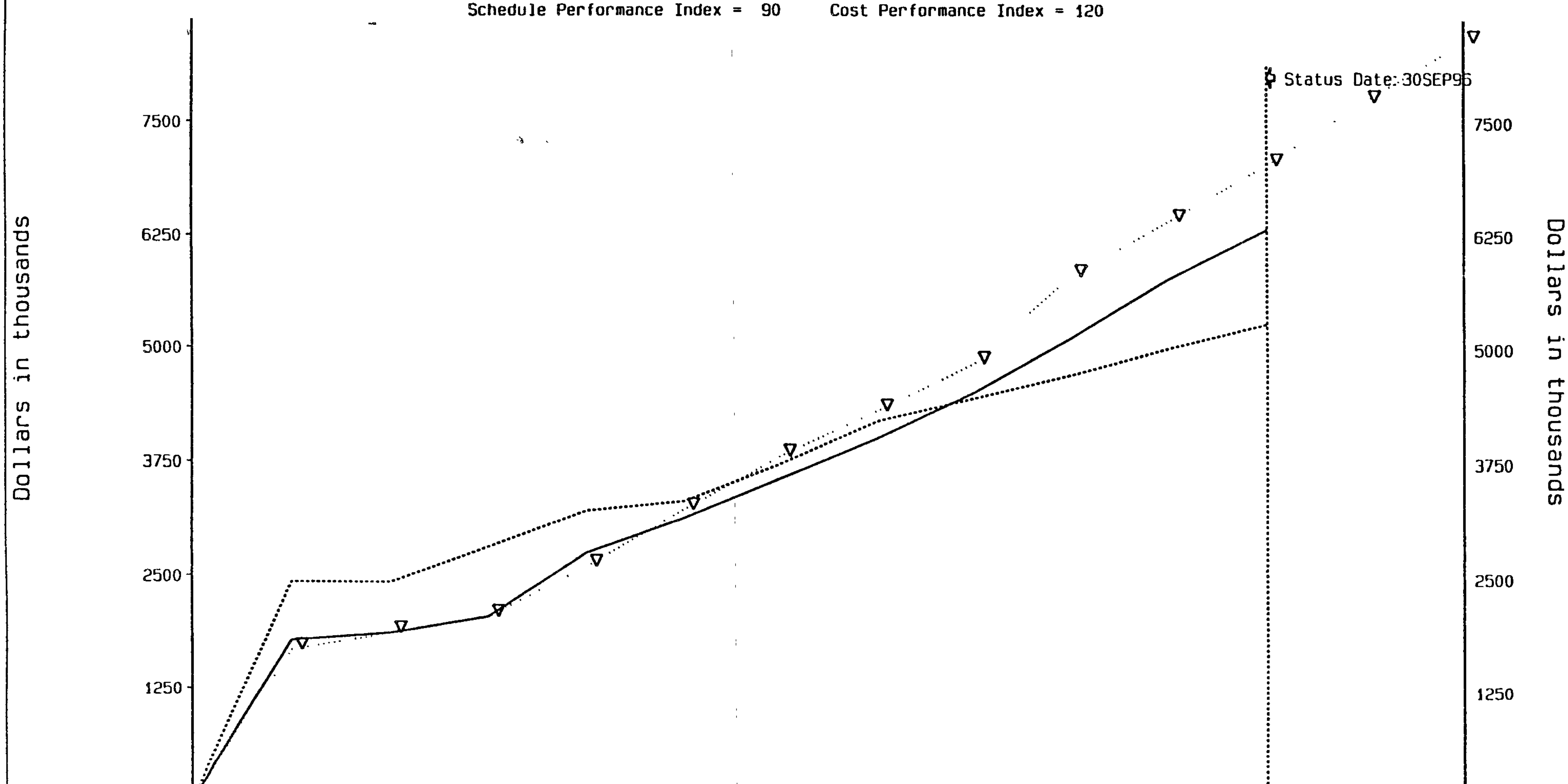
Interferometer Sensing & Control Task Leader: *M. Zucker*

Control & Data Systems Task Leader: *R. Bork*

LEGEND	LIGO PROJECT	Date: 15OCT96
Bud ▽ ▽ ▽	1.2 Detector	Program: LIGOPMB2
Per		Report: LIGOSPA
Act		COBRA (R)

Budget vs Performance vs Actual

Schedule Performance Index = 90 Cost Performance Index = 120



	FY95	DEC95	JAN96	FEB96	MAR96	APR96	MAY96	JUN96	JUL96	AUG96	SEP96	OCT96	NOV96	SCALE
Planned Budget	1,679	1,871	2,054	2,610	3,236	3,820	4,314	4,839	5,804	6,421	7,036	7,732	8,382	K$
Performance	1,791	1,872	2,054	2,759	3,141	3,582	4,013	4,521	5,117	5,780	6,322			K$
Actuals	2,429	2,429	2,820	3,218	3,330	3,738	4,199	4,456	4,713	5,011	5,269			K$
Schedule Variance	112	1	0	149	-95	- 238	- 301	- 318	- 687	- 641	- 714			K$
Cost Variance	- 638	- 557	- 766	- 459	- 189	- 156	- [illegible]86	65	404	769	1,053			K$

Schedule [illegible]iance = Perf-Budg Cost Variance = Perf-Actual Schedule [illegible]formance Index = Perf/Budg Cost Performance Index = Perf/A.

Key Near Term Detector Activities-----SEP96

10/17/96

Activity Identification	Milestone Description	Plan Dates	Current Month End Status SEP96	Schedule Change	Status
12009100	Award Contract for Nd:YAG Laser Development	Jun-96	May-96	20	Complete
12045020	PDR for Optics Suspension System	Jun-96	Jun-96	0	Complete
12033425	DRR II Alignment Sensing Control	Jun-96	Aug-96	-40	Complete
12003020	Test of new Suspension Design on 40m	Jul-96	Aug-96	-20	Complete
12085065	PDR for Global CDS	Jul-96	Sep-96	-30	Complete
12039059	Core Optics Polishing Procurement	Dec-96	Oct-96	40	
12009020	Completion of Nd: YAG Master Oscillator Stabilization	Aug-96	Nov-96	-60	
13220442	Completion of PNI recycling experiments (with AR Laser)	Aug-96	Dec-96	-80	
12024075	PDR for Length Sensing Control	Oct-96	Dec-96	-33	
12039122	Demonstration of Coating Uniformity	Dec-96	Dec-96	0	
12033445	PDR for Alignment Sensing Control	Oct-96	Jan-97	-52	
12057020	PDR for Seismic Isolation Stacks	Jan-97	Jan-97	0	
13221935	First Operation of 40m with Recycling Mirror	Apr-97	Mar-97	20	
12012120	IR PSL FDR	Apr-97	Apr-97	0	
12062035	PDR for Data Acquisition System	Mar-97	May-97	-45	

R&D Progress

see presentation G960219-00-D by

Mike Zucker

Detector System Engineering: Progress and Status

- **Set of consistent detector subsystem requirements developed and nearly ready for review**
- **Several inter-subsystem trade studies in progress**
  - ››Suspension drive range vs. Seismic isolation actuation
- **Definition of key detector-wide parameters**
  - ››Optical configuration, modulation frequencies, cavity lengths
  - ››Wedge angles for Core Optics
  - ››Parameters for 2 km interferometer

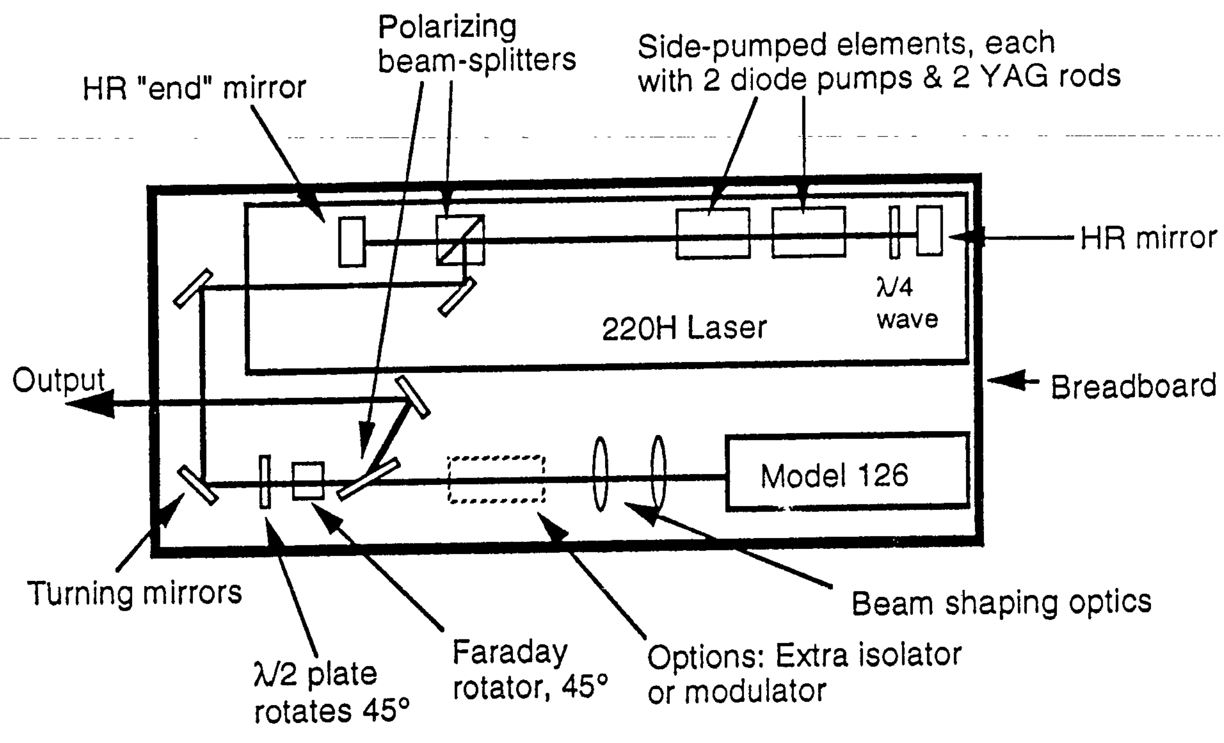
Nd:YAG Laser: Progress and Status

- **Goal: Develop 10 W diode-pumped Nd:YAG laser suitable for LIGO**
  - ››Single Frequency
  - ››Diffraction-Limited, Single Transverse Mode
  - ››Intensity and Frequency Stabilization
- **Contract awarded to Lightwave Electronics for 10W laser**
  - ››Proposed MOPA design using commercial 700 mW NPRO laser as Master Oscillator
- **Started parallel effort in-house to stabilize Lightwave NPRO for use on PNI and 40 m interferomerers**
- **Experience will be directly applicable to 10W laser**

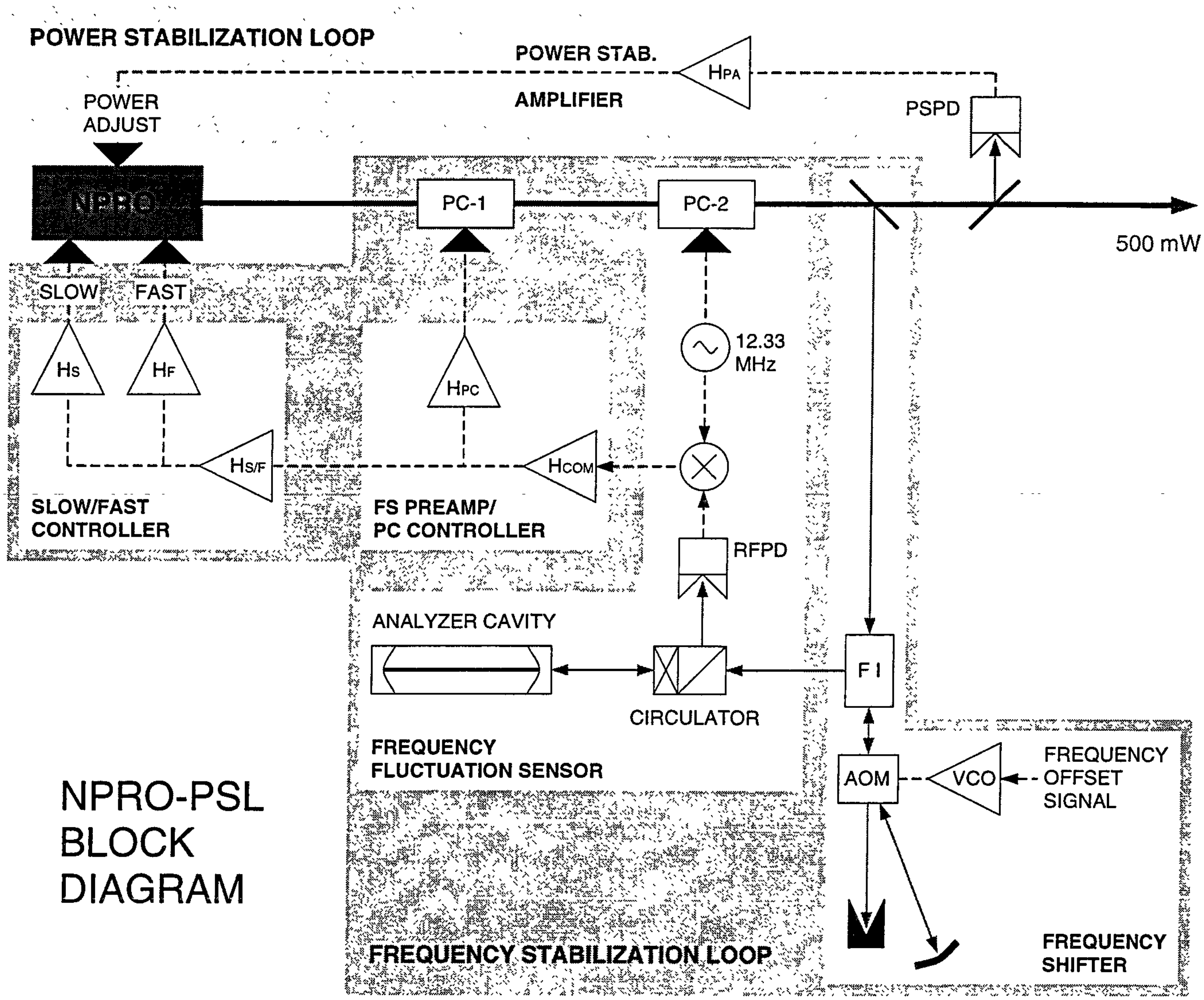
Nd:YAG Laser:
Lightwave MOPA Design

- **4-Pass amplifier using polarization to extract final pass**
- **Based on existing commercial lasers**

System configuration:
Co-linear beams with Polarization and directional multiplexing



Nd:YAG Laser: NPRO Stabilization



NPRO-PSL
BLOCK
DIAGRAM

Input Optics:
Progress and Status

- Change to infrared forced delay in Input Optics design
- Collaboration being established with University of Florida, with UF group taking responsibility for Input Optics
- Refined scope of Input Optics to simplify interfaces to other subsystems for UF group
- Extended visits to LIGO by senior UF staff (Tanner and Reitze) to kickoff design effort
- Revew of requirements and conceptual design scheduled for November 7

Core Optics: Progress and Status

- **Specification written and orders placed for fused silica blanks for core optics (>400 kg)**
- **Pathfinder polishing investigation completed**
    - ››Comparative measurements made at NIST and REO
    - ››Three polishers qualified for LIGO polishing
- **One polishing order placed (End Test Masses), remaining polishing proposals being evaluated**
- **Coating uniformity test apparatus and analysis developed, preliminary uniformity data encouraging**

Core Optics: Pathfinder Polishing Results

- **NIST measurements of surface figure errors**

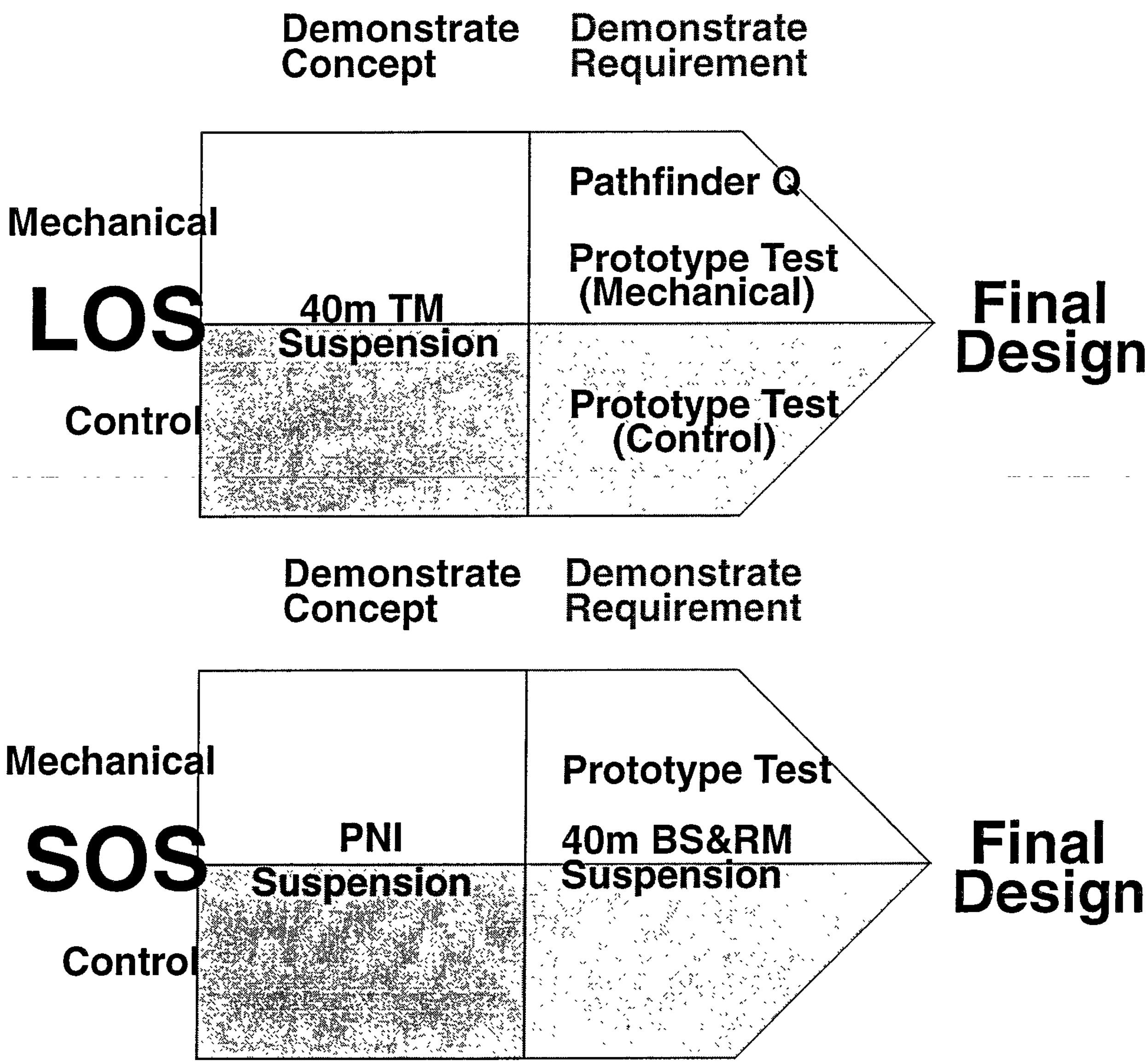
Core Optics: Pathfinder Polishing Results

- **Comparative surface roughness measurements made at REO**

Suspension Design: Progress and Status

- **Preliminary Design completed and reviewed**
- **Final design underway**
- **Small Optics Suspension (SOS)**
  - ››Suitable for mode cleaner mirrors, other small components
  - ››Prototype fabricated, being tested (Available for demo tomorrow)
- **Large Optics Suspension (LOS)**
  - ››Designed for Core Optics
  - ››Prototype being fabricated

LIGO Suspension: Design Heritage



Extrapolation to the LIGO

Large Optics Suspension (LOS)

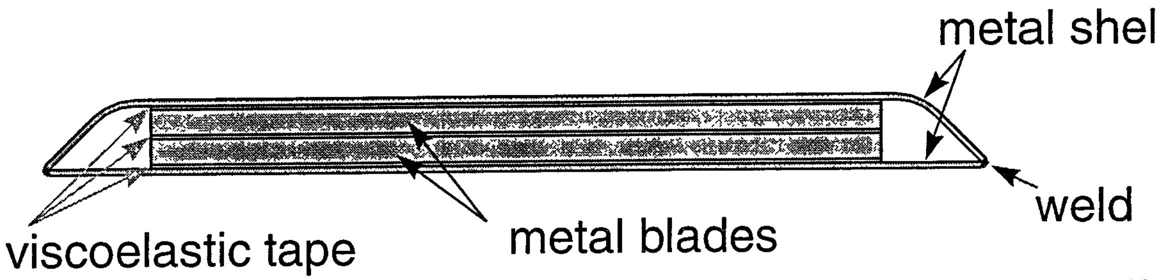
Items	40m TM Suspension or Pathfinder Q measurement	Extrapolated to LIGO	LIGO Requirements
Residual Q when damped	< 3	< 3	< 3
Internal Mode Loss	3×10^{-7}	3×10^{-7}	$< 4 \times 10^{-7}$
Pendulum Mode Loss	2×10^{-5} (Violin Mode)	7×10^{-6}	$< 7 \times 10^{-6}$
Actuator Range ($f < 0.15$ Hz)	$44\ \mu m_{pp}$	$8\ \mu m_{pp}$	$> 80\ \mu m_{pp}$
Driver Noise (at 40 Hz)	$6 \times 10^{-19} m/\sqrt{Hz}$	$9 \times 10^{-20} m/\sqrt{Hz}$	$< 5 \times 10^{-20} m/\sqrt{Hz}$
Sensor Noise (at 40 Hz)	$4 \times 10^{-20} m/\sqrt{Hz}$	$4 \times 10^{-20} m/\sqrt{Hz}$	(Option) $< 5 \times 10^{-20} m/\sqrt{Hz}$

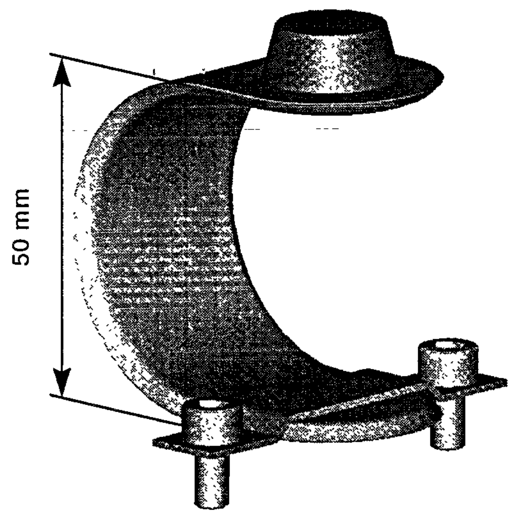
Seismic Isolation: Progress and Status

- **Requirements and conceptual design completed and reviewed**
- **Contract given to HYTEC to perform design of seismic isolation system**
- **Trade study to investigate constrained layer metal springs yielded two promising designs**
  - ››Prototypes to investigate fabricability and performance under construction
- **Preliminary design continuing in parallel with spring development**

Metal Spring Concept: Constrained Layer Coil Spring

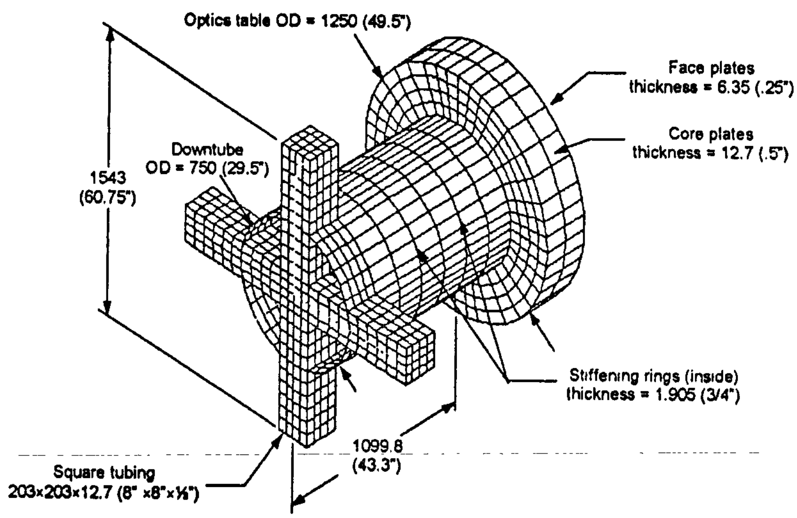
Metal Spring Concept: Semicircular Leaf Spring





Seismic Isolation: Preliminary Design

- **Detailed modal analysis of seismic isolation structures**



- **Working with vendors to improve fabricability and cost**
- **Current seismic stack weight estimates**

Chamber Type	Original LIGO Estimate	Current HYTEC Estimate
HAM	6850 lbs	3835 lbs
BSC	13020 lbs	6321 lbs

Seismic Isolation: Design Issues

- **Vacuum penetrations (bellows)**
  - ››Large range of motion
  - ››Constrained volume
- **Q of stack resonances**
  - ››Important to get test data from constrained layer springs
- **Actuators for "Drift Compensation"**
  - ››Must compensate for tidal motion (~400 μm)
  - ››May need to compensate for microseismic peak (0.15 Hz)
- **Cost**

Alignment Sensing & Control: Progress and Status

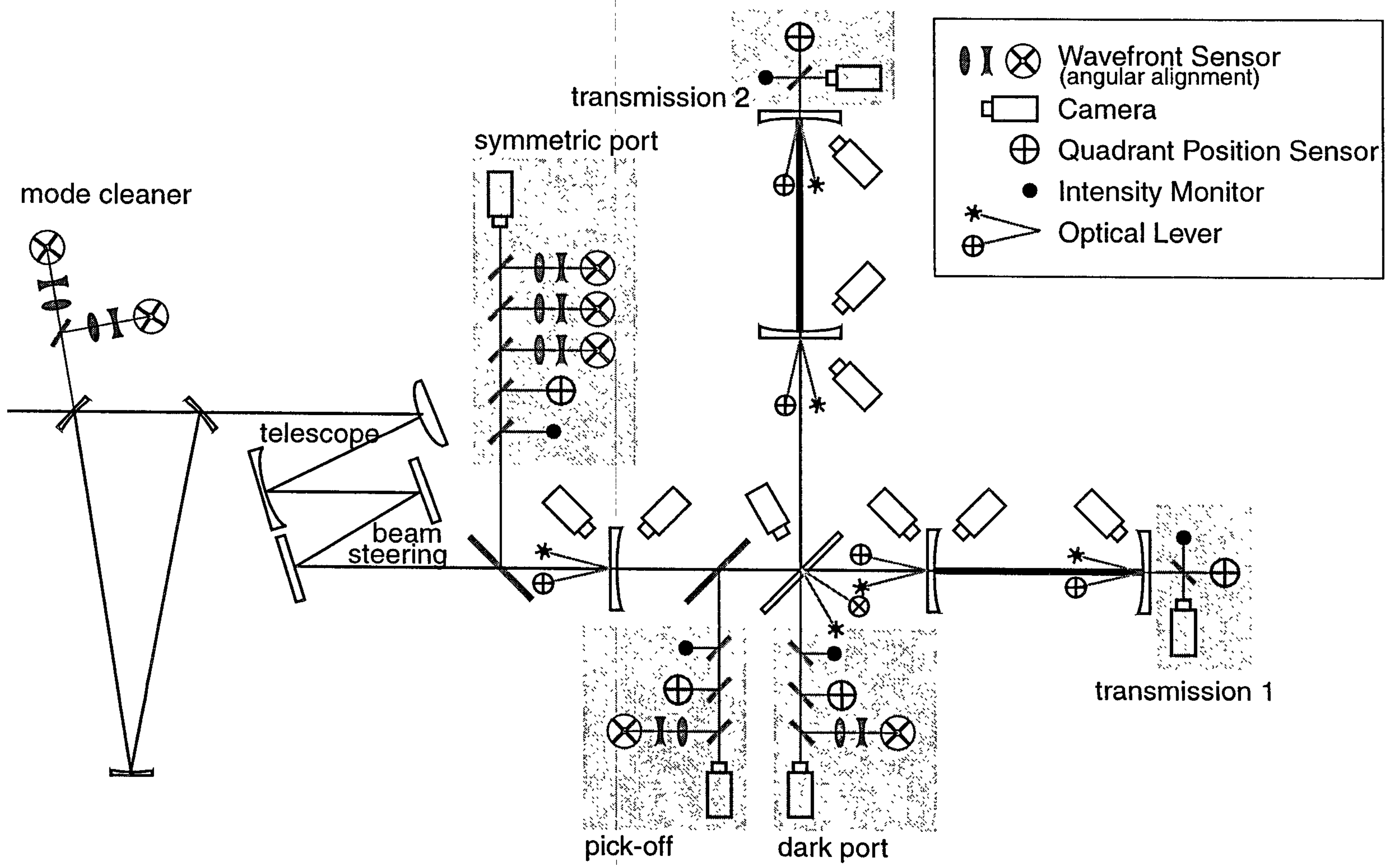
- **Design Requirements Review held, currently in preliminary design phase**
- **Alignment requirements for mirror angles and beam centering were refined and frozen**
- **Significant progress was made in modeling the environmentally induced alignment fluctuations expected at the sites**
- **Detection mode alignment strategy developed:**

  ›› Wavefront Sensor system will be used to detect the mirror orientation degrees-of-freedom

  ›› Modeling of the alignment sensor signals for the full interferometer was completed

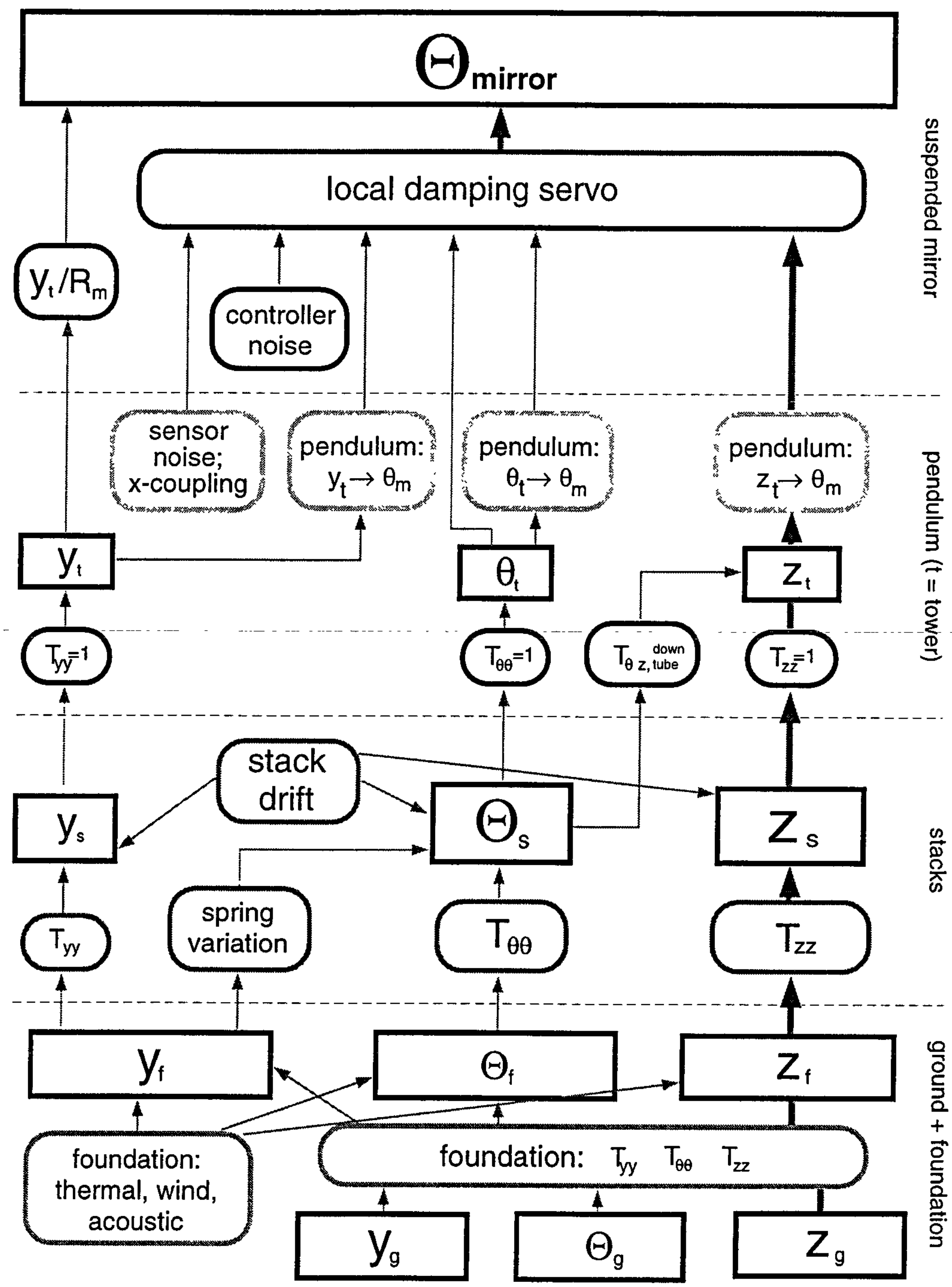
- **Strategies identified for determining and maintaining proper alignment during the interferometer lock acquisition period**

DETECTORS AND SENSORS FOR THE ASC



LIGO-G960218-00-D

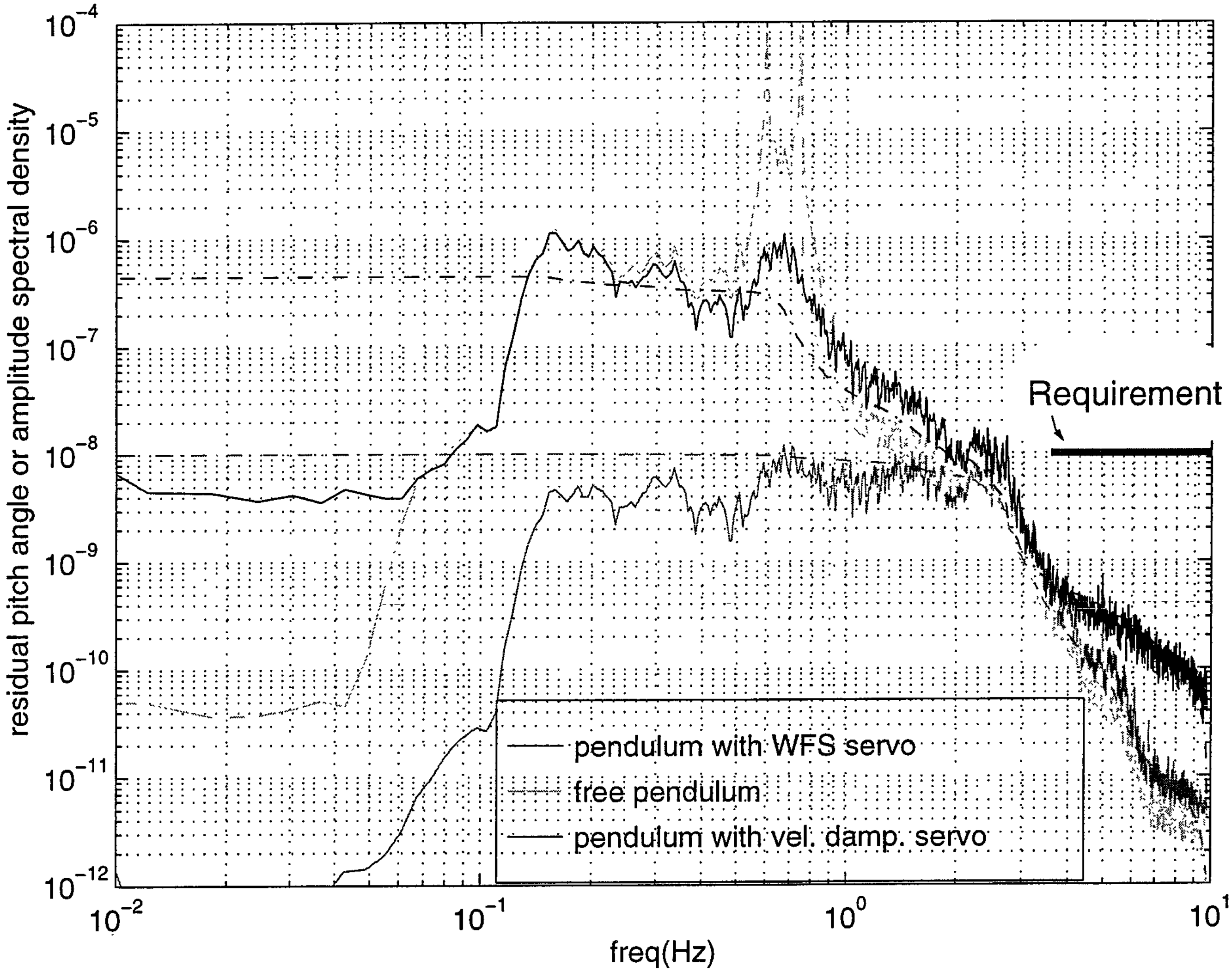
Modeling Alignment Fluctuations



Propagation paths from environment inputs to mirror angle fluctuations

Dominant path shown in red

Alignment Servo Modeling

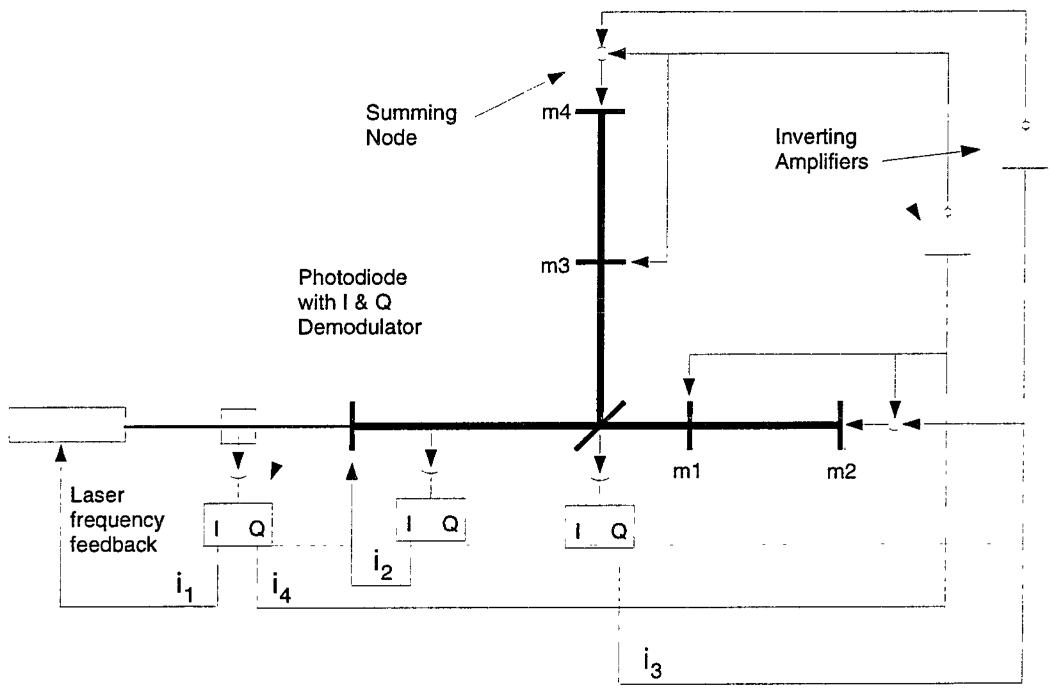


- solid lines: amplitude spectral density, radians/√Hz
- dashed lines: integrated rms fluctuation from freq →10Hz

Length Sensing & Control: Progress and Status

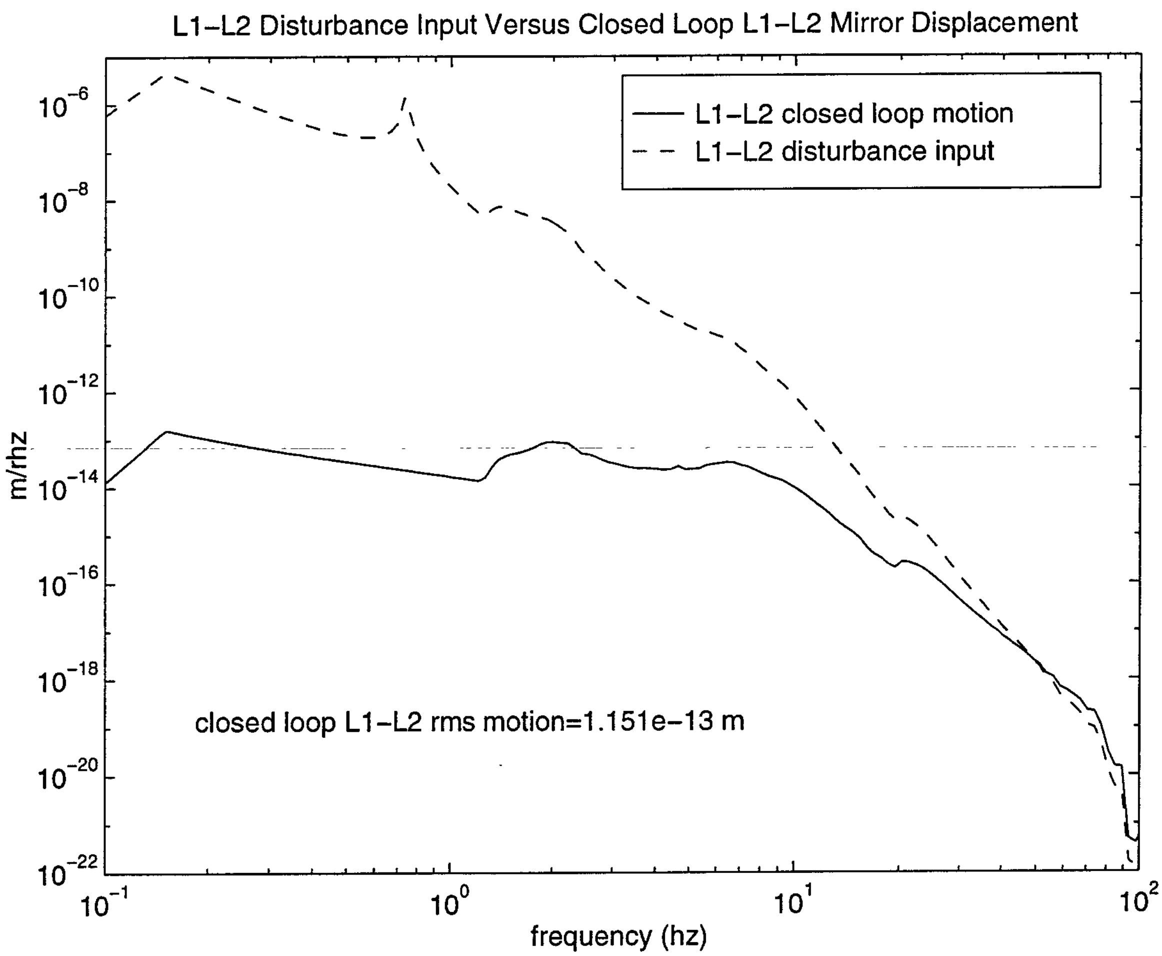
- **Reviewed requirements and conceptual design**
- **Sample control loops analyzed to demonstrate viability**
- **Senior EE hired and assigned to length control electronics design**
- **Full nonlinear optical response model completed for use in lock acquisition studies**

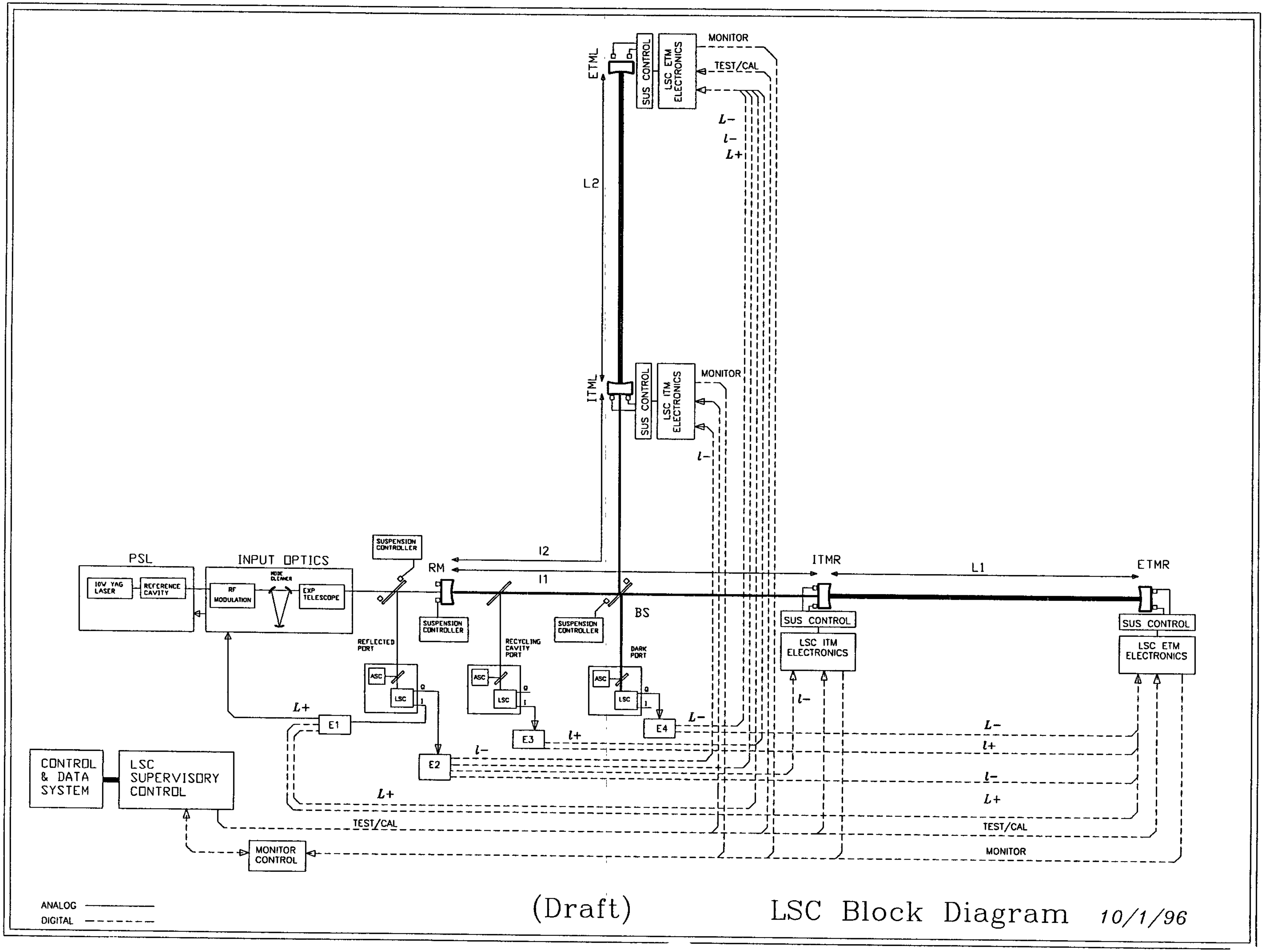
Length Sensing & Control: Control Loop Configuration



Length Sensing & Control: Performance Example

- **Suppression of seismically driven arm length difference**





(Draft)

LSC Block Diagram 10/1/96

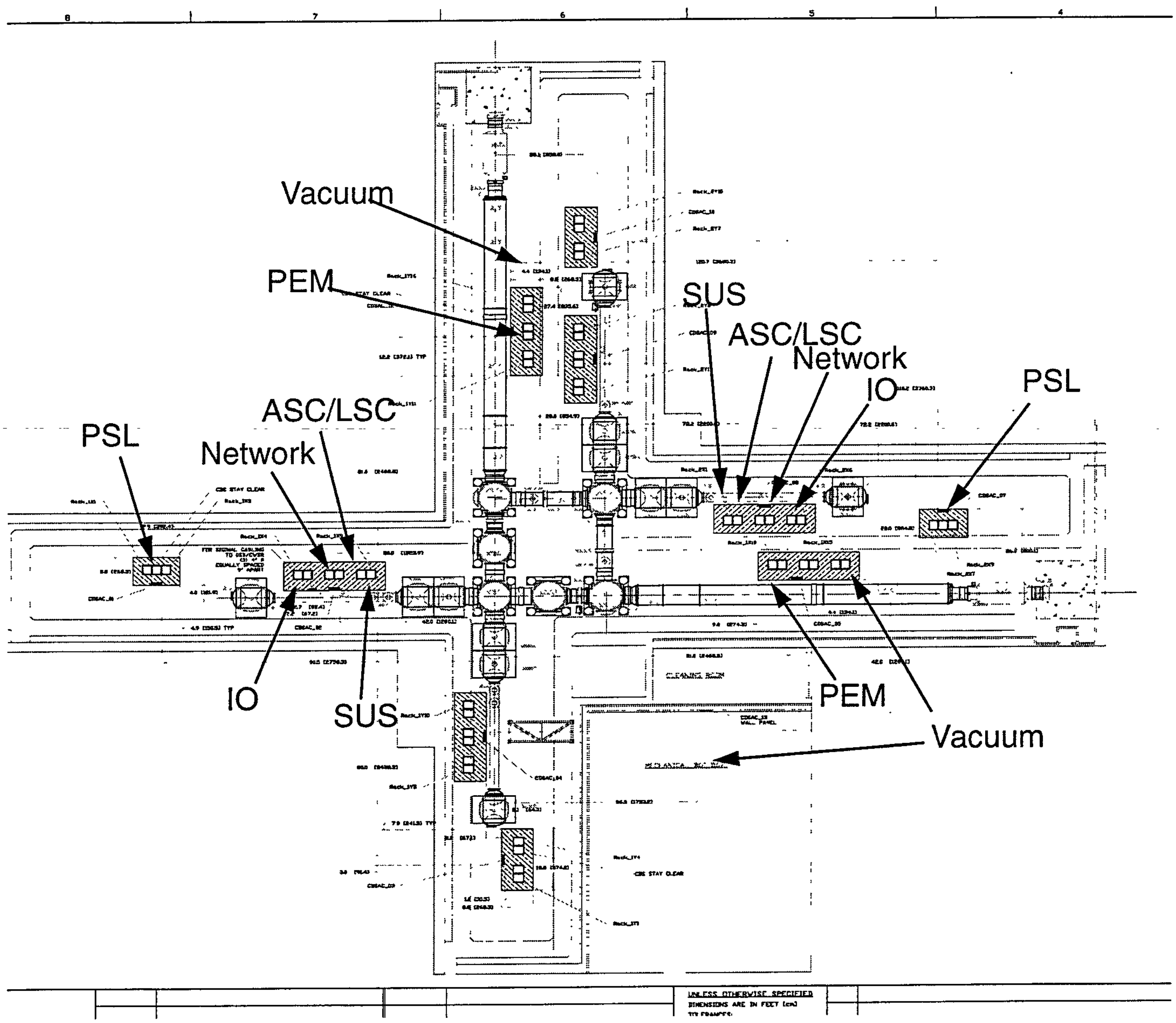
Control & Data System: Progress and Status

- **Completed preliminary design of CDS infrastructure**
  - ››Operator systems
  - ››Data networks
  - ››Timing system
  - ››Front end standards (hardware and software)
  - ››Software tools and standards
- **Completed preliminary design of in-vacuum cabling**
- **Reviewed requirements and conceptual design for Data Acquisition System**
- **Prototyping and testing of communications links, data acquisition hardware, etc.**
- **Preliminary design of vacuum control system nearly complete**

Control & Data System: Control and Monitoring Network

- **Asynchronous Transfer Mode (ATM) backbone.**
  - ››Point to point throughput : 3.8MBytes/sec between two Sparc10, CPU limited
  - ››Single ATM line to 155Mbits/sec (OC-3)
  - ››Aggregate bandwidth to 4Gbits/sec (Switch limit)
- **ATM to Ethernet Switches**
  - ›› 16 ethernet ports / ATM uplink
  - ›› Provides full 1MByte/sec to each connected processor
- **Video to ATM uplinks**

Control & Data System: Rack Locations and Functions



Detector and R&D Overview

- **"Project Management should monitor the technical interactions with the vendors of the Laser/Detector/ Suspension areas and arrange mechanisms to control potential change orders and cost overruns as presently being implemented in the conventional construction and vacuum areas."**
  - ››Technical representative assigned to each major contract
  - ››Use Technical Direction Memorandum (same as for Facilities) for giving all significant inputs to contractors
    - Must be approved by appropriate level of management
    - By definition (in contract), cannot change cost or scope
    - Any change of cost or scope must be made through the contract
  - ››Frequent interactions with contractors to avoid surprises

Recommendations From Last Review

Lasers

- **"A contract with well-defined milestones should be placed expeditiously for the development and delivery of 10W Nd:YAG lasers, and this contract should be supported through intensive technical exchange with the vendor."**
  - Contract placed with Lightwave Electronics approximately one month after last Review
  - Key Milestones:
    - Kick-off Meeting -- June 1996
    - Breadboard demonstration of Power and Beam Quality -- December 1996
    - Preliminary Design Review -- March 1997
    - Delivery of first Units -- Sept 1997
  - On-going technical interchange established; proprietary agreement signed to allow detailed technical discussions
  - Collaborating with Byer group (Stanford) for laser testing and technical consultation

Recommendations From Last Review

Seismic Isolation

- **"Continue to monitor carefully the progress of HYTEC in developing the seismic isolation system for the optics mounting"**
  - ››Regular and frequent contact with HYTEC
    - — Weekly email progress reports to cognizant Detector personnel
    - — Weekly telephone conference call to assess progress and to address areas of technical/programmatic concern
    - — Detailed technical reports on major results for LIGO information and review

Recommendations From Last Review

Seismic Isolation

- **"The combination springs appear to be attractive but their R&D should not be allowed to generate schedule risk for the final seismic isolation system design and construction."**
  - Design of seismic stacks compatible with either viton or constrained layer springs
  - Prototype fabrication efforts give information about possible impact on fabrication schedule
  - Decision on constrained layer springs to be reviewed at Seismic Isolation PDR January 1997

Recommendations From MIT Review

Conversion to Nd:YAG Laser

- **"With the switch to 1.06 μm system and the lead time that this must entail, the Panel strongly recommends the successful pursuit and addition of a scientist to lead the conversion of the PNI at MIT as soon as possible. Otherwise, the risk factor to the successful operation of the initial detector without this PNI experience base grows uncomfortable to the Panel."**
  - Haisheng Rong added to MIT Staff
    - Ph.D + 4 years Experience in High Precision Laser Spectroscopy
    - Assigned full-time to PNI Conversion
  - Long-lead IR optics for PNI conversion ordered at early date to enable fast start

Recommendations From MIT Review

Laboratory Space

- **"The Panel recommends that every effort be made to explore creative approaches that would allow the new laboratory space for the MIT LIGO group to remain on campus and still satisfy their seismic isolation needs."**
  - ››Suitable MIT building (WW15) identified just a few blocks off campus
    - Seismic levels 3-4 x less than current lab, fewer large pulses
    - MIT to provide active seismic isolators to give further isolation
  - ››Adequate floor space for up to 15 m long interferometer
  - ››Adjacent office space to be supplemented by office space in CSR to maintain close contact with other MIT groups
  - ››Take advantage of move to upgrade MIT vacuum system, minimize interuption of MIT laboratory effort
    - More like LIGO, longer cavities (to permit operation of realistic interferometers at correct RF frequencies)
    - Improve cleanliness and ease of operation

Summary

- **New detector organization functioning well**
- **Significant results from R&D program**
  - ››PNI optical phase sensitivity advances state of the art
  - ››Completion of 40 m optical recombination
- **Good progress on detector design and prototyping activities**
  - ››Most detector subsystems have completed requirements/ conceptual design review, and are well into preliminary design phase
  - ››First orders of detector hardware placed
- **Some detector milestones have slipped (typically ~2 months), but have recovered schedule along Critical Path**
- **No indication of significant cost growth**

Detector Research & Development

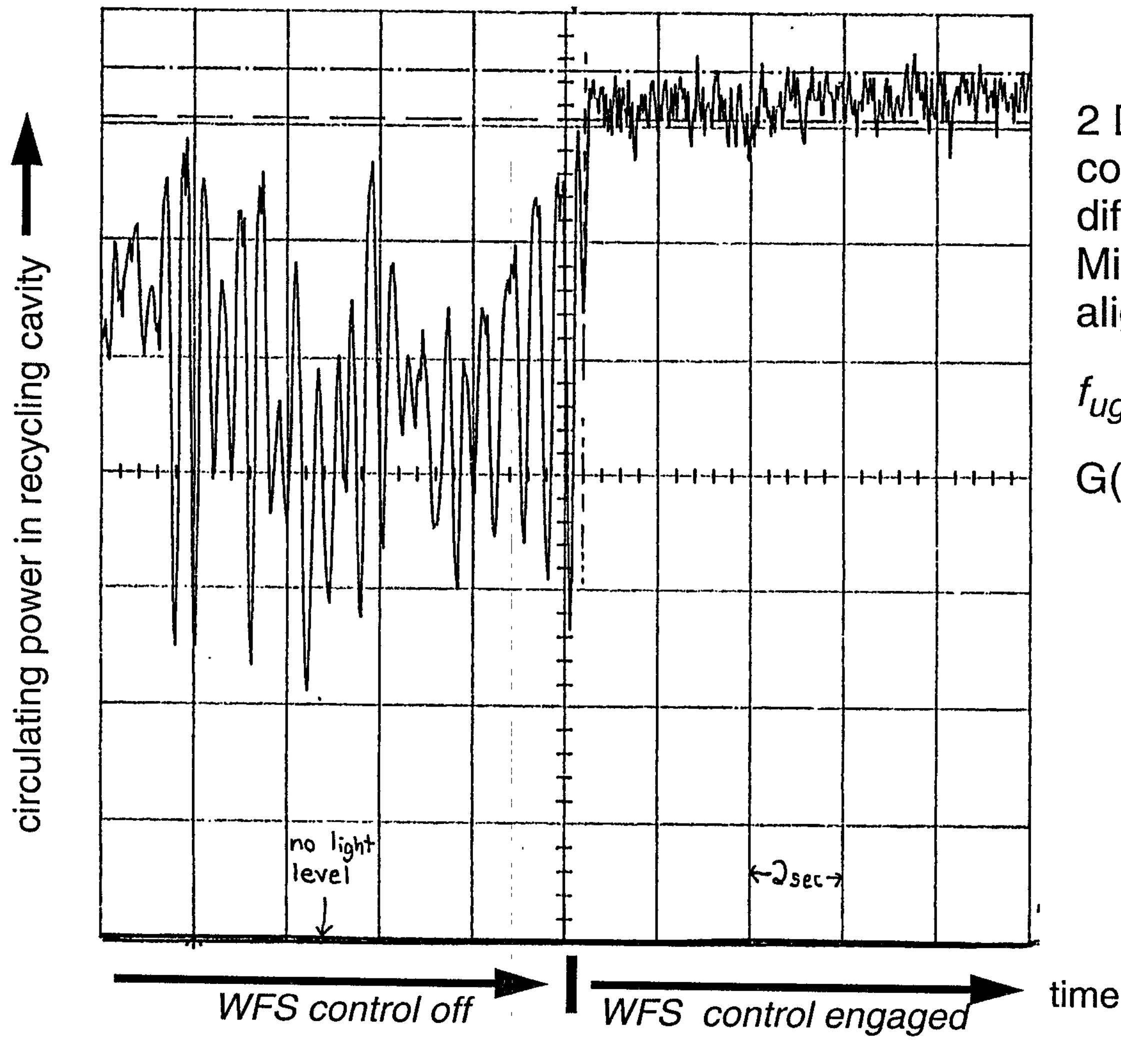
M. E. Zucker

- Phase Noise Interferometer (PNI) program
- 40-meter Interferometer program
- Fixed Mirror Interferometer (FMI) program

Phase Noise Interferometer (PNI)

- Goals: to demonstrate optical phase measurement sensitivity, understand technical sensing noise sources, and test LIGO length sensing/control (LSC) components
- Recent advances:
  - ››Barry STACIS active isolation systems added for second vacuum chamber
  - ››Recycling mirror installed, RF modulation & control systems upgraded
  - ››Wavefront sensing control system installed for differential MI alignment
- Results:
  - ››Recycling gain G = 450
  - ››Power incident on beamsplitter 60 W (carrier only; P_{in} = 200 mW total)
  - ››High-frequency phase sensitivity ~ 3.5 x 10^{-10} rad/$Hz^{1/2}$

PNI: WFS-based Alignment Control

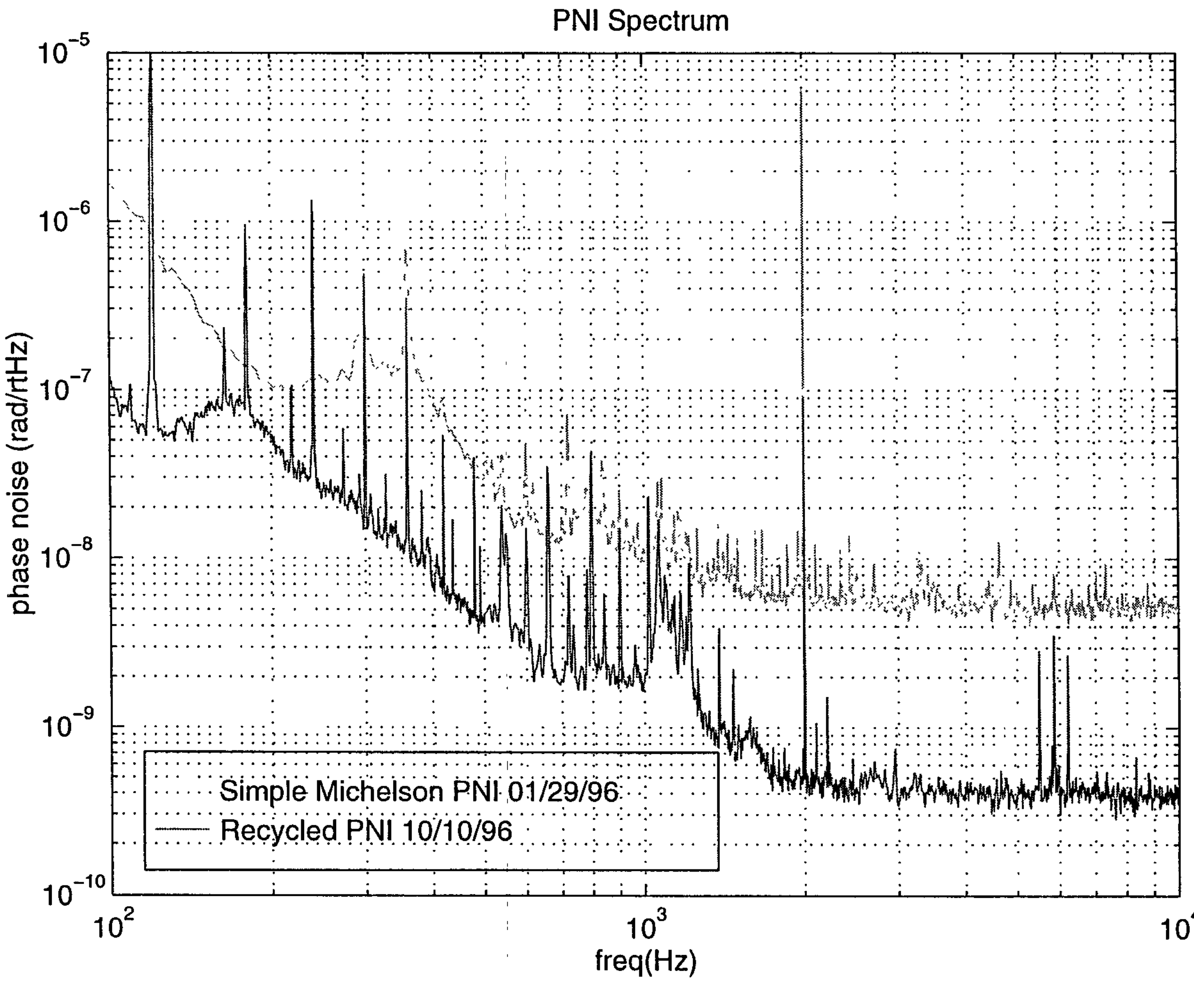


2 D.O.F. WFS control of PNI differential Michelson alignment;

$f_{ug} \sim 7$ Hz,

G(2 Hz) ~ 20 dB

PNI: Progress on noise spectrum



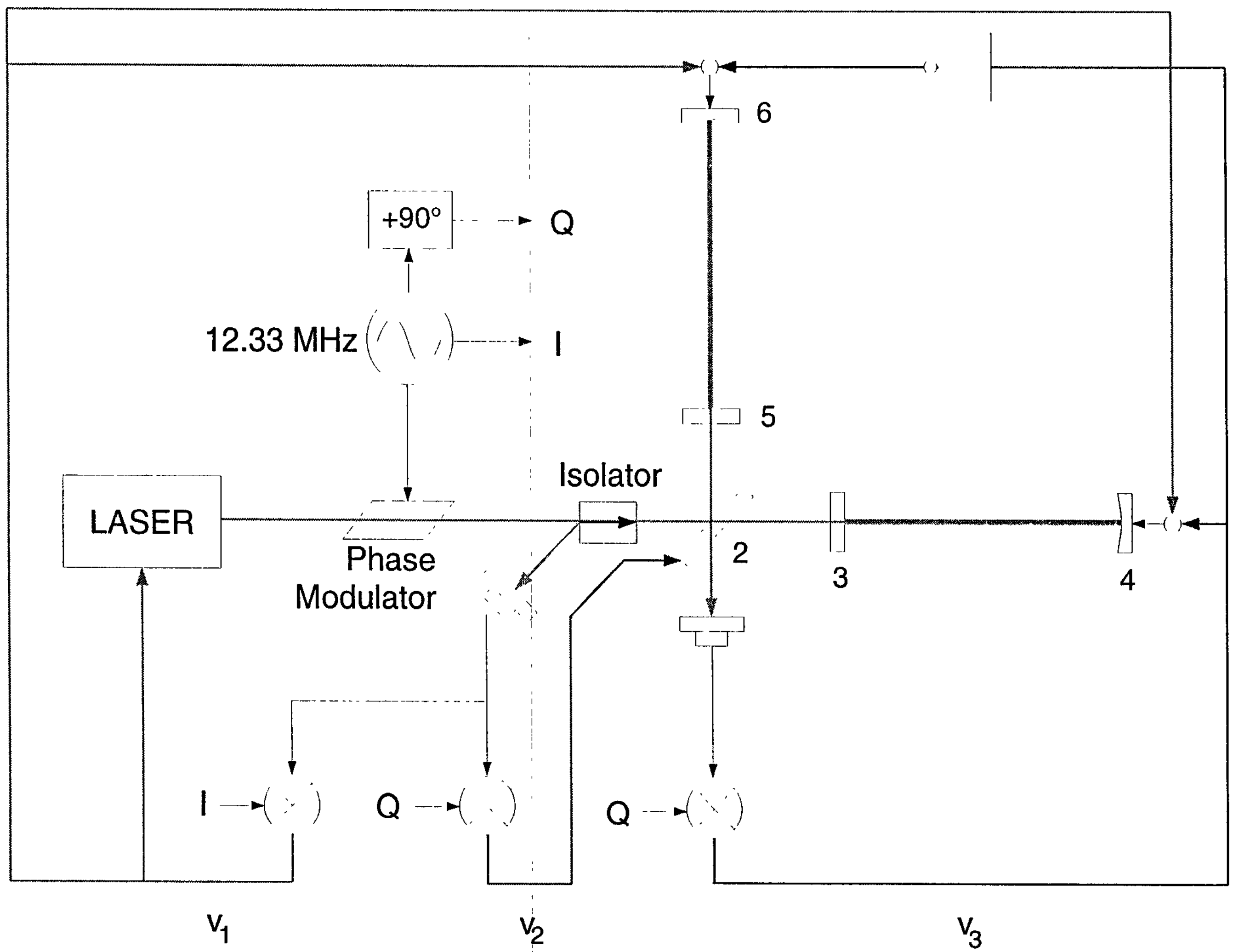
PNI: plan & schedule

- Wrapup of Ar^+ laser experiments next month
- Conversion to Nd:YAG (NPRO, .7 W) starting in December
  - ››optics & laser ready
  - ››laser prestabilization system being assembled/tested at Caltech
- First phase: linear cavity
  - ››test PSL frequency noise
  - ››debug new frequency control servo
- Second phase: Recycled Michelson configuration (as now)
  - ›› prototype test of LSC high-power photodetector
  - ››test of LSC digital controls (still tentative)
- Tests to wrap up last quarter of '97

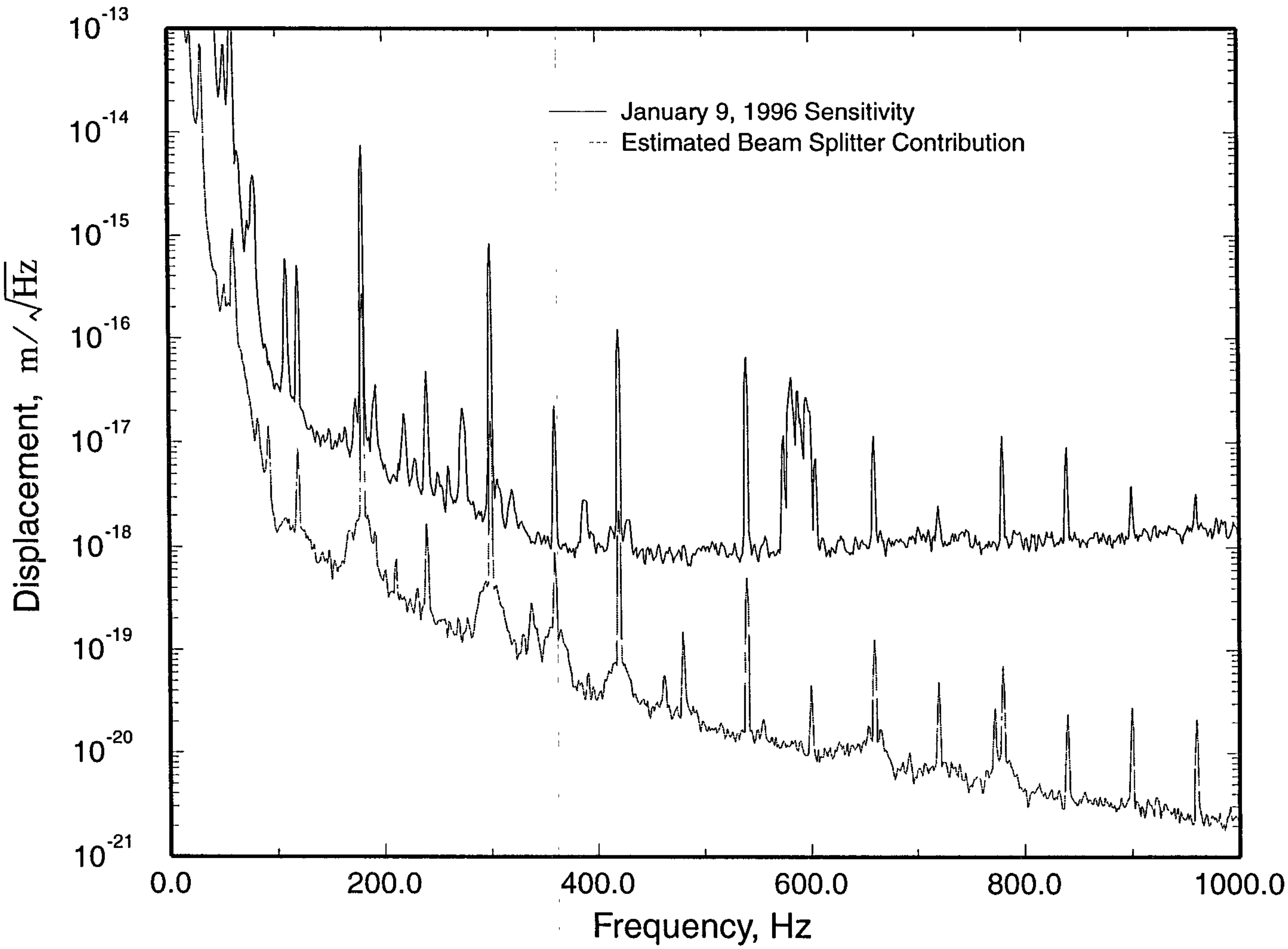
40-m Optical Beam Recombination

- Focus on role as a LIGO configuration testbed; reduced emphasis on displacement noise
- Key first step toward LIGO power-recycled configuration
- Explored new features & noise couplings:
  - ››Coupled control discriminants (nondiagonal readout)
  - ››Sign reversals in Michelson differential readout during lock acquisition
  - ››Greater dependence on uniform mirror figure (new alignment constraint)
  - ››First-order sensitivity to beamsplitter motion
- First test of a recombined Fabry-Perot Michelson interferometer at high sensitivity

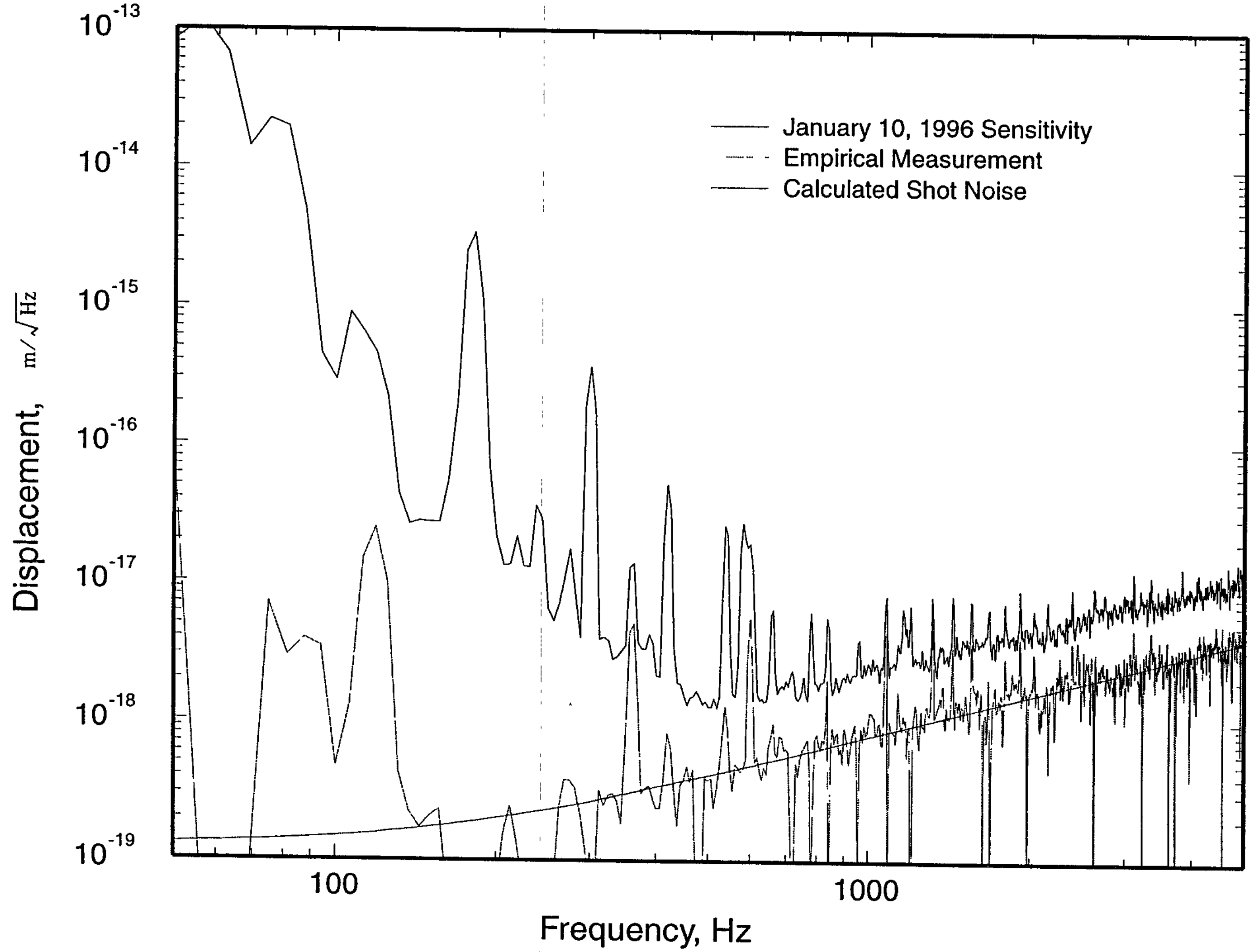
40-m: Recombined Control Topology



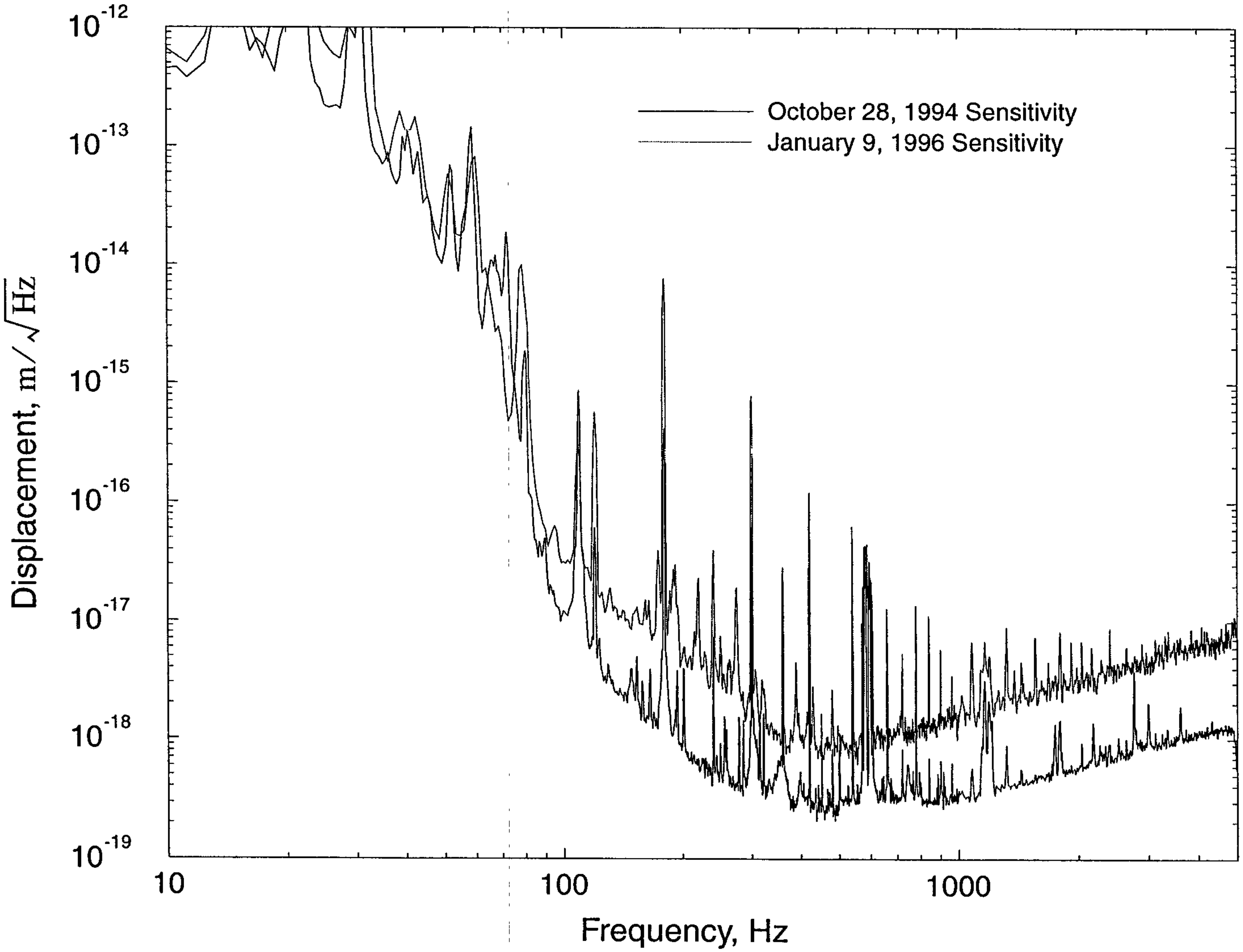
40-m: Beamsplitter Motion Sensitivity



Calculated and measured shot noise



40-m: Sensitivity Comparison



40-m: Suspension prototype test

- Trial of LIGO-type suspension at high displacement-sensitivity
  - Single-loop suspension
  - Integrated sensor/actuators for pitch, yaw, position
  - High-Q attachments
- Integrated test of prototype suspension control electronics
  - Dynamic range, noise
  - Diagnostics & tuning/setup functions
- Existing 40-m suspensions limit sensitivity, repeatability & ability to generalize other tests (=>other 3 pending)
- Significant impact on SUS Preliminary Design

40-m: Power Recycling

- Program concurrent with LIGO LSC design phase; results support LSC final design
- Focus on validating
  - »cavity lock acquisition sequence
  - »alignment technique
  - »modeling codes and design tools
  - »control electronics prototypes
- Integrated system tests
- Diagnostics and commissioning exercises
- Training

40-m: Recycling Status/Plans

- Installed higher-transmission input couplers
  - ››target recycling factor of 5 (T_{in} = 5600 ppm)
  - ››installation complete, currently shaking down
- Next: reconfigure vacuum envelope & input optics layout
  - ››scheduled to start in November; offline preparations underway
  - ››new side chamber & seismic isolation for expanded input optics
  - ››new beamsplitter to be installed (in LIGO SOS suspension prototype)
  - ››new RF modulation frequency to satisfy resonant condition in final stage
- Final stage: install recycling mirror
  - ››Currently on track for March

FMI: Wavefront Sensing Research

- Goals:

  ›› Validate Modal Model and its predictions for sensitivity of Wavefront Sensing (WFS) angle readouts, a critical technology for LIGO

  ›› Develop WFS sensor and signal processing hardware and software

  ›› Test concepts on a "full-configuration" power-recycled Fabry-Perot michelson

- Apparatus now complete

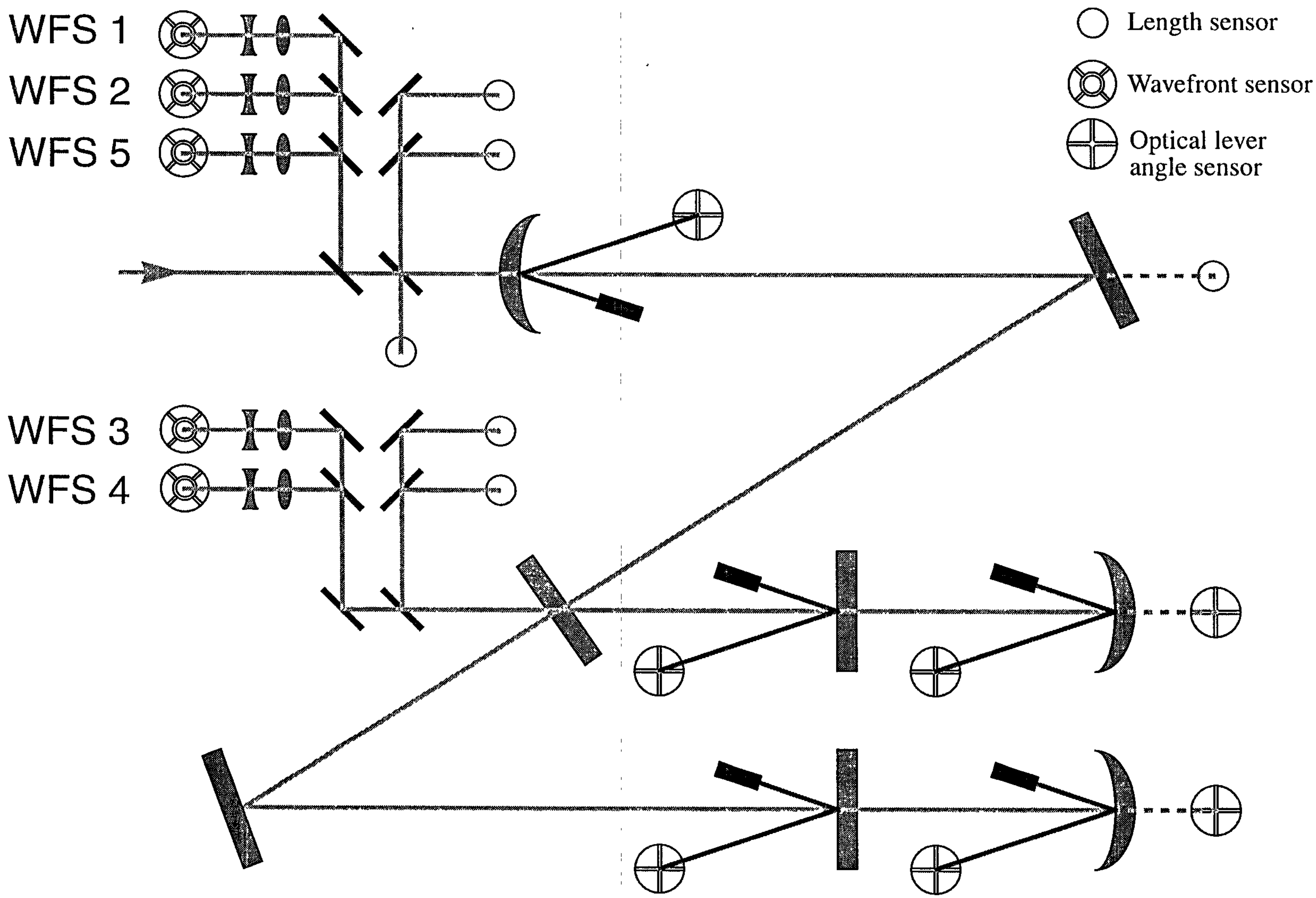
  ›› Prestabilized Ar^+ laser, LIGO-like RF length control

  ›› Multifrequency phase modulation + frequency-shifted subcarrier generator

  ›› Tabletop interferometer with PZT tip/tilt and fast/slow piston mirror actuators; aux. laser diode optical lever angle calibrators

  ›› 5 WFS prototype heads & demodulator modules, VME digital signal processing system

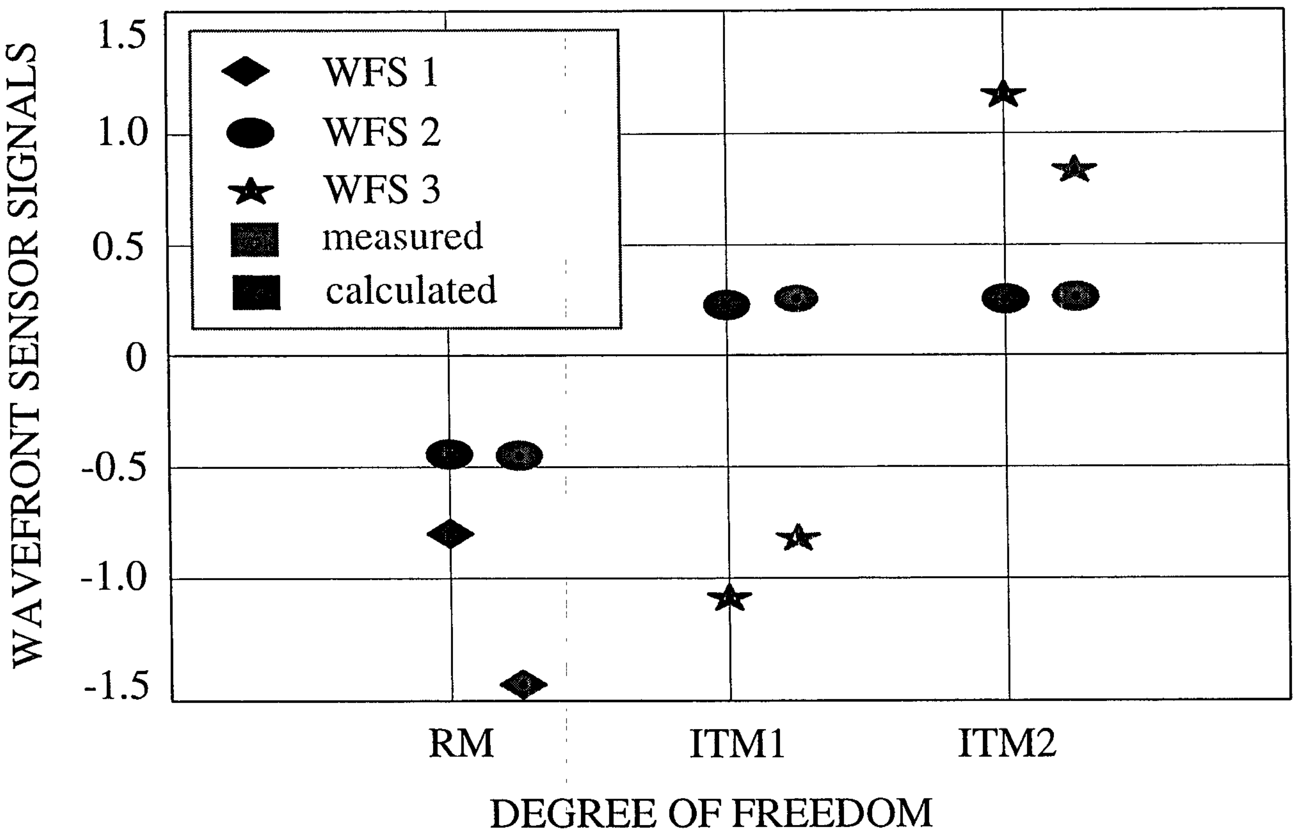
FMI Configuration (schematic)



FMI: Status

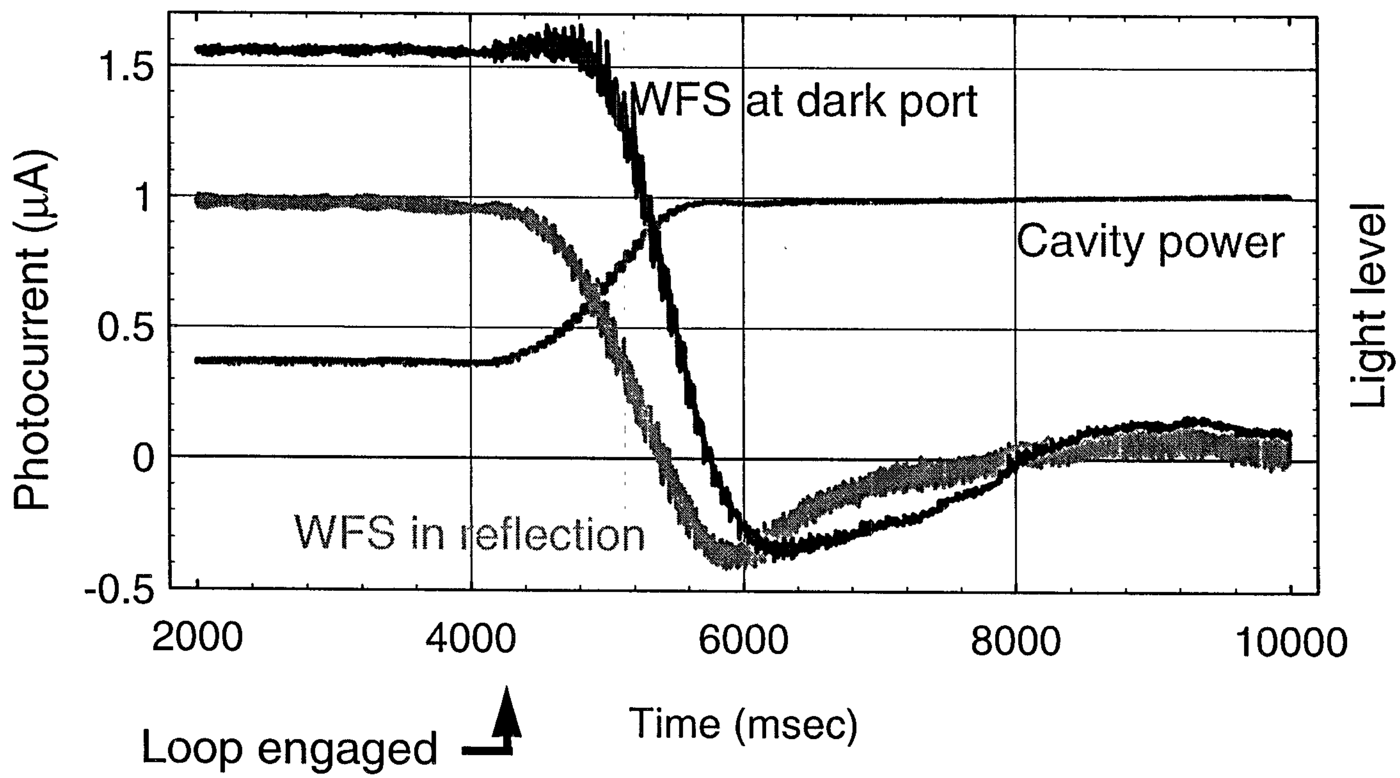
- Good preliminary results with arm cavities disabled (power-recycled simple Michelson only)
- WFS prototype hardware performance consistent with LIGO ASC requirements
- Successful trial of digital MIMO control system; correctly optimized all 6 degrees of freedom (d.o.f.)
- Now bringing arm cavities online for complete data run with all 10 d.o.f.

FMI: Preliminary Results vs. Model



FMI: Digital WFS Control Test

- Closed Loop Control of a Recycled Michelson Interferometer



1 of 1

LIGO-G950000-00-M

LIGO Advanced Detector R&D Proposal

Gary Sanders

NSF Technical Review

October 22 - 24, 1996

LIGO Research and Development Program Components

NSF "Task"	Period	R&D Activity
LIGO Construction (MRE + RRA)	1991 - 1997	in support of design and fabrication of initial LIGO
LIGO Operations	1997 - 2001	characterize initial detector systems and do gravity wave research
Visitors Program (pending)	1997 - 2001	support intermediate and long term visitors for LIGO R&D
Research Experience for Undergraduates (REU) Site (pending)	1997 - 2001	support undergraduate research within LIGO
Advanced Detector R&D (pending)	1997 - 2001	Support R&D to define new subsystems and new types of detectors

Operations Supported R&D

- Gravitational wave research
- Physics environment monitoring and correlations
- Diagnostics and correlations with interferometer output
- Materials, mechanical, electronic stability
- Optical contamination, materials outgassing, laser cleaning
- Residual gas instability
- Light scattering from tubes
- Linear and nonlinear servo operation, acquisition, stability
- Availability, reliability modeling
- Site to site correlations
- Geodesy, optical, GPS

This research will contribute to physics bottom line of LIGO

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

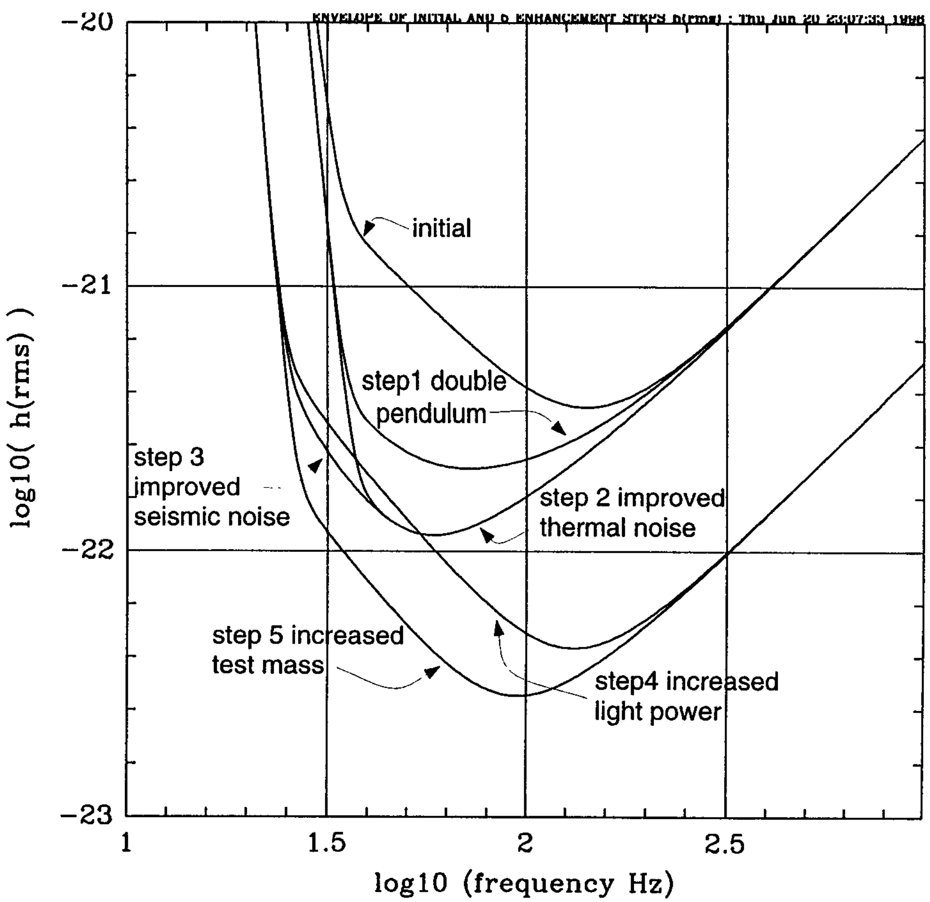
  ›› Some research areas will not be completed and will become part of a following R&D proposal

- 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

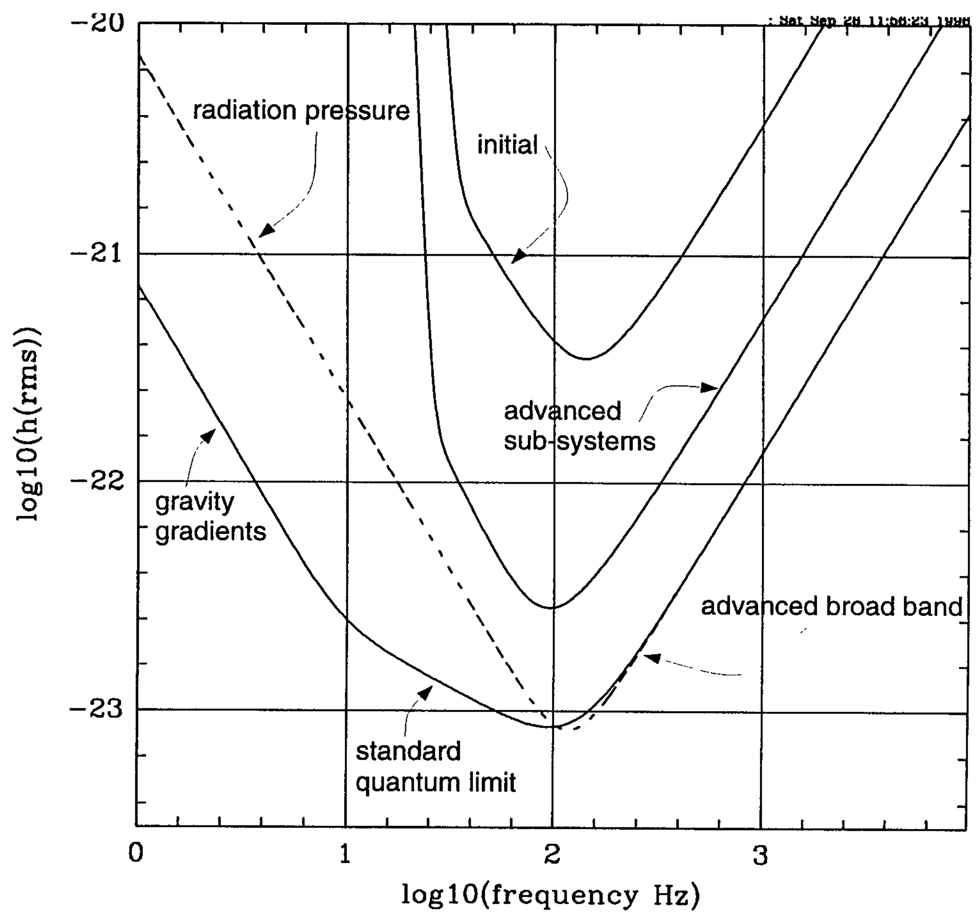
Collaboration

- Most proposed tasks are highly collaborative, involving institutions outside the LIGO Project
- These institutions will separately propose their required resources
    - ››very few subcontracts from LIGO to collaborators
- The proposed program is the LIGO R&D program and collaborators may propose other activities for their institutions
- It is our intention that this collaboration is the “training wheels” for the larger LIGO Collaboration. This is an important development in building this experimental field and it follows the recommendations of the McDaniel Report.

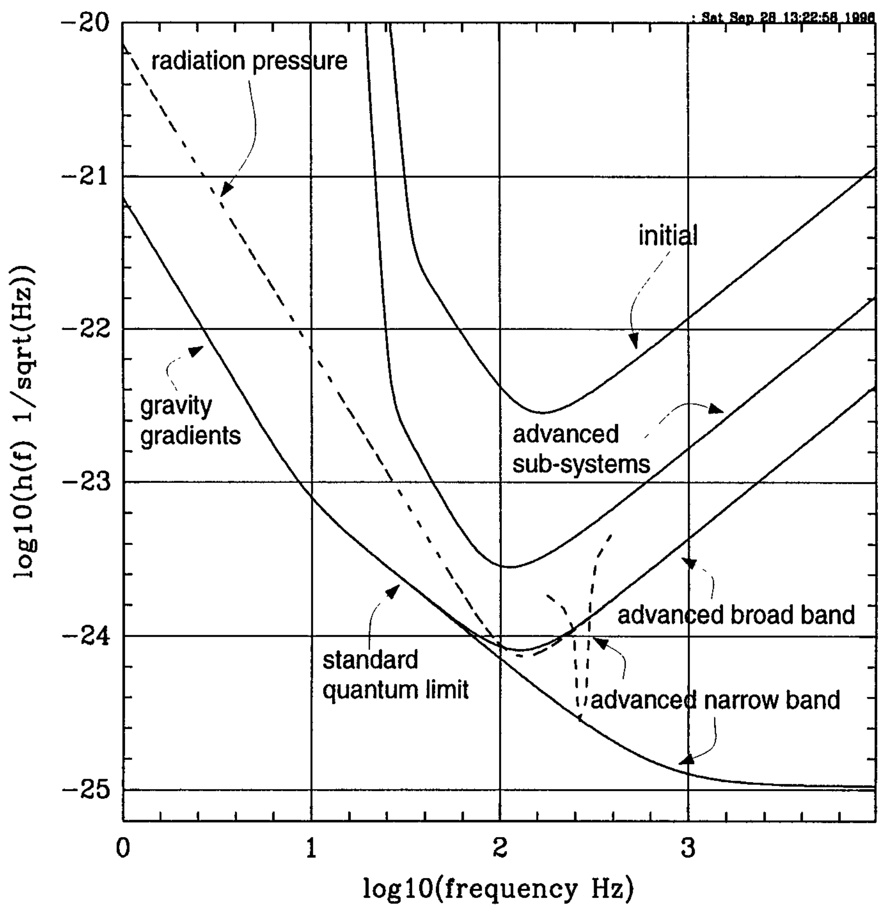
Steps in the Advanced Subsystems Research



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



Amplitude Spectral Strain Noise Expressed as an Equivalent h(f)



Astrophysics Motivations

Kip Thorne will discuss this subject

LIGO Funding by NSF Task and by Year

Fiscal Year	*Construction*	*R&D*	*Operations*	*Proposed* *Advanced R&D*	*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**	**1.7**	**58.6**
1998	**27.1**		**7.3**	**2.7**	**37.1**
1999			**20.9**	**2.7**	**23.6**
2000			**21.1**	**2.7**	**23.8**
2001		**10 months >**	**19.1**	**2.6**	**21.7**

All funds shown in 'then'-year $M

Noise Classification

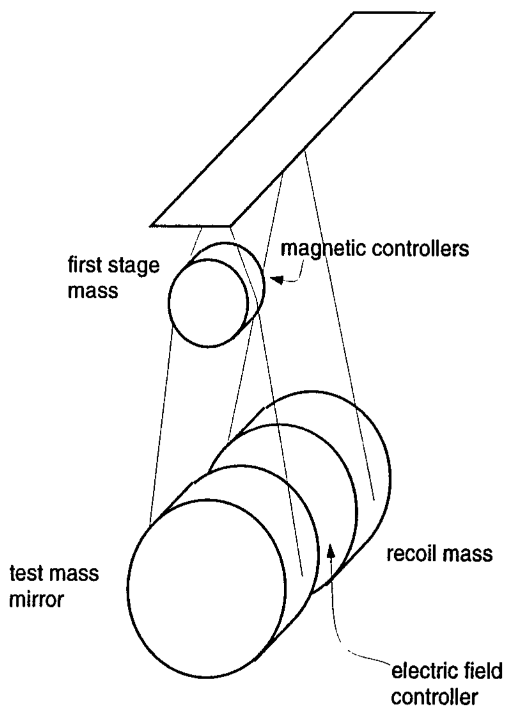
- *Sensing noise* - errors in the measurement of the optical phase introduced by scattered fields and the finite number of quanta being counted
- *Random forces* - stochastic processes that induce apparent test mass motions including thermal excitation of test masses, suspensions, seismic excitation, classical gravity gradients induced by terrestrial and atmospheric density fluctuations, radiation pressure fluctuations, etc.
- *Technical noise* - Non-fundamental sources of measurement noise such as electromagnetic interferences, environmental disturbances, imperfections in the instrumentation, etc.

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)

Double Pendulum Suspension

One Concept:



- Added isolation from thermal noise of seismic isolation
- Reduce actuator force dynamic range
- Remove test mass magnets which degrade Q
- Reduce magnetic field and domain jump noise on test mass
- Additional stage of $(f_0/f)^2$ isolation

Double Pendulum Suspension R&D

- Initial Phase

  ››Stanford, GEO and LIGO will study GEO design and LIGO requirements, leading to a design configuration suitable for LIGO

  ››Syracuse will study test mass losses vs. materials and attachments

  ››Stanford will continue fiber growing studies

  ››GEO will carry out realistic suspended element performance tests

  ››GEO actuator development will be used by LIGO to support studies of actuators suitable for LIGO

- Prototype Test Phase

  ››A set of LIGO-compatible prototypes will be fabricated and tested in a LIGO test interferometer

  GOAL IS CONSTRUCTION PROPOSAL AT END OF THIS RESEARCH

Double Pendulum Work Plan

Significant Events	*Responsible*	*Date*
Control system requirements developed	Stanford	Fall 1997
GEO control system analyzed	GEO	Fall 1997
Configuration chosen	LIGO, GEO	Fall 1998
Suspension fibers research mature	Stanford, Syracuse	Fall 1998
Attachment system research mature	Syracuse, GEO, LIGO	Fall 1998
Actuator technology research mature	LIGO	Fall 1998
Integration/selection of technologies	All	Winter 1998
Initial prototype constructed	LIGO, Stanford	Spring 1999
Initial prototype testing finished	LIGO or GEO	Fall 1999
Final design ready for fabrication, unification with thermal noise research	LIGO, Stanford	Spring 2000
Final design installed in test interferometer	LIGO	Spring 2001
Interferometer tests finished	All	Spring 2002

Reduced Thermal Noise Research

- Early phases support double pendulum suspension
- This research continues through double pendulum work and beyond, as an ongoing activity

Reduced Thermal Noise Work Plan

Topic	*Responsible*
SiO_2 Materials	Syracuse
SiO_2 Materials	Moscow State
Al_2O_3 Materials (sapphire)	See separate section on sapphire
Si Materials and flexures	Stanford
Attachments	Moscow State, Syracuse,Stanford
Test mass Q measurement	Syracuse
Noise correlations	*LIGO (Adv. Detector research)*
Test suspension design and construction	Part of double suspension research
Complete system test in sensitive ifo	Part of double suspension research

Reduced Test Mass Internal Noise: Sapphire Development

- Develop the techniques to grow, polish and coat sapphire with all of the required tolerances to enable them to be used as end test masses in LIGO and VIRGO.
- Investigate the absorption, birefringence and optical homogeneity with the goal of demonstrating suitability for the input test masses in LIGO and VIRGO.
- Investigate alternatives to the current wire suspensions which would not degrade the high intrinsic Q of the sapphire and which give higher suspension Q's.

Reduced Test Mass Internal Noise: Sapphire Development

Significant Events	*Responsible*	*Date*
Sample Characterization Complete	LIGO, VIRGO, UWA	July 1997
Test Masses (2) Delivered	LIGO, VIRGO	Jan. 1998
Test Mass Polishing and Figure Characterization Complete	CSIRO	July 1998
Test Mass Q, Absorption Birefringence Characterization Complete	LIGO, VIRGO, UWA	Dec. 1998
First Monolithic Suspension Results	UWA	July 1999

Higher Laser Power

- Continues LIGO development of 10 W 1064 nm for initial LIGO with Stanford and Lightwave
- Lightwave will continue development with rod geometry master oscillator-powered amplifier (MOPA) with an SBIR proposal
- LIGO will work with Stanford to apply LIGO requirements to a slab geometry design
  - ››A Lightwave 10 W laser will be used as the master oscillator for the resulting 100 W prototype which will be fully investigated
- This program is planned for three years, leading to an engineering proposal to be carried out with industry

Core Optics for Higher Power

- Goal of 100 W laser is phase sensitivity of 3×10^{-11} rad/$\sqrt{Hz}$
- Achieve this by raising laser power OR by reducing optical losses OR by both
- This program proposes to follow on to LIGO Pathfinder program by extension to more demanding:

  ››optical metrology - principally of mirror polish and coating phase distortions

  ››optimum polishing technique for LIGO requirements

  ››control of coating uniformity and absolute optical characteristics such as reflectivity and loss

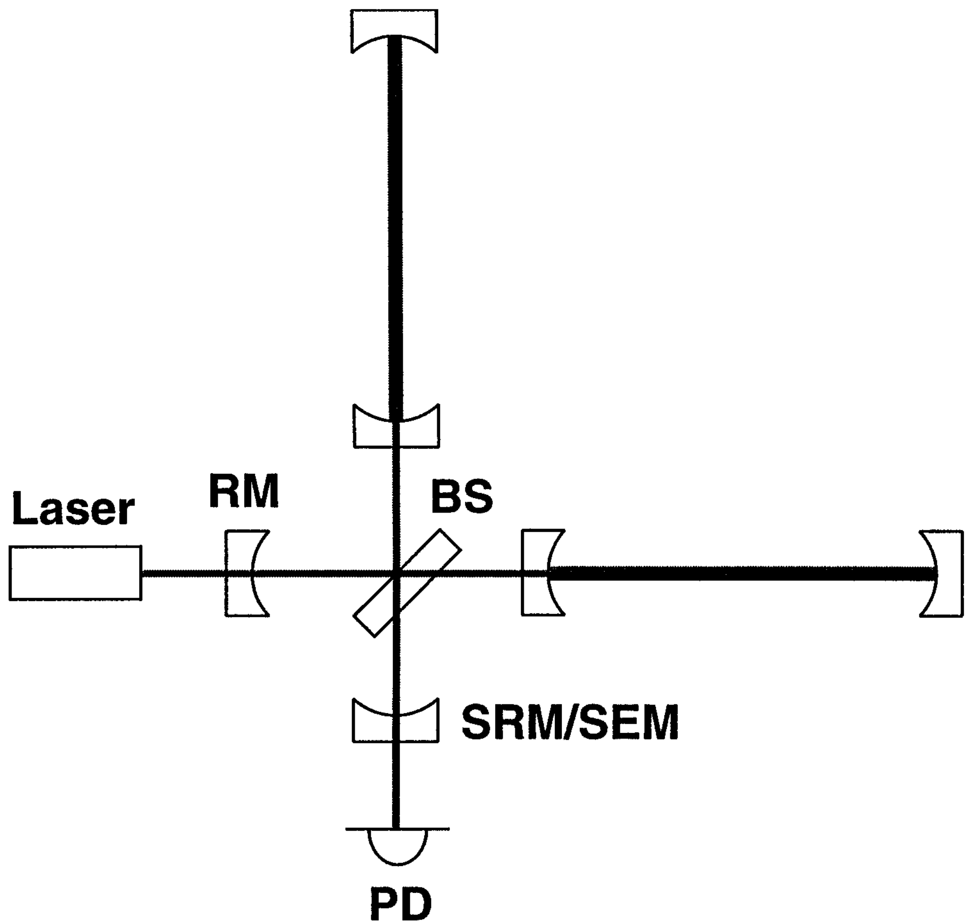
Core Optics for Higher Power

Responsibilities	*Collaborators*	*Schedule Initiate--- Complete*
Full precision phase mapping @ 1064 nm of surface figure (upgrade)	LIGO and industry	1998 (mid)--- 1999(late)
Acquire, install, characterize micro-roughness instrument	LIGO and industry	1997(mid)--- 1998(early)
Fully calibrated surface scatter/loss test bed (upgrade)	VIRGO LIGO and industry	1998(early)--- 1998(late)
≤ 1ppm level coating loss measurements. ≤ ± 10% bulk substrate loss mapping	EMU / VIRGO	1999(mid)--- 2001
Design and fabricate developmental silica mirror substrates (quantity ~30)	LIGO and industry	1998 (early)--- 1998(mid)
Surface polishing optimization	LIGO and industry	1998(late)--- 2002(early)
Coating uniformity development	LIGO and industry, VIRGO	1998(late)--- 2002(mid)

Advanced Detector R&D

- Resonant Sideband Extraction and Signal Recycling
- Advanced Seismic Isolation
- Signal Processing
- Measurement and Feedback of Thermal Noise

Resonant Sideband Extraction and Signal Recycling



Signal Recycling (Dual Recycling)

- Additional recycling mirror placed at the antisymmetric (signal) port to increase signal storage time
- Signal recycling can be used to narrow band the interferometer by adjusting sensitive peak frequency

Resonant Sideband Extraction

- Same general arrangement of antisymmetric port recycling mirror, but arm cavities have much higher finesse and mirror is used to reduce signal storage time
- Sensitivity can be same as in signal recycling with reduced optical power on the beam splitter
- Can also be used in a narrow band configuration

RSE/SR Research Program

- University of Florida will study dual recycling in a tabletop experiment lasting two years
- LIGO will study resonant sideband extraction in a tabletop experiment lasting two years
- An analytic study will be made by LIGO of suitable future interferometer configurations using the entire range of possibilities promised by these two techniques
  - ››modeling of interferometer sensitivity and response
  - ››modeling of optical sensitivity to distortions using paraxial FFT methods
- Following tabletop experiments, one of the techniques will be studied in a large scale test in a LIGO test interferometer

Advanced Seismic Isolation

- Initial LIGO measurement band limited by seismic noise at 40 Hz
- Goal of research is to:

  ››push this envelope down to about 1 Hz such that the limiting noise source for the interferometer becomes gravity gradients

  ››reduce the dynamic range required of the fine control actuators by providing isolation to frequencies as low as the microseismic peak (0.17 Hz).
- Three approaches:

  ››LIGO MIT Stacis active system from Barry Controls does not meet low frequency requirements

  ››JILA 3-stage active system promises low frequency performance

  ››Virgo passive stack is tall and requires additional material qualification

Advanced Seismic Isolation Work Plan

Pgm	Significant Events	Responsible	Date
Near Term	Improved Stacis Isolators: Design, Fab & Unit Test	LIGO, Stanford	Dec 1999
	Improved Stacis Isolators: 2km IFO Tests Completed	LIGO, Stanford	Dec 2000
Long Term	Requirements & Interface Definition	LIGO, JILA, Stanford	Mar 1998
	Preliminary Design	JILA, Stanford, LIGO	Jan 1999
	Final Design	JILA, Stanford, LIGO	Jan 2000
	Fabrication Completed	JILA	Jan 2001
	Unit Test Completed	JILA	Dec 2002

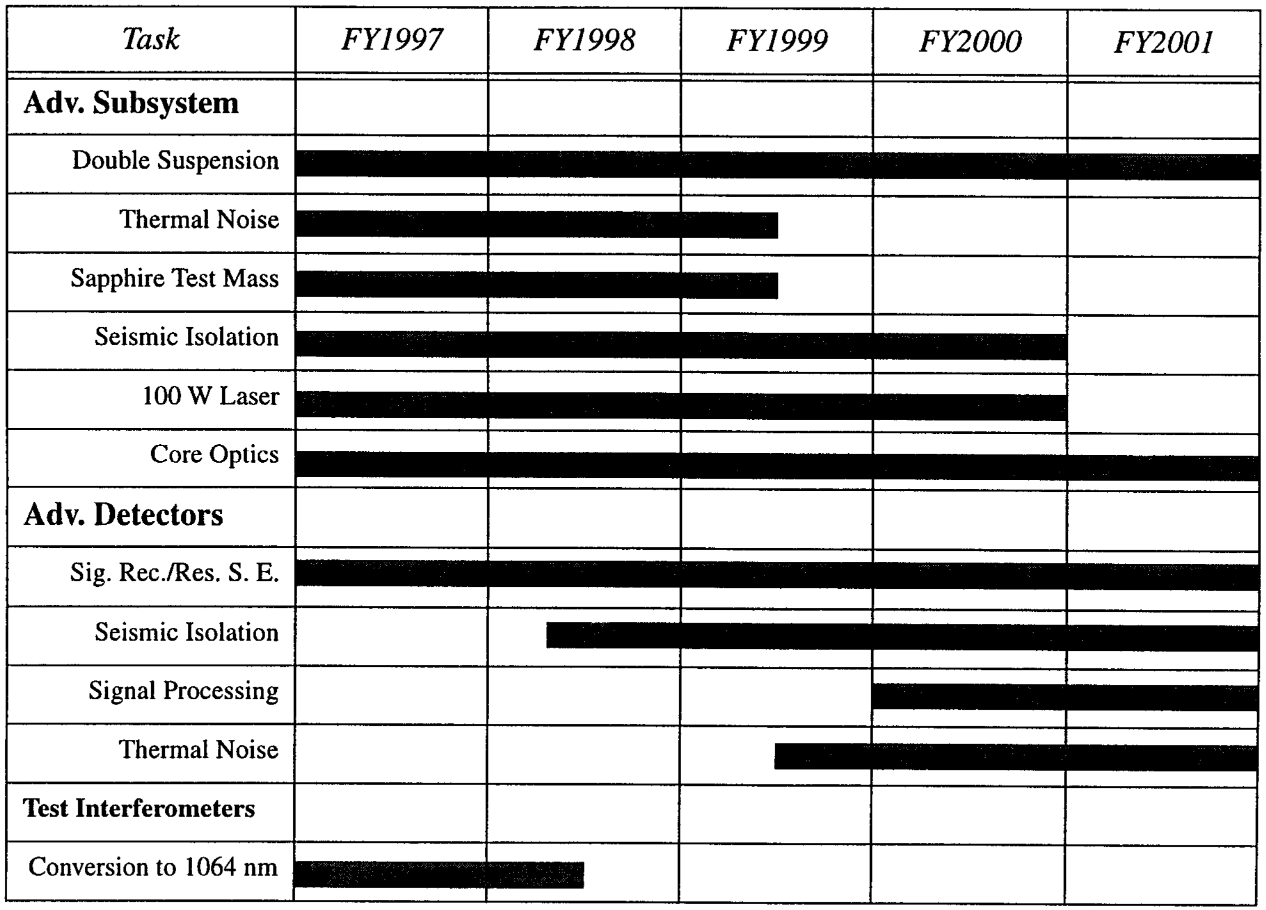
This research is expected to extend into the next five year research period

Staffing

LIGO (MIT and Caltech) Staffing Requirements

Category	*FY1997 FTE*	*FY1998 FTE*	*FY1997-2001 FTE Total*
scientist	2	4.5	20
postdoctoral	2.5	3	14.5
graduate student	2	3	14
engineer	0	0.5	2.5
technician	2	2.5	12
Total FTE	8.5	13.5	63.0

Top Level Activity Plan



LIGO Funding Request

Task	*FY1997*	*FY1998*	*5 YEAR TOTAL*
Adv. Subsystem			
Double Suspension	$211K	$281K	$809K
Thermal Noise	$22K	$42K	$134K
Sapphire Test Mass	$106K	$38K	$227K
Seismic Isolation	$10K	$31K	$177K
100 W Laser	$181K	$231K	$725K
Core Optics	$85K	$116K	$835K
Adv. Detectors			
Sig. Rec./Res. S. E.	$116K	$146K	$578K
Seismic Isolation	0	$28K	$305K
Signal Processing	0	0	$151K
Thermal Noise	0	0	$20K
M&S TOTAL	$732K	$912K	$3960K
STAFF TOTAL	$1009K	$1752K	$8460K
TOTAL	$1741K	$2664K	$12420K

Collaboration

- For 1997, LIGO has appointed Seiji Kawamura and Mike Zucker as Task Leaders for Advanced Detector R&D
- We will work with our collaborators to form effective coordination of this research
  - ››Periodic group meetings of each task group
  - ››Periodic meetings of the LIGO Collaboration
  - ››Widely circulated progress reports
  - ››An annual comprehensive workshop
  - ››Institutional representation

Collaboration

- This collaborative proposal combines
  - ›› LIGO expertise in system design and LIGO capability to integrate into detector system
    - expertise in system tradeoffs
    - unique facilities
    - extensive research with suspended optics interferometers
  - ›› expert research groups (including LIGO) around the world
- During the next six months, the collaboration will be formed
- January, 1997 Aspen Meeting will focus on Advanced Detector R&D

During 1997...

- Modify 40 Meter Interferometer and MIT Interferometer to accommodate double pendulum, 100 W laser, RSE/SR research
- Analyze double pendulum control system with GEO
- Complete sapphire sample characterization
- Define 100 W laser research with Lightwave
- Acquire micro-roughness instrument and initiate characterization research
- Commence resonant sideband extraction table top experiment and supporting analytical work

THESE ACTIVITIES INDEPENDENT OF NSF REVIEW OF COLLABORATORS

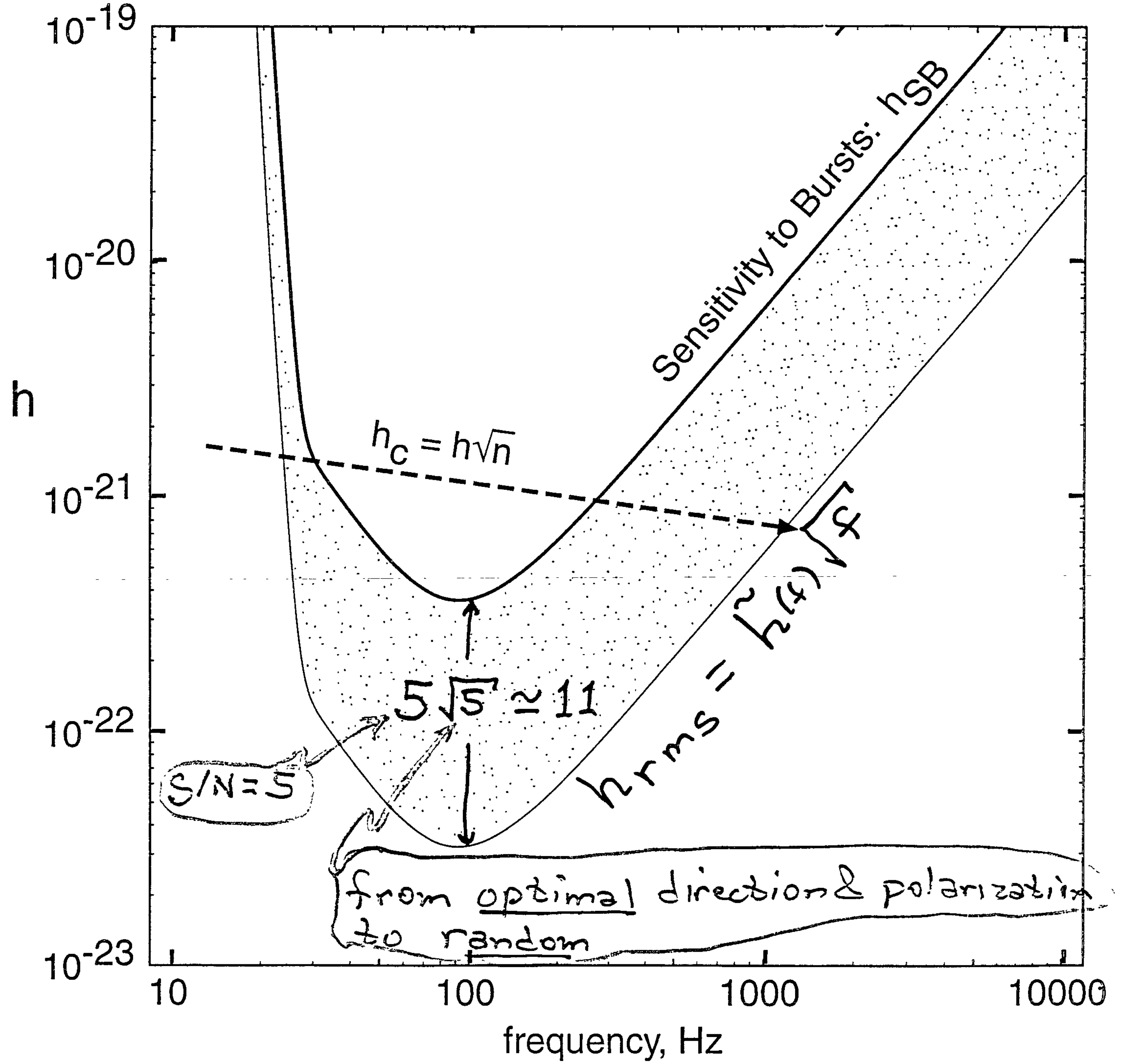
NSF Technical Review of the LIGO Project

Advanced R & D Proposal

Kip Thorne

October 22, 1996

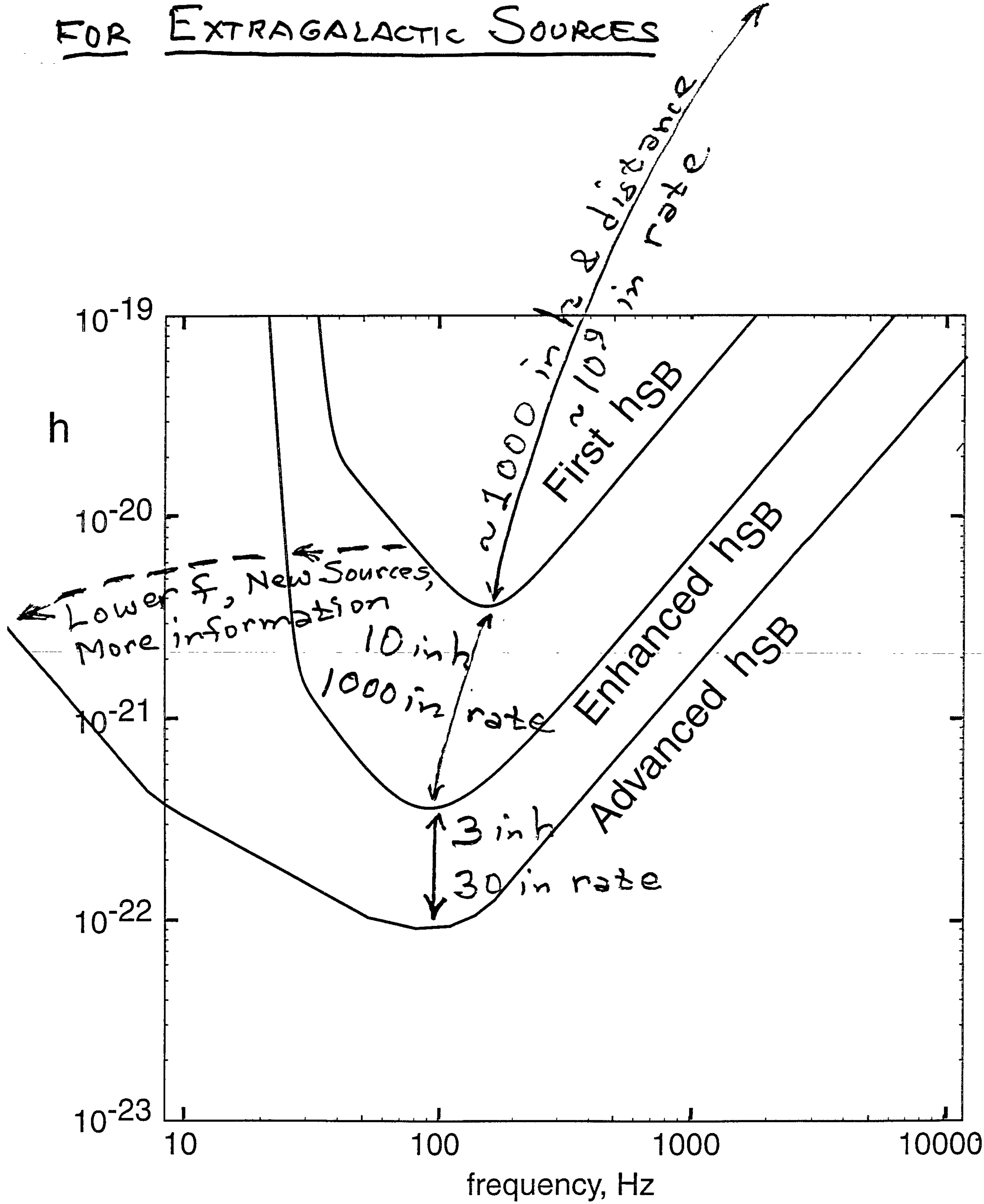
SENSITIVITIES AND SOURCE STRENGTHS



If: Source line h_c anywhere lies above h_{SB}

Then: detectable with high confidence in absence of EM or ν signal.

EVENT RATE IMPROVEMENTS Search FOR EXTRAGALACTIC SOURCES

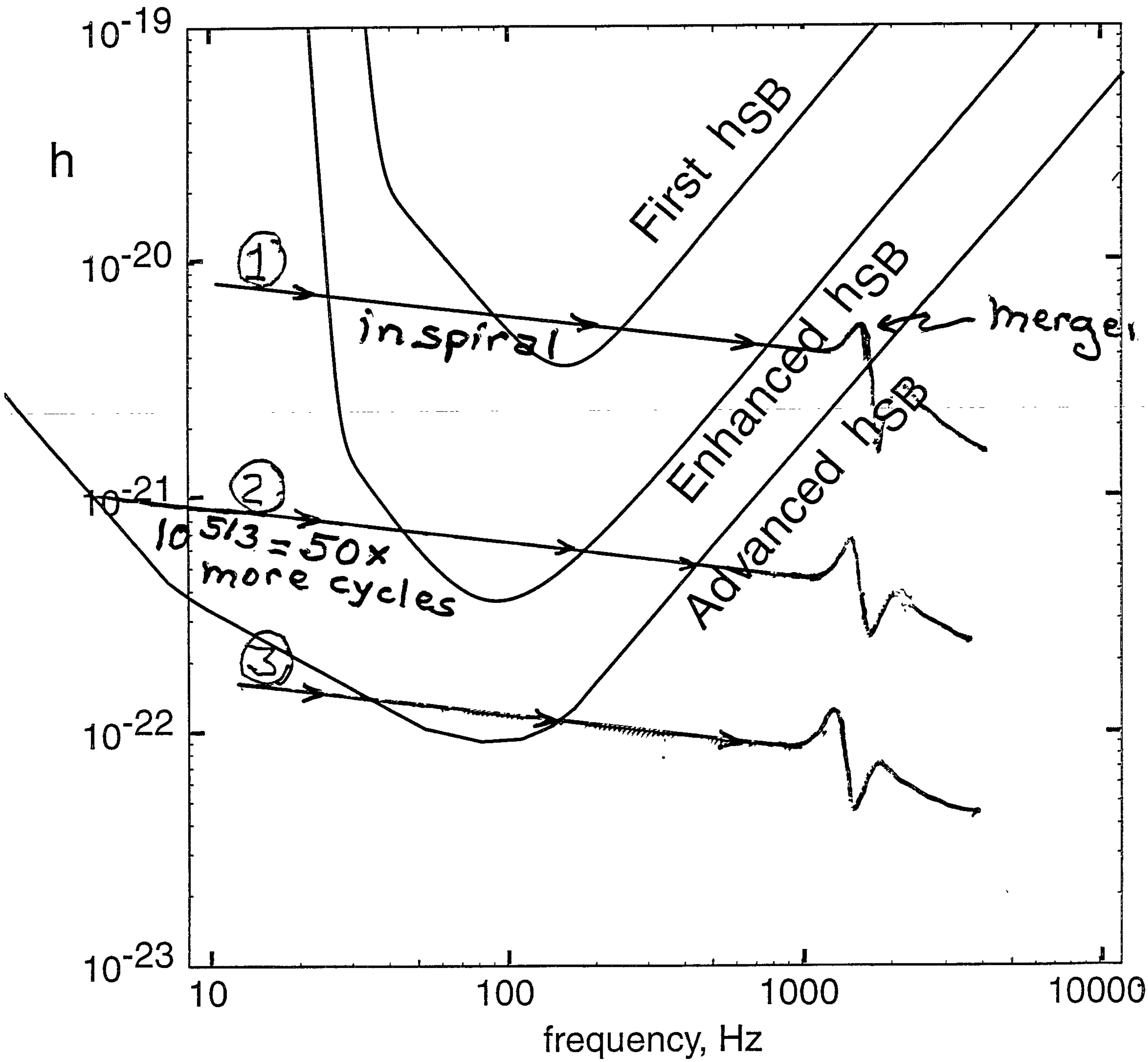


NEUTRON STAR BINARY INSPIRAL & MERGER

(our best understood source)

Estimated Distances for One Event Per Year

1. Extreme Optimistic: 50×10^6 l.yrs. (VIRGO)
2. Conservative Best Guess: 500×10^6 l. yrs.
3. Extreme Pessimistic: 2×10^9 l. yrs.

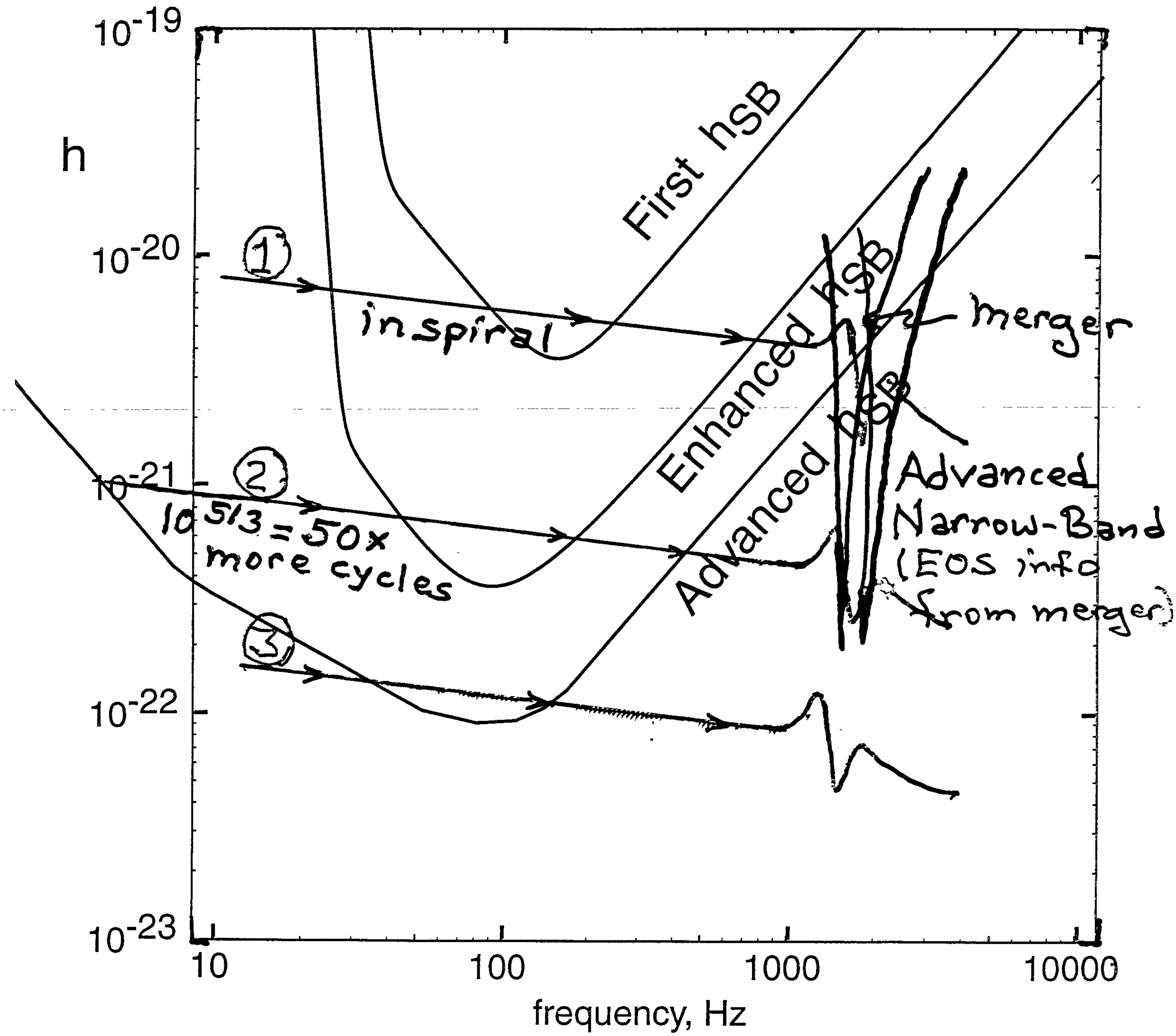


Neutron Star Binary Inspiral & Merger

(our best understood source)

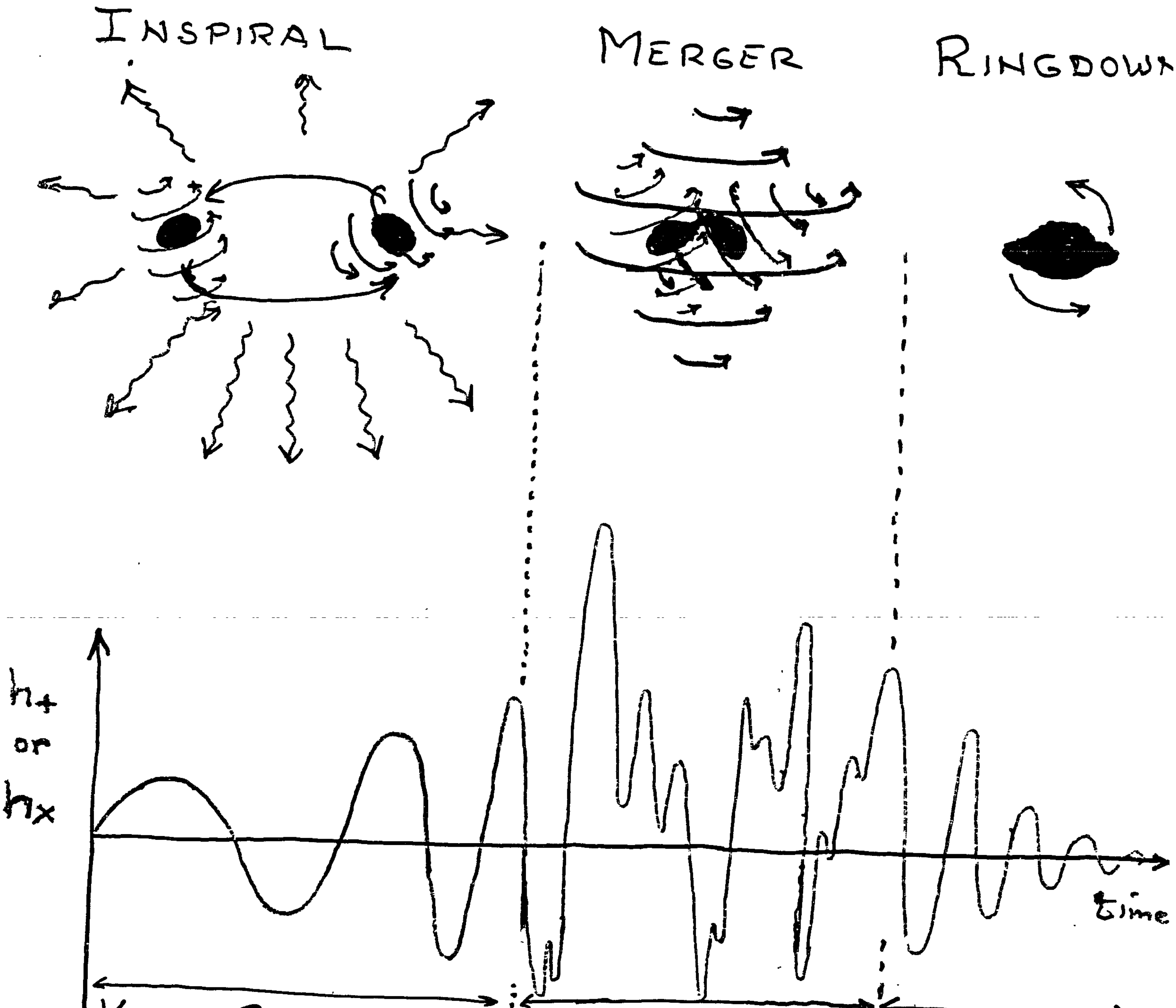
Estimated Distances for <u>One</u> Event Per Year

1. Extreme Optimistic: 50×10^6 l.yrs. (VIRGO)
2. Conservative Best Guess: 500×10^6 l. yrs.
3. Extreme Pessimistic: 2×10^9 l. yrs.



Black-Hole Binary Coalescence, $M_1 \sim M_2$

(Perhaps the Strongest Source)



Known: Post-Newton Expansions...

- Blanchet - Damour - Iyer
- Will - Wiseman

Numerical Relativity

A. Einstein Institute - Schutz, Seidel, ...

BBH Alliance:

- Texas, • Cornell,
- Illinois (NCSA),
- North Carolina,
- Northwestern, • Penn

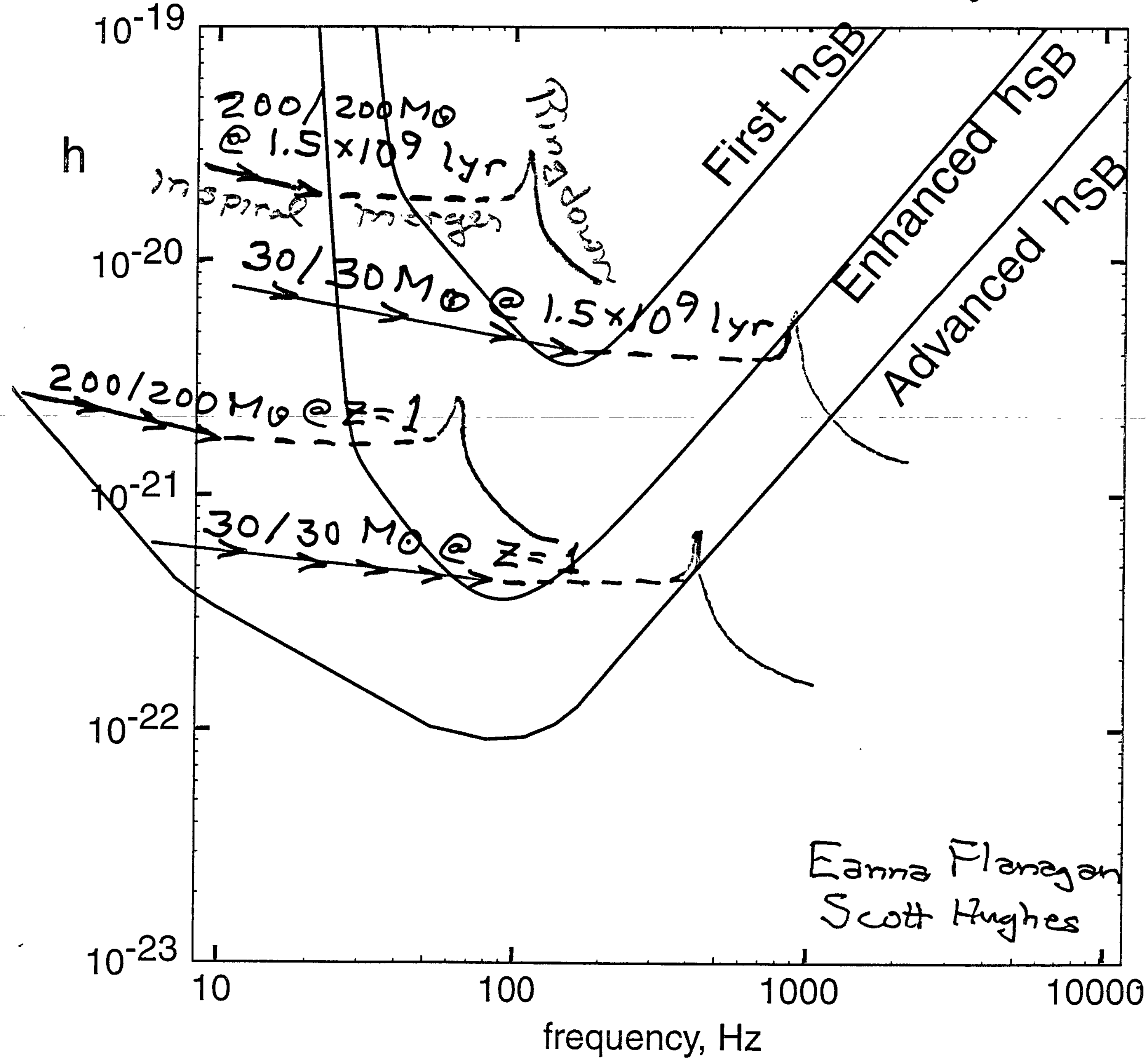
Known: Teukolsky Formalism

Detweiler
Chandrasekhar
Sasaki, Nakam.
Leaver

BH / BH

First Interf's: to ~ 10^9 l.yrs.

Enhanced Interf's: to ~ 10^{10} l.yrs. (z = 1)



OTHER SOURCES

Source	First	Enhanced	Advanced
Nonaxisymmetric Stellar Core Collapse (Supernovae) [<u>if</u> can develop near optimal data analysis algorithms]	$\sim 50\times10^{6}$ l.yr.	$\sim 500\times10^{6}$ l.yr.	$\sim 1.5\times10^{9}$ l.yr.
Spinning N.S.'s (pulsars)	$\left(\frac{\varepsilon}{10^{-6}}\right)\left(\frac{30{,}000\ \text{l.yr.}}{r}\right)\left(\frac{1\ \text{msec}}{P}\right)^2 \gtrsim$		
Broad-Band	1	0.2	....
Narrow-Band	....	....	2×10^{-3}
Stochastic Background	$\Omega_g = \left(\frac{\text{GW energy in } \Delta f = f}{\text{Energy to close Universe}}\right) \gtrsim$		
Broad-Band	$\sim 3\times10^{-7}$	$\sim 3\times10^{-9}$	$\sim 3\times10^{-10}$
Narrow-Band	....	....	$\sim 1\times10^{-10}$

Facilities and Vacuum Equipment

Mark Coles

Presentation Objectives

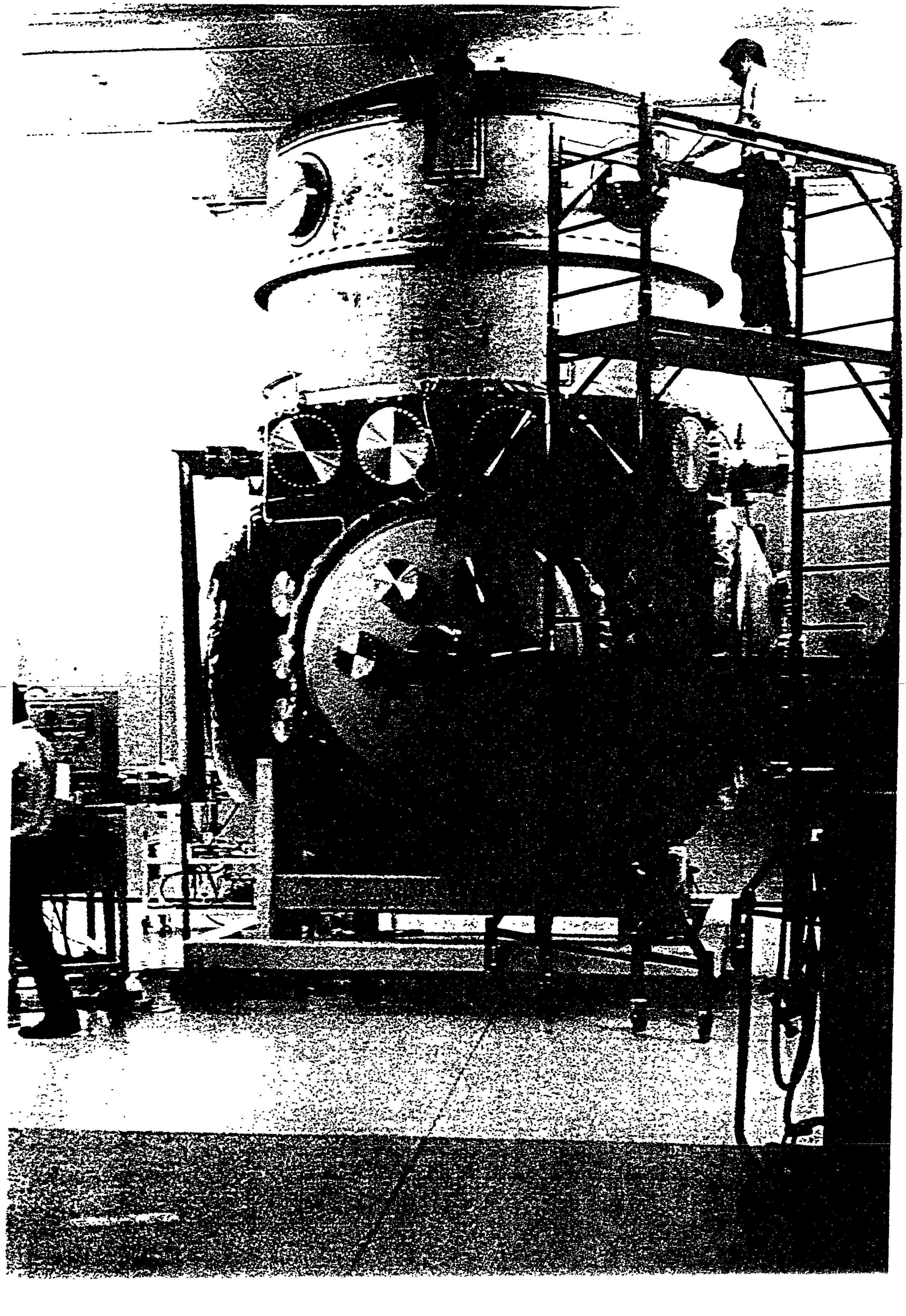
- Review project objectives of last 6 months
- Show how we are implementing designs that satisfy design requirements.

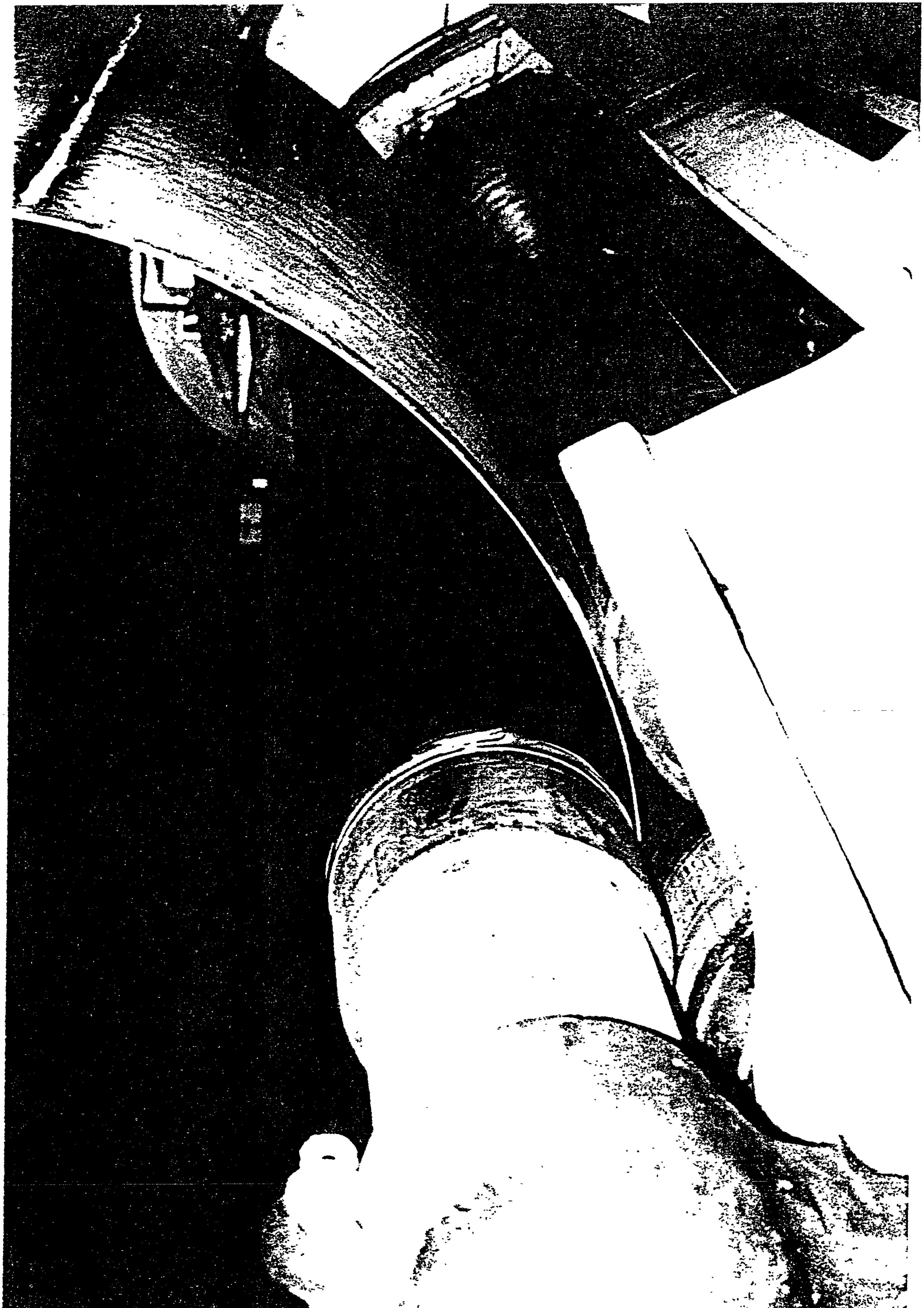
Vacuum Equipment

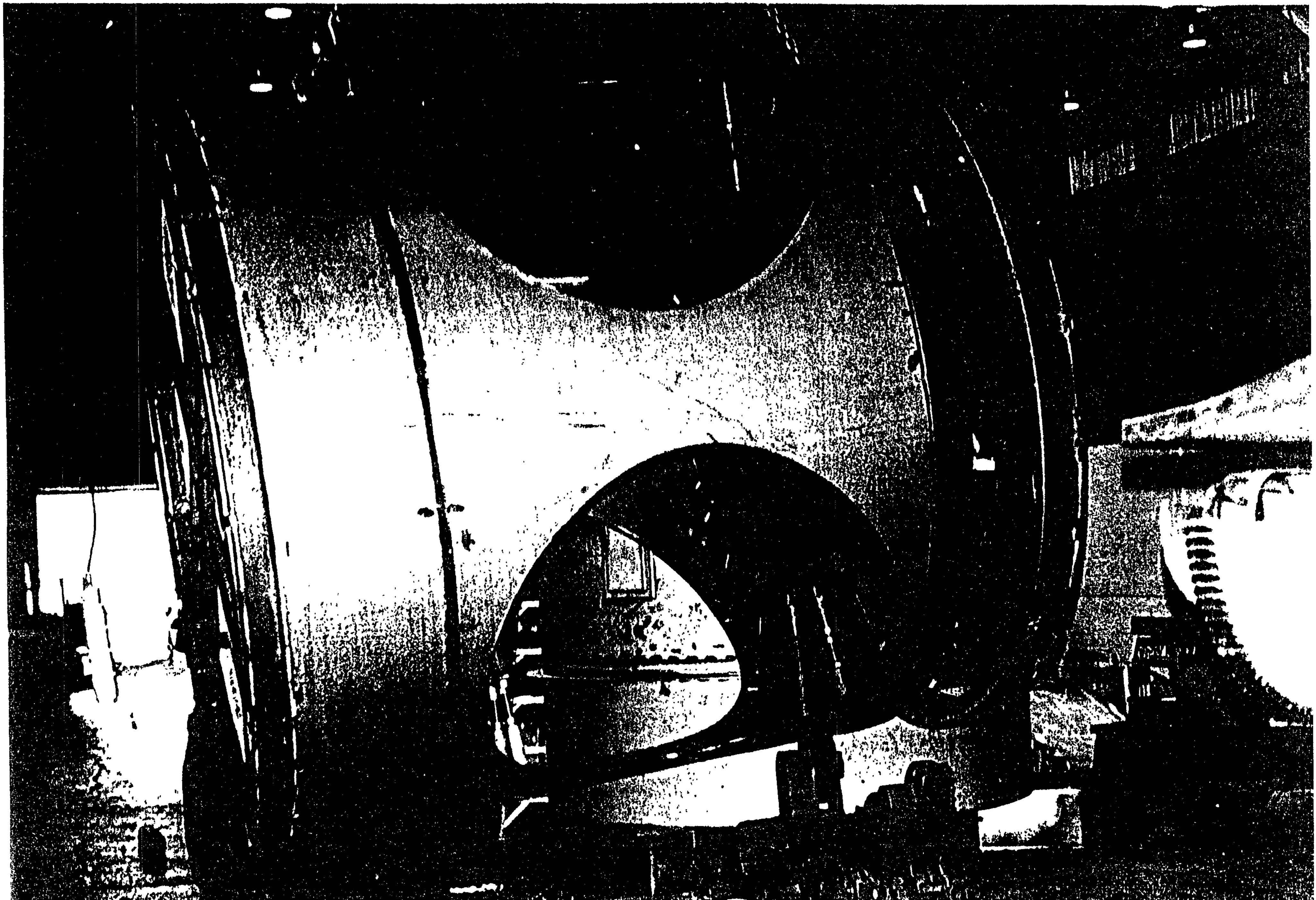
John Worden, Cecil Franklin, Allen Sibley

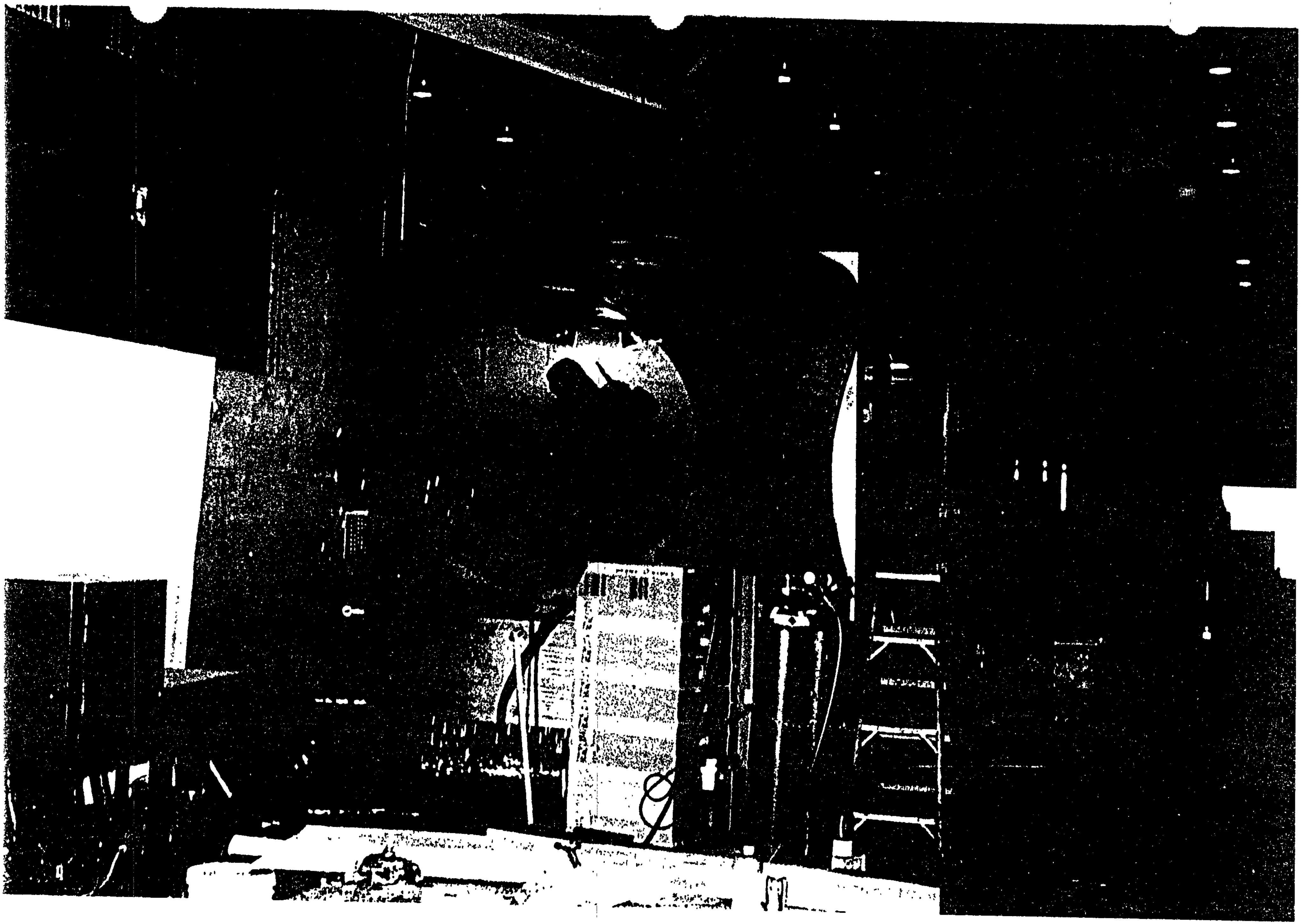
Objectives for Last 6 Months:

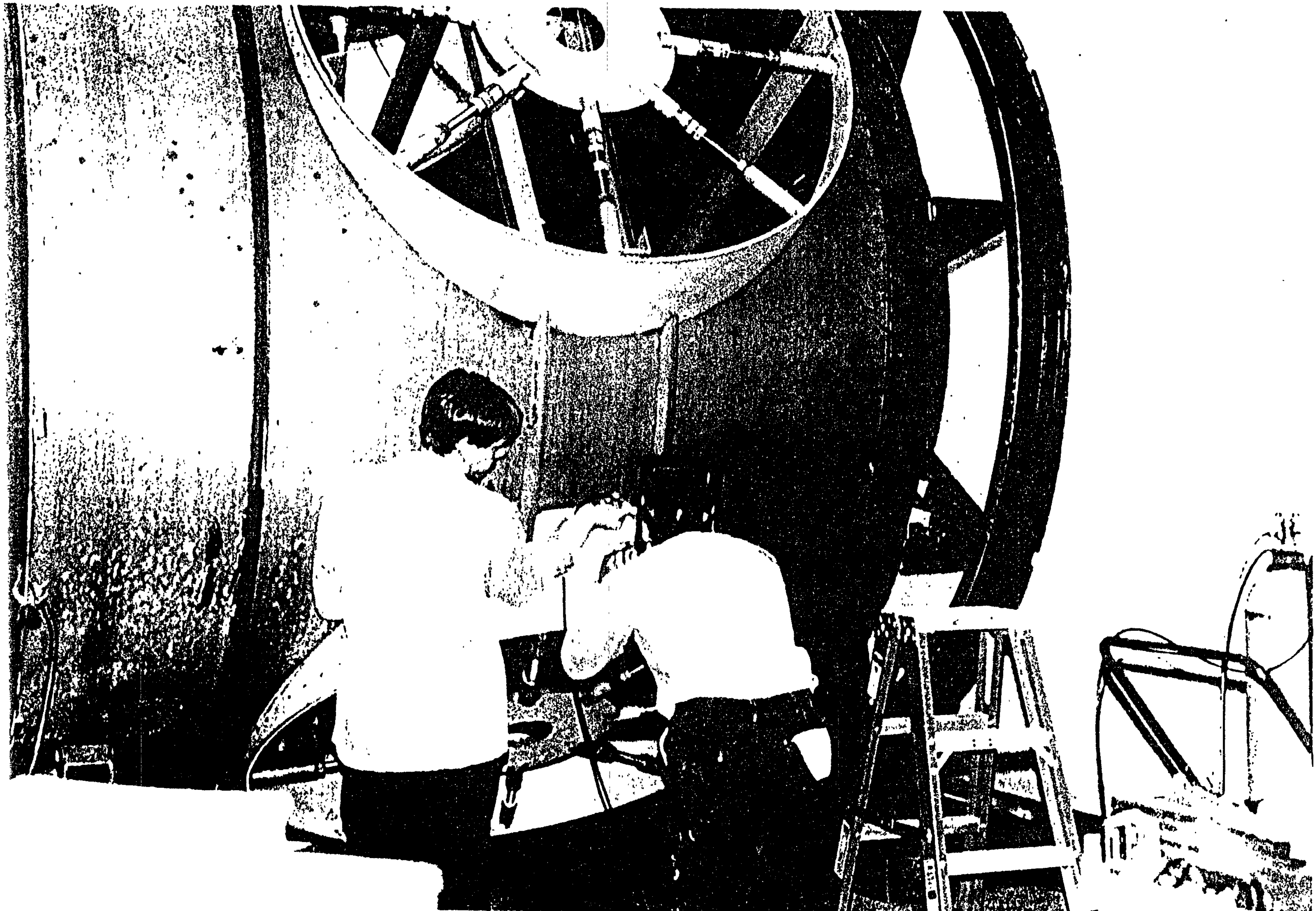
- **Chamber fabrication:**
  - BSC prototype fabrication, cleaning, and test
  - Prototype bakeout heater blankets/controller delivery and test
  - Raw material order - steel plate, forgings, heads
  - Initiate fabrication of HAM chambers
- **Purchased equipment:**
  - Delivery of 4 main turbopump carts, 2 auxiliary turbo carts
  - Delivery of 2 main roughing pump carts
  - Delivery of eight 48" gate valves
  - Delivery of prototype large ion pump
  - Clean rooms ordered

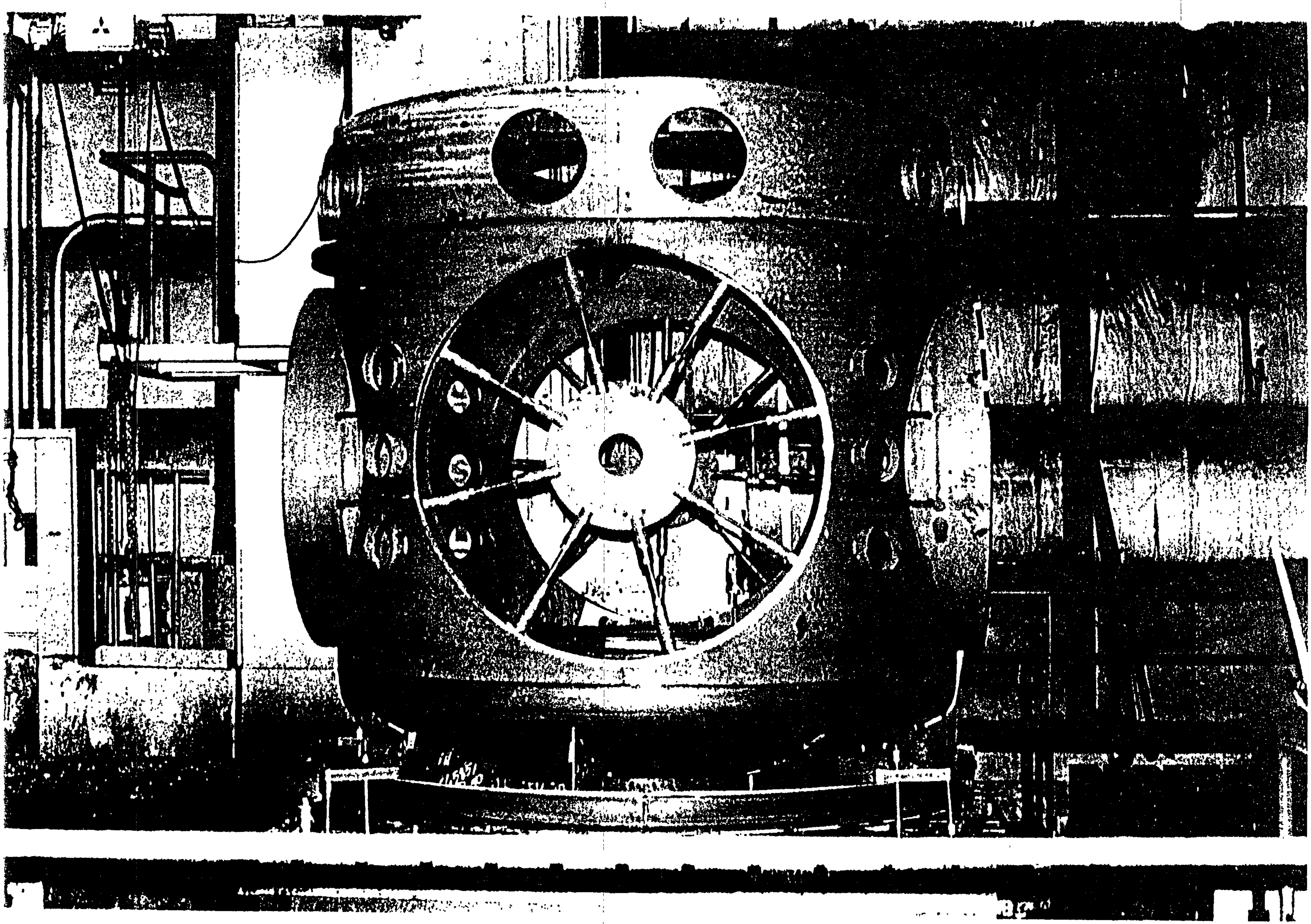


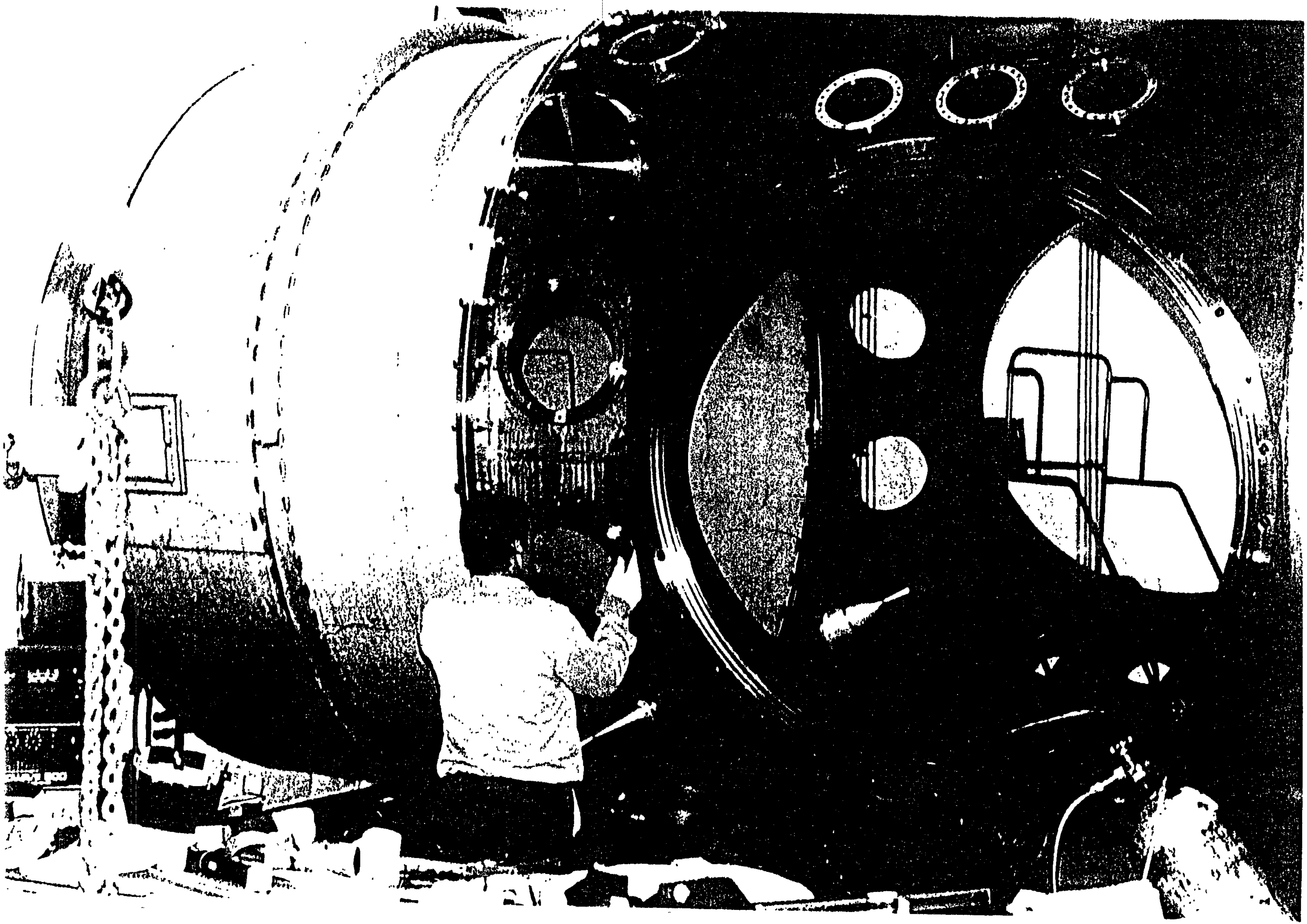


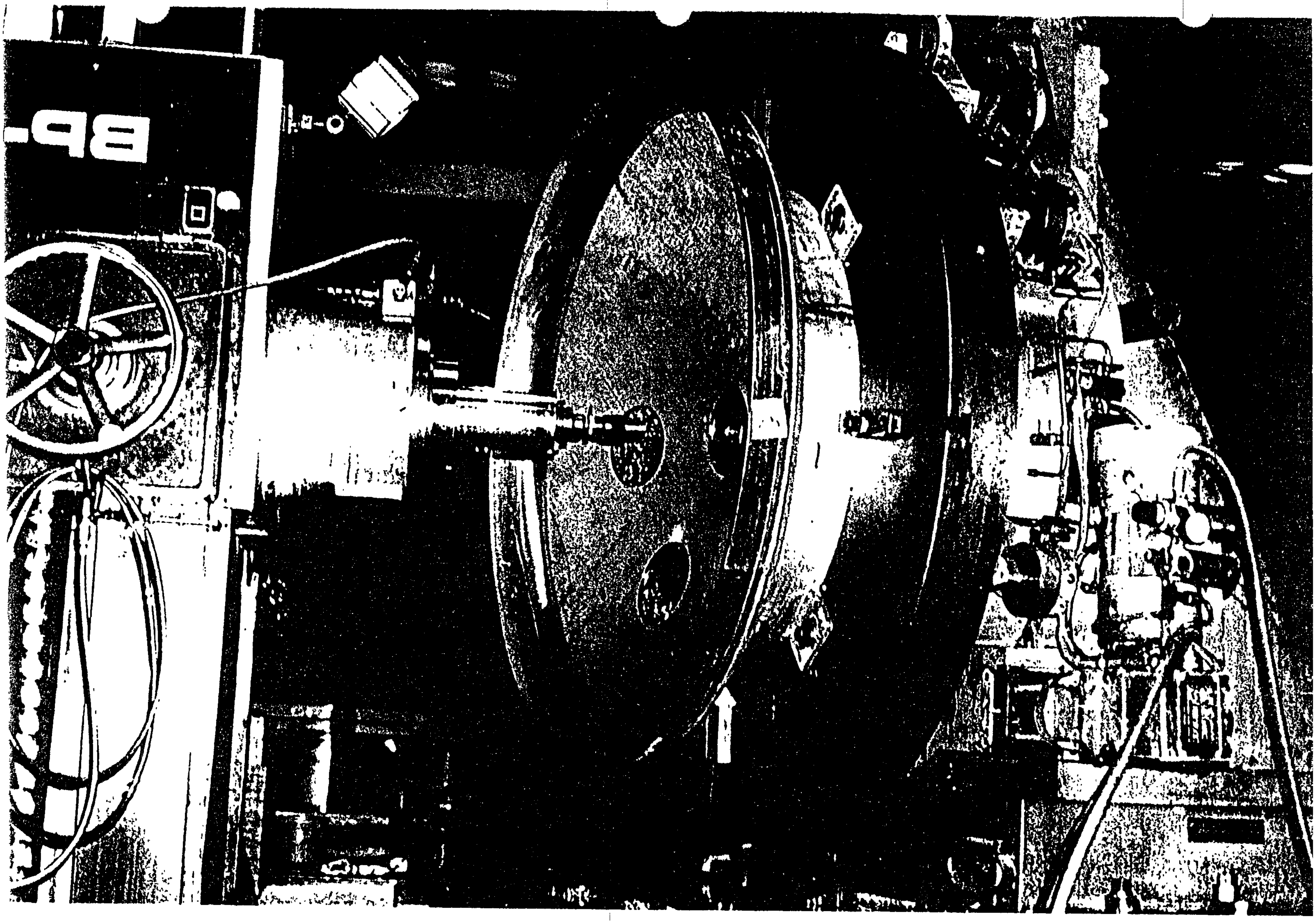


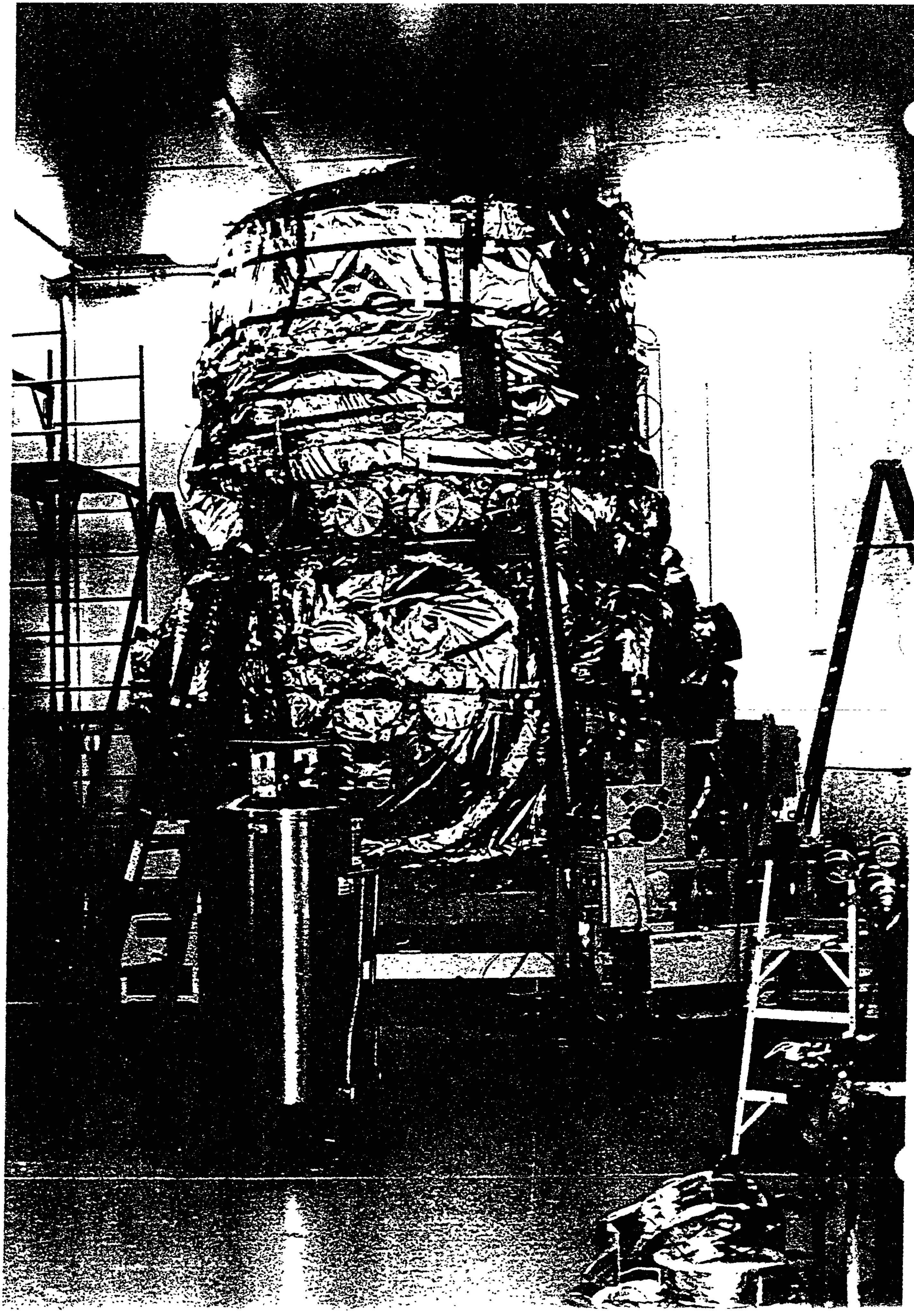








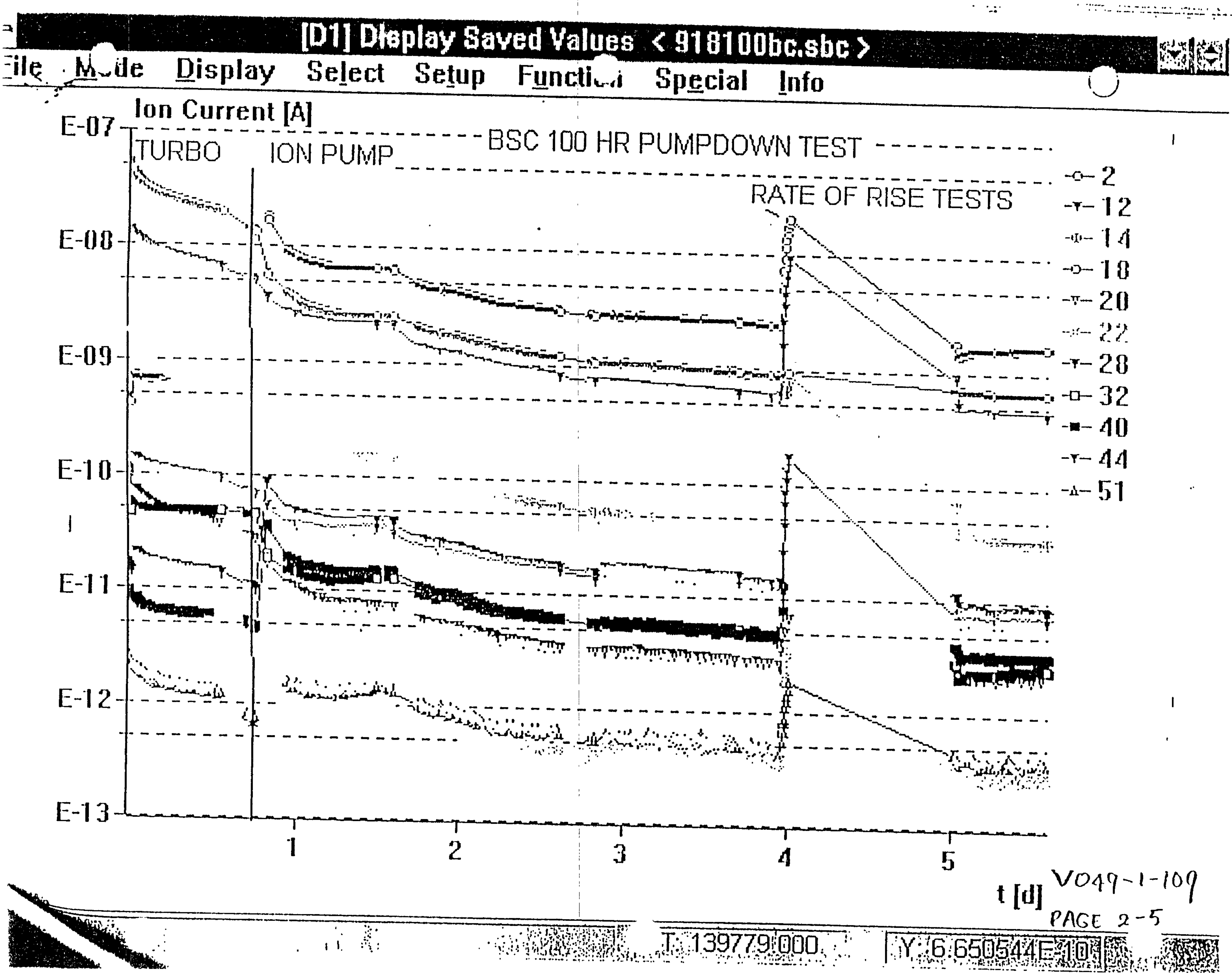




Preliminary
100 Hour bakeout test results

- The cleaning and baking procedures were very effective.
- There was little evidence of hydrocarbon contamination after the bakeout. Partial pressures of hydrocarbons were 3 to 4 orders of magnitude below hydrogen.
- Principal gas loads after the nitrogen soak are hydrogen, water, nitrogen.
- 100 gas load for nitrogen exceeds LIGO goals. Additional testing underway to determine source of N2.

- **Formal data review meeting Oct. 30 at PSI**



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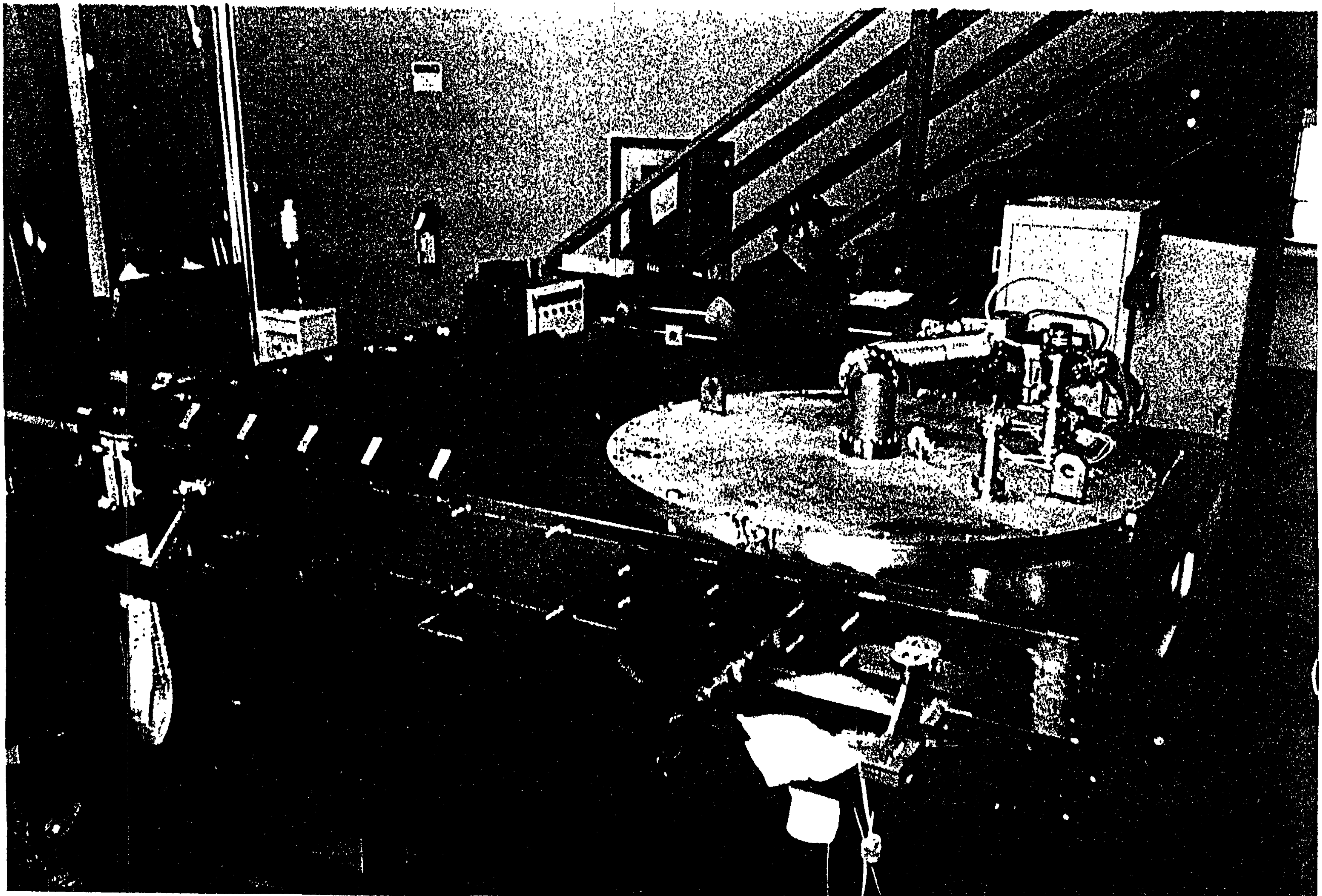
PAGE 2-5

TABLE 1.7
BSC 100 HR TEST
VERTEX+BEAMMANIFOLD PREDICTED

	BSC				VERTEX+ MANIFOLD			
LINEAL LENGTH VITON (CM)	2650				37639			
AREA (M^2)	55				478			
VITON/SS_AREA	48.18				78.74			
	GAS LOAD Torr-L/s	SPECIFIC RATE Torr-L/s-cm^2	SPEED approx. L/S	Pressure Torr	RATE Torr-L/s-cm^2	SPEED L/S	Pressure Torr	Pressure GOALS Torr
H2	5.5E-06	1.0E-11	535	1.03E-08	1.00E-11	12000	3.983E-09	5.0E-09
H2O	5.5E-06	1.0E-11	290	1.90E-08	1.00E-11	20000	2.39E-09	5.0E-09
N2	5.5E-06	1.0E-11	237	2.32E-08	1.00E-11	8000	5.975E-09	5.0E-10
CO	2.8E-06	5.0E-12	237	1.16E-08	5.00E-12	8000	2.988E-09	5.0E-10
CO2	2.8E-07	5.0E-13	190	1.45E-09	5.00E-13	8000	2.988E-10	2.0E-10
CH4	8.3E-07	1.5E-12	290	2.84E-09	1.50E-12	8000	8.963E-10	2.0E-10
OTHER	6.1E-07	1.1E-12	190	3.18E-09	1.10E-12	8000	6.573E-10	5.0E-10
SUM				7.15E-08			1.719E-08	1.19E-08

48" gate valve status

- 2 of 8 gate valves delivered (the 2 we need now)
- Design problems encountered due to LIGO's unique requirements:
  - no lubricants
  - vacuum load either side
  - low shock and vibration req't



Remaining Gate Valve Deliveries for Hanford

- 48" Gate valves
  - items 3 & 4 10/31 (electric)
  - items 5 & 6 11/30 (pneumatic)
  - items 7 & 8 12/19 (electric)

Need dates are not on critical path

LIGO-M960113-00-P

QUALITY ASSURANCE PROCEDURE

FOR

EQUIPMENT/MATERIAL RECEIVING INSPECTION
OF
ROUGHING PUMP SYSTEM

OCTOBER 18, 1996

From Bill Tyler

Equipment / Material Receiving Inspection Procedure
Roughing Pump System

1.0 The Receiving Inspector will verify that all equipment and material received is listed on the shipping documents and properly identified.

1.1 The Receiving Inspector will inspect all items for any evidence of shipping or handling damage.

1.2 The Receiving Inspector will verify dimensions of critical components, when required by LIGO documents.

1.3 The Receiving Inspector will document his inspection on a receiving Inspection Report (RIR, JPL form # 1898 or equivalent).

1.4 Any nonconformists found including missing items, incorrectly made items, incorrectly, identified items and damaged items will be documented and reported to the LIGO Contract Manager and /or LIGO Procurement Officer.

1.5 After receipt the equipment or material they will be properly stored and maintained in an appropriate location to insure proper protection again the elements.

1.6 Storage and maintenance will be performed in accordance with the manufacture's requirements.

2.0 The End Item Data Package (EIDP) will contain all critical data pertinent to each systems.

- Evidence of acceptance by Vendor or Supplier's
- A set of Drawing and Procurement Specification.
- Copy of Purchase Order.
- Requirement for Test Certification
  A. Acceptance Test Report / Data
  B. Dimensional Inspection Report
- Calibration Records
- Applicable Maintenance Procedures and Schedule.
- Safety constraints applicable to the equipment / material or personnel handling it.
- Any other data which may be required for preservation storage continued operation or repair of the equipment.

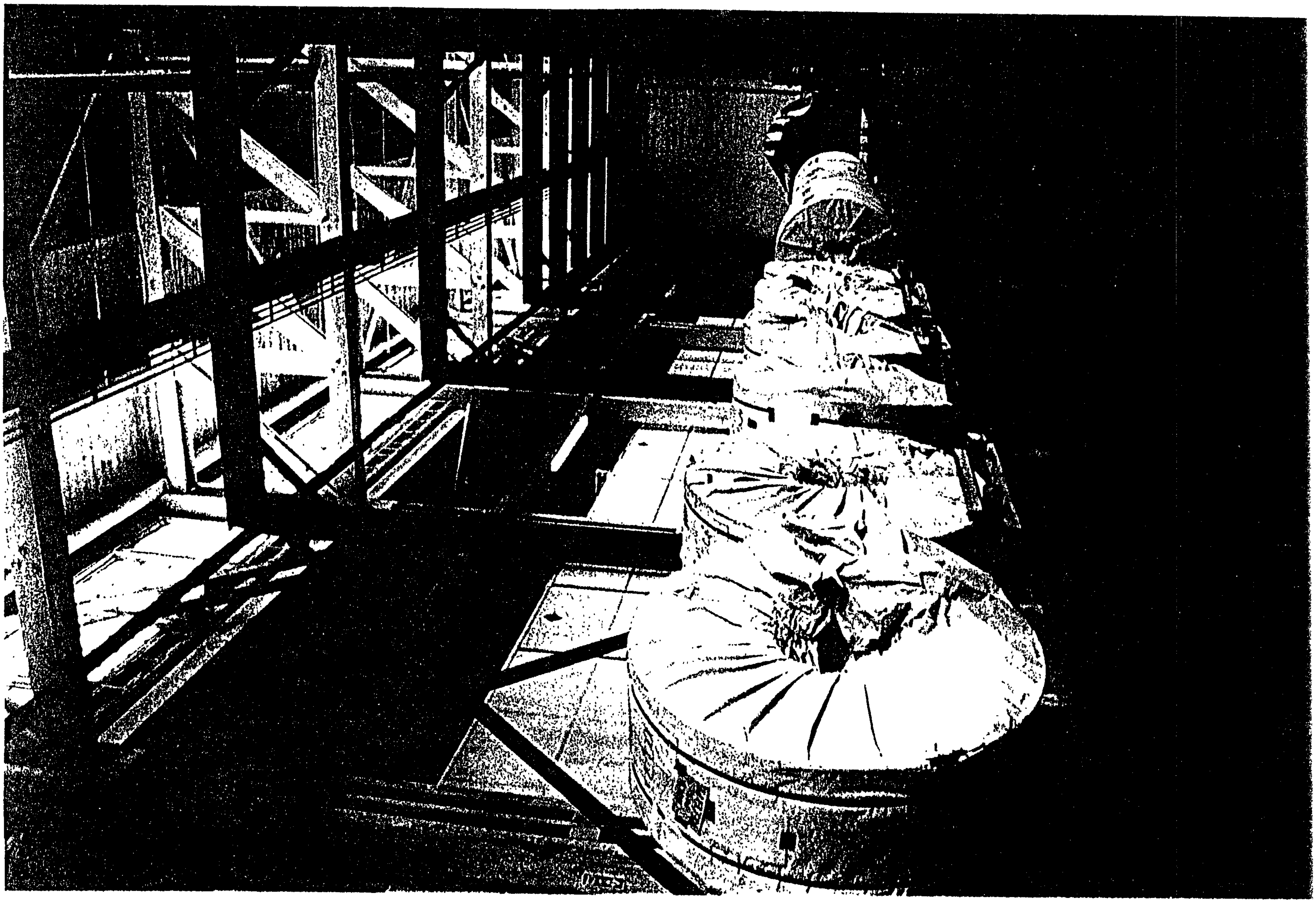
2.1 On completion of the (EIDP) acceptance, delivery, installation,qualification, operation or other processes for which availability of the (EIDP) may be a requirement the (EIDP) will be forwarded to the LIGO Project Document Control Center for recording and storage.

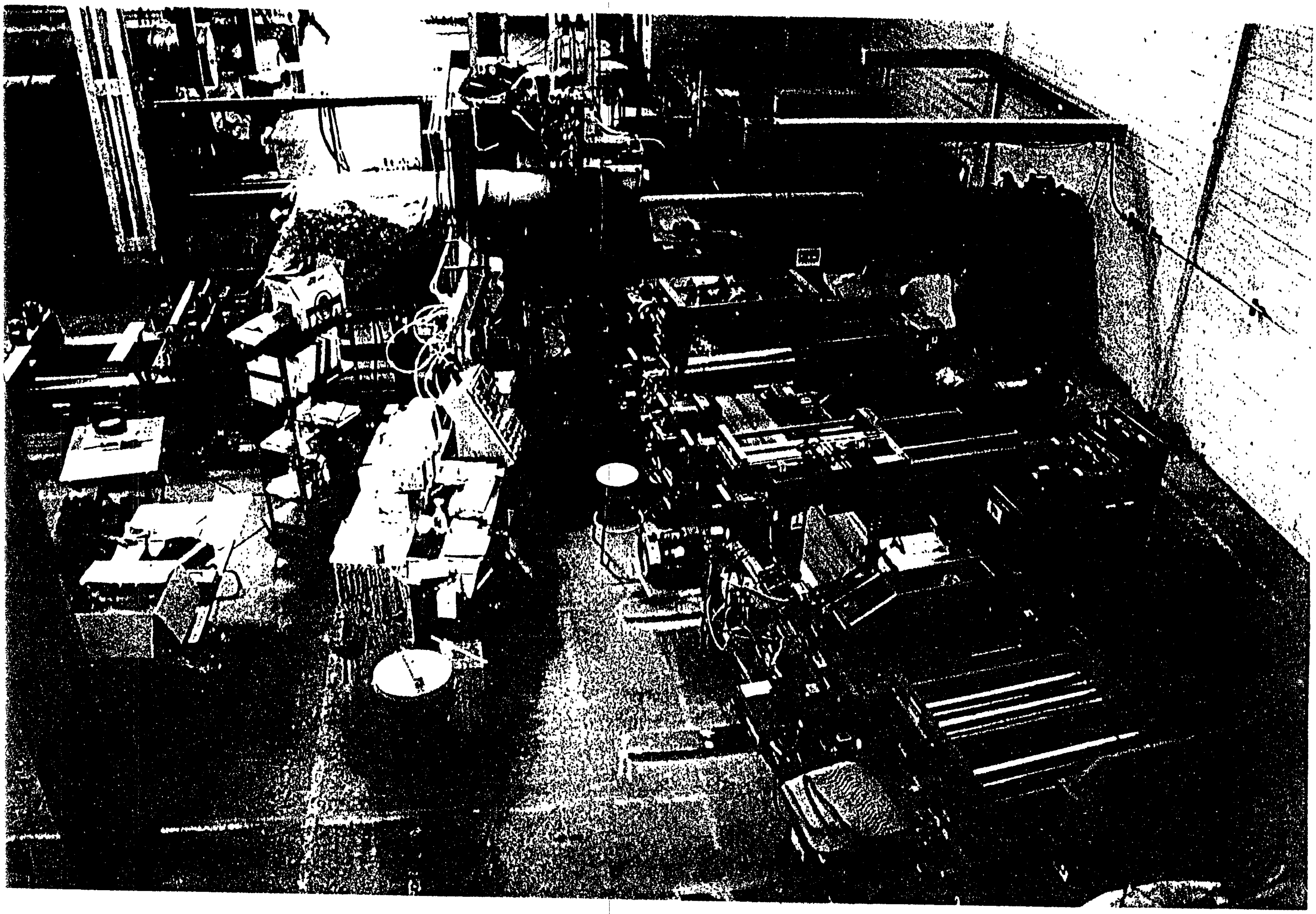
2.3 The End Item Data Package and the Receiving Inspection Report together with any associated documentation received with the equipment or material are part of the contract / procurement record and will be maintained / availability the LIGO Purchasing Officer.

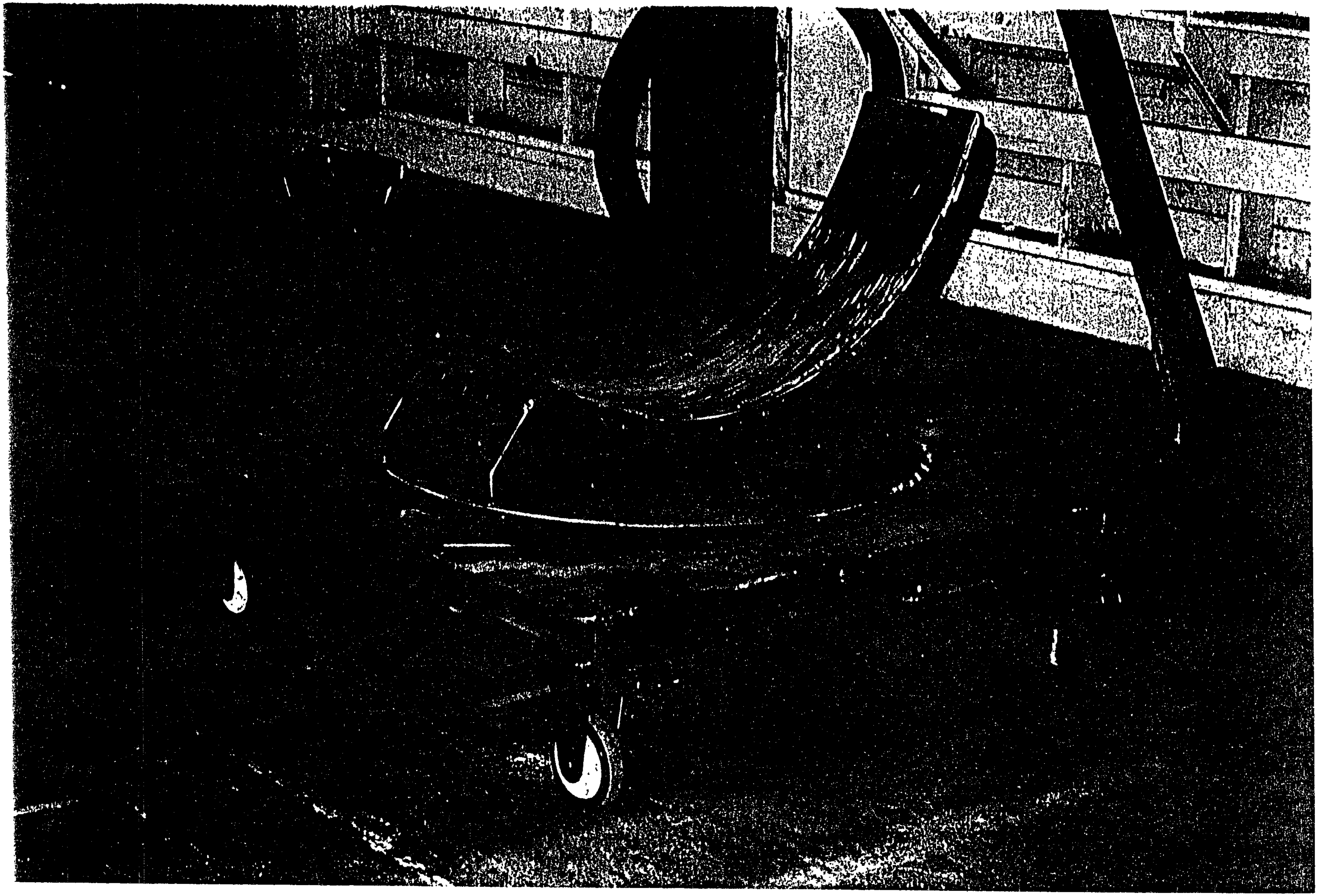
Beam Tube

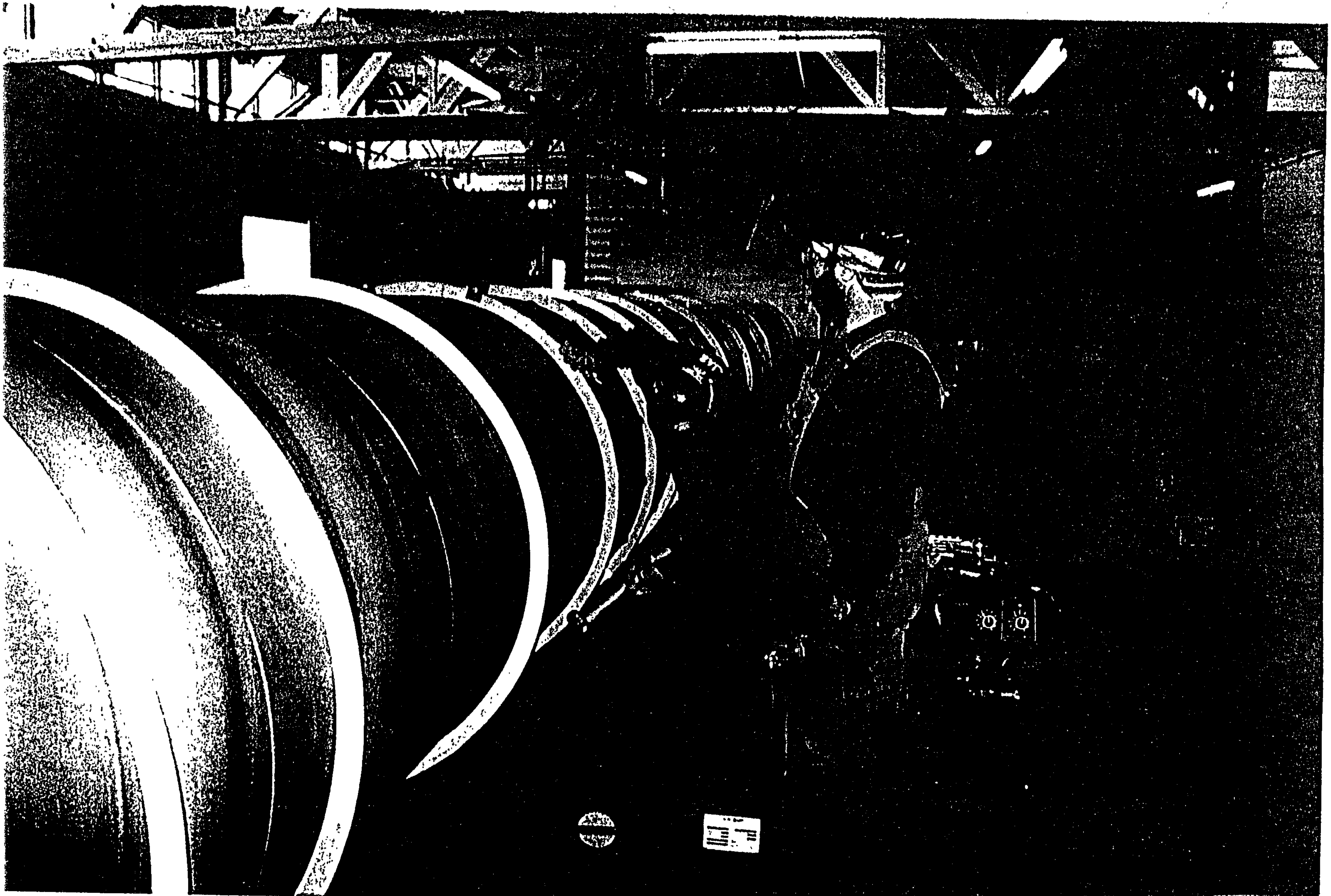
Larry Jones, Rai Weiss, Cecil Franklin, Rich Riesen, Allen Sibley

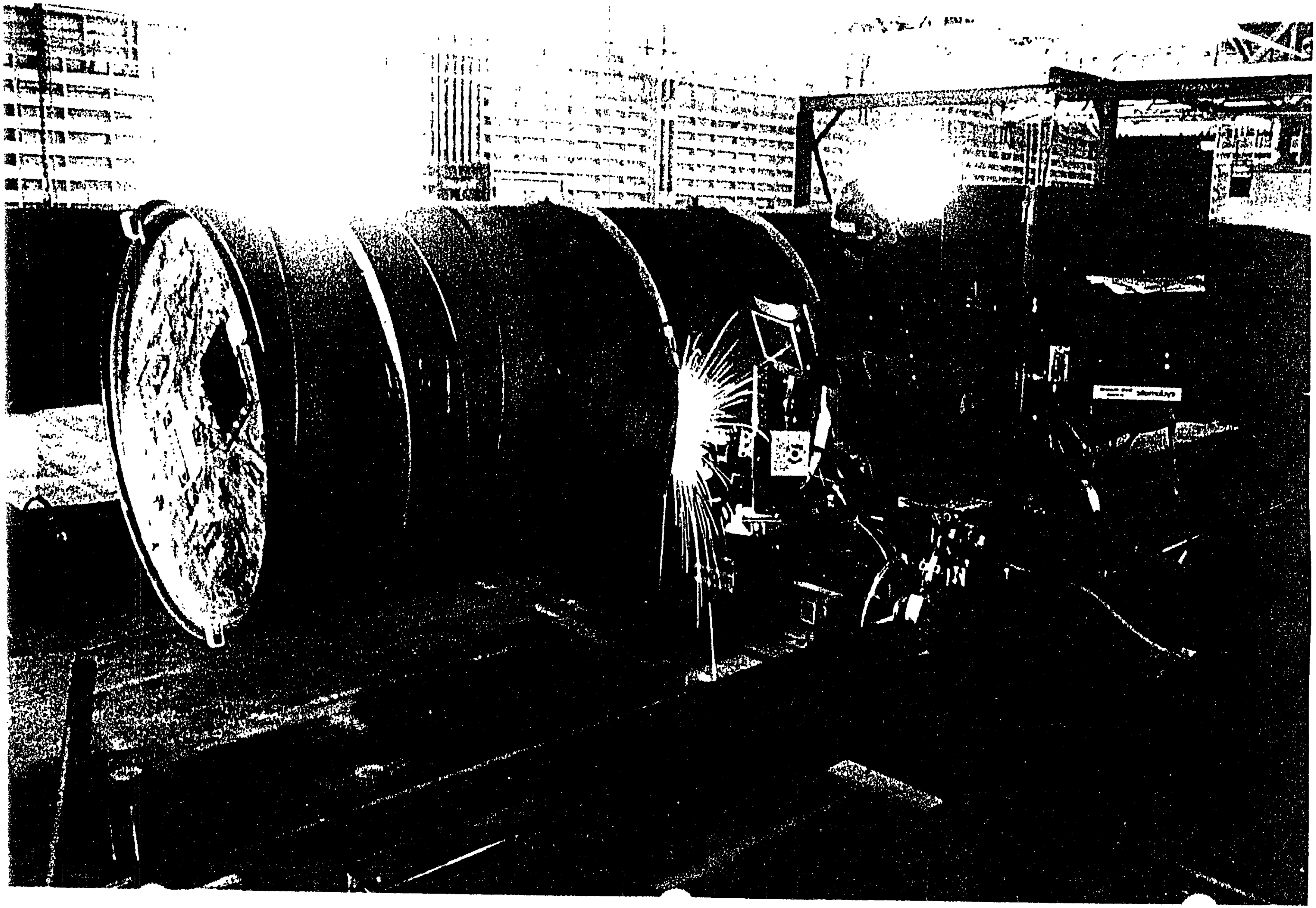
- Beam tube fabrication achievements of preceding 6 months:
  - Delivered spiral tube mill and qualified performance
  - Qualified other fabrication eqpt and fixtures
  - Processed stainless steel batch #2
  - fabricated and delivered 16 expansion joints
  - 300 fabricated and 200 delivered baffles
    - 55 tubes fabricated
    - 27 leak checked (no failures!)
    - 7 cleaned

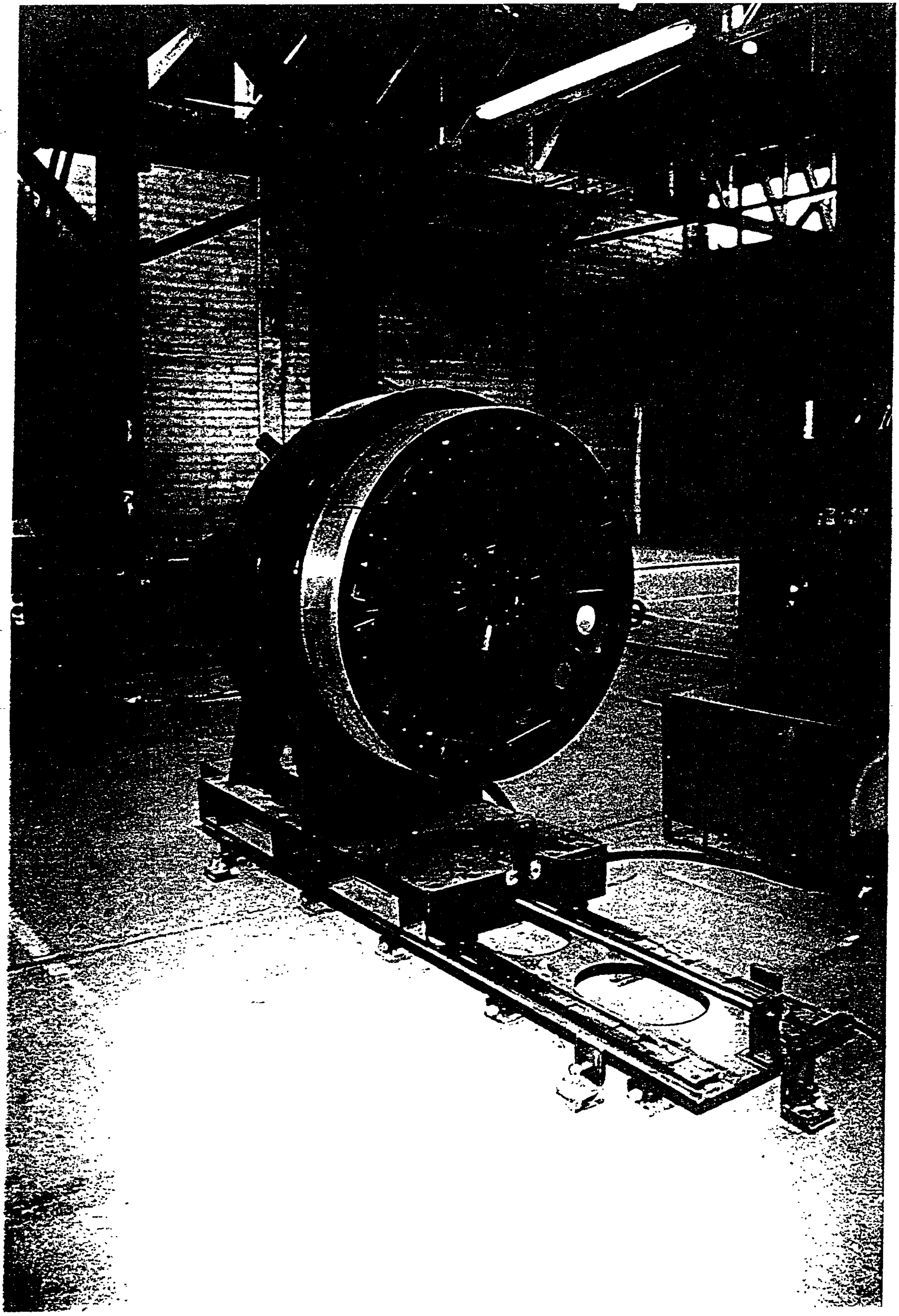


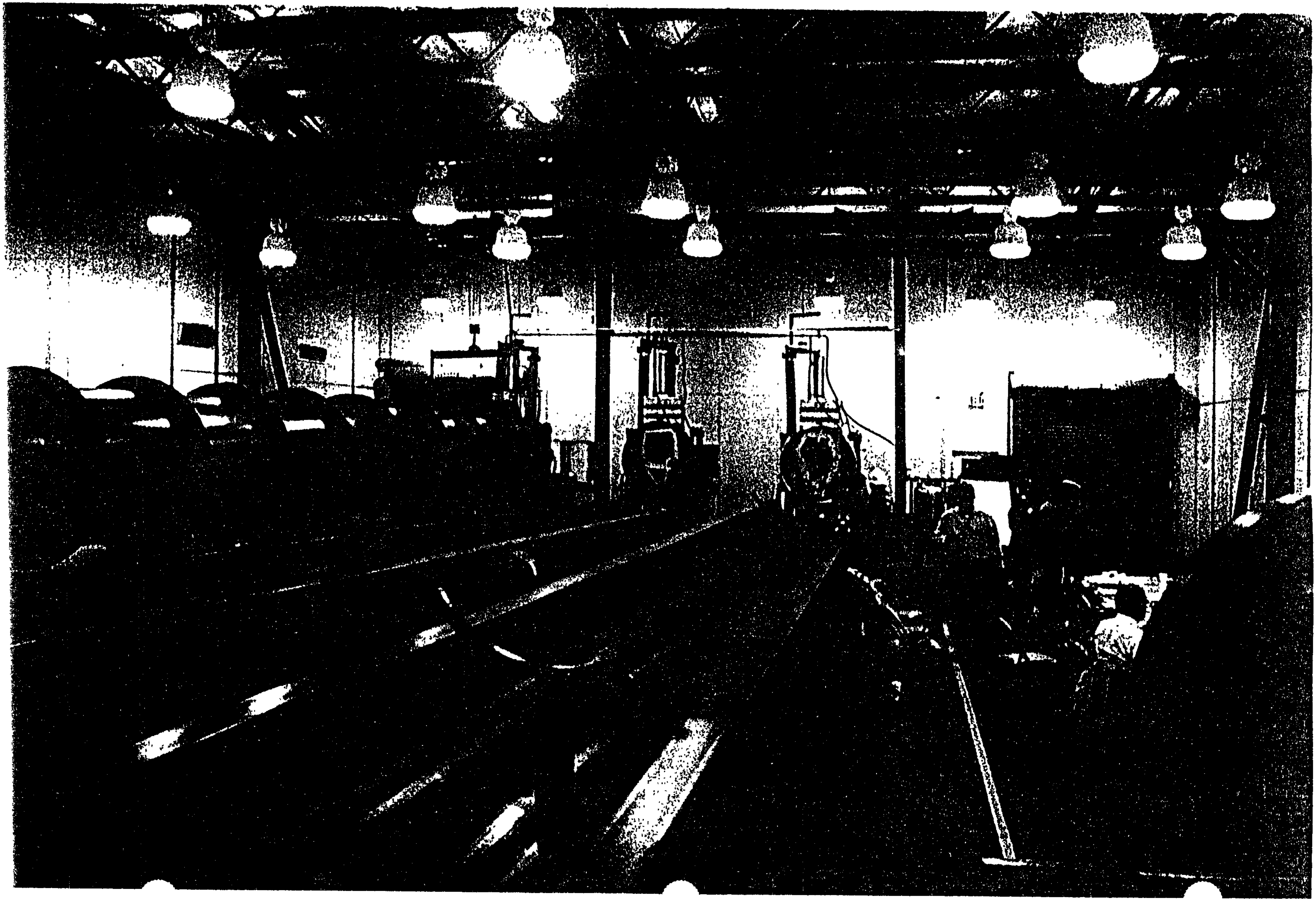


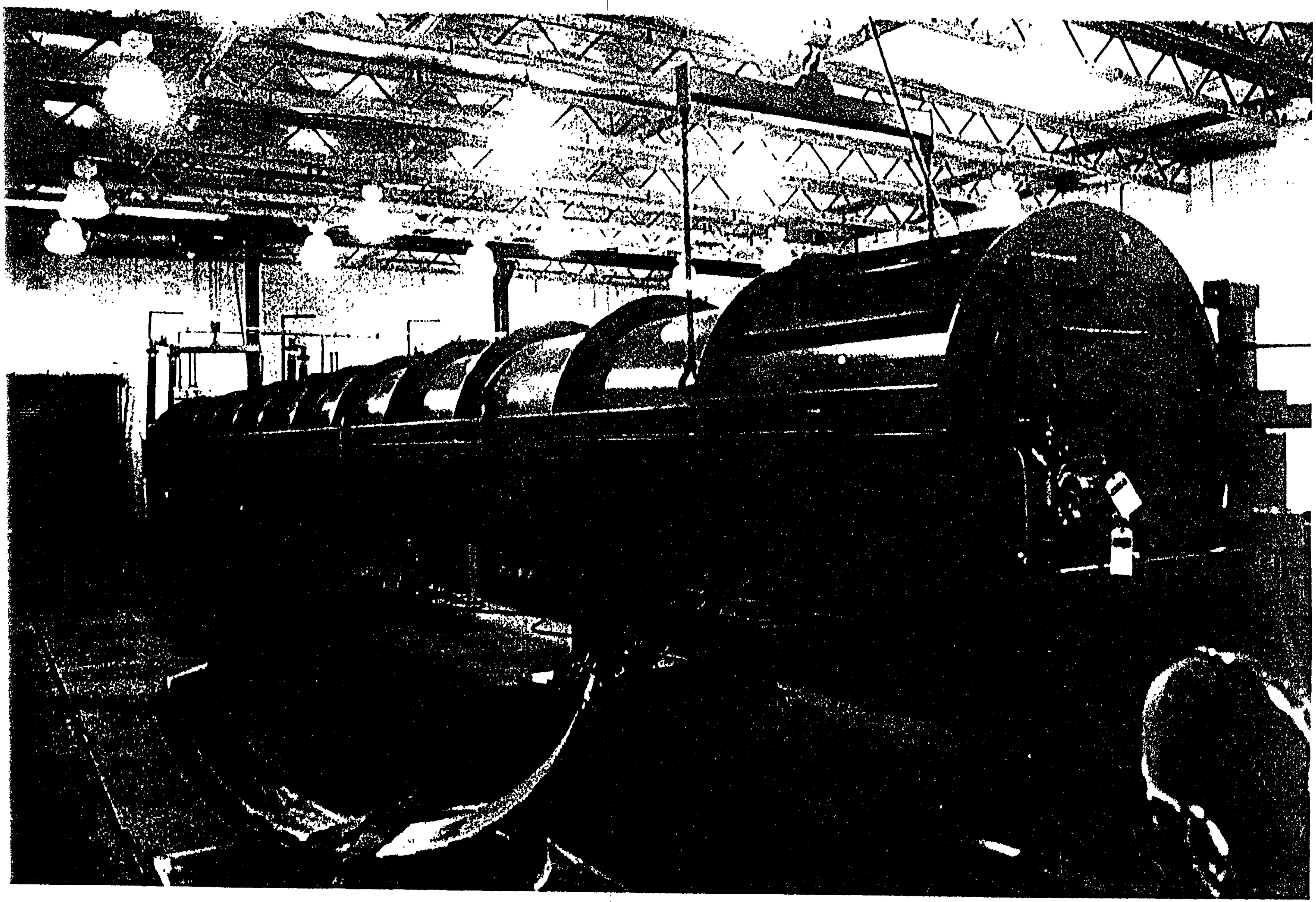


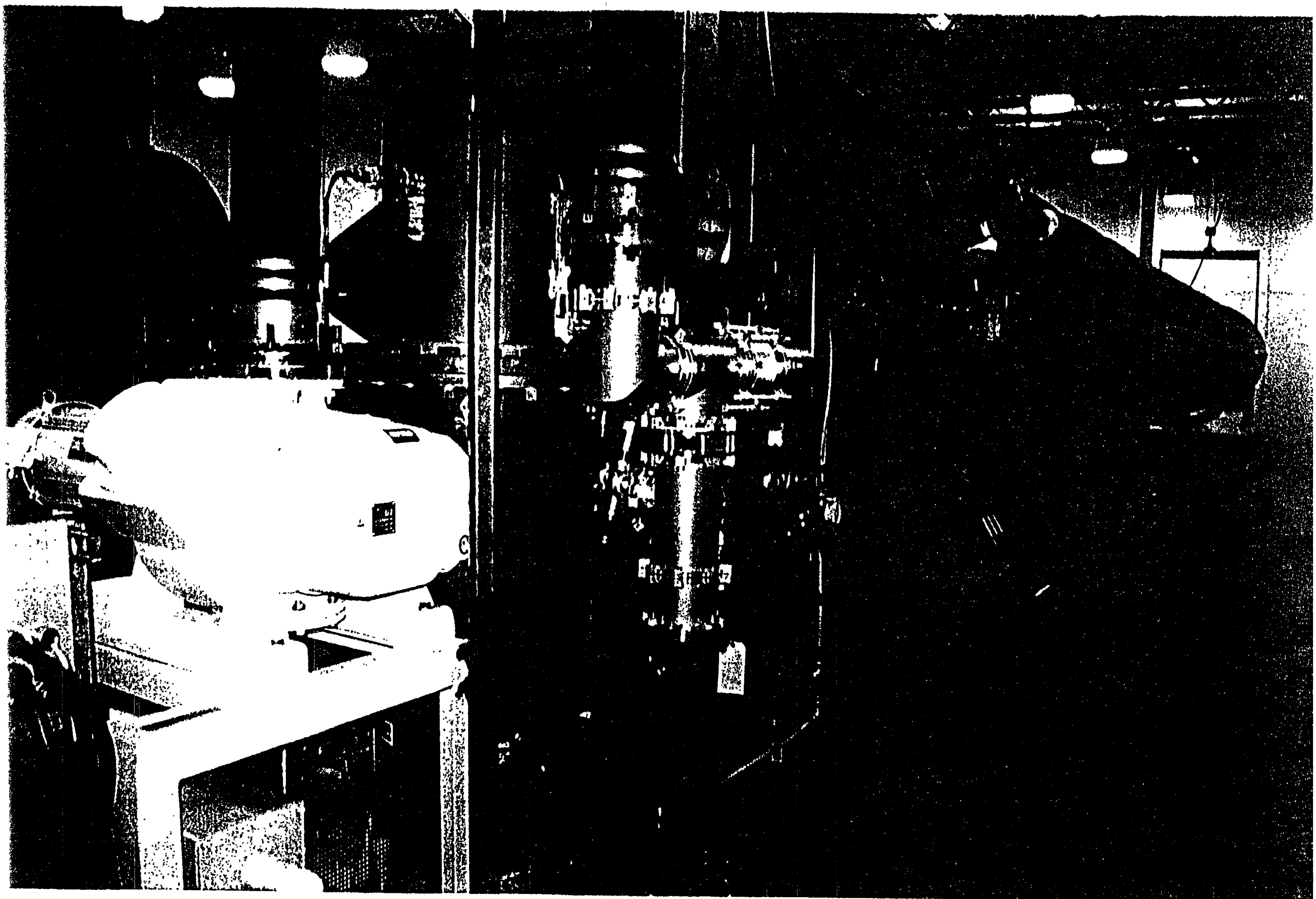


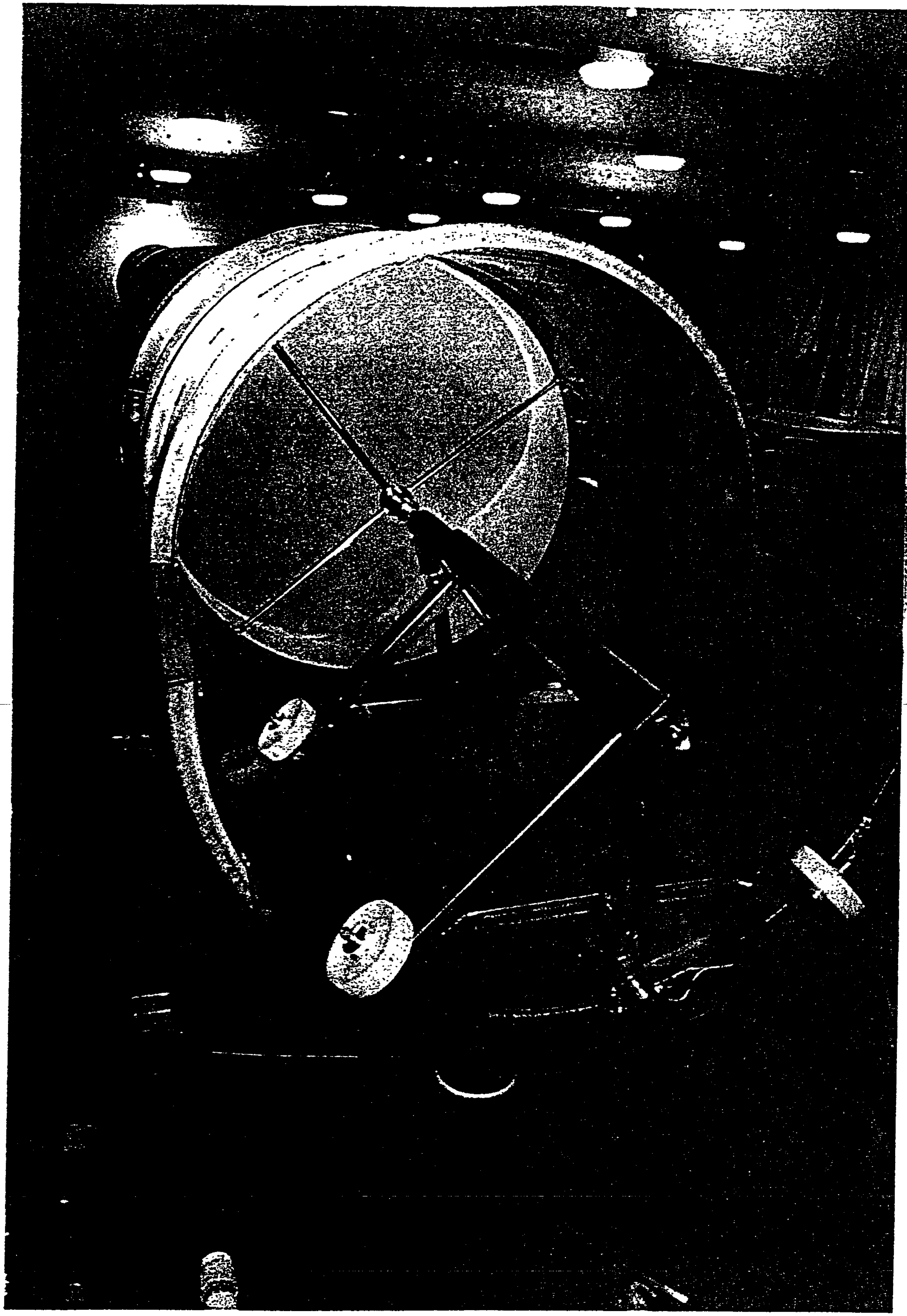












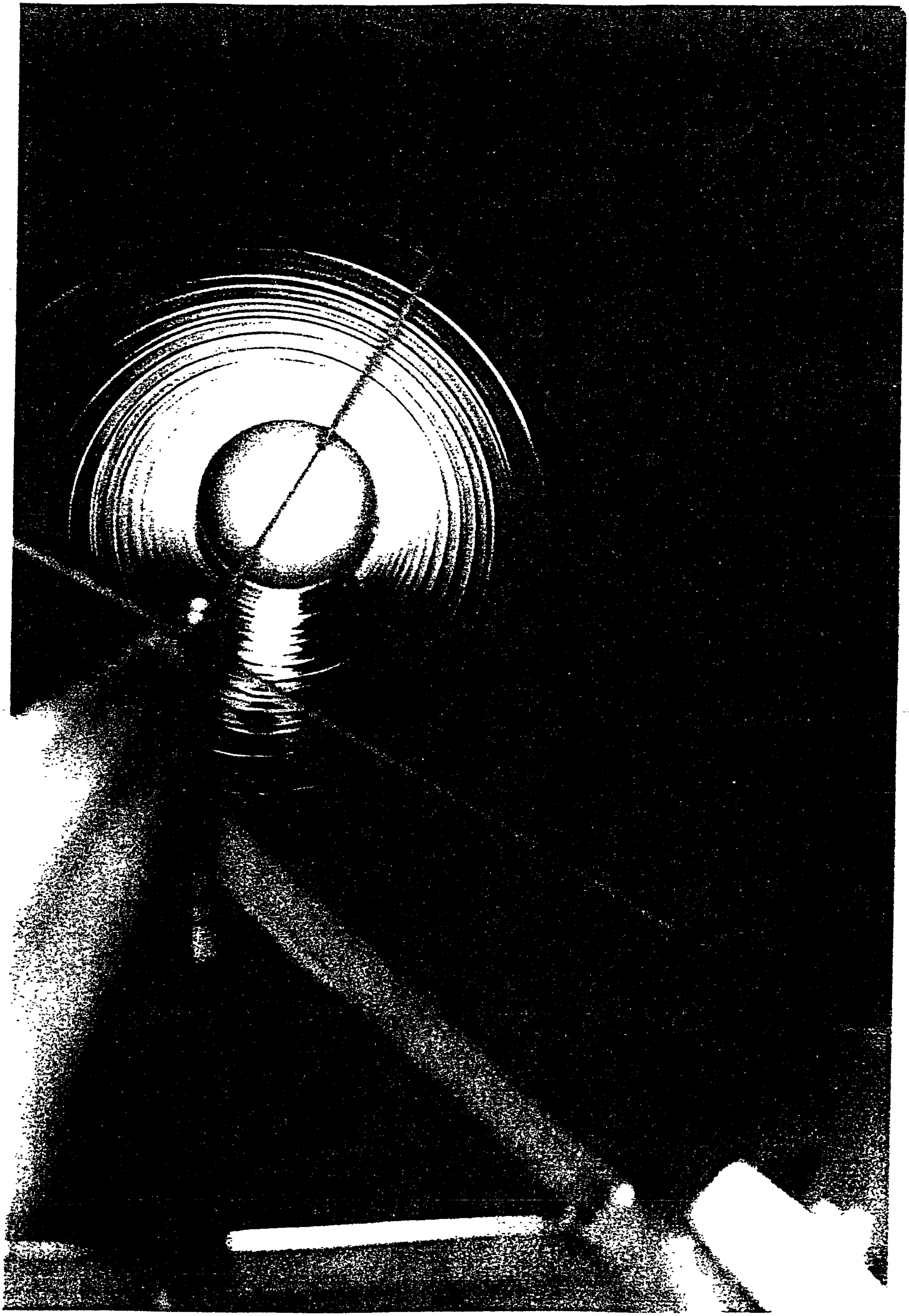
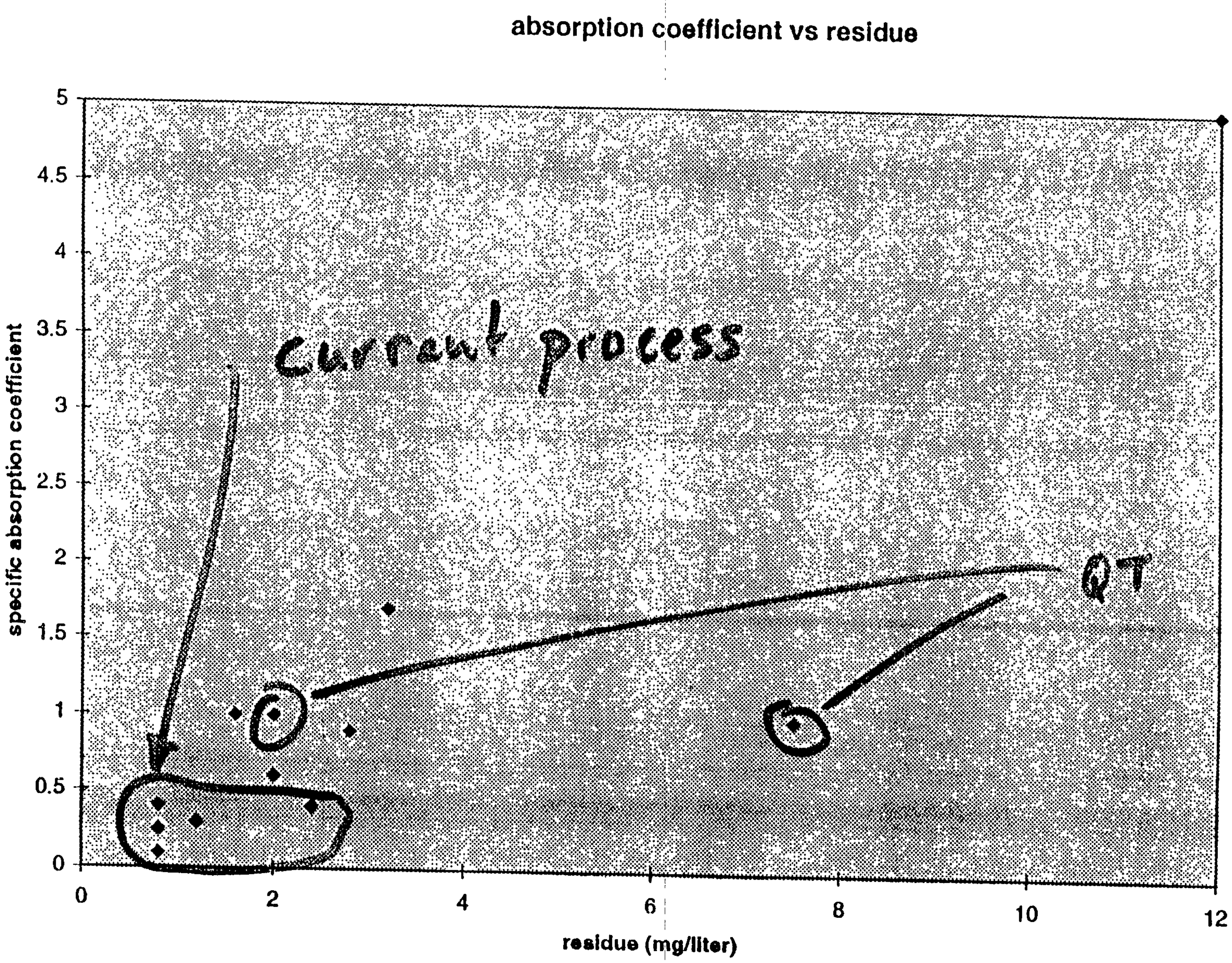


Table 1: Summary of FTIR measurements

Date	*Tube#*	*cond,*	*residue*	*evap.*	*KBr*	*gain*	*absorp.@*	*z*
			mg/liter	*cc*	*cm*^{2}		*2950cm*$^{-1}$	*x10*$^{-4}$
12/14/94	22A	uncl	14.5(6.0)	200	0.64	1	1.2(0.55)	5.0
12/14/94	22A	cl	7.5(6.0)	200	0.64	1	0.7(0.55)	1.0
12/15/94	22B	uncl	9.0(6.0)	100	0.64	1	0.95(0.27)	10.0
12/15/94	22B	cl	2.0(6.0)	100	0.64	1	0.35(0.27)	1.0
09/25/96	B001	cl	12.0(1.6)	100	0.32	1	0.70(0.04)	5.0
10/01/96	B003	uncl	4.8(1.6)	100	0.32	5	0.08(0.04)	1.1
10/01/96	B003	cl(on)	3.2(1.6)	100	0.32	5	0.10(0.04)	1.7
10/02/96	B002	uncl	3.2(1.6)	200	0.64	5	0.08(0.03)	0.4
10/02/96	B002	cl(on)	2.0(1.6)	200	0.64	5	0.10(0.03)	0.6
10/02/96	B002	cl(off)	0.8(1.6)	200	0.64	5	0.07(0.02)	0.4
10/03/96	B004	uncl	3.2(0.8)	200	0.64	5	0.20(0.02)	1.3
10/03/96	B004	cl(on)	1.6(0.8)	200	0.64	5	0.14(0.02)	1.0
10/03/96	B004	cl(off)	0.8(0.8)	200	0.64	5	0.10(0.02)	0.6
10/04/96	B005	cl(on)	2.8(0.8)	200	0.64	5	0.15(0.02)	0.9
10/04/96	B005	cl(off)	2.4(0.8)	200	0.64	5	0.05(0.02)	0.2
10/09/96	B001	cl(on)	2.4(0.8)	200	0.64	5	0.09(0.03)	0.4
10/09/96	B002	cl(on)	0.8(0.8)	200	0.64	5	0.04(0.03)	0.1
10/09/96	B003	cl(on)	0.8(0.8)	200	0.64	5	0.08(0.03)	0.4
10/11/96	G001	cl(on)	0.8(0.8)	200	0.64	5	0.06(0.03)	0.25
10/11/96	I001	cl(on)	1.2(0.8)	200	0.64	5	0.07(0.03)	0.3

The samples for FTIR analysis are taken by pouring 2 liters of HPLC 2-isopropanol along the length of the tube in a channel about 10 cm wide. The fluid is collected in clean beakers at one end and samples are sent to an analytic chemistry laboratory for evaluation. The laboratory evaporates


absorption coefficient vs residue
specific absorption coefficient
residue (mg/liter)
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
0
2
4
6
8
10
12
Current process
QT

a known quantity (usually 200 cc) of the isopropanol onto a Potasium Bromide crystal slide for insertion into the beam of a Michelson interferometer with sensitivity between 400 to 4000 cm^{-1}. The results of the measurements are given to CB&I and the LIGO project in the form of transmission and absorption curves. The laboratory provides the absorption as $A = -\log_{10}\left(\frac{1}{T}\right)$

The notation used in Table 1 is the following. Numbers in parantheses are the values for the isopropanol reference. During the QT there was a large variation in the reference values ultimately traced to the use of "dirty" sample collection vessels. The sampling method has been changed in Pasco and the consistency and reliability of the measurements has been greatly improved. In the column indicating the conditions, the designation uncl means sample taken before the tube was cleaned, cl(on) is a sample taken along the same azimuthal position in the tube as the drain during the cleaning and rinse while the designation cl(off) is a sample taken after the tube has been rotated to provide more typical surface conditions in the tube. Samples taken on the drain line have more contamination than those off the line. During routine production CB&I will be measuring every tenth tube by sampling on the drain line. The column labeled residue is a first order measurement of the contamination provided by weighing the residue after the sampling isopropanol has been evaporated. The columns labeled evaporated volume, area of the KBr spectrometer sample plate, gain and absorption at the C-H stretch band at 2950 cm^{-1} are used for internal checks of the FTIR data. The last column listing the specific absorption, z, at 2950 cm^{-1} is the best estimator for the hydrocarbon contamination on the surface. The specific absorption is defined as

$$z = \frac{(\ln(I/I_0)_{sample} - \ln(I/I_0)_{reference}) \times \text{KBr area} \times \text{sample volume in tube}}{\text{sample volume evaporated on KBr} \times \text{area of tube exposed}}$$

Table 2: Auger analysis 270 ev Carbon line given in terms of 10^3 counts in 1.64 minutes vs A^+ milling time

tube #	*condition*	*0 min*	*1 min*	*2 min*	*3 min*	*4 min*
22B	uncl	57.4	24.3	16.5	11.8	10.8
22B	cl	26.1	8.1	6.5	4.4	5.1
B-005	uncl	59.5	17.6	10.6	8.3	7.1±1.0
B-005	cl 1	24.3	5.2	2.3	1.0±1.0	0.0±1.0
B-005	cl 2	21.9	6.7	2.1	1.0±1.0	0.0±1.0

Auger electron spectra are taken on strips of the steel that have been cut from the same material as the tube. One coupon is not cleaned (uncl) and another (cl) is placed at the drain end of the tube a few mm above the surface. This sample experiences the same cleaning as the tube itself.
When analysed in the Auger electron spectrometer the Auger electron peak for Carbon is mea-

Oversite of Beam Tube Fab

- Cecil Franklin, Rich Riesen providing fulltime surveillance of factory and site installation activities.
- Daily log kept, copies sent to Caltech each week.
- Specific fab activities that are witnessed get logged on QA sheets

BEAM TUBE ASSEMBLY ACTIVITIES

NOTE: CLEAN CLOTHING AND SHOE COVERS SHALL BE WORN FOR WORK INSIDE THE BEAM TUBE

INSPECT TUBES	1. MONITOR TUBE CIRCUMFERANCE AND VARIATION 2. TUBE STRAIGHTNESS MEASURE/VARIATION
LAYOUT TUBES	1. STIFFENER LOCATION/SPACING 2. PUMP PORT LOCATION 3. TUBE INDEX, REFERENCE MARKS
PURGING OF TUBES	1. PERIODIC CHECK OF RESIDUAL O2 LEVEL 2. PURGE GAS (N2) PURITY 3. END COVERS INSTALLED
FITTING OF STIFFENERS AND SUPPORTS	1. VERIFY PURGE GAS FLOW 2. STIFFENER SPLICE LOCATION OVER SPIRAL WELD AND MINIMUM UNWELDED STIFFENER? 3. LOCATION, SPACING AND LENGTH OF TACK WELDS 4. TIGHT FIT OF STIFFENER 5. VERIFY ALIGNMENT OF SUPPORT RINGS AND BEAM TUBE CARDINAL LINES
WELDING OF STIFFENERS AND SUPPORTS	1. LOCATION OF WELD START 2. NO WELDING OVER SPIRAL WELDS 3. MAX TILT OF STIFFENER < 10 DEGREES
PUMP PORT FITTING AND WELDING	1. REINFORCING RING DOES NOT CROSS SPIRAL WELD 2. RING IN CORRECT LOCATION 3. ADEQUATE PURGE FOR WELDING? 4. PUMP PORT PROTECTIVE COVER IN PLACE?
PUMP PORT WELD INSPECTION	1. WELD APPEARANCE 2. EXTENT OF UNDERCUT, RIDGES OR VALLEYS 3. ADEQUATE FILLET?
EXPANDING AND MACHINING TUBE ENDS	1. FINAL END FINISH 2. END PLANE FLATNESS AND PERPENDICULARITY 3. EXPANDED END CIRCUMFERENCE
EXPANSION JOINT FITTING AND WELDING	1. MONITOR CENTERING OF WELD JOINT 2. TACK WELDING AND UNIFORMITY OF WALL (THICKNESS) MATCH 3. RESIDUAL O2 IN PURGE GAS
DIMENSIONAL INSPECTION	1. BUTT WELD OFFSET IN-SPEC VARIATIONS? 2. TUBE LENGTH

LEAK TESTING ACTIVITIES

SETUP TUBE IN TEST ENCLOSURE

1. INSTALLATION OF BEAM TUBE IN TEST COFFIN
2. CONFIRM EXPANSION JOINT IS RESTRAINED BY LEAK TEST FIXTURE

↓

ATTACH TEST HEADS

↓

DRAW VACUUM ON TUBE

1. OBSERVE ABSOLUTE PRESSURE IN TUBE SECTION
2. OBSERVE DIFFUSSION PUMP FORELINE ABSOLUTE PRESSURE
3. HELIUM MASS SPEC ELEMENT PRESSURE DURING TEST

↓

ENCLOSE TUBE IN TEST HOOD

↓

EVACUATE TEST ENCLOSURE

1. OBSERVE PARTIAL PRESSURE

↓

CHECK MASS/SPEC INTERNAL/STANDARD LEAKAGE REATE OF STD LEAK

1. OBSERVE SYSTEM STANDARD HELIUM LEAK I.D.
2. OBSERVE SYSTEM STANDARD LEAK HELIUM LEAK RATE AND RECORD READING

↓

CHECK MASS/SPEC SENSITIVITY TO SYSTEM

1. OBSERVE CLEANUP TIME AND RESPONSE TIME AND RECORD ACTUAL TIME
2. OBSERVE PRELIMINARY SYSTEM SENSITIVITY AND RECORD READING

↓

PERFORM MASS SPECTROMETER LEAK TEST

↓

PRESSURIZE TEST ENCLOSURE WITH HELIUM

1. OBSERVE HELIUM MASS SPEC RESPONSE DURING PRESSURIZING TEST ENCLOSUE WITH HELIUM AND RECORD ANY INCREASE IN READING

↓

HELIUM CONCENTRATION IN TEST ENCLOSURE

1. OBSERVE HOOD PRESSURE AND RECORD READING
2. OBSERVE HELIUM CONCENTRATION % ON ANALYZER AND RECORD READING (GOWVAC MODEL 20-160)

↓

FINAL OBSERVED LEAKAGE RATE

1. OBSERVE HELIUM MASS SPEC INDICATOR FOR INCREASE IN HELIUM LEAKAGE RATE

CBI LIGO TUBE SECTION LEAK TEST REPORT

TUBE SECTION I.D. NO.	CONTRACT	LOCATION (Circle One)
TUBE ASSY. B-005	953571	(Hanford) / Livingston

Procedure and Rev. HMST1N Rev. 4D	HMS Leak Detector (Mfg., Model and Serial Number) VARIAN 960 S/N DRAF 6003
System Standard Helium Leak ID VTI S/N # 2128	System Standard Leak Helium Leakage Rate S/N 2128 2.6 $\times 10^{-10}$ atm. cc/sec.
Basis for HMS Leak Indicator Division Unit of 2 on 10^{-11} Scale (50 divisions to a scale)	HMS Element Pressure During Test BOTTOM OF SCALE Torr
Tube Section Absolute Pressure (P_1) During Test 2.2×10^{-6} Torr	D.P. Foreline Absolute Pressure (P_2) During Test 1.7×10^{-2} Torr

Observed Clean up time: 25 SECONDS RESPONSE TIME 10 SECONDS

M_1 (Initial Helium Signal) [7 div on 10^{-10} scale, x 10] = 70 divisions on 10^{-11} scale 1.5×10^{-10}

M_2 (Background Signal) [____ div on 10^{-10} scale, x 10] = 1 divisions on 10^{-11} scale

Preliminary system sensitivity $(S_1) = \frac{\text{Leakage Rate of Std. Leak}}{M_1 - M_2}$ = 3.77 $\times 10^{-12}$ atm cc / sec / division *

Hood Pressure (P_{hood}) = 718 torr. Helium concentration = 74 %

Helium concentration correction factor $(C_{he}) = \frac{P_{hood} \times 100}{760 \text{ torr} \times \text{ \% Helium}}$ = 1.28

M_3 (Test Helium Signal) [____ div on 10^{-10} scale, x 10] = 1 divisions on 10^{-11} scale

M_4 (Final Calibration Signal) [9 div on 10^{-10} scale, x 10] = 90 divisions on 10^{-11} scale 1.8×10^{-10}

Final system sensitivity $(S_2) = \frac{\text{Leakage Rate of Std. Leak}}{M_4 - M_3}$ = 2.92 $\times 10^{-12}$ atm cc / sec / division *

Final Test Sensitivity (S_F)

$S_F = S_2 \times C_{he}$ = 3.73 $\times 10^{-12}$ atm cc / sec / division *

Final Observed Leakage Rate (Q_F) = (M_3 - M_2) x S_F = 0 * x 10 ___ atm cc / sec. No observable leakage.

Check Applicable Box(es):

☐ Weld repairs were made during leak testing and have been visually inspected and re-tested and found acceptable. See VT Report No. ____________

☑ No welded repairs made during leak testing.

Tests were performed and all leakage was evaluated in accordance with the referenced procedure.
Defects not repaired and retested during testing are recorded above as to location and disposition.
All other tested areas included in this report were found acceptable.

COMMENTS: * Minimum change in Signal on 10^{-11} scale of Varian 960 can be 4 divisions. ∴ S_1 ≥ 1.508×10^{-11} ; S_2 ≥ 1.17×10^{-11} ; S_F ≥ 1.49×10^{-11} resolution/sensitivity.

[signature] 9/18/96
OPERATOR/EVALUATOR DATE

Results reviewed by: [signature] 9-19-96
DATE

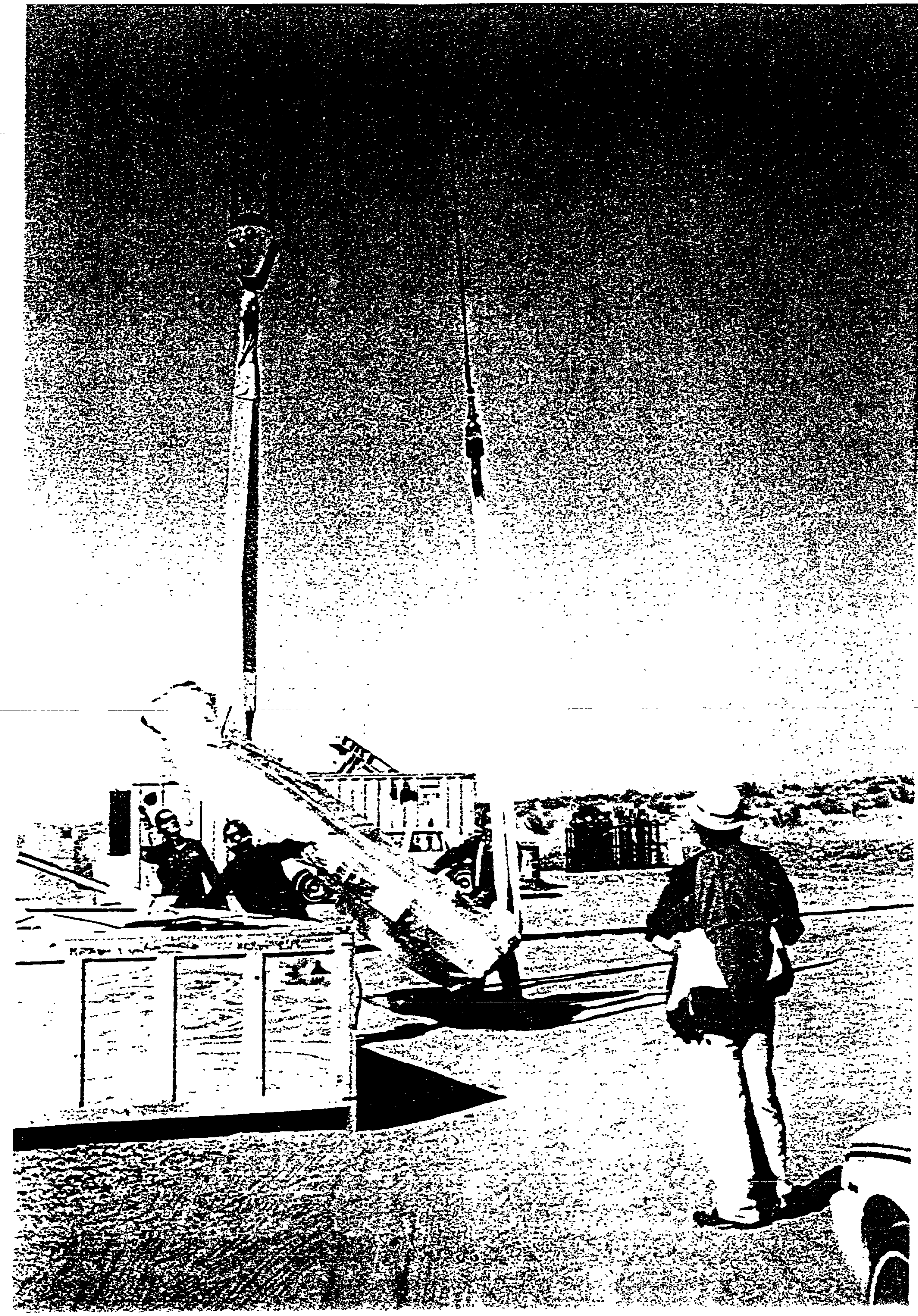
LIGO

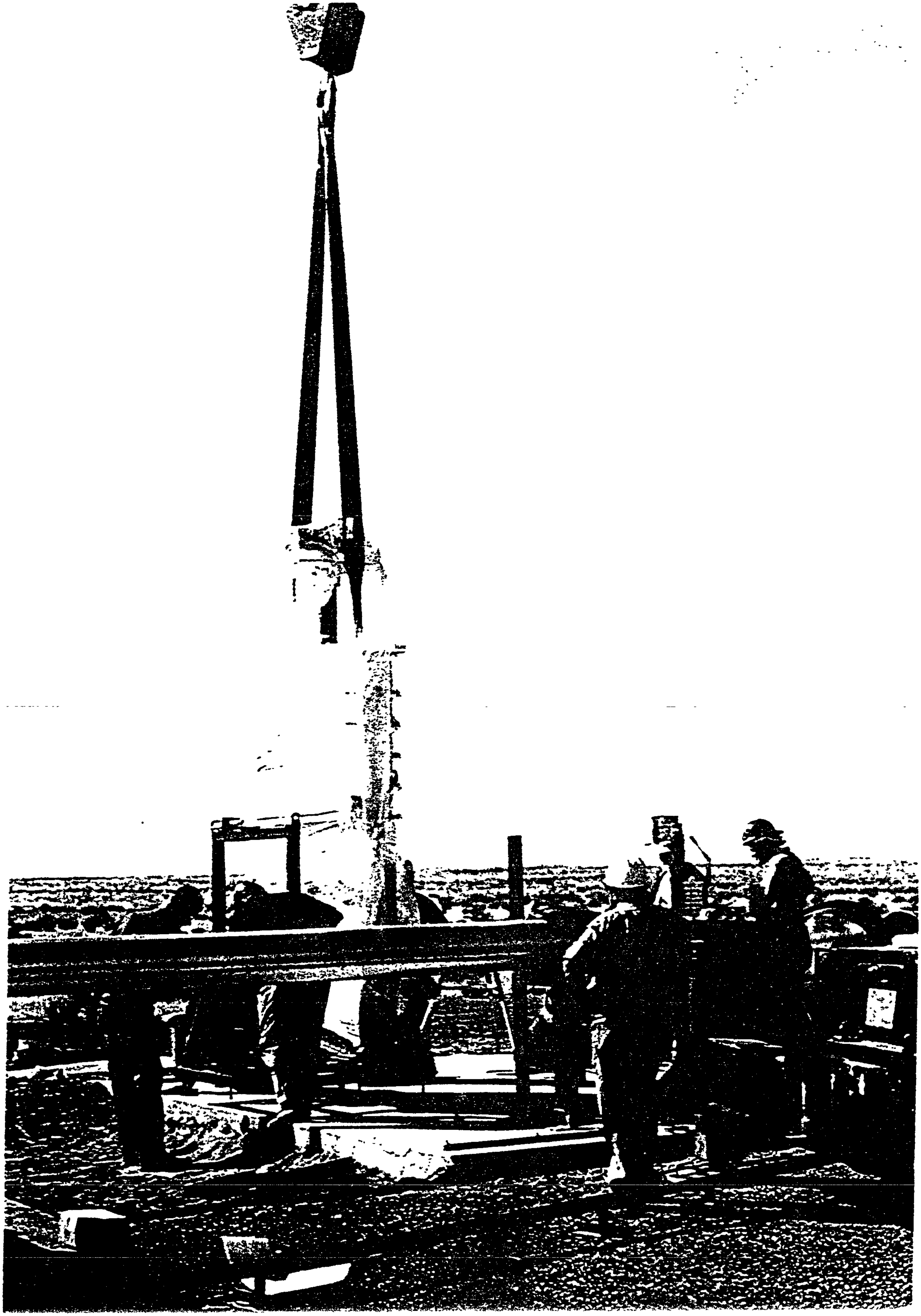
ACTIVITY BEAM TUBE ASSEMBLY MONITORING LOG

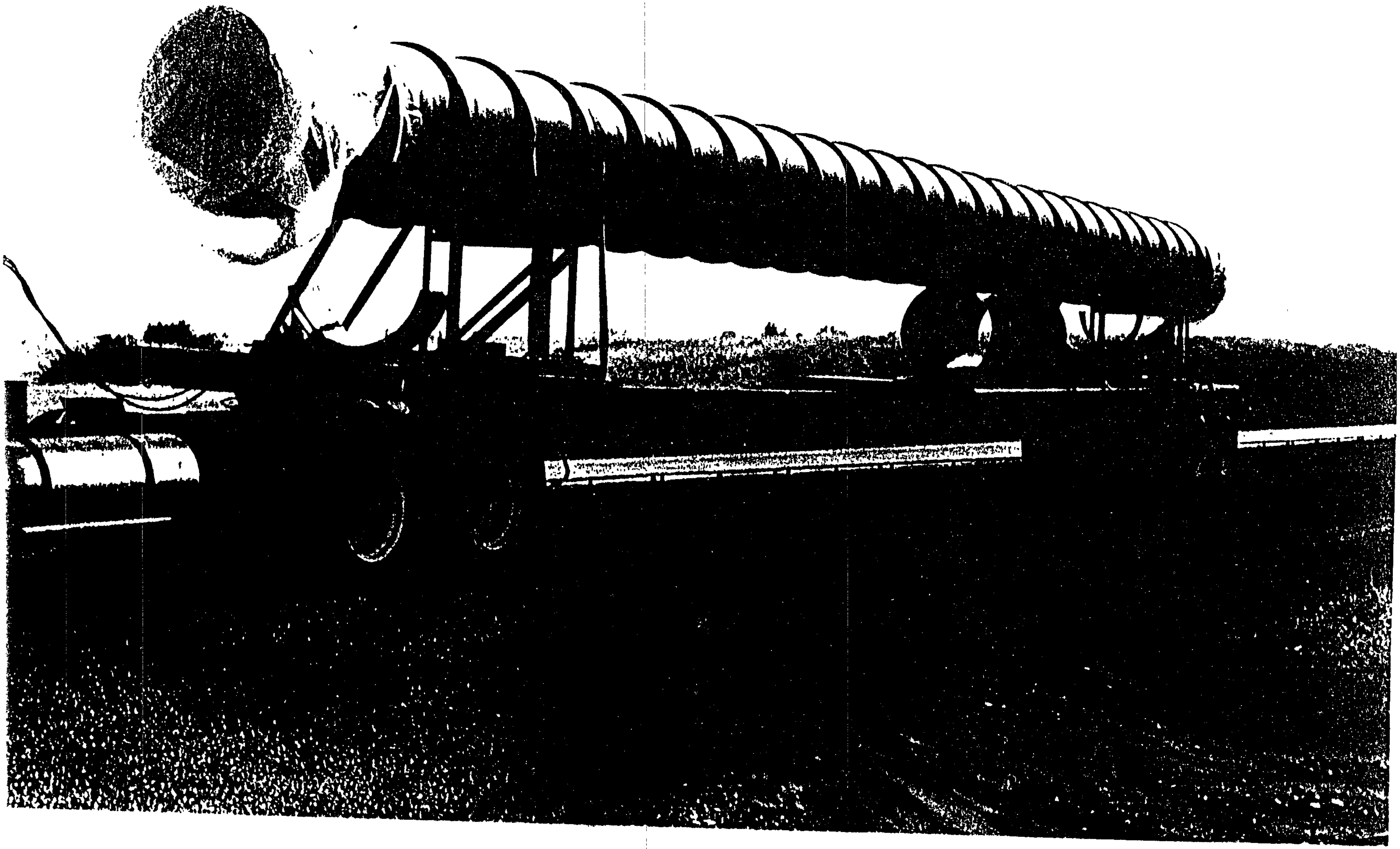
DATE	PERSON	TUBE NO.	ACTIVITIES
10-9-96	C W FRANKLIN	B-020	Splicing of Coils - Joint preps/alignment of gap/ W/S insp.
10-9-96	C W Franklin	I-001	Verify steam cleaning inside of B/T assy.
10-9-96	C W Franklin	I-001	Verify removable of water trapped in Pump Port.
10-9-96	C W Franklin	A-017	Monitor expansion joint fit-up and welding.
10-9-96	C.W. Franklin	A-016	Monitor fitting of stiffener and support rings
10-9-96	C.W. Franklin	A-013	Monitor Helium Mass Spec. Test of B/T ASSY
10-7-96	C.W. Franklin	A-011	Monitor Helium Mass Spec. Test of B/T Assy
10-10-96	C.W. Franklin	I-001	Monitor installation and helium Mass Spec.
			leak testing of Pump Port Shut off valve.
10-10-96	C.W. Franklin	A-005	Monitor Helium Mass Spec. Leak Testing
10-10-96	C.W. Franklin	A-012	Verify expansion joint fit-up and welding
10-10-96	C.W. Franklin	B-016	Verify visual inspection and Weld pick-up
10-10-96	C.W. Franklin	B-021	Spiral forming Gap and Alignment
10-10-96	C.W. Franklin	B-021	Spiral forming and Gap and alignment
10-11-96	C.W. Franklin	I-001	Monitor Helium mass spec. [illegible] TC#123
10-11-96	C W Franklin	B015	Monitor Helium mass spec. Testing
10-11-96	C W Franklin	I-001	Monitor wrapping and loading on truck for
			shipment to [illegible] site on 10-14-96
10-11-96	C.W. Franklin	A-021	Witness Macro Exam.
10-11-96	C.W. Franklin	A-022	Witness Macro Exam.
10-11-96	C.W. Franklin	A-019	Witness Macro Exam.

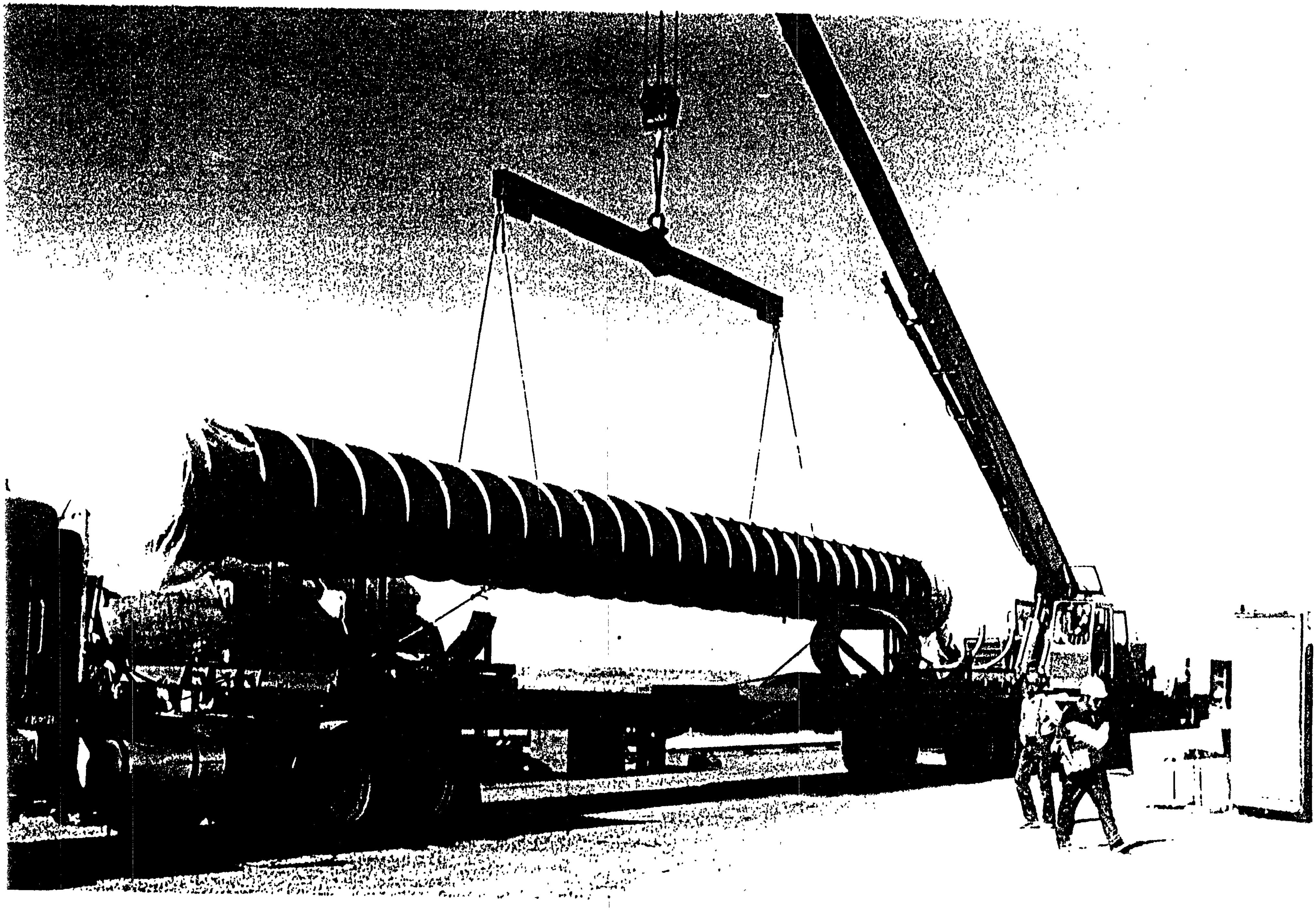
BT installation

- 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



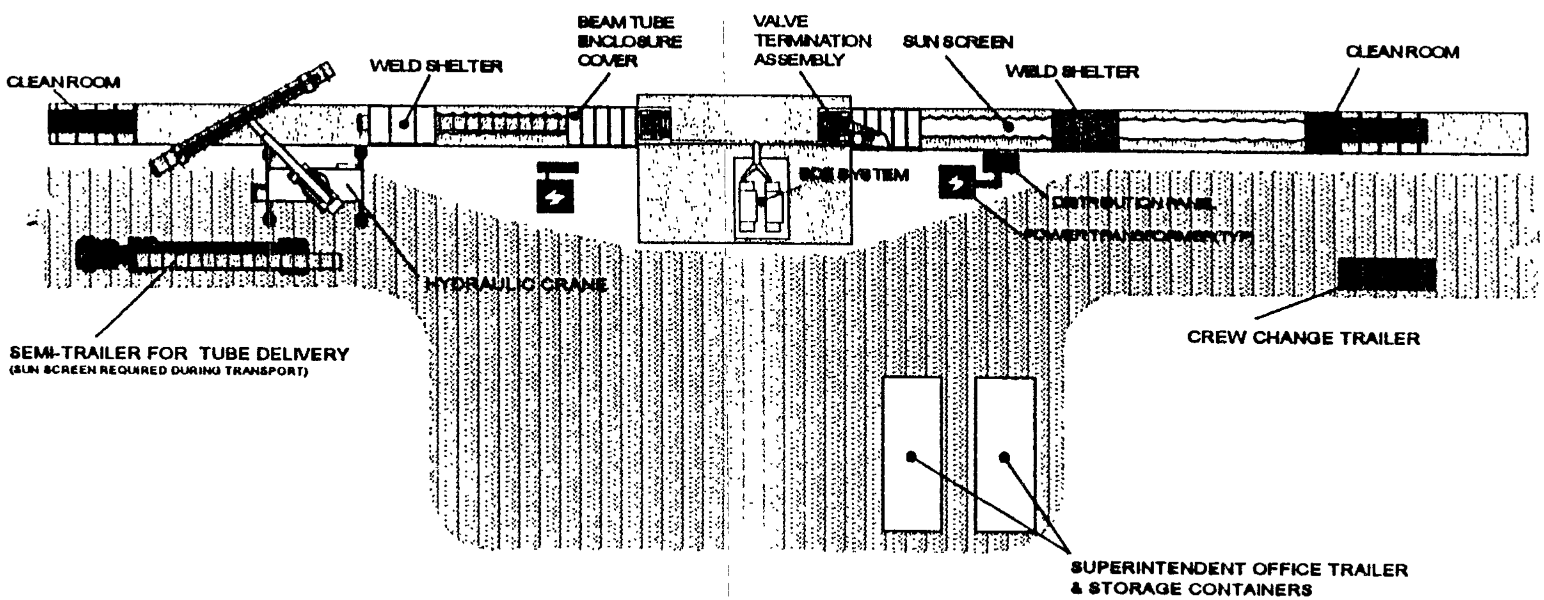






GENERAL INSTALLATION WORK AREA

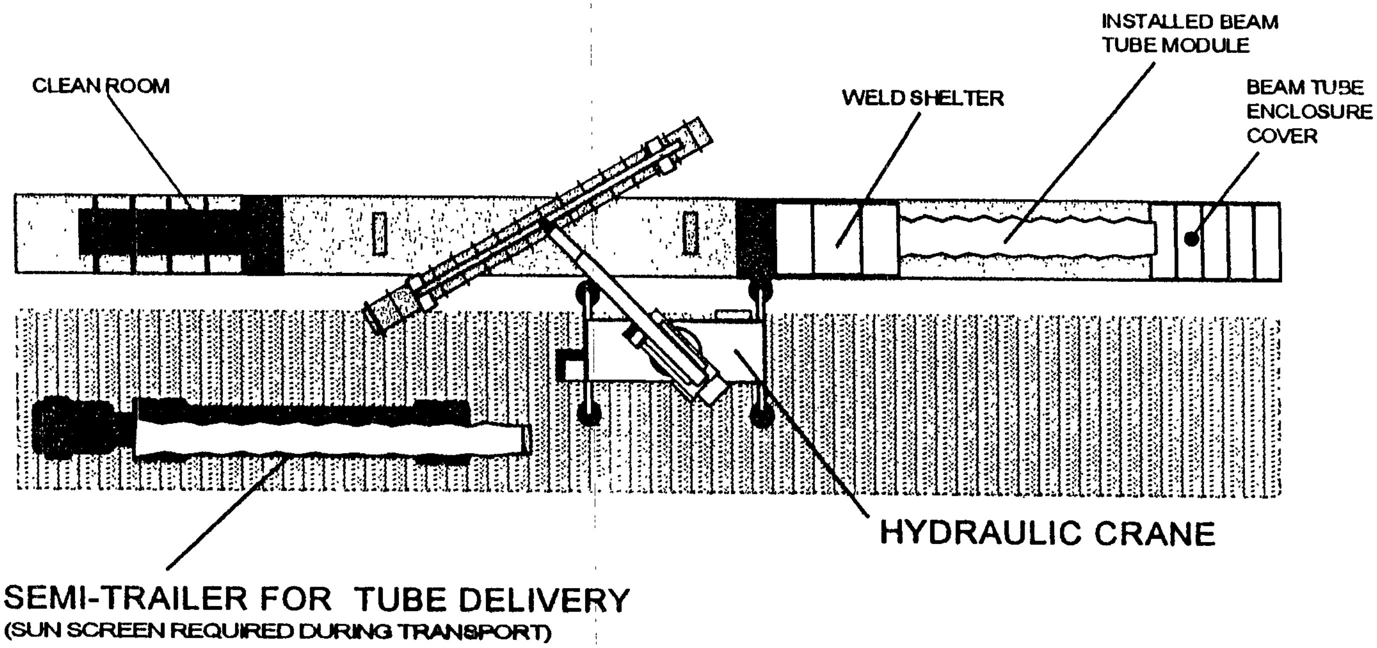
ATTACHEMENT "C"



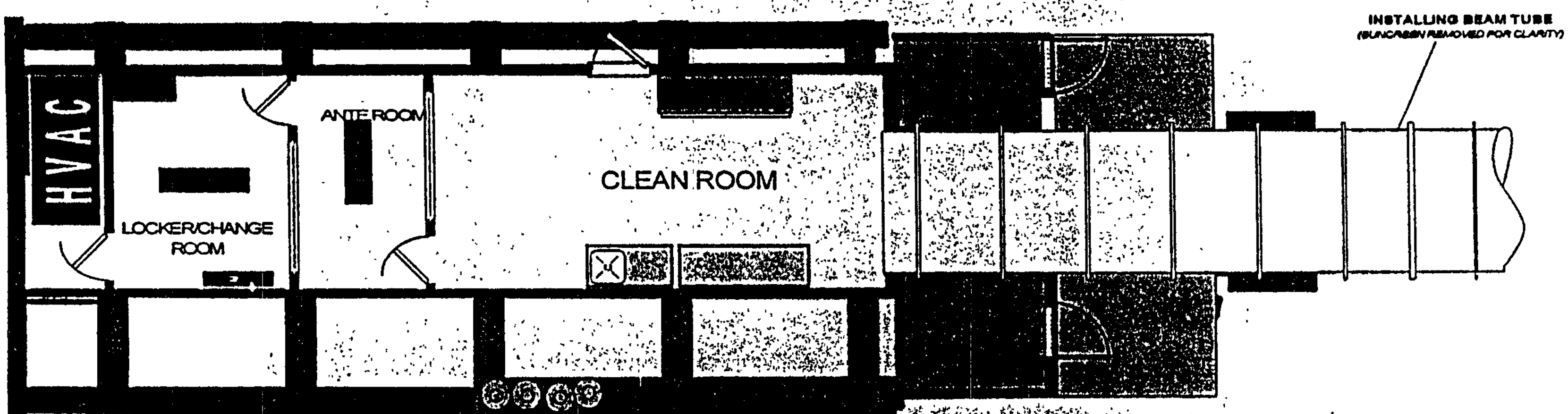
TYPICAL MID STATION ARRANGEMENT

INSTALLATION WORK AREA - INSTALLING TUBES

ATTACHEMENT ""D""



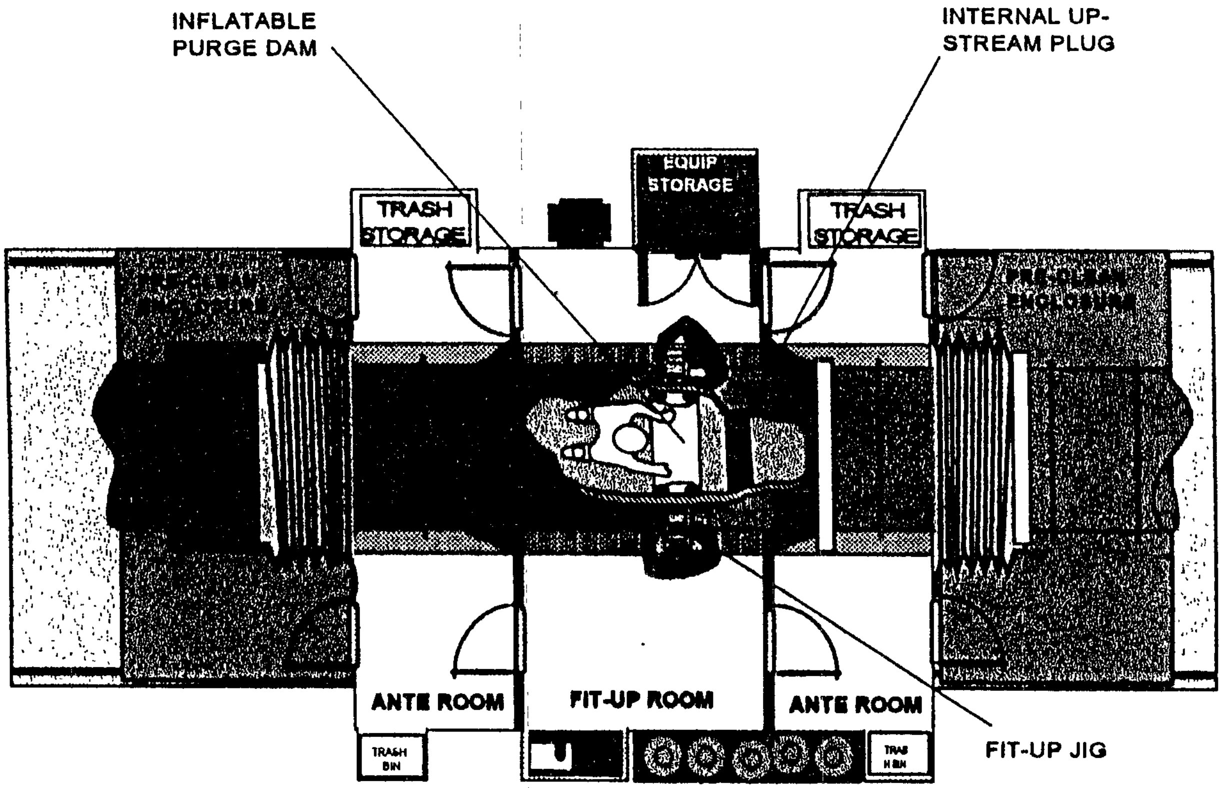
PLAN VIEW AT TYPICAL TUBE LOCATION

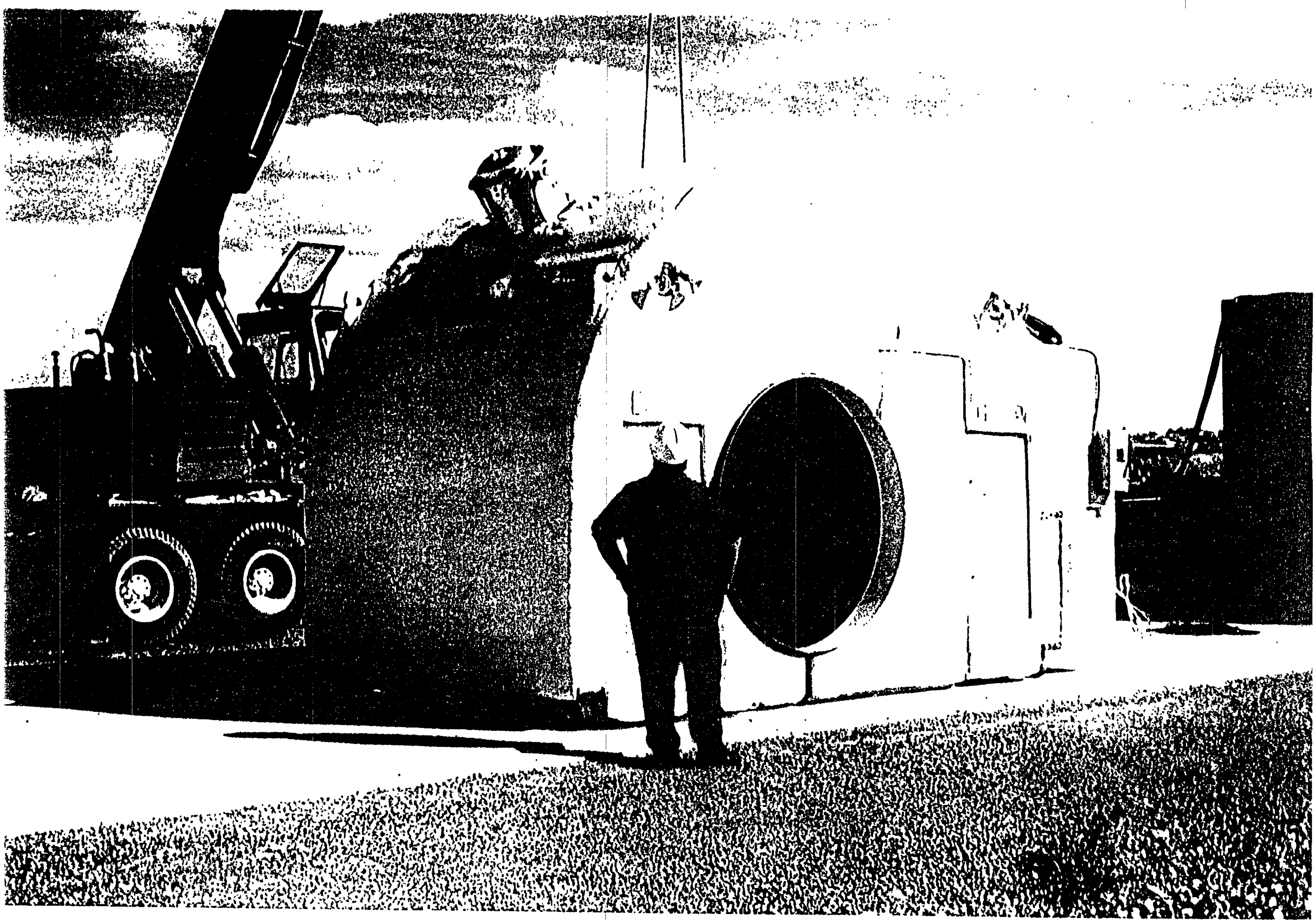


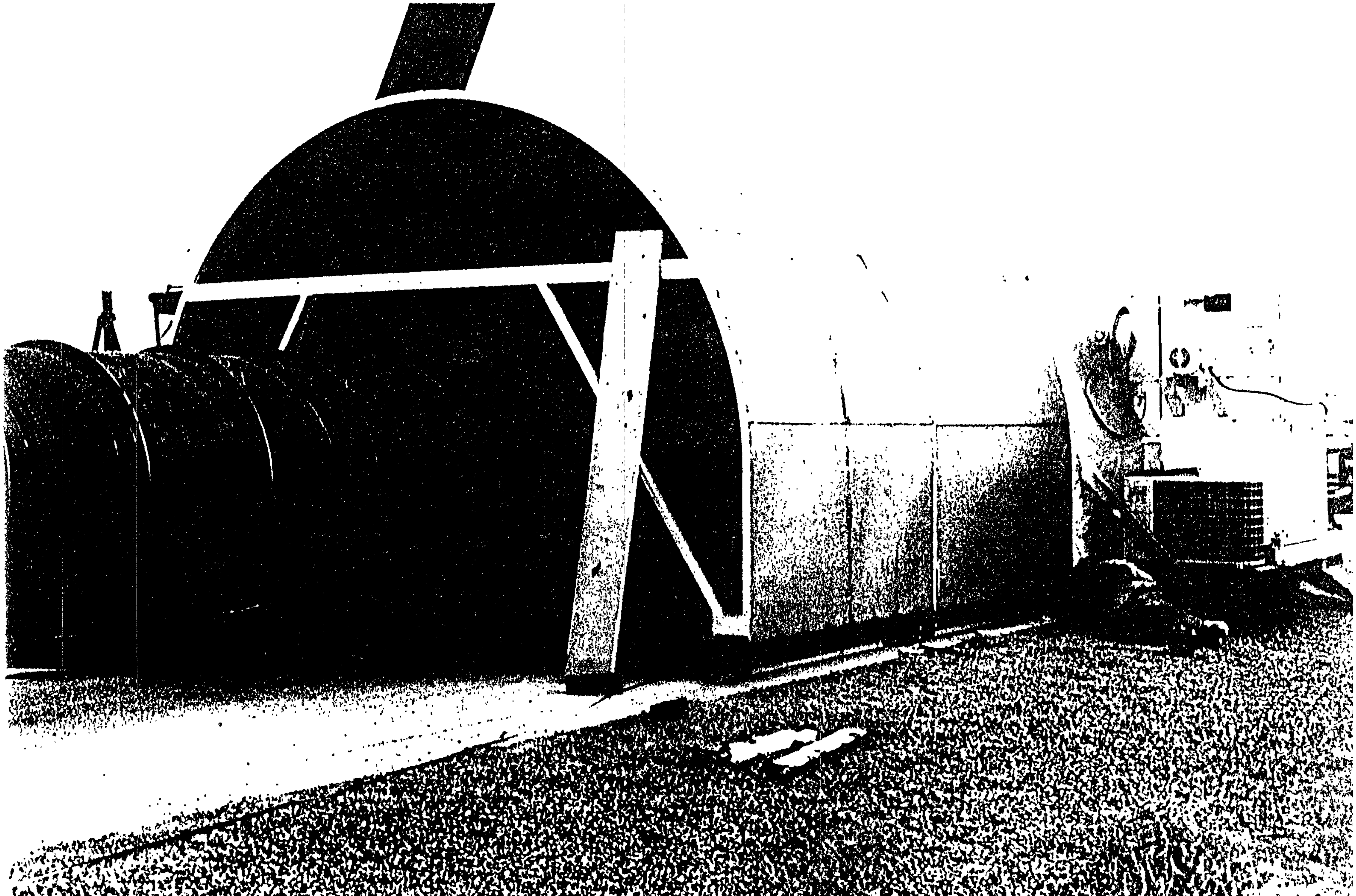
CLEAN ROOM SYSTEM

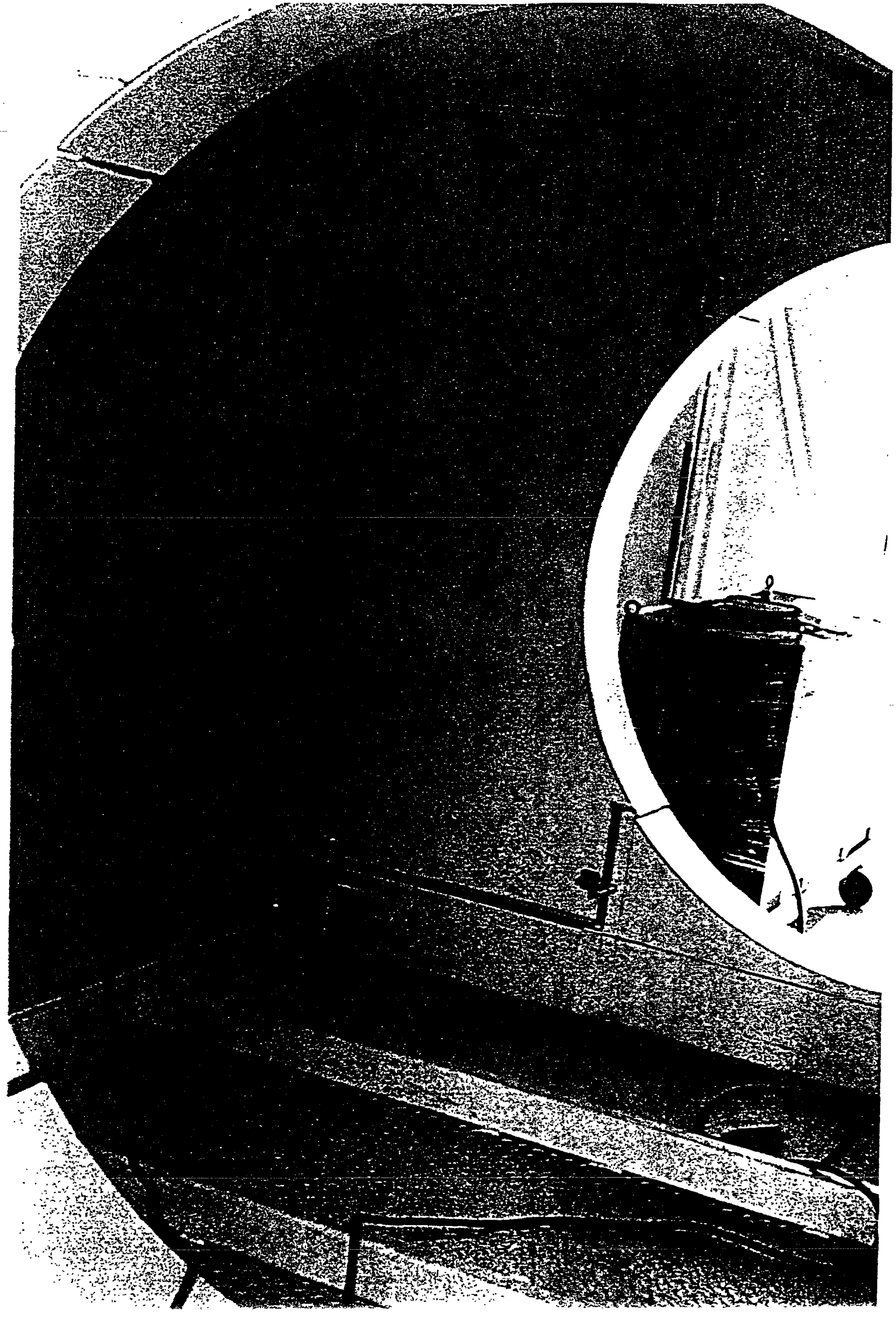
INSTALLATION WORK AREA - FIT/WELD

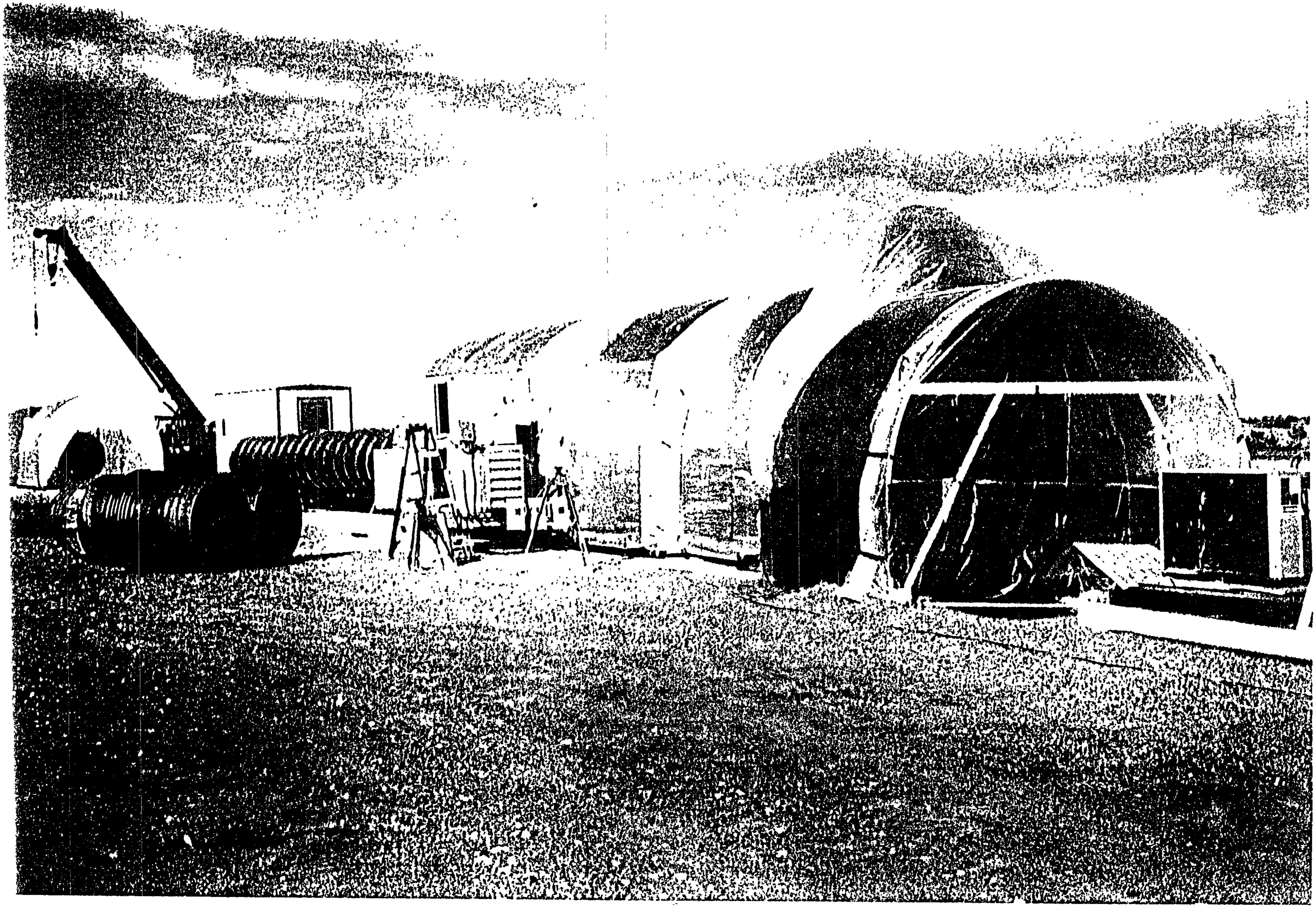
ATTACHEMENT "I"

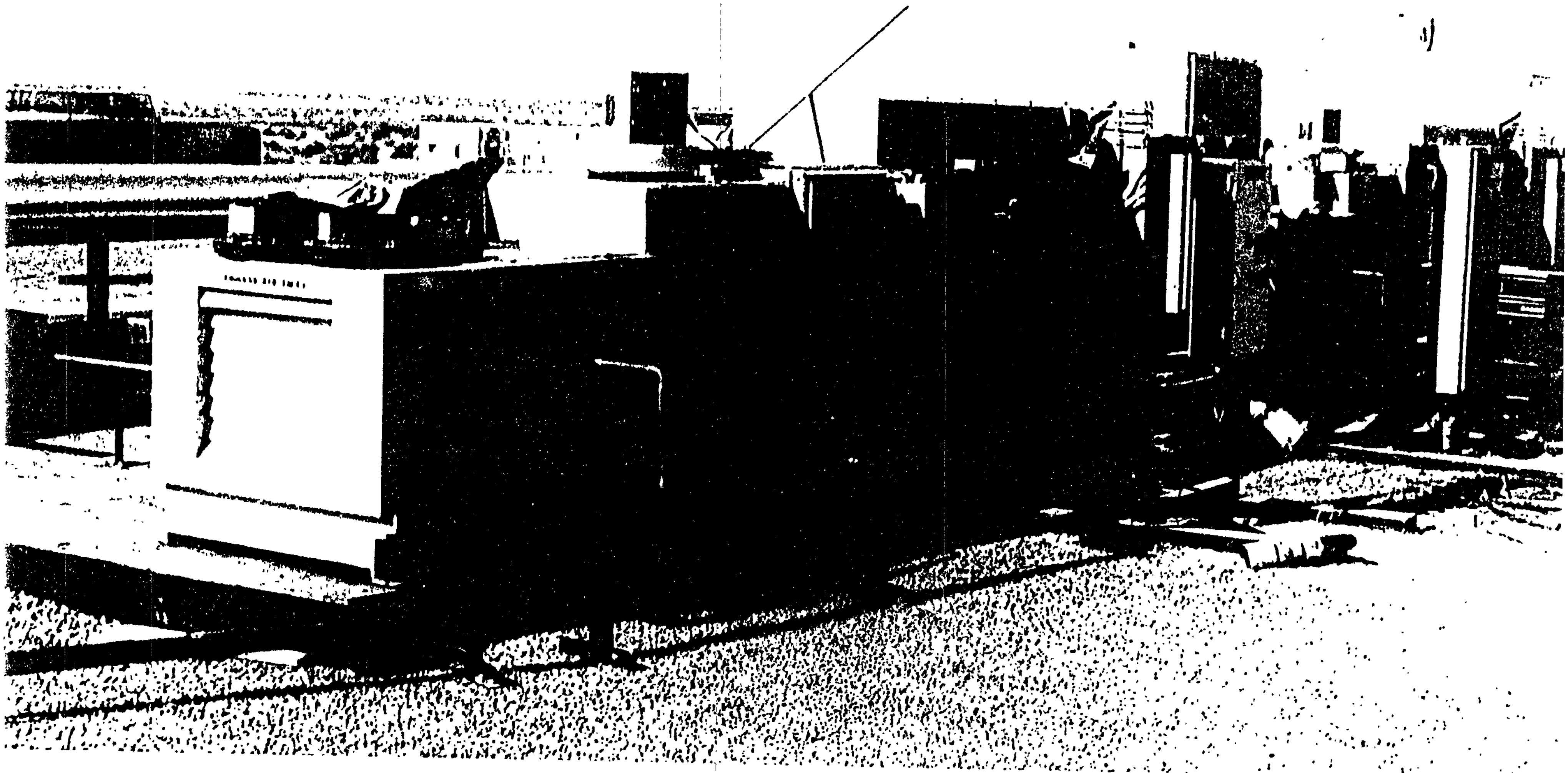








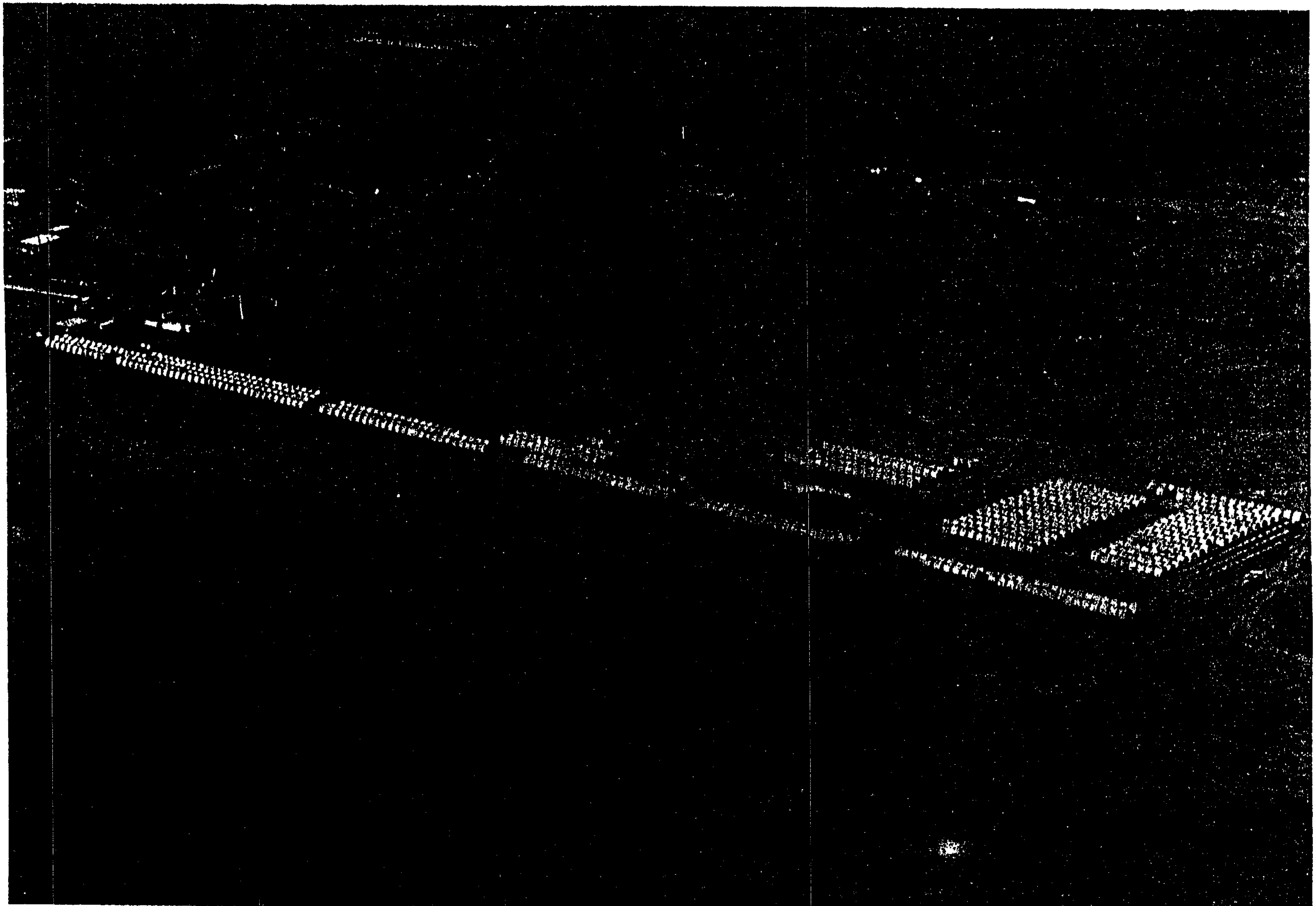




Beam Tube Enclosure

- 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

C[illegible]147-21-040

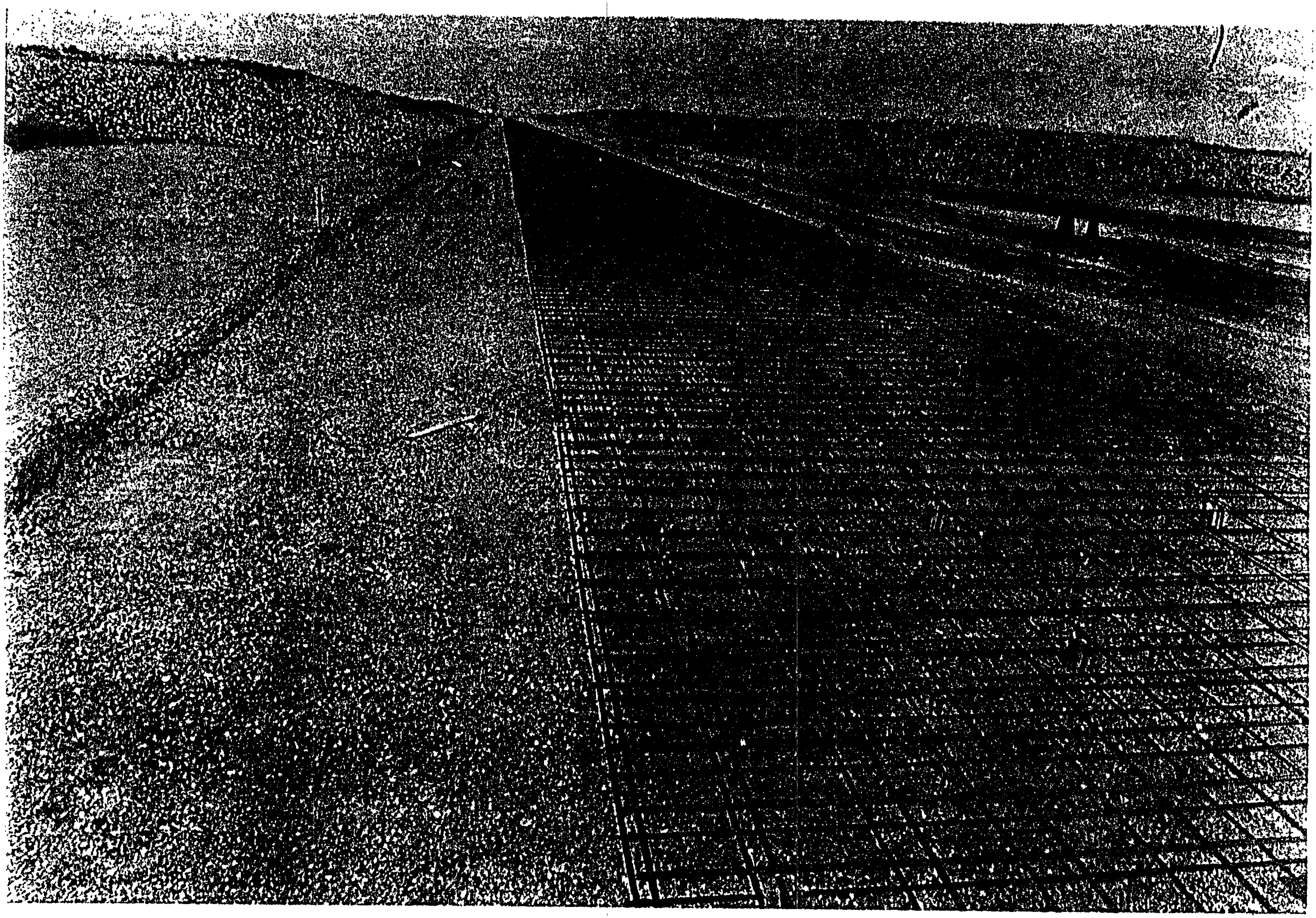


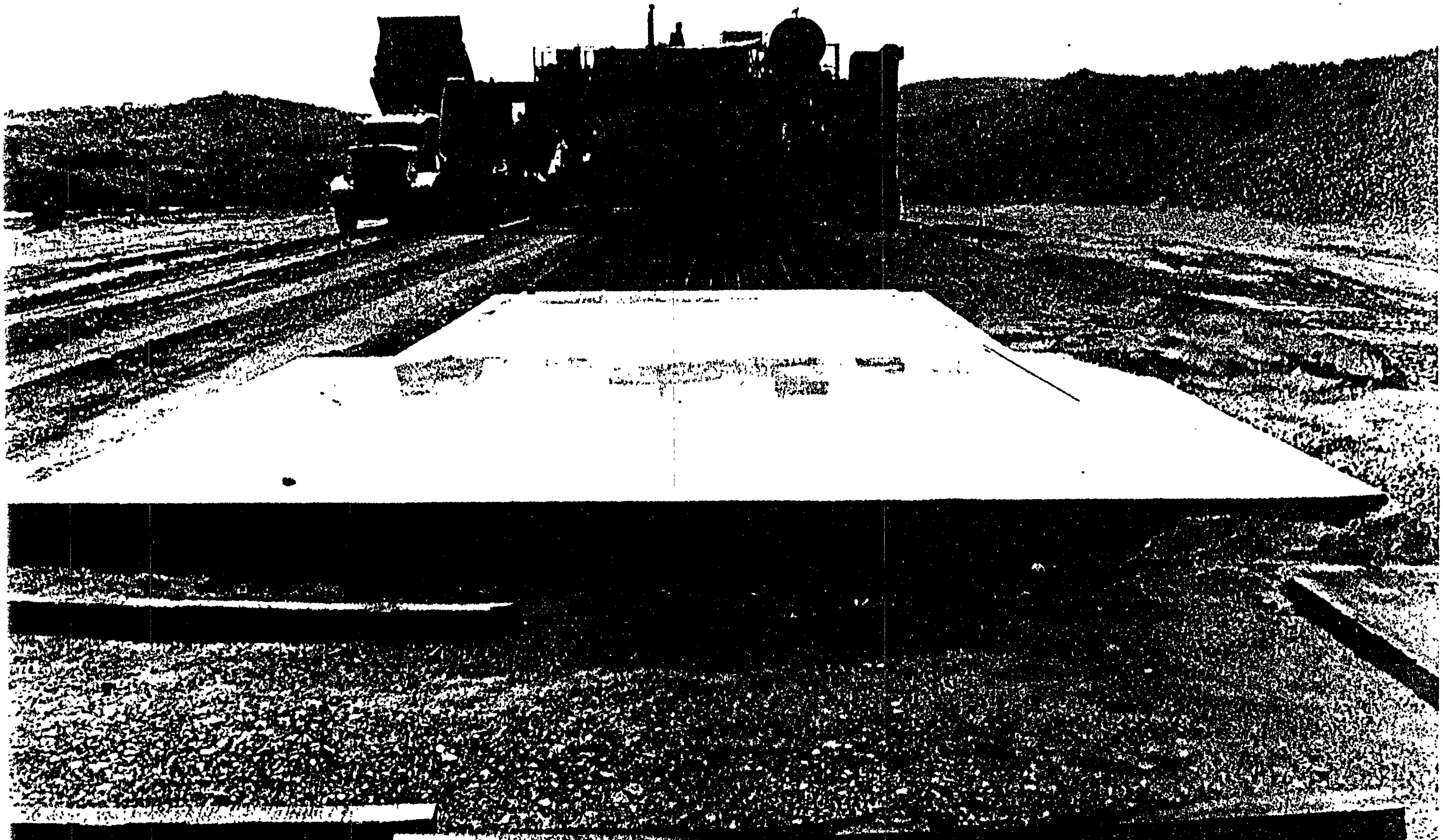
BTE Fab QA

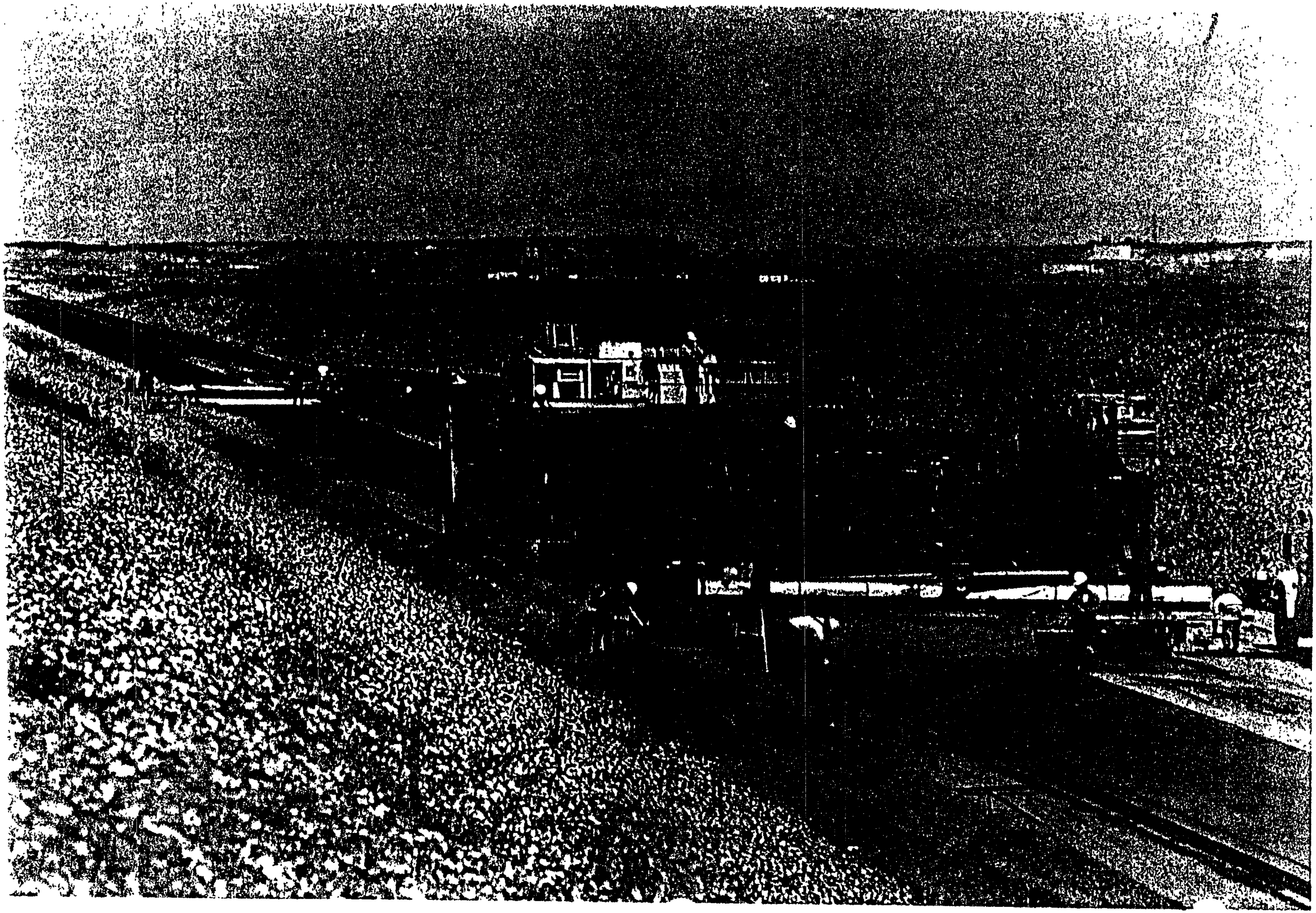
- BTE's inspected by RMP in ACME yard.
- Rejection is 10/1000
- No stress cracking found. Normal shrinkage cracks only

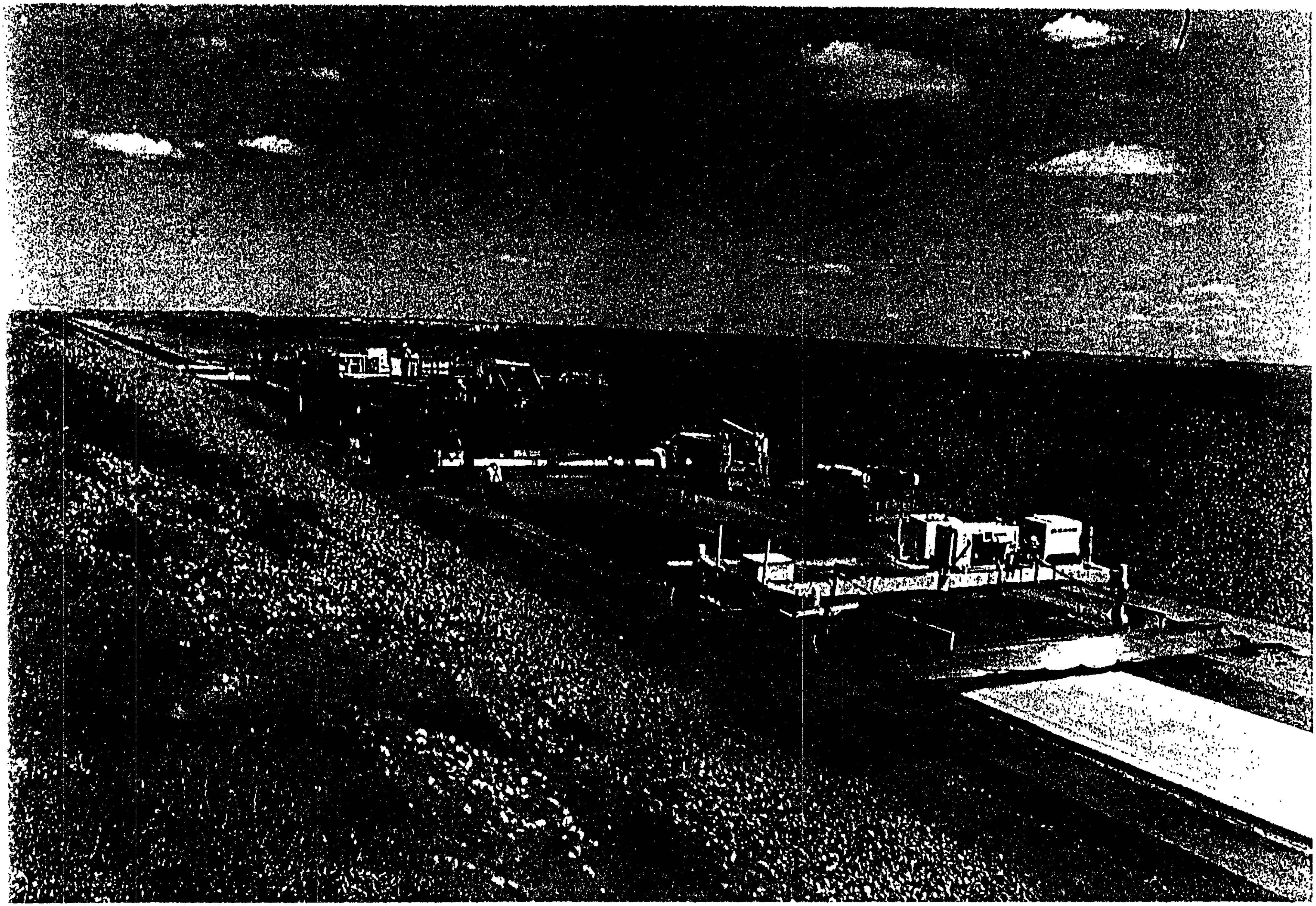
Civil Construction

- 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









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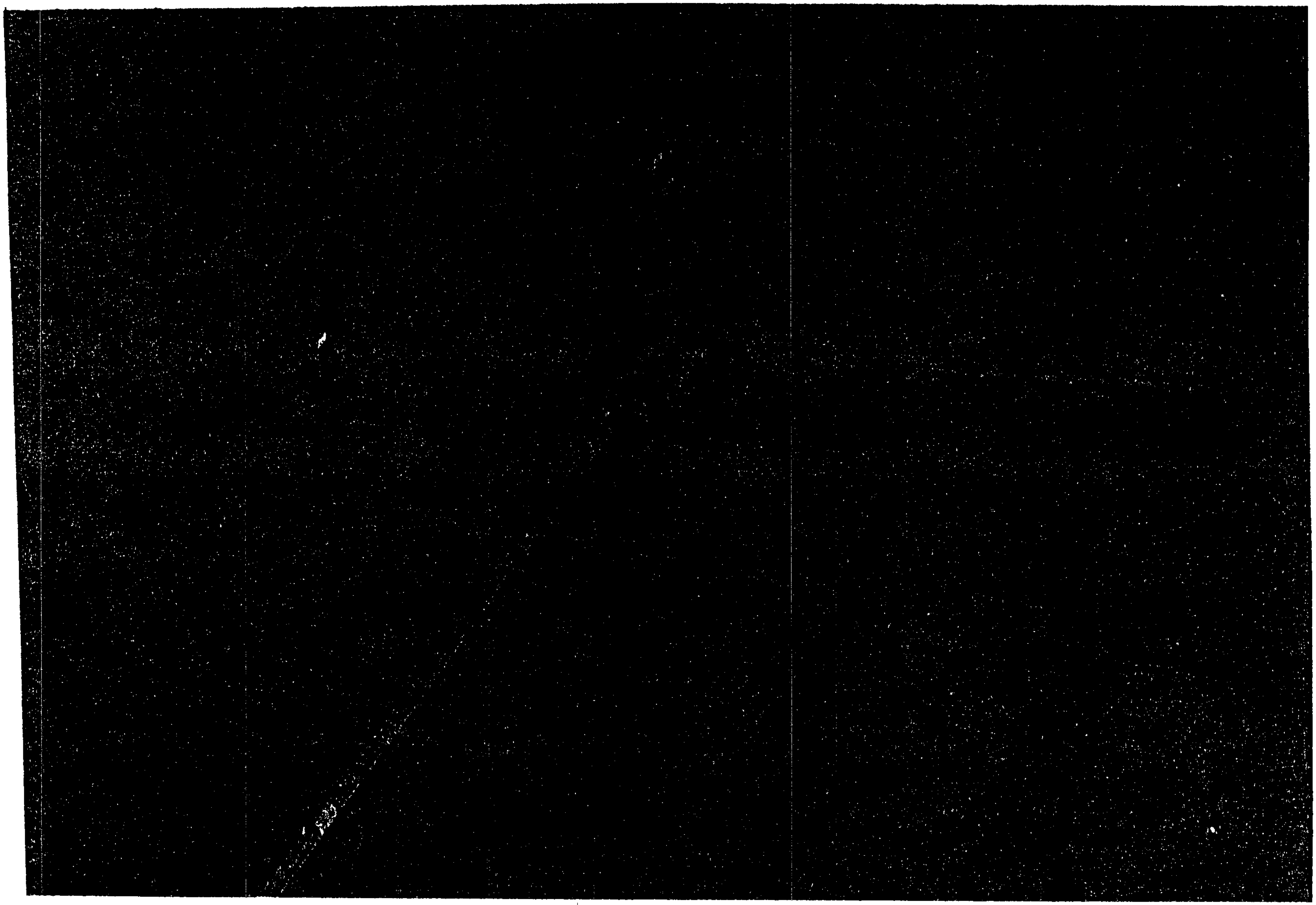
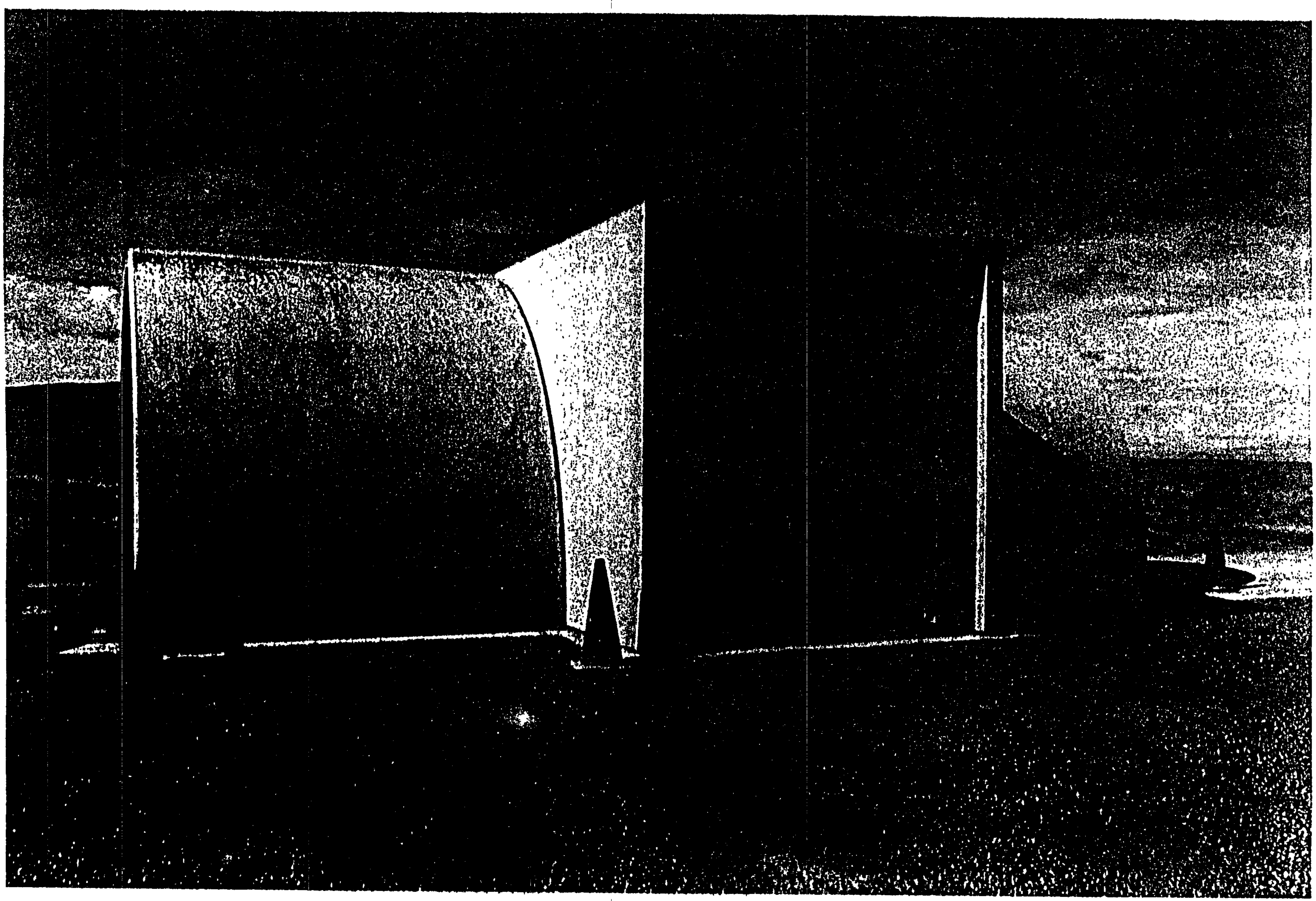


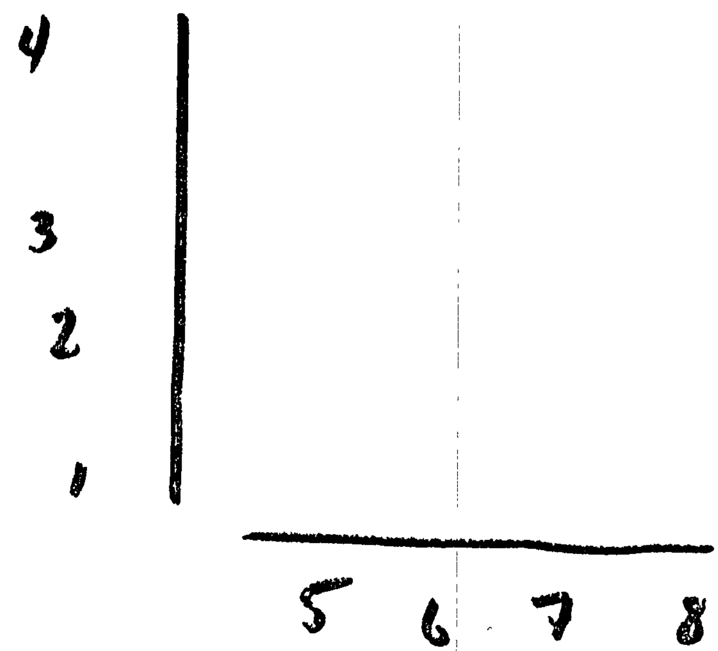


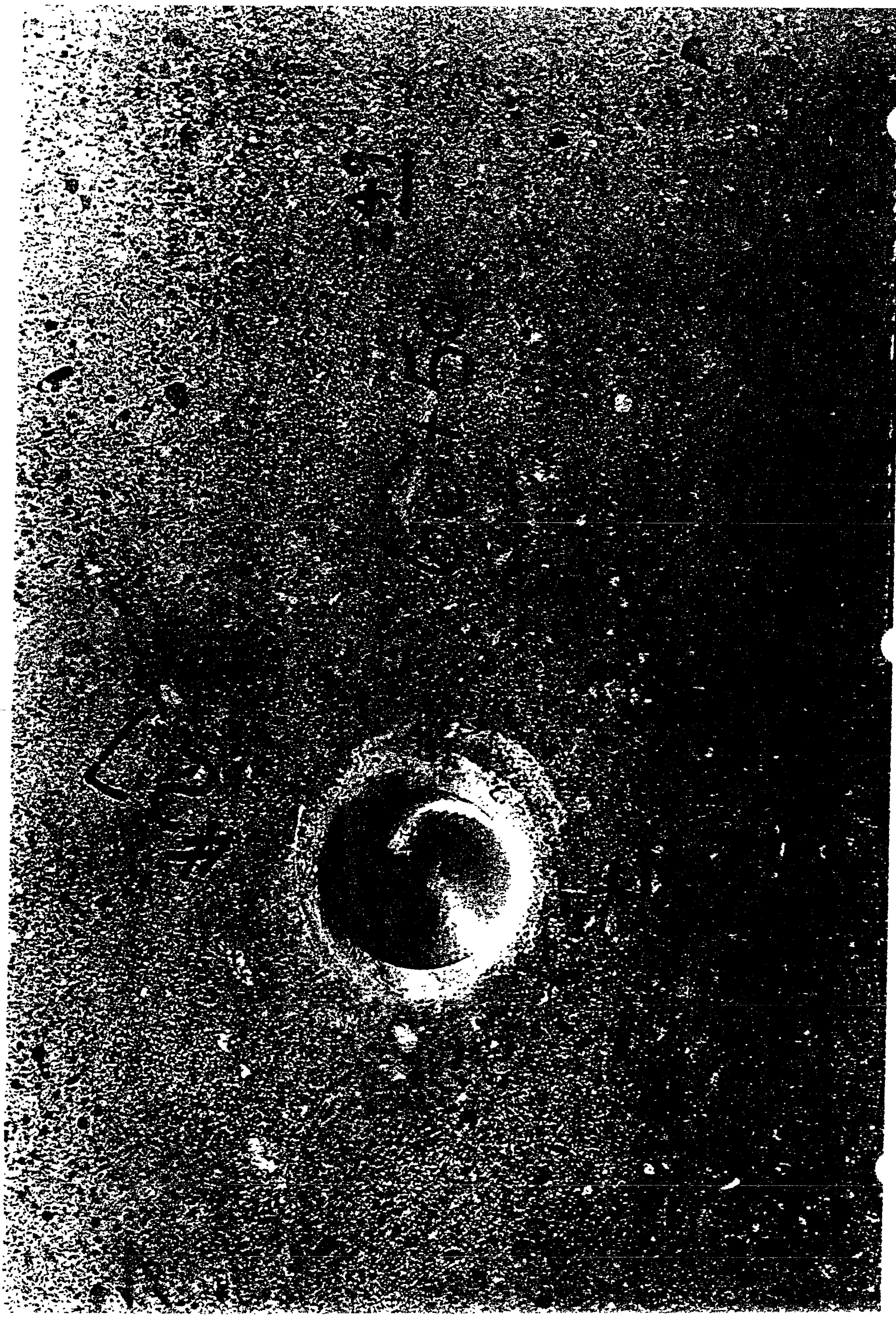
Precision Survey

Allen Sibley

- Site fiducialization by Rogers (local) and IMTEC (Kansas City)
- Combination of differential GPS and optical methods
- Rogers - elevations and ranges - dGPS
- IMTEC - elevations and lateral - optical

Point	Rogers survey relative to RMP model (mm)	IMTEC survey relative to RMP model (mm)	Delta (Rogers - IMTEC)	IMTEC best fit plane
1	0	0	0	0
2	-6	-4	-2	0
3	-6	7	-13	-5
4	6	-5	11	0
5	-3	0	-3	-1
6	3	5	-2	4
7	3	2	1	4
8	3	0	3	0
		IMTEC statistical uncertainty +/- 1 mm		





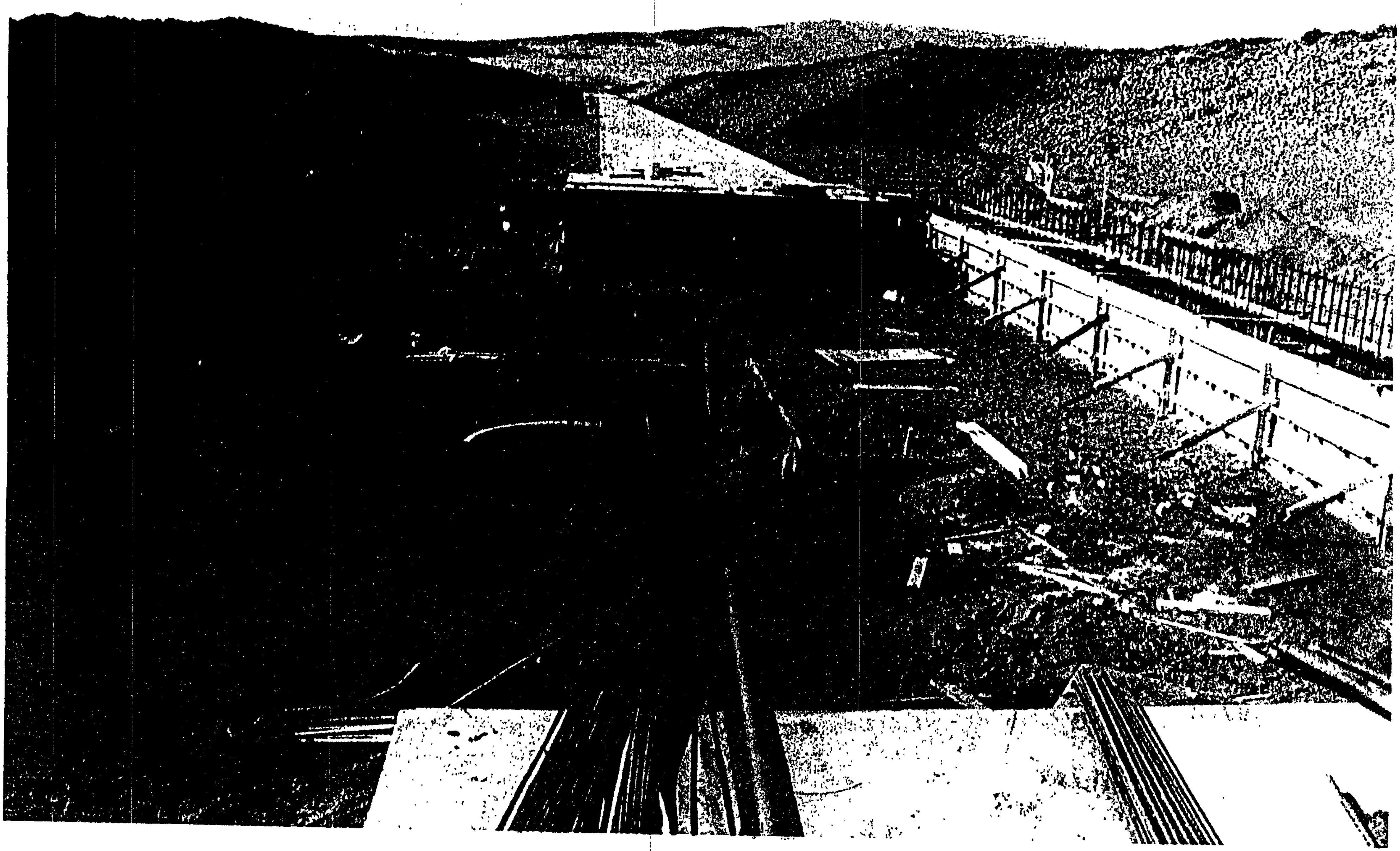
BT Alignment

- QA contract with Rodgers to spot check early CBI measurements
- CBI will use differential GPS
- Max alignment range of BT support is 3 inches. Want to center BT within this range.

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 site civil construction

- completed final design for LA bldgs
- completed bid on bldgs, BT enclosures/slab
- close to completing rough grade work in LA
- power lines raised over site

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.

LA Bldg Design

Fred Asiri

- Final design completed May 96
  - 2 IFO design
- Reviewed by Baton Rouge architectural firm for standard practices and materials
- Recommendations incorporated into final design
- Architectural approval obtained from LSU per site agreement

LA Civil Construction QA

- PSI (LA) monitors compaction work
- Parsons Construction Mgr on-site
- QA audit of record keeping LIGO QA (Bill Tyler)
- CM record keeping audit by Otto, Fred

LEGEND			
Bud	∇	∇	∇
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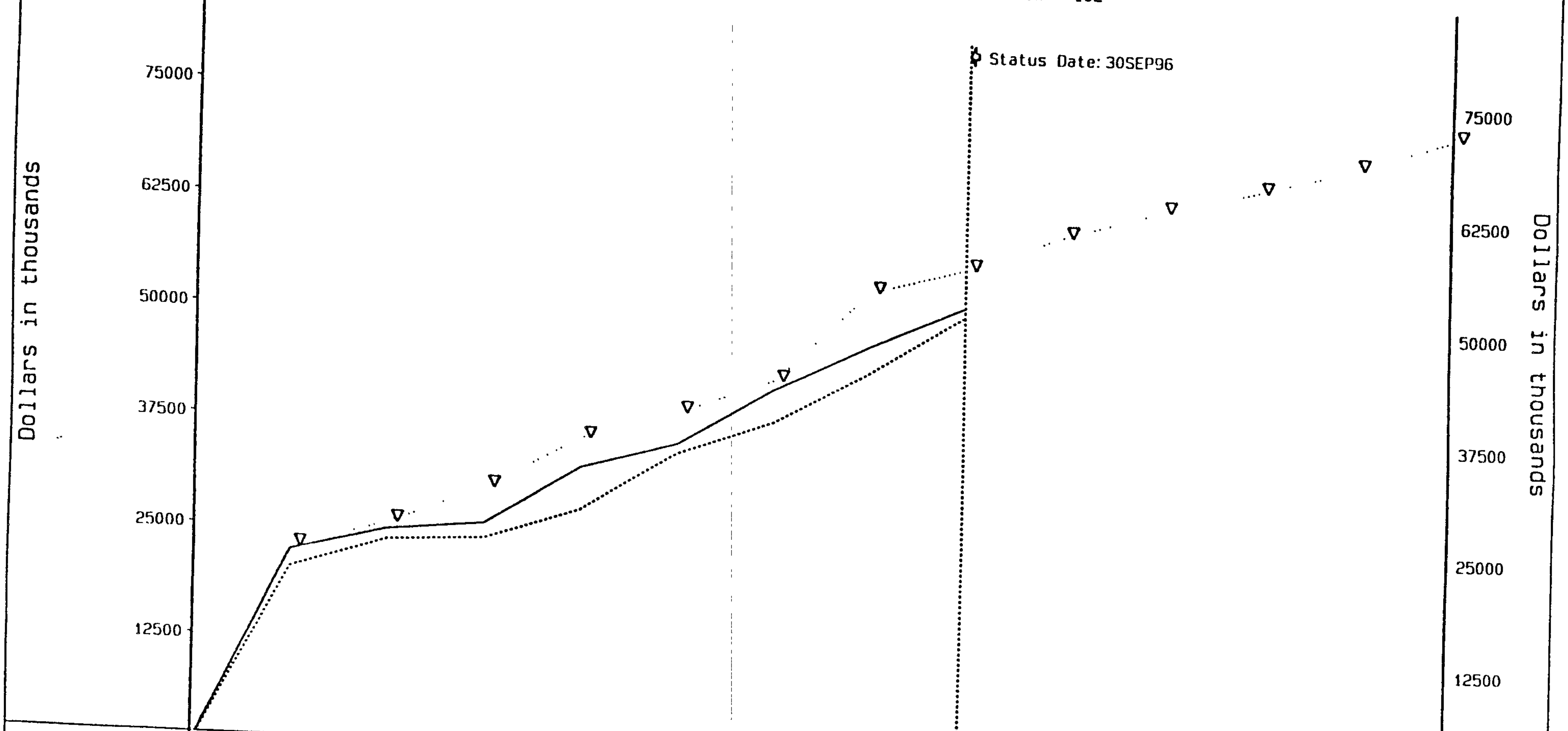
LIGO PROJECT
1.1 Facilities and Vacuum Systems

Date: 17OCT96
Program: PMB_0996
Report: LIGOSPA
COBRA (R)

Budget vs Performance vs Actual

Schedule Performance Index = 92 Cost Performance Index = 102



	FEB96	MAR96	APR96	MAY96	JUN96	JUL96	AUG96	SEP96	OCT96	NOV96	DEC96	JAN97	FEB97	SCALE
Planned Budget	22,468	25,600	29,885	35,829	39,053	42,969	53,137	55,958	59,940	63,084	65,631	68,499	71,923	K$
Performance	22,179	24,885	25,895	32,502	35,510	41,939	47,095	51,731						K$
Actuals	20,212	23,695	24,217	27,745	34,461	38,269	44,112	50,713						K$
Schedule Variance	-289	-715	-3,990	-3,327	-3,543	-1,030	-6,042	-4,227						K$
Cost Variance	1,967	1,190	1,678	4,757	1,049	3,670	2,983	1,018						K$

Schedule Variance = Perf-Budg Cost Variance = Perf-Actual Schedule Performance Index = Perf/Budg Cost Performance Index = Perf/Actual

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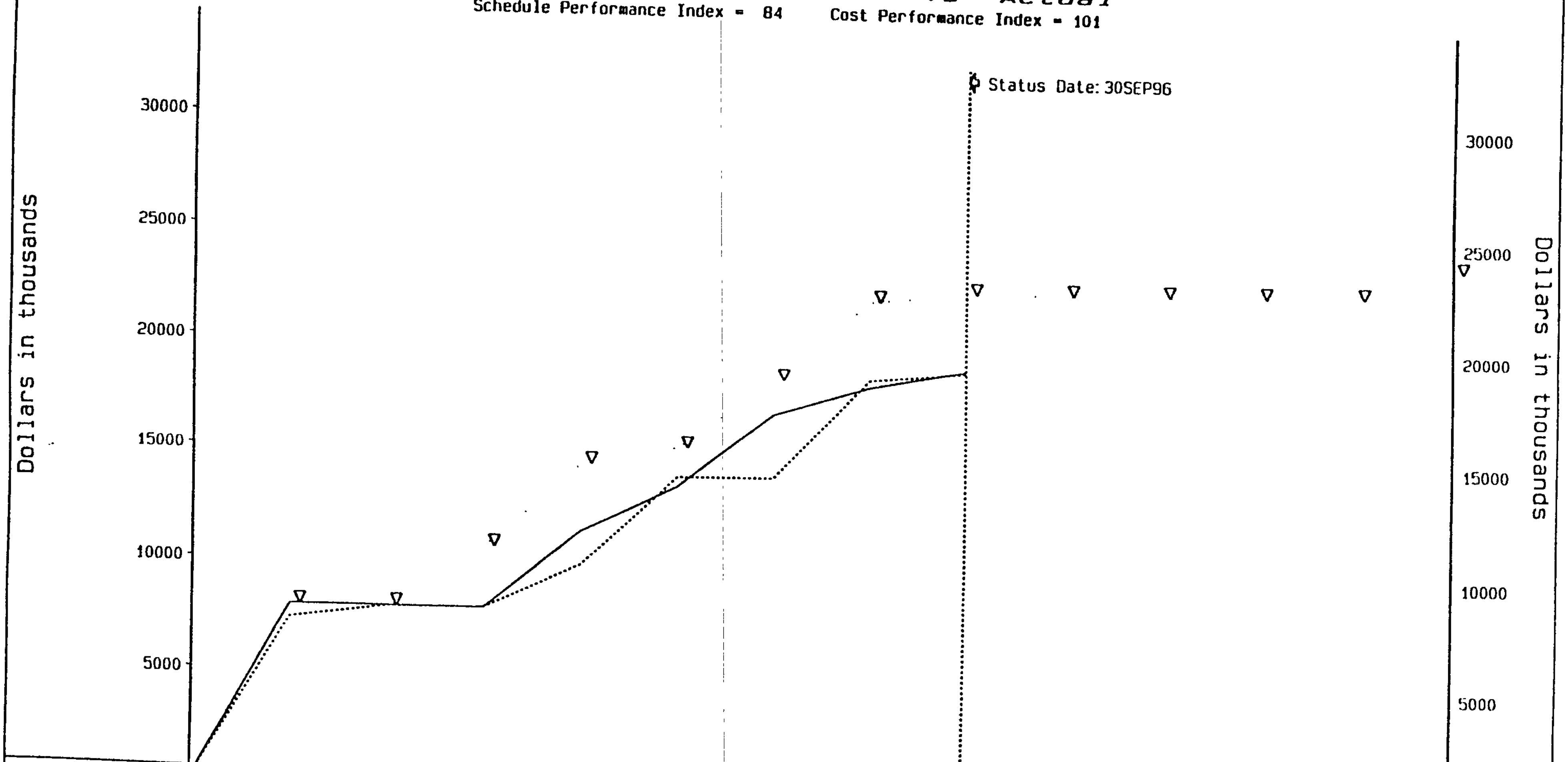
LIGO PROJECT

1.1.1 Vacuum Equipment

Date: 17OCT96
Program: LIGOPMB1
Report: LIGOSPA
COBRA (R)

Budget vs Performance vs Actual

Schedule Performance Index = 84   Cost Performance Index = 101



	FEB96	MAR96	APR96	MAY96	JUN96	JUL96	AUG96	SEP96	OCT96	NOV96	DEC96	JAN97	FEB97	SCALE
Planned Budget	7,925	7,958	10,728	14,475	15,285	18,441	22,094	22,521	22,555	22,589	22,642	22,698	23,928	K$
Performance	7,935	7,968	8,001	11,527	13,593	16,893	18,189	19,025						K$
Actuals	7,322	7,931	8,000	10,022	14,005	14,065	18,505	18,920						K$
Schedule Variance	10	10	-2,727	-2,948	-1,692	-1,548	-3,905	-3,496						K$
Cost Variance	613	37	1	1,505	- 412	2,828	- 316	105						K$

Schedule Variance = Perf-Budg   Cost Variance = Perf-Actual   Schedule Performance Index = Perf/Budg   Cost Performance Index = Perf/Actual

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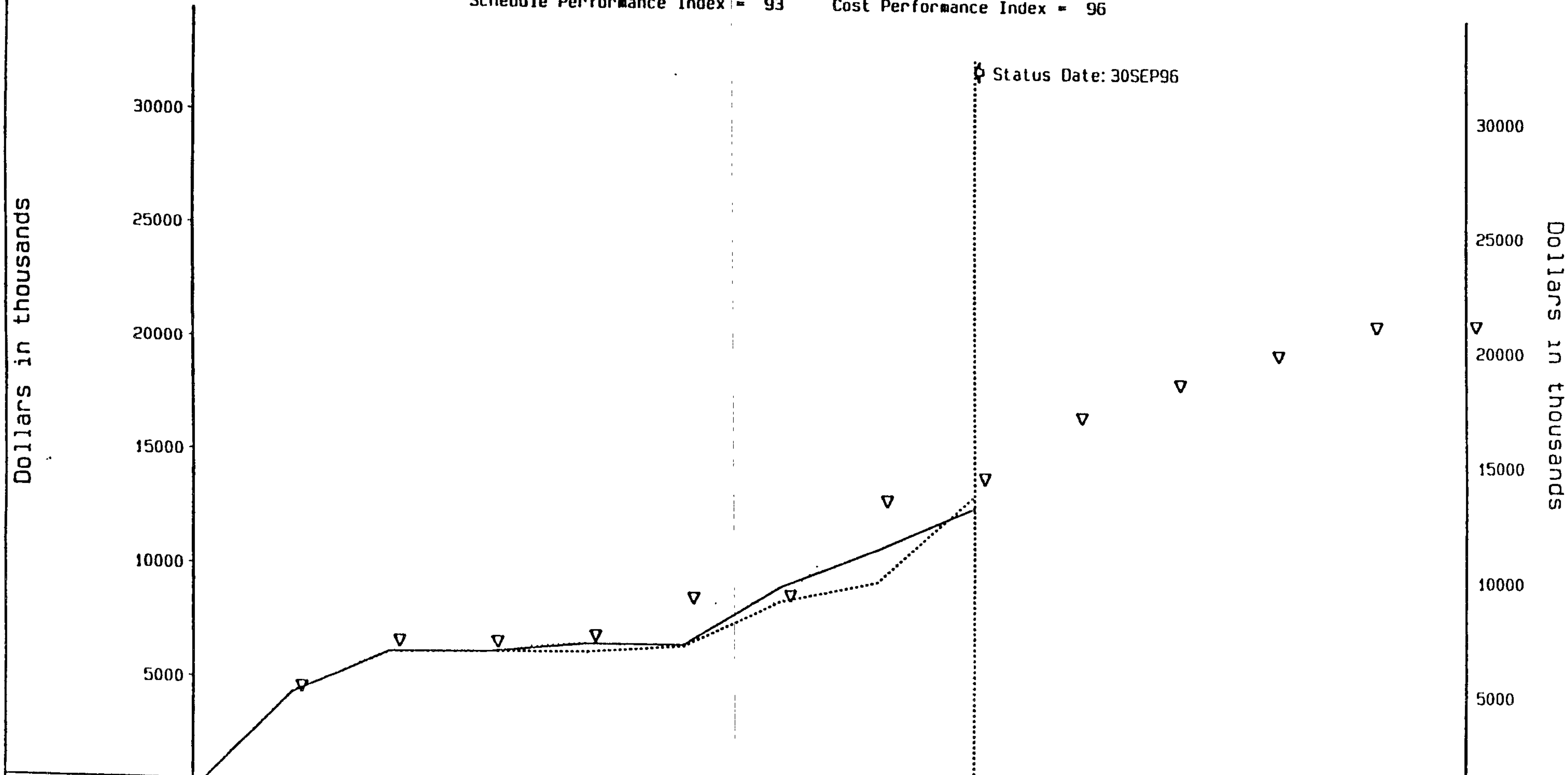
LIGO PROJECT
1.1.2 Beam Tubes

Date: 16OCT96
Program: LIGOPMB1
Report: LIGOSPA
COBRA (R)

Budget vs Performance vs Actual

Schedule Performance Index = 93 Cost Performance Index = 96

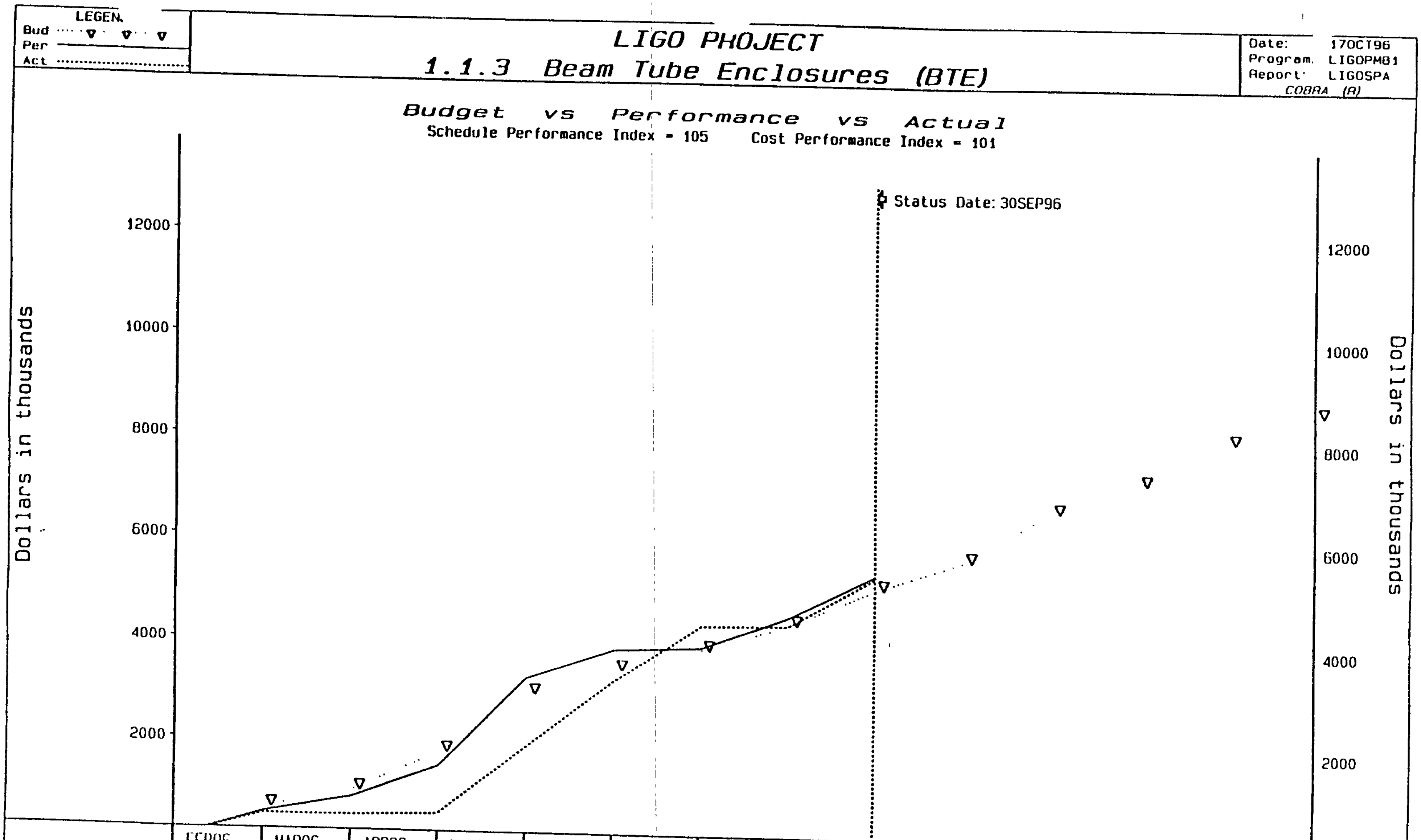


	FEB96	MAR96	APR96	MAY96	JUN96	JUL96	AUG96	SEP96	OCT96	NOV96	DEC96	JAN97	FEB97	SCALE
Planned Budget	4,334	6,371	6,402	6,743	8,493	8,646	12,873	13,887	16,603	18,087	19,408	20,738	20,832	K$
Performance	4,326	6,204	6,250	6,648	6,680	9,306	10,976	12,892						K$
Actuals	4,355	6,164	6,238	6,297	6,597	8,659	9,557	13,419						K$
Schedule Variance	-8	-167	-152	-95	-1,813	660	-1,897	-995						K$
Cost Variance	-29	40	12	351	83	647	1,419	-527						K$

Schedule Variance = Perf-Budg Cost Variance = Perf-Actual Schedule Performance Index = Perf/Budg Cost Performance Index = Perf/Actual

LIGO PROJECT
1.1.3 Beam Tube Enclosures (BTE)

Date: 17OCT96
Program: LIGOPM81
Report: LIGOSPA
COBRA (R)



	FEB96	MAR96	APR96	MAY96	JUN96	JUL96	AUG96	SEP96	OCT96	NOV96	DEC96	JAN97	FEB97	SCALE
Planned Budget	608	971	1,773	2,934	3,454	3,874	4,395	5,112	5,683	6,655	7,245	8,085	8,641	K$
Performance	528	839	1,498	3,258	3,858	3,933	4,551	5,390						K$
Actuals	492	496	549	1,914	3,220	4,363	4,391	5,338						K$
Schedule Variance	-80	- 132	- 275	324	404	59	156	278						K$
Cost Variance	36	343	949	1,344	638	- 430	160	52						K$

Schedule Variance = Perf-Budg Cost Variance = Perf-Actual Schedule Performance Index = Perf/Budg Cost Performance Index = Perf/Actual

LEGEND
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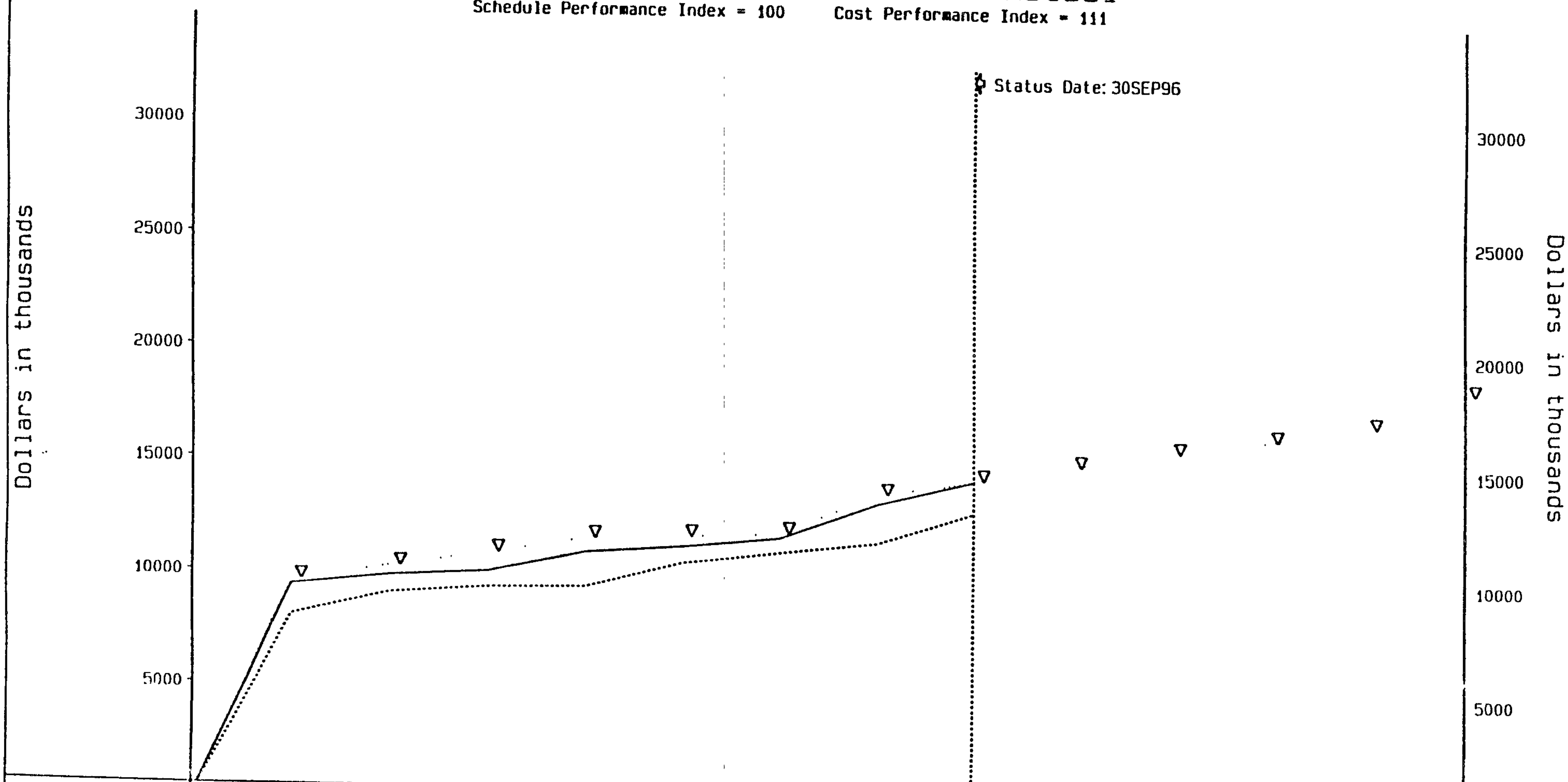
LIGO PROJECT
1.1.4 Facility Design & Construction

Date: 16OCT96
Program: LIGOPMB1
Report: LIGOSPA
COBRA (A)

Budget vs Performance vs Actual

Schedule Performance Index = 100 Cost Performance Index = 111



	FEB96	MAR96	APR96	MAY96	JUN96	JUL96	AUG96	SEP96	OCT96	NOV96	DEC96	JAN97	FEB97	SCALE
Planned Budget	9,602	10,300	10,982	11,676	11,820	12,008	13,775	14,439	15,098	15,753	16,337	16,978	18,523	K$
Performance	9,390	9,875	10,144	11,069	11,379	11,808	13,379	14,424						K$
Actuals	8,042	9,102	9,429	9,510	10,638	11,180	11,658	13,035						K$
Schedule Variance	- 212	- 425	- 838	- 607	- 441	- 200	- 396	-15						K$
Cost Variance	1,348	773	715	1,559	741	628	1,721	1,389						K$
														K$

Schedule Variance = Perf-Budg Cost Variance = Perf-Actual Schedule Performance Index = Perf/Budg Cost Performance Index = Perf/Actual

Summary

- All major facility contracts obligated or about to be.
- We have entered a very busy phase of activity - civil construction, fabrication, and installation activities underway at both observatory sites and at vendors
- We are executing QA oversite plans to maintain requirements and schedule.
- No indications of significant cost growth
- No show stoppers so far

LIGO Data Analysis
Data Formats
and
Modeling Activities

Albert Lazzarini
LIGO Integration Group

NSF Fall Review
22 - 24 October 1996

OUTLINE

1. Data Analysis System for the Initial LIGO Detector

- ›› Science requirements/computational requirements
- ›› Preliminary concept
  - — Data analysis flow
  - — Distribution of computing resources
  - — Access to resources -- network options
- ›› Ongoing & planned activities; issues

2. Data Formats for LIGO Detector

- ›› Status of collaboration with VIRGO
- ›› Common format -- VIRGO model
- ›› Unresolved issues

3. Modeling & Simulation Activities in LIGO

Data Analysis for Initial LIGO

- LIGO Construction Phase includes Data Acquisition System (LIGO DAQ)
- Archival & Analysis Systems fall within scope of Operations Phase.
  - Need will grow gradually during detector commissioning
- McDaniel Panel Report to NSF identified need to develop analysis capability to support both Laboratory and Collaboration research:
  - Computing systems for LIGO; networks -- WAN; maintenance & management of resources
  - Greater computing power required for more complex searches
  - Data distribution and availability -- PAC consultation
- LIGO is developing a conceptual plan for initial data analysis system which will be accessible to both Laboratory and Collaboration:
  - Outline prepared for Fall 1996 NSF Review
  - Refinement of requirements and concept to be conducted in conjunction and in consultation with broader community (LRC).
  - White paper to be available Spring/Summer 1997.

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 $\Delta T < 1$ s	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 $M_{NS} \sim 0.3 M_{SUN}$	~ 2 GFLOPS ~ 50 GFLOPS	Templates/Data ~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	

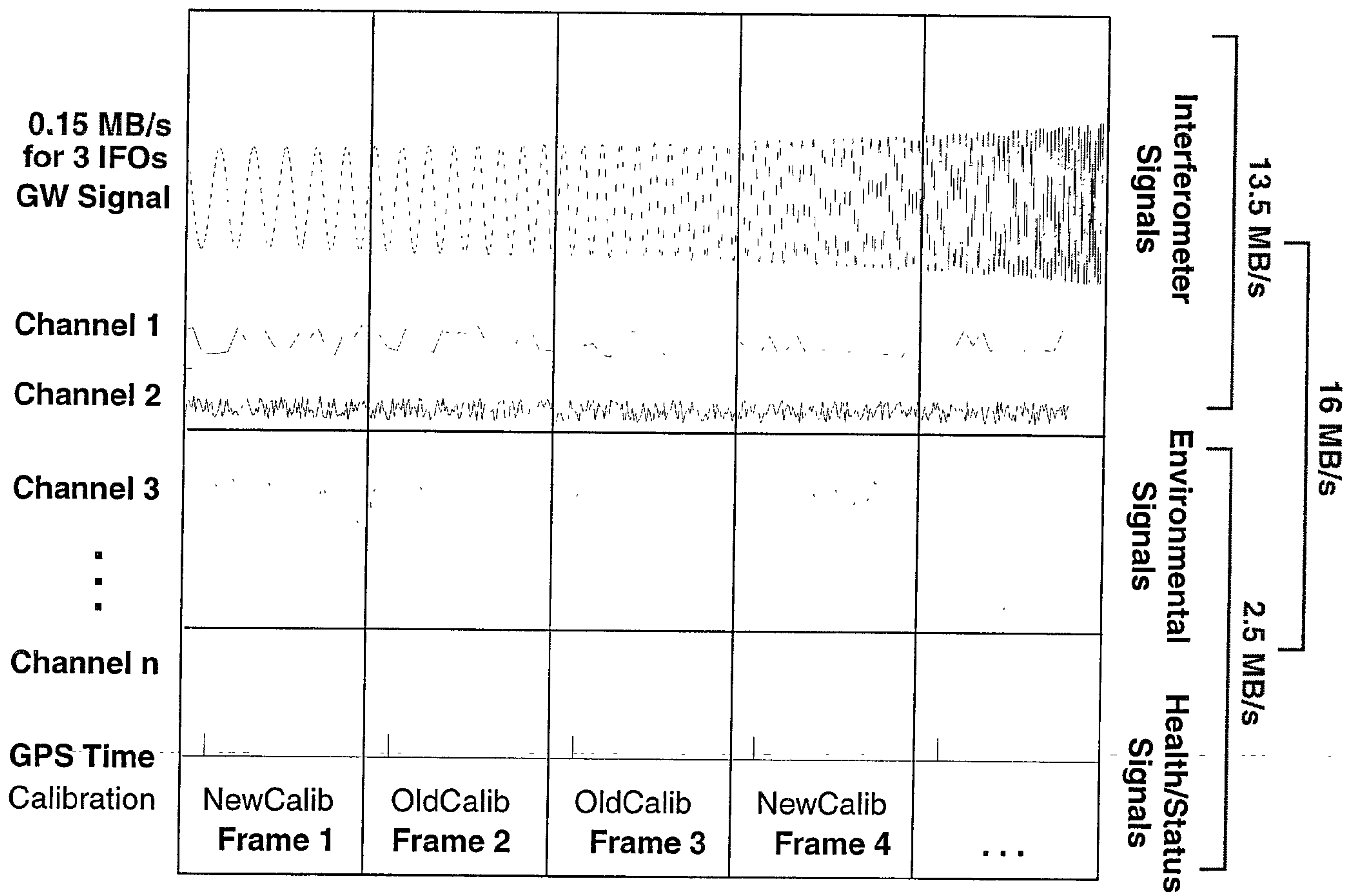
Data Analysis Requirements

Science & Computational Requirements

Initial LIGO Sources and Estimated Analysis Capability Requirements

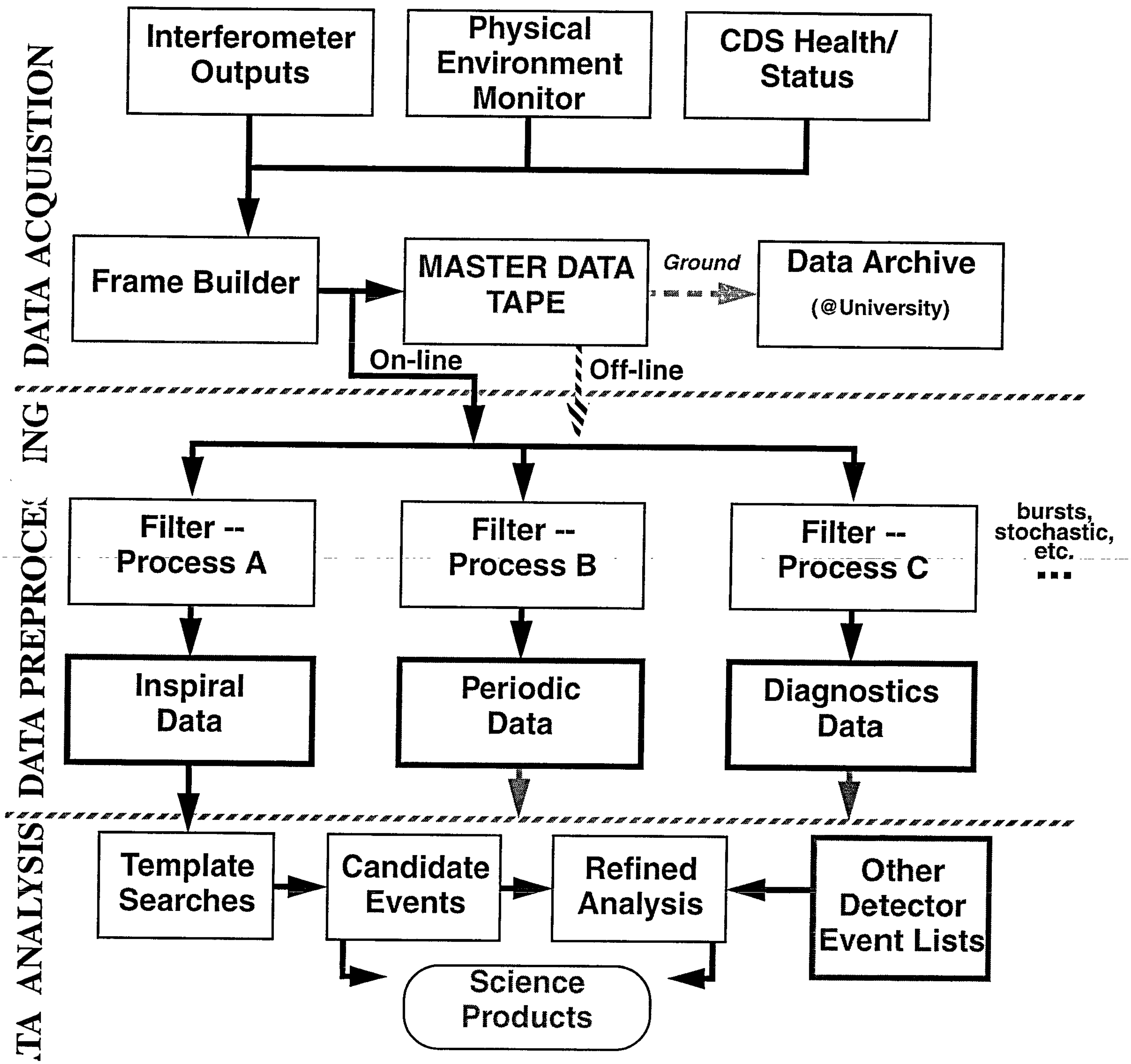
	Sources	Initial LIGO Performance Estimate	Data Analysis Requirements: CPU	Data Analysis Requirements: Storage	Data Analysis Requirements: Comments
Periodic Signal $\Delta T \sim 10^6 - 10^7 s$	Pulsars with mass asymmetry $h \propto \left(\frac{\varepsilon}{10^{-6}}\right)\left(\frac{10kpc}{r}\right)\left(\frac{1ms}{P}\right)^2$	$\varepsilon = 3x10^{-5}$; r=10kpc ; P=1ms $T_{int} = 10^6 s$ $SNR \approx 5$	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 $\Omega \equiv \frac{\Omega_g}{\Omega_0}$	$\Omega \geq 3\times10^{-6}$ $\Delta f, f \approx 100Hz$ $T_{int} = 10^7 sec$	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 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 Data Analysis Flow -- Baseline



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 ($\Delta T < 1\,s$) -- GW + superveto/QA
    - Inspiral & coalescence waveforms ($10s < \Delta T < 1000s$) -- events
- System configuration (target: $\mathbf{M_{NS} > 0.3\ M_{SUN}}$)
  - 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*

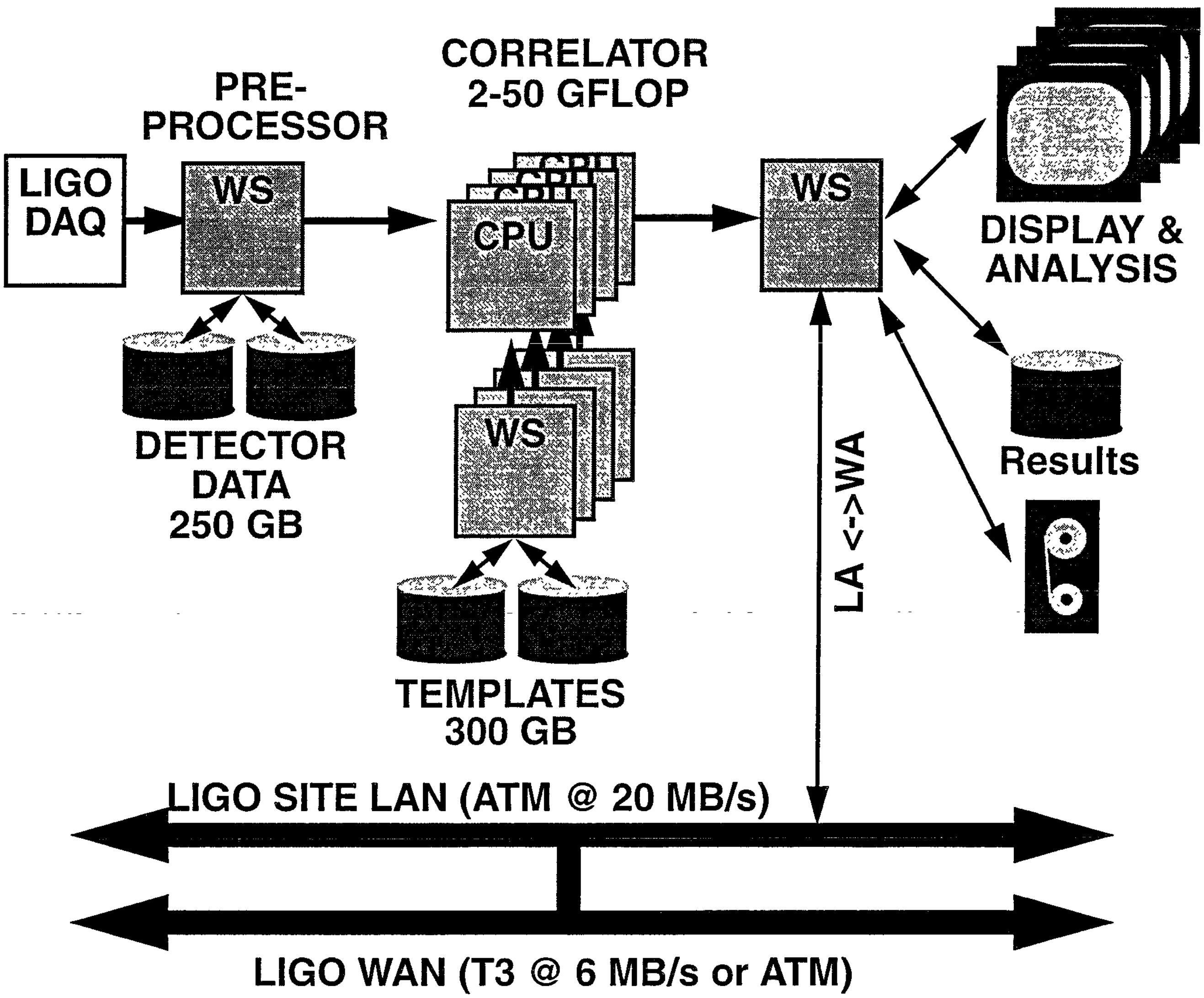
Data Analysis for Initial LIGO

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.

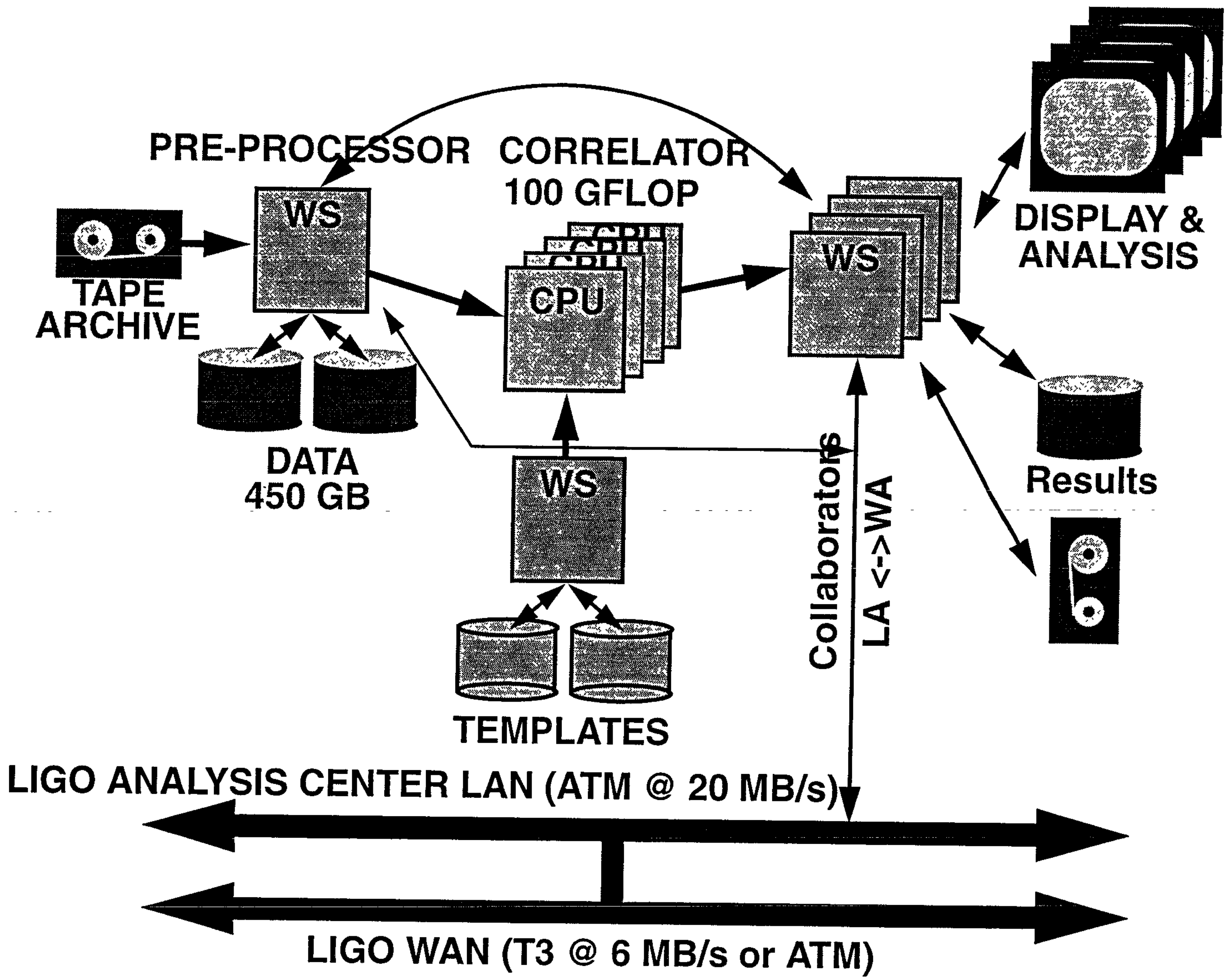
Data Analysis for Initial LIGO

Off-line Processing Computing Resources & Distribution

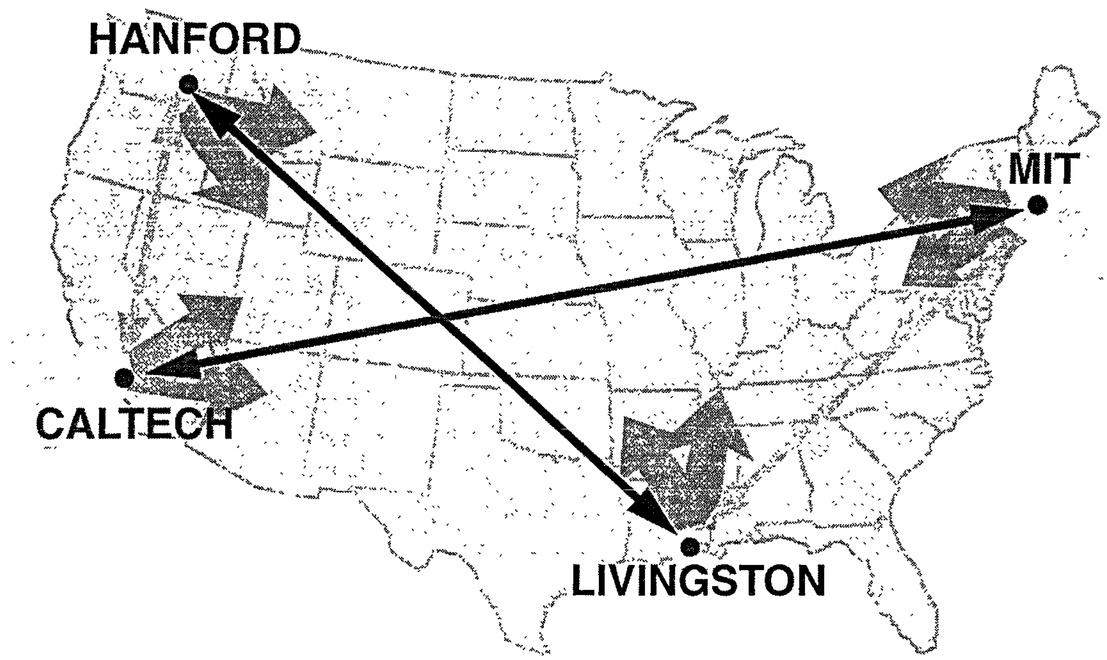
- System configuration (target: max. capability for multiple users)
  - Large data archive
    (~ 500 TB/yr => 10k tapes/yr @ 50 GB/tape => $0.5M/yr @ $50/tape)
  - Robotic tape access -- size TBD
  - Disc cache system capable of storing 450GB of data
    - 8 hours of 100% data ~ 450 GB
    - ~ 5 weeks 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 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

Site Communications

- Options for utilizing existing resources -- these are being explored:
  - ›› Caltech:
    - HEP link to MIT/CERN (DOE:ESNET; plan: OC12@70+MB/s)
    - IPAC/JPL link to NASA backbone (NASA)
    - CACR link(s) to SC centers (NSF: VBNS->OC12@70+MB/s))
  - ›› MIT:
    - HEP link to Caltech/CERN (DOE - ESNET)
    - NASA backbone (NASA)
    - Link(s) to SC centers (NSF - VBNS)
  - ›› Livingston:
    - LSU link to MSFC/NASA backbone (NASA)
    - LSU link to SC centers (NSF - VBNS)
  - ›› Hanford:
    - HNR/BNWL (DOE - ESNET)

Planned Activities

Timeline for Development

Milestone or Event	Date	Communications	Hardware	Software
Begin Coincidence Operations	7/00	Common		
On-Line System Available	1/00	Common		
	3/99-12/99	Implementation	Procurement & Integration	Verification
	11/98	Agreements	Specifications	Development
System FDR	11/98		Design & Prototyping	Specifications
System PDR	11/97	Definition		Design & Prototyping
System DRR	5/97			

Ongoing Activities
Prototyping

- Detector construction phase is developing a prototype DAQ system for the 40m facility
  - Utilize 40m to acquire datasets of substantial length (1/2 day) on a regular basis
  - Experimental use of ancillary channels for data qualification
- LIGO co-authored joint proposal for IBM Sponsored University Research (SUR) Grant funding - $800k of processor hardware will be awarded
  - LIGO will participate in hardware configuration definition; to be shared with other campus groups
  - Hardware to be installed at Center for Advanced Computing Research (CACR)
  - CACR already has similar NSF-funded hardware for astrophysics data analysis
- Use ongoing work to provide realistic scaling of parallel analysis algorithms for large data sets
- Establish data link from 40m to CACR

Issues

- LIGO Analysis System design must contend with two conflicting needs...
  - Rate of technology growth argues for delaying investment in hardware to the latest possible moment...
  - Need to develop/debug analysis software on specific platform(s) to support detector commissioning. COTS & strict adherence to standards.
- Efficient utilization of 40m prototype DAQ system and CACR is key to developing an extensible, modular system which is capable of providing LIGO Laboratory & Collaboration adequate analysis tools for the first generation detectors:
  - Validation of software
  - Identification of best hardware approaches
  - Benchmarks for on-line processing

Issues
(cont.)

- Efficient use of detector ancillary data channels is key to containing archive growth
  - 100% data stream corresponds to $>10^4$ tapes/year;
  - GW channels correspond to $<10^2$ tapes/year
- Actual cost of archival is bounded...
- Two approaches possible...
  - Start with minimum channel count and add channels as experience dictates through commissioning phase
  - Start with 100% channel count and pare back as experience dictates
  - First option more reasonable and less costly.
- During definition phase, LIGO will actively seek LRC representation in design inputs.
  - This is the first presentation by LIGO
  - Process will take a year or more

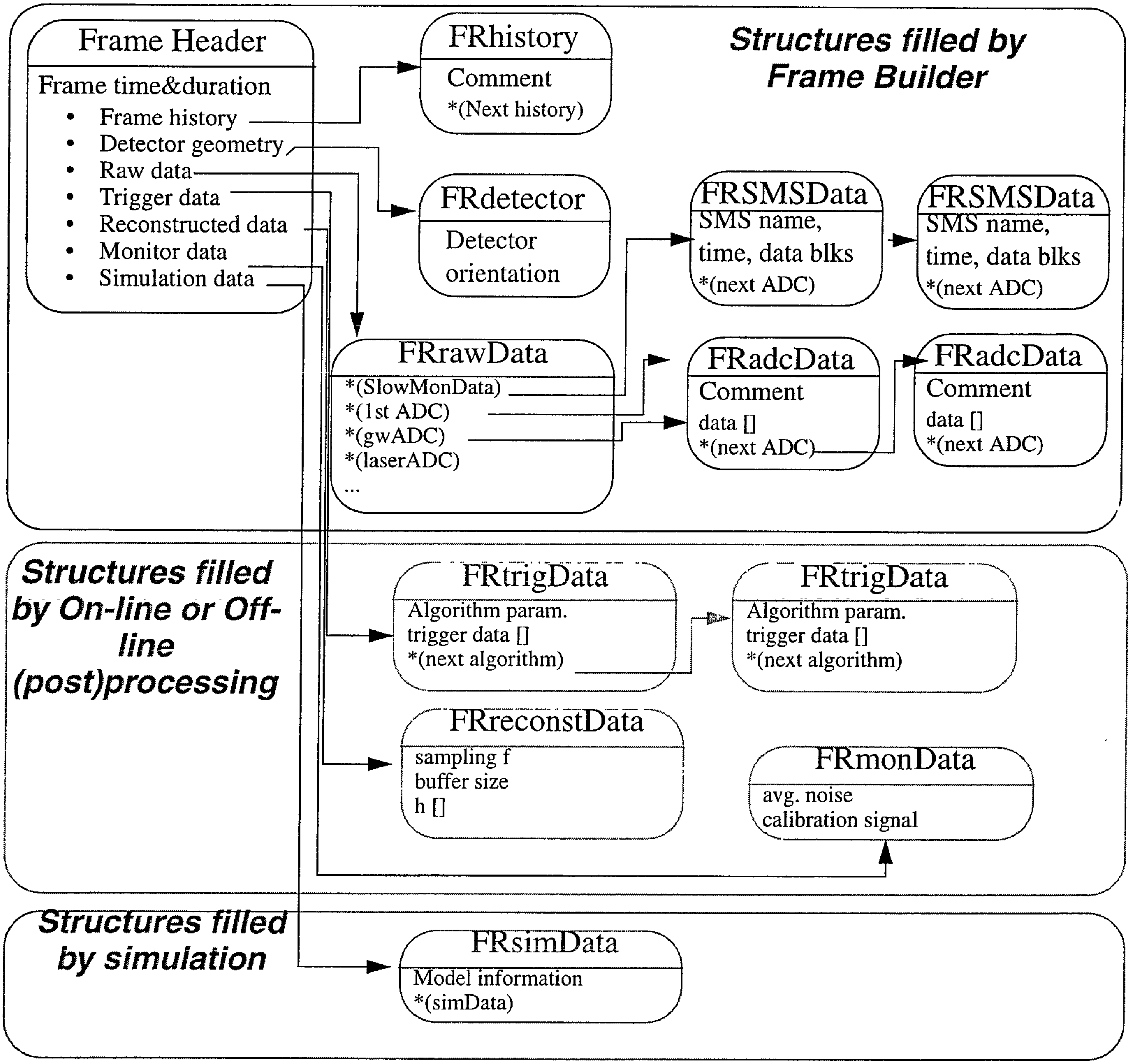
LIGO-VIRGO DATA FORMAT
Status

- Initial meeting with VIRGO in April hosted by LIGO
  - VIRGO format presented, compared with LIGO needs
  - Attractive (to LIGO) because of maturity & availability of existing I/O libraries
  - Tuned for time-series data stream (vs. events or images)
- Alternatives explored by LIGO
  - Public domain standards - CDF/HDF
  - Used for image frame data distribution (NASA)
  - Greater overhead per frame than VIRGO
  - Well suited for eventual data distribution
- Continued interaction with VIRGO
  - Format evolving under collaborative effort
  - Software availability: commited to public domain access
  - Joint approach to be presented at TAMA Fall Meeting in Japan

LIGO-VIRGO DATA FORMATS

- PROPOSED FORMAT (Adopted from VIRGO)
  - FRAMES (unit of information containing all information needed to understand the interferometer behavior over a finite time interval)
  - C STRUCTURES (frames are organized as a set of C structures)
  - FRAME HEADER (holds pointers to additional structures that contain all information)
  - LINK LISTS (used to collect generic data types, PEM, ADC, etc.)
  - HEADER HOOKS (pointing to frame elements used by on-line processing or by off-line reprocessing)
  - 2^N DATA POINTS (allowing faster FFT analysis on individual frames)
  - DICTIONARY (acts as a catalog of C structures and pointer offsets)

LIGO-VIRGO DATA FORMAT



- **Frame has tree structure:**
- **Individual blocks are C structures**
- **Extensible to arbitrary length with design evolution**
- **Utilized for both on-line & off-line analyses**

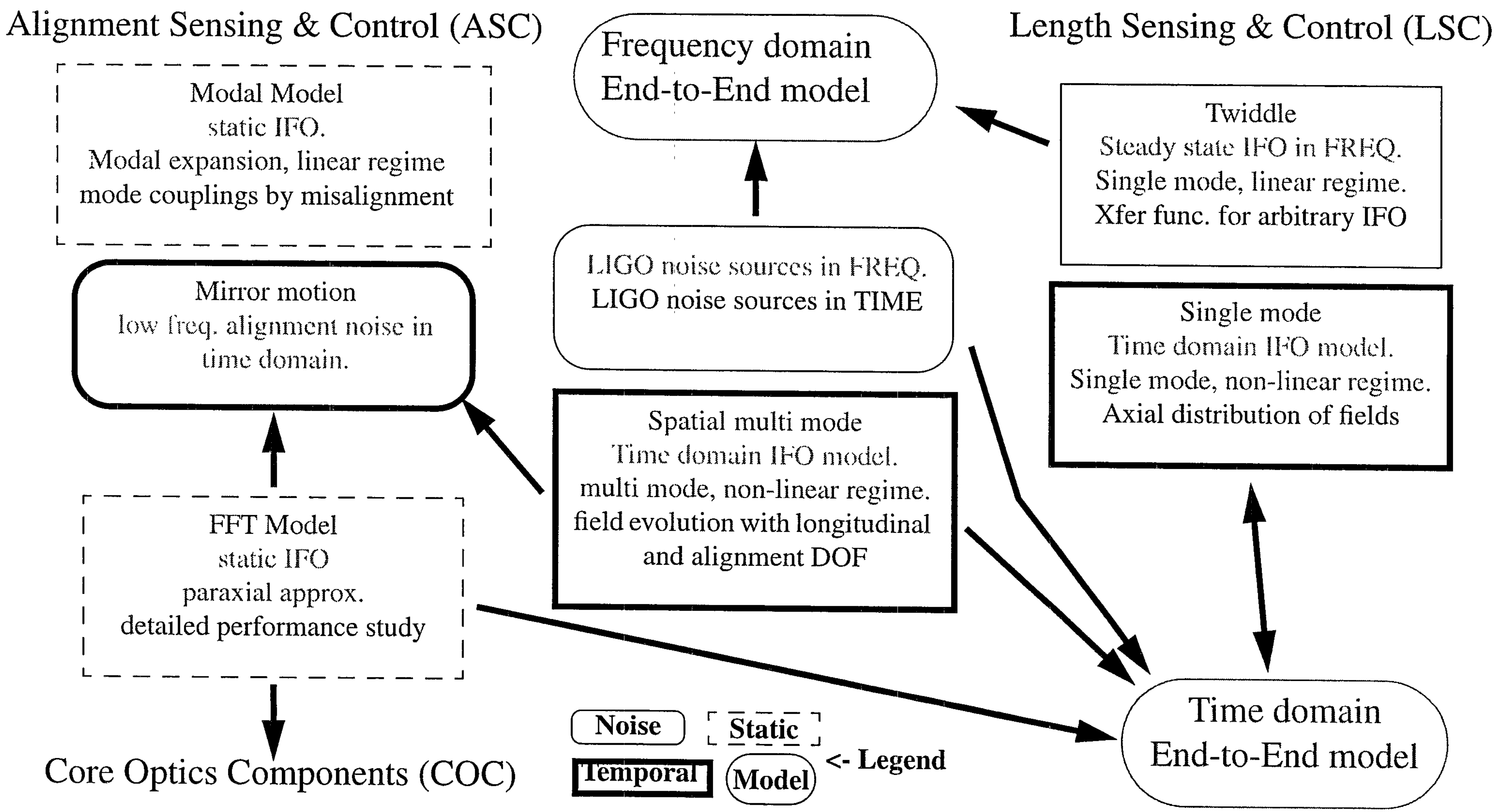
LIGO-G960211-00-E

LIGO-VIRGO DATA FORMAT

Issues

- Testing & verification at LIGO using I/O libraries for tape uncovered problems with C function calls between platforms (DEC vs. SUN)
  - LIGO wants to adhere to established software-hardware interface standards (i.e., POSIX) to minimize cost of code transportability/maintainability/upgrade/compatibility
- LIGO is discussing concerns with VIRGO; depending on outcome, LIGO may adopt VIRGO paradigm but implement its own code.
- Issue to be resolved by Spring 1997.
- *QA is the key to code extensibility, adaptability& maintainability.*

Modeling Activities
Overview



Modeling activities

- Time domain interferometer model with length and alignment D.O.F.
  - ›› Objective
    - – Demonstration of lock acquisition
    - – dynamic stability of coupled alignment and length controllers
    - – transfer functions between Length and Alignment DOF
    - – Pseudo-data for noise analysis
  - ›› Parallel efforts by D. Redding/JPL and R. Beausoleil/Cygnus
    - – different approaches
    - – model cross-validation
    - – different application - speed vs. accuracy
  - ›› D. Redding - time difference equations; iterative solution
    - – Length (single D.O.F.) part complete
    - – Used for the design of LSC
  - ›› R. Beausoleil - forward time propagator kernel
    - – single Fabry-Perot cavity with length and alignment DOF complete -- being validated

Modeling activities

- FFT model
  - Detailed study of interferometer performance
    - e.g., sensitivity study of mirror phase/reflectivity error due to coating & polishing
  - Code is parallelized
    - running on PARAGON in CACR - 10 x faster than SS20
  - Interface improved:
    - GUI interface for input data
    - Remote scripting
    - Database for maintaining the run summaries

End-to-End model

- Frequency domain (steady state model) version
  - ›› Interferometer: *Twiddle* by M.Regeher/H. Yamamoto
  - ›› Noise models: K. Blackburn (& R. Weiss et al.)
- Transition to time domain
  - ›› Interferometer and noise in freq. domain are essentially done
  - ›› Control system for LIGO is still in design stage
  - ›› Time domain model will be developed and is more suited when modeling control system
    - – Time domain IFO model with length and angular DOF - JPL/Cygnus models
    - – Time domain noise models need to be developed
- Time domain version - just started
  - ›› First target is 40 m testbed - serve as a prototype for the full version
  - ›› Inclusion of control system - use design for 40m recycling
  - ›› Include fundamental building blocks for LIGO