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ROBOTICS AND INTELLIGENT SYSTEMS PROGRAM

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A HISTORICAL PERSPECTIVE OF REMOTE OPERATIONS AND ROBOTICS IN NUCLEAR FACILITIES

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Abstract of paper for
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November 17, 1992

*Managed by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy.

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ROBOTICS AND INTELLIGENT SYSTEMS PROGRAM

A HISTORICAL PERSPECTIVE OF REMOTE OPERATIONS AND ROBOTICS IN NUCLEAR FACILITIES

J. N. Herndon
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ABSTRACT

The field of remote technology is continuing to evolve to support man's efforts to perform tasks in hostile environments. Remote technology has roots which reach into the early history of man. Fireplace pokers, blacksmiths' tongs, and periscopes are examples of successes in removing humans from hostile environments. The technology which we recognize today as remote technology has evolved over the last 45 years to support human operations in hostile environments such as nuclear fission and fusion, space, underwater, hazardous chemical, and hazardous manufacturing.

The four major categories of approach to remote technology have been (1) protective clothing and equipment for direct human entry, (2) extended reach tools using distance for safety, (3) telemanipulators with barriers for safety, and (4) teleoperators incorporating mobility with distance and/or barriers for safety. The government and commercial nuclear industry has driven the development of the majority of the actual teleoperator hardware available today. This hardware has been developed largely due to the unsatisfactory performance of the protective-clothing approach in many hostile applications. Manipulation systems which have been developed include crane/impact wrench systems, unilateral power manipulators, mechanical master/slaves, and servomanipulators. Viewing systems have included periscopes, shield windows, and television systems. Experience over the past 45 years indicates that maintenance system flexibility is essential to typical repair tasks because they are usually not repetitive, structured, or planned. Fully remote design (manipulation, task provisions, remote tooling, and facility synergy) is essential to work task efficiency.

Work for space applications has been primarily research oriented with relatively few successful space applications, although the shuttle's remote manipulator system has been quite successful. In the last decade, underwater applications have moved forward significantly, with the offshore oil industry and military applications providing the primary impetus.

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Over the next decade, nuclear fission and fusion applications, along with Department of Defense needs, will continue to be major technology drivers, with environmental restoration and waste management applications presenting major new challenges for the remote technology community. New challenges presented by the Space Exploration Initiative will require significantly more emphasis on autonomous systems research and development.

A Historical Perspective on Remote Operations and Robotics in Nuclear Facilities

Joseph N. Herndon
Oak Ridge National Laboratory

40th Conference on Remote Systems Technology
November 17, 1992

Presentation Outline ...

- Background on Remote Systems (Nuclear)
- Historical Evolution of Teleoperators and Telerobotic Systems
- Observations Regarding Remote Systems

Background on Remote Systems

Remote Technology Has Evolved To Support Human Efforts In Hostile Environments

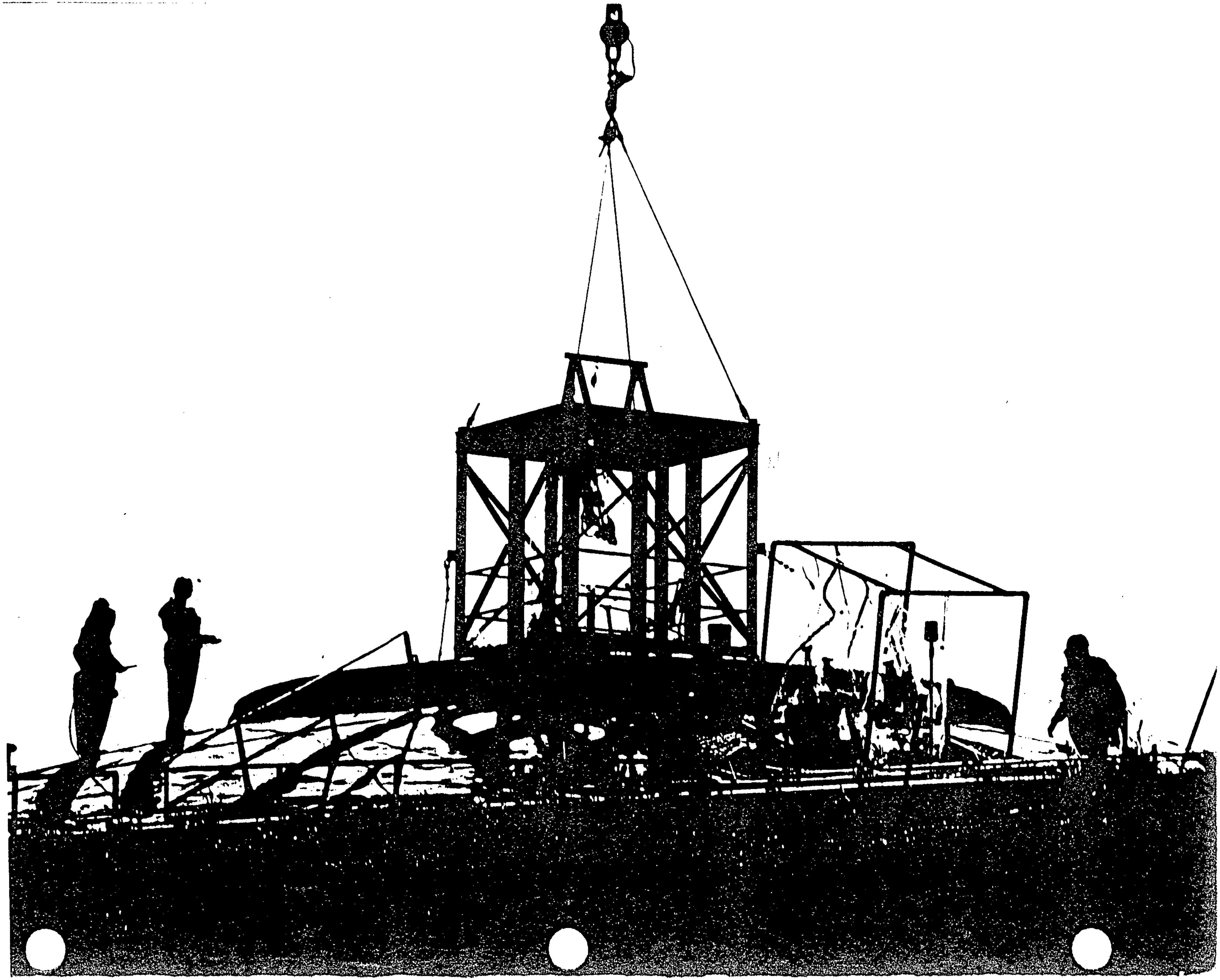
- Humans, since very early, have utilized Remote Technology ... examples include ...
  - fireplace poker
  - blacksmith's tongs
  - periscope

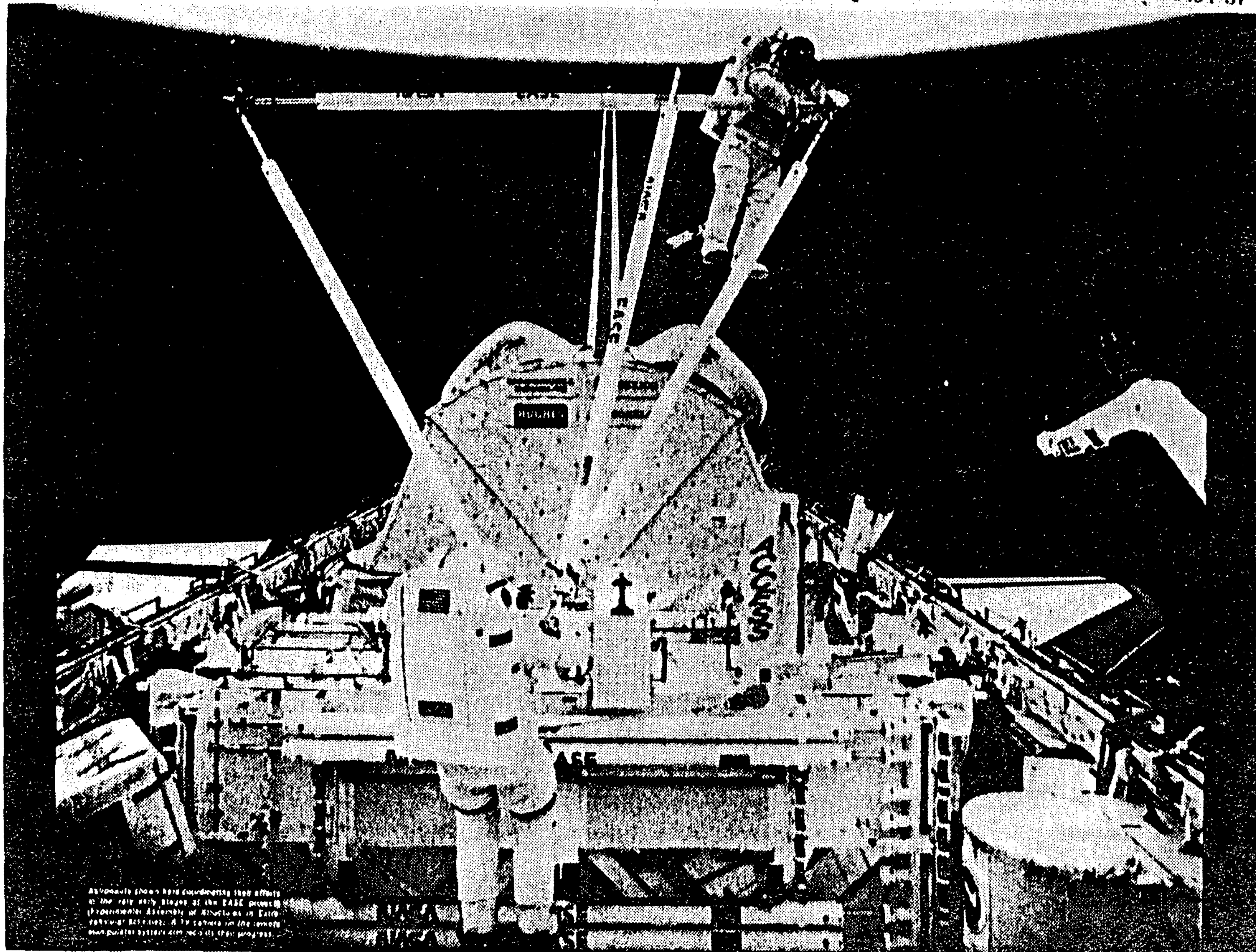
- Over the past 45+ years, Remote Technology has been developed in earnest to support human endeavors in hostile environments
  - nuclear fission
  - nuclear fusion
  - space
  - underwater
  - hazardous chemical
  - waste management

There Are Four Major Categories of Approach to Remote Technology In The Nuclear Industry

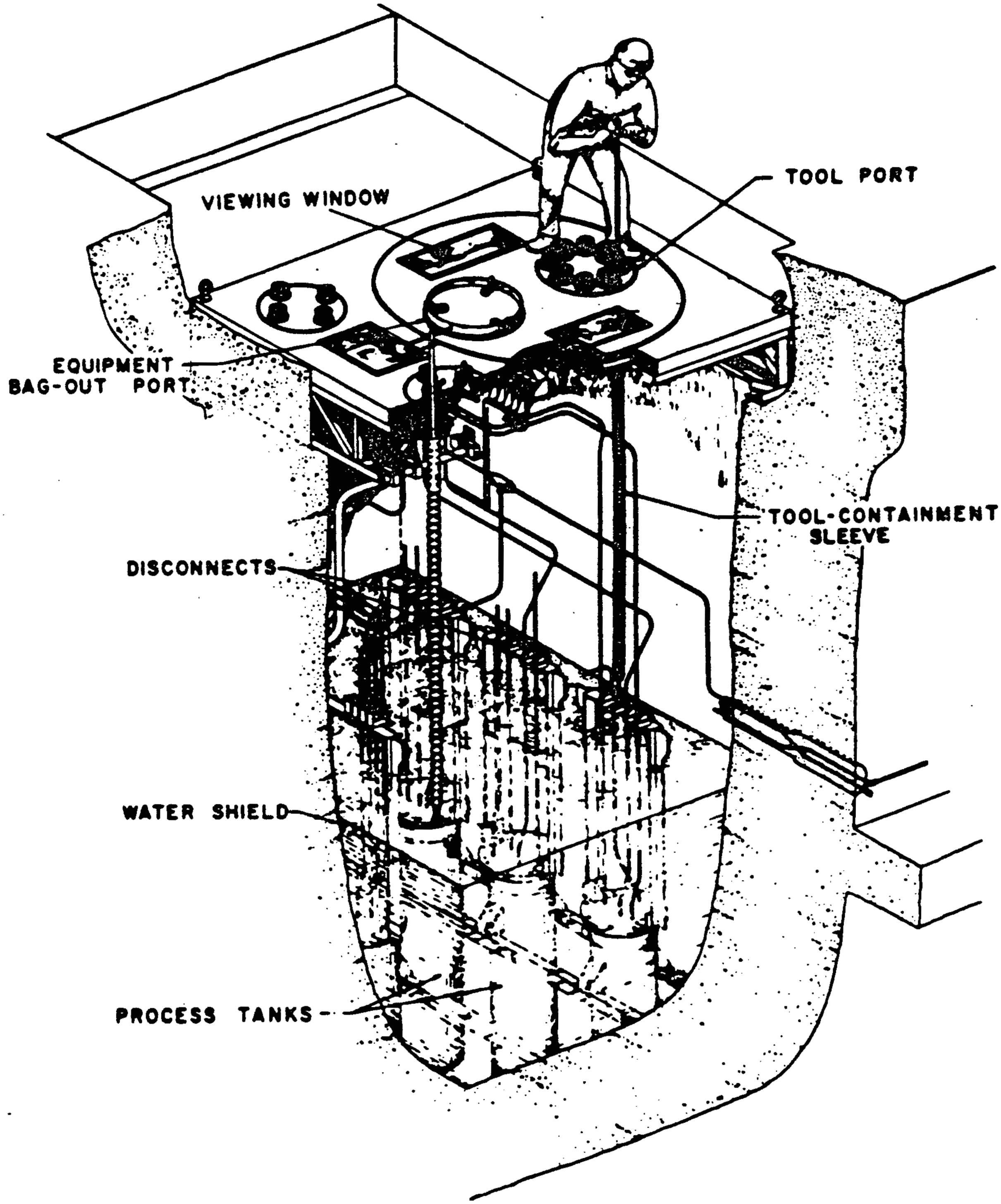
- PROTECTIVE CLOTHING ... an approach that utilizes special body coverings and/or worn equipment with direct viewing

- EXTENDED REACH TOOLS ... an approach that extends the idea of blacksmith's tongs ... long tools with distance from the hazard for safety, vision is usually direct or supplemented with television





Astronaut EVA Space Structure Assembly



TRU tank-pit maintenance shield.

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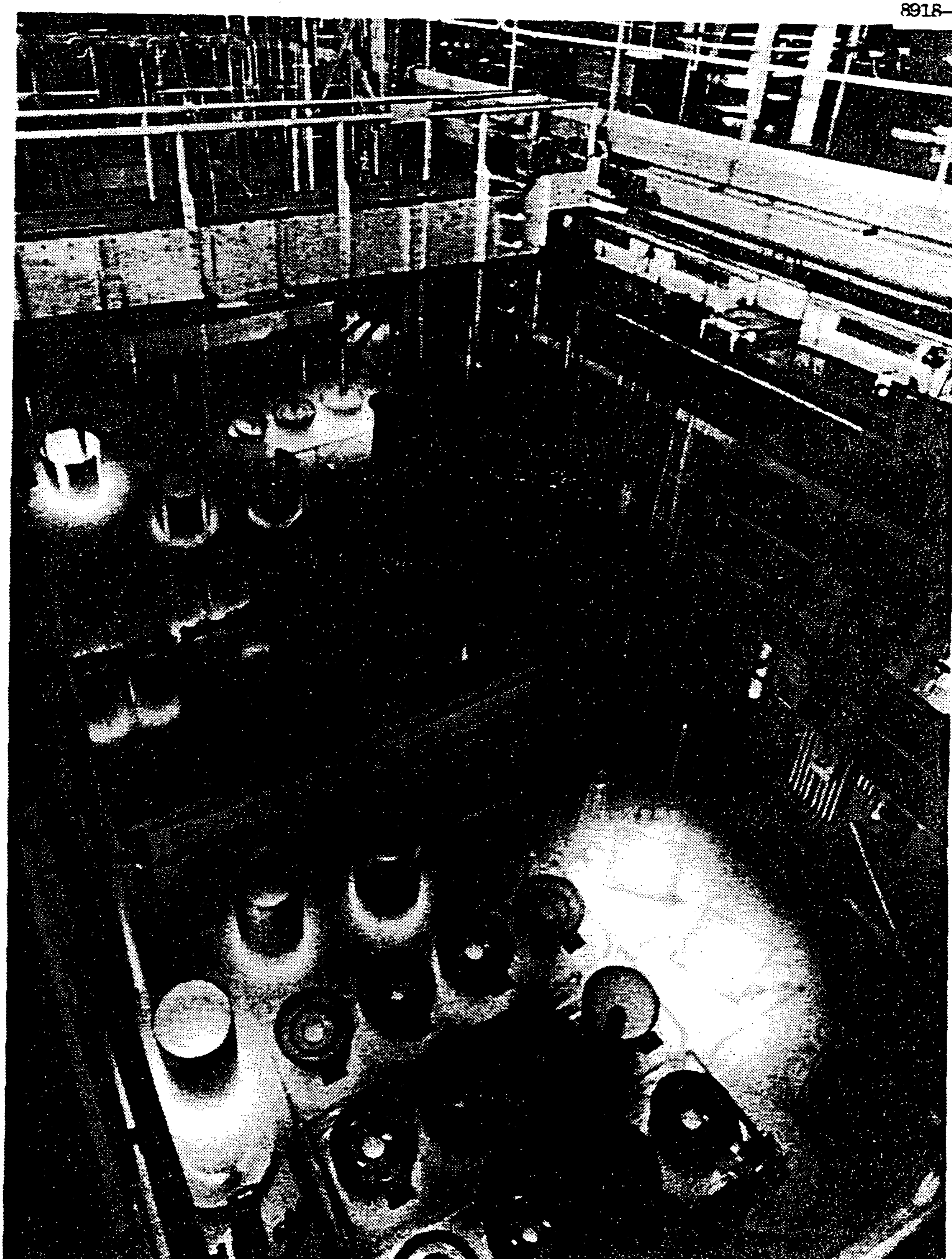

Spent fuel pool maintenance bridge with extended reach tools.

There Are Four Major Categories of Approach to Remote Technology In The Nuclear Industry (Cont.)

- TELEMANIPULATORS (Ref. 1)
  - an approach which utilizes highly dexterous "extended reach tools" and physical barriers between the human and the hazard
  - manipulation is by mechanical master/slave manipulator and vision is direct through protective windows
  - usually limited to fixed locations, work volume typically ~ one cubic meter
  - some mobile systems used (undersea, etc)

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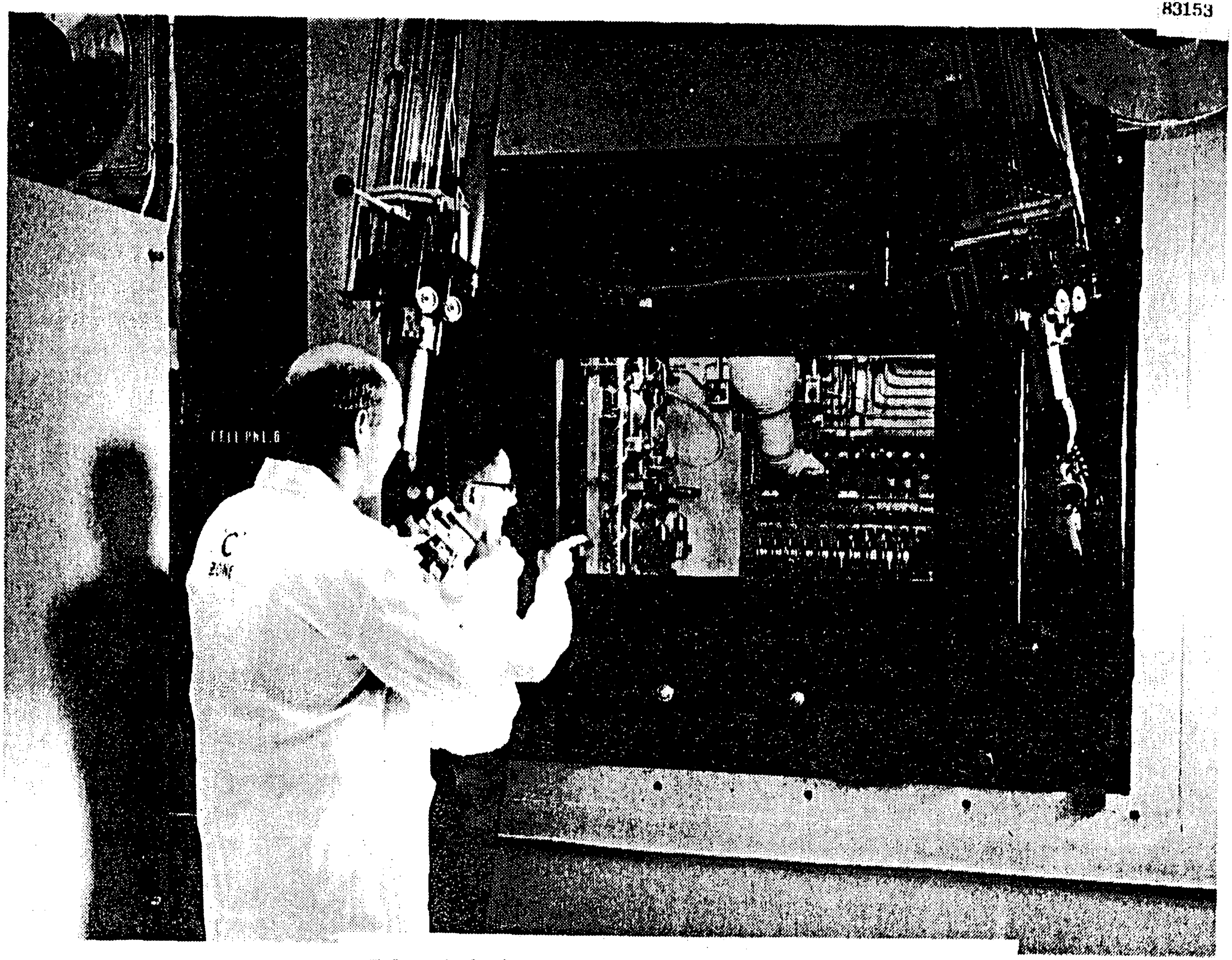
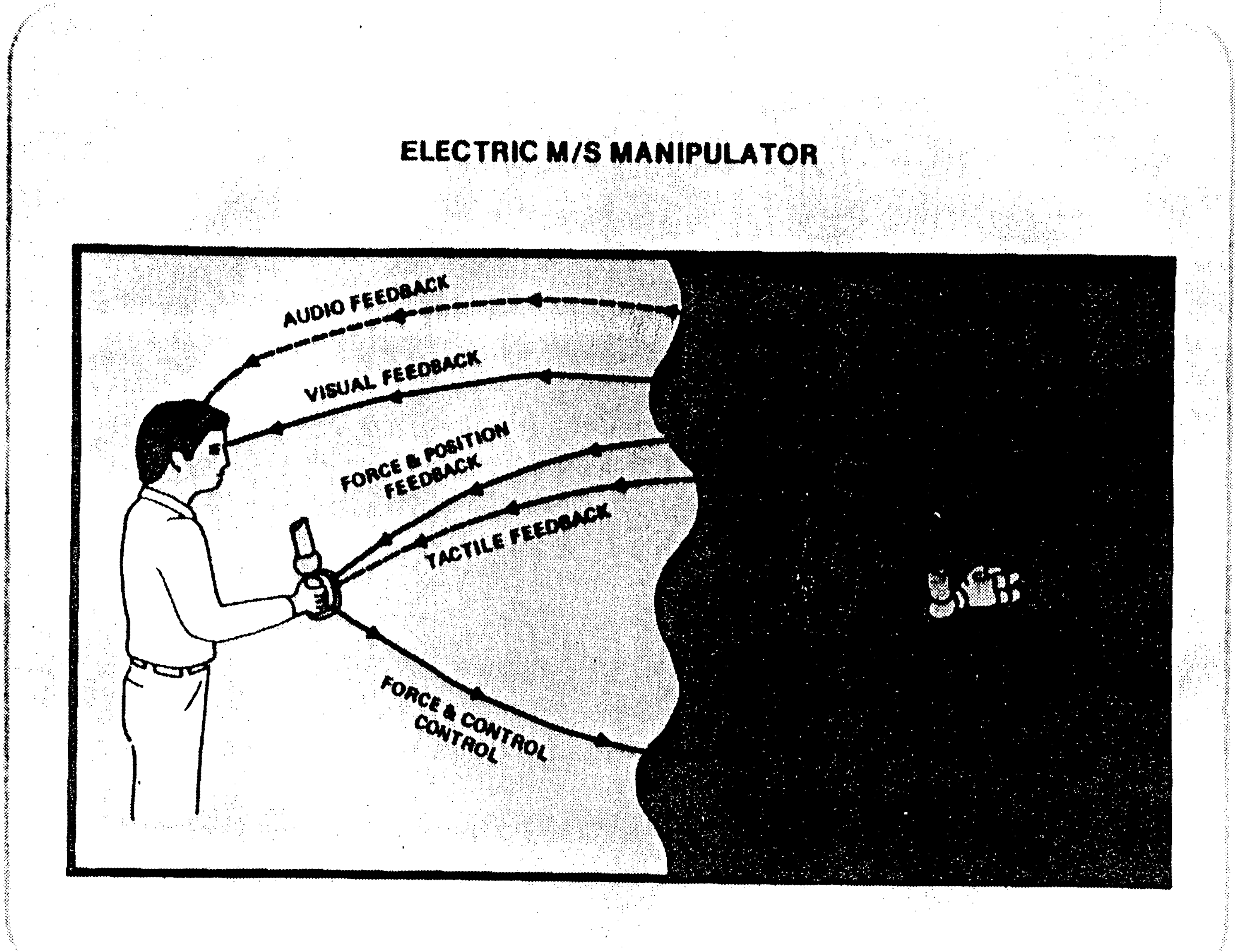


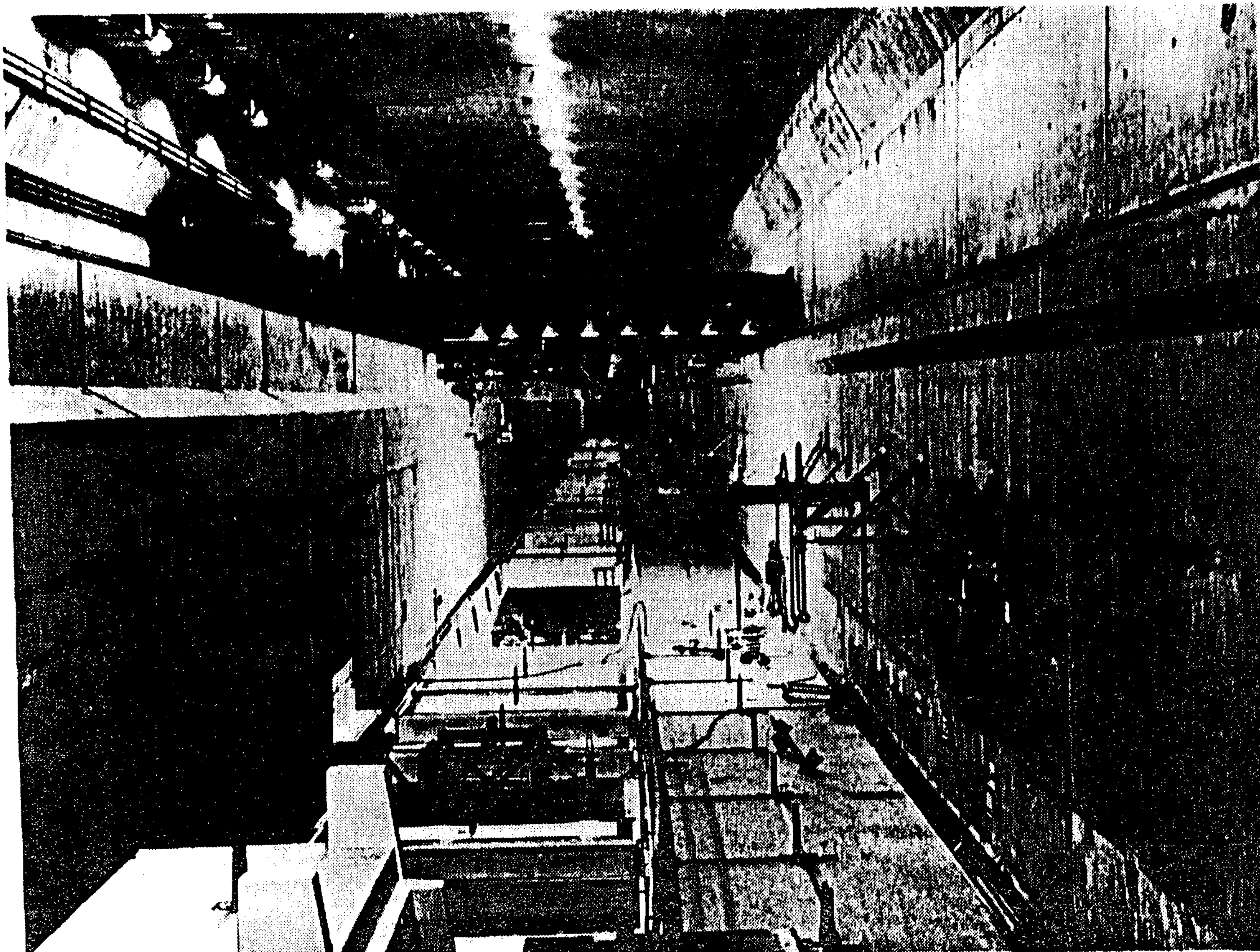
Telemanipulation with master-slaves and shielding window.

There Are Four Major Categories of Approach to Remote Technology In The Nuclear Industry (Cont.)

- TELEOPERATORS
  - "A teleoperator is a general purpose, dexterous, man-machine system that augments man by projecting his manipulatory and pedipulatory capabilities across distance and through physical barriers into hostile environments" (Ref. 2)
  - Manipulation is by a movable mechanism (crane hook, servomanipulator), and vision is either direct or indirect (protective window, periscope, television camera)
  - The human operator is <u>ALWAYS</u> directly in the control loop



Ray Goertz's Concept for Dexterous Teleoperations.



Hanford Purex Plant remote canyon.

ORNL PHOTO 1853-85

CENTRAL RESEARCH LABORATORIES MODEL M-2

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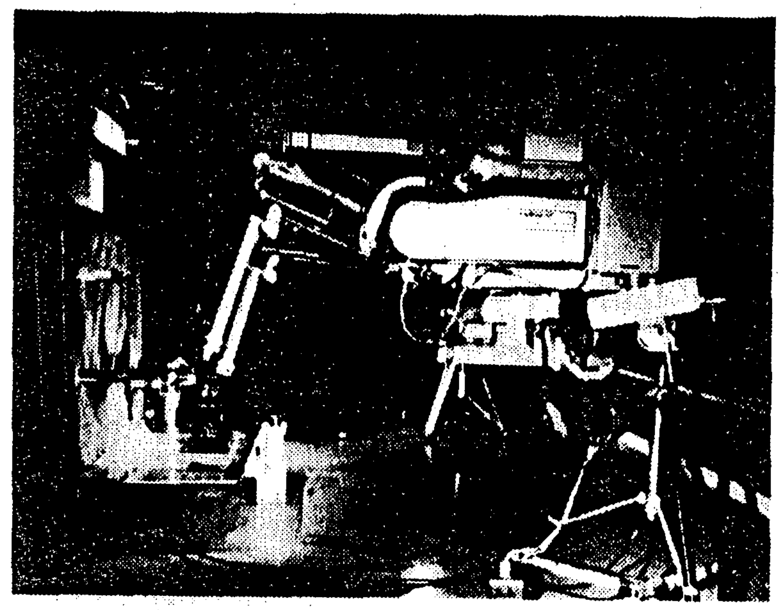
MASTER CONTROLLER



SLAVE

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Fully Remote Maintenance Has Been Implemented Since the Beginning of the Nuclear Era ... Hanford Bismuth Phosphate Plants

- MOTIVATION
  - new highly radioactive plant
  - new process technology
  - unsurpassed design and construction schedule
- RECOGNITION
  - difficulties are certain, build in recovery capabilities
- DEVELOPMENT REQUIREMENTS
  - shielded-cab crane with perescope viewing
  - remote tooling concepts
  - remotely operable process components
- PROGENY
  - a series of remote fuel cycle, PIE, and analytical chemistry cells
  - most successful of the high radiation facilities (Ref. 3)

MAJOR REPROCESSING FACILITIES IN THE UNITED STATES[3]				
Process	Plant Location or Name	Number of Facilities	Date of Construction	Type of Maintenance
Bismuth phosphate precipitation	Hanford	3[a]	1944	Remote crane canyon[b]
Redox	Handford	1	1948	Remote crane canyon[b]
Electrochemical and chemical dissolution; TBP and hexone solvent extraction	Idaho Chemical Processing	1	1953	Contact
Purex	Hanford	1	1956	Remote crane canyon[c]
Purex	Savannah River	2	1954	Remote crane canyon[c]
Pyromet	EBR-II Fuel Cycle Facility	1	1963	Total remote
Chop-leach, Purex	Nuclear Fuel Services	1	1966	Remote/contact
Aquafluor	Midwest	1	1974	Remote
Chop-leach, Purex	Barnwell Nuclear Fuel Plant	1	1976	Remote/contact

[a]Only two were operated.

[b]Limited to removal and replacement.

[c]Minimal repair of process equipment, and that only by contact means after decontamination.

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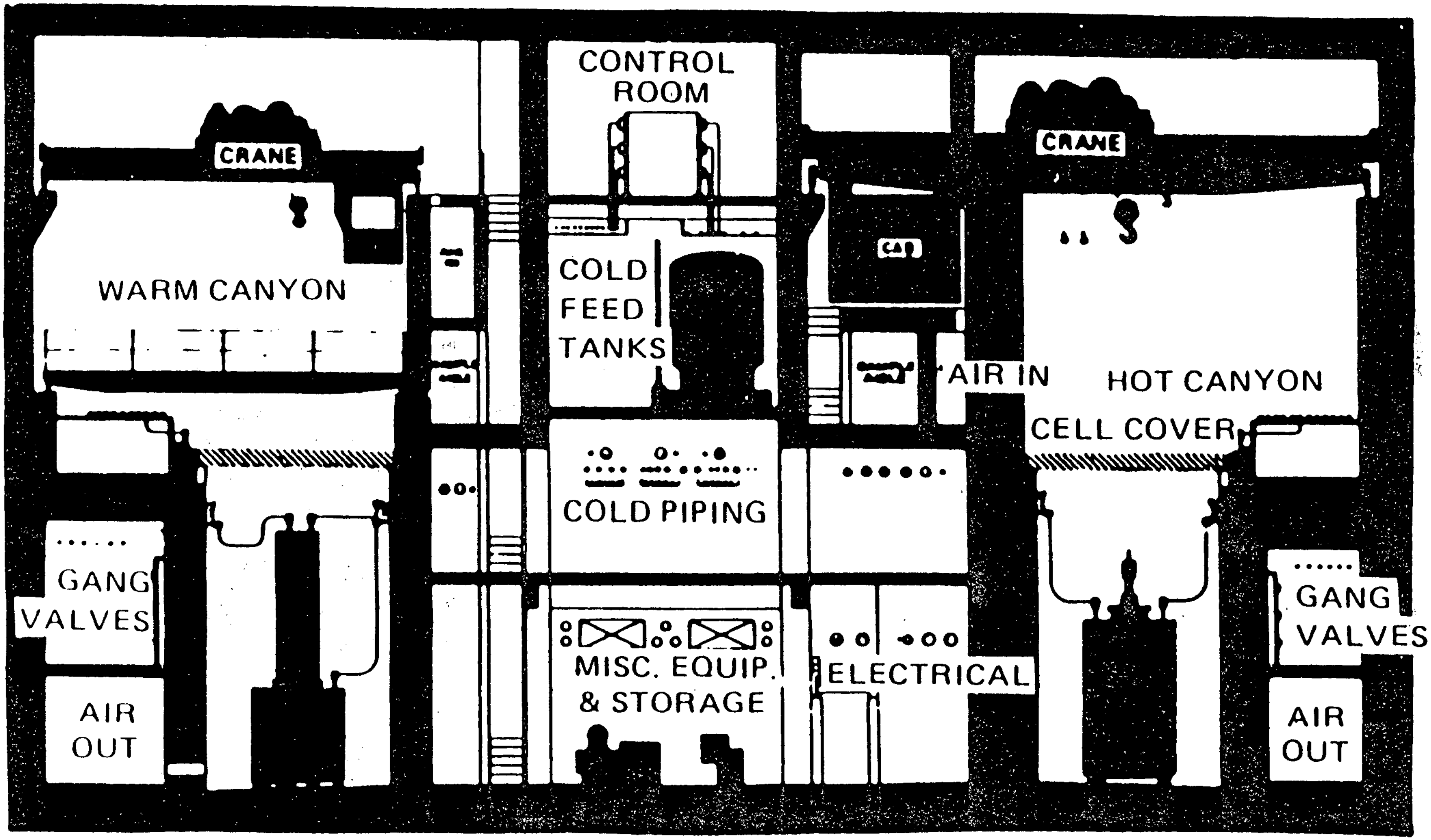

Savannah River Plant typical cross section.

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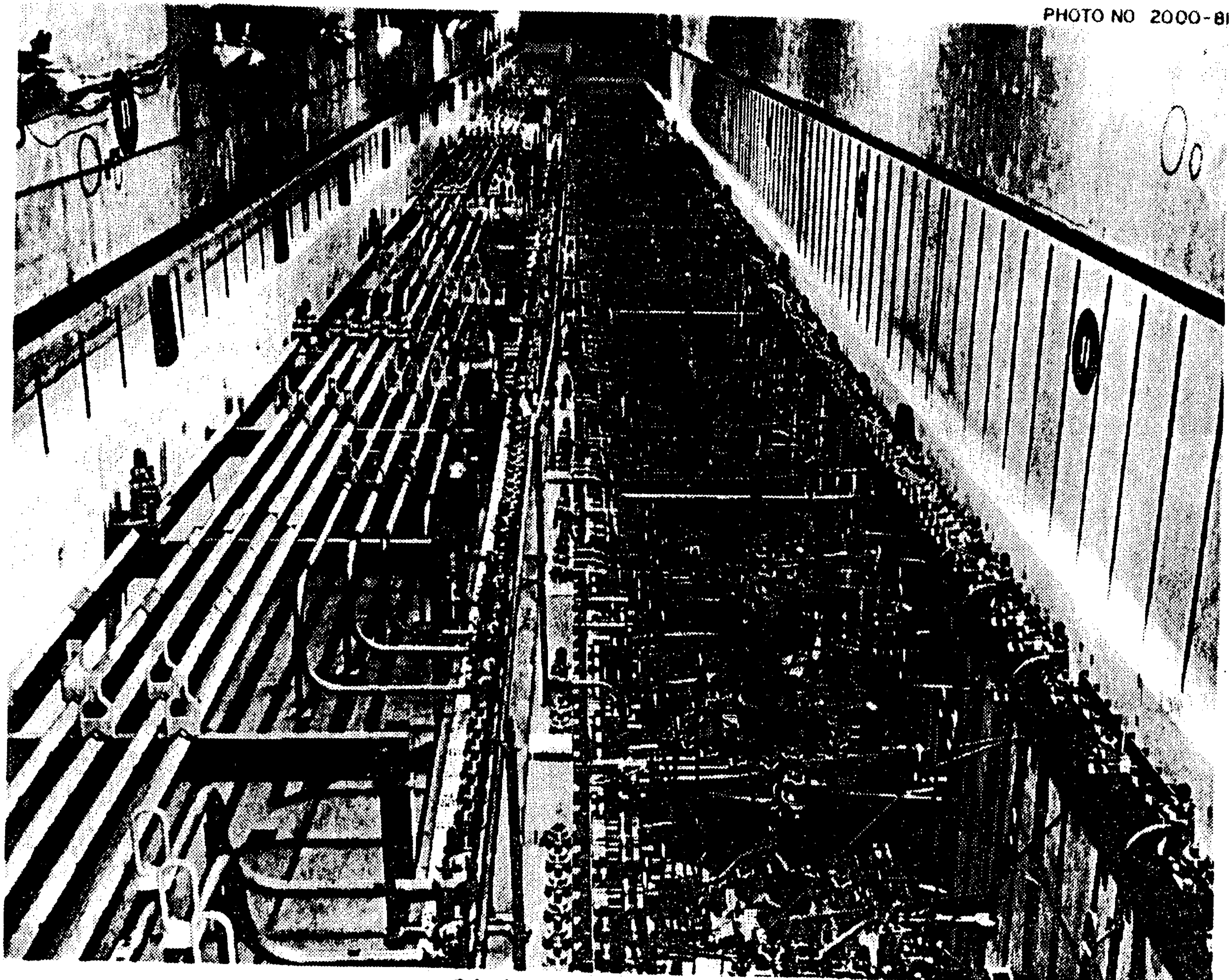

SAVANNAH RIVER PLANT

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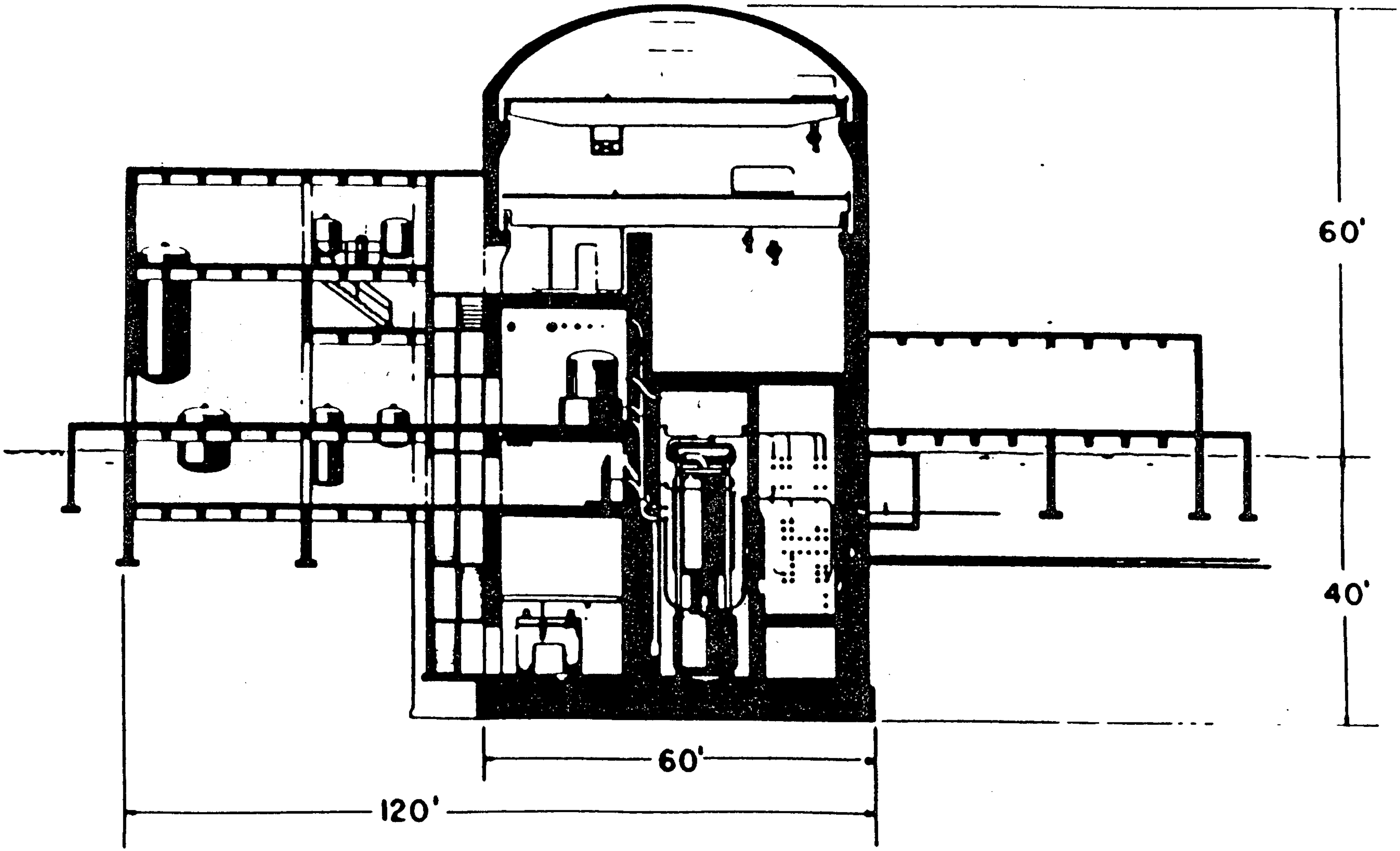
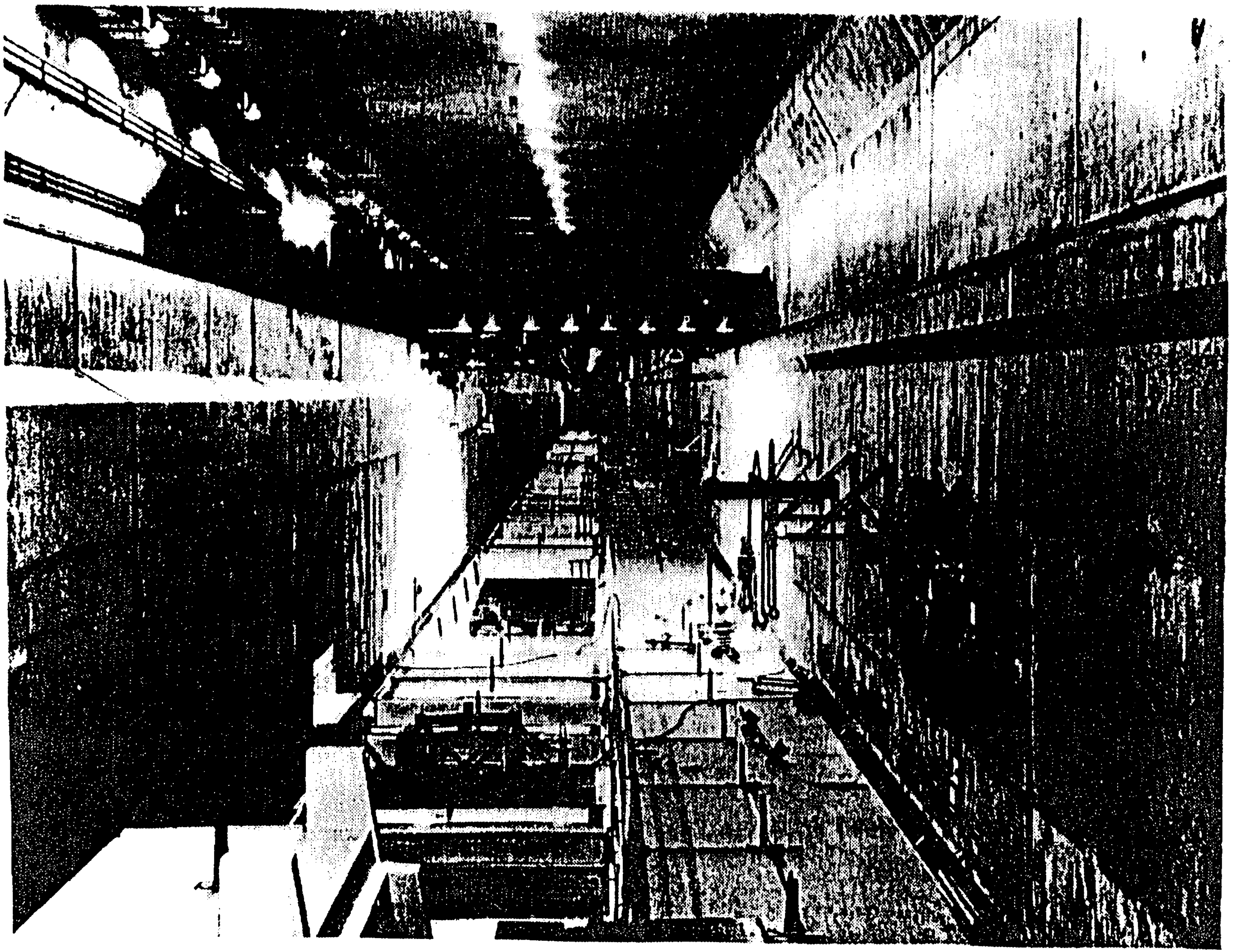


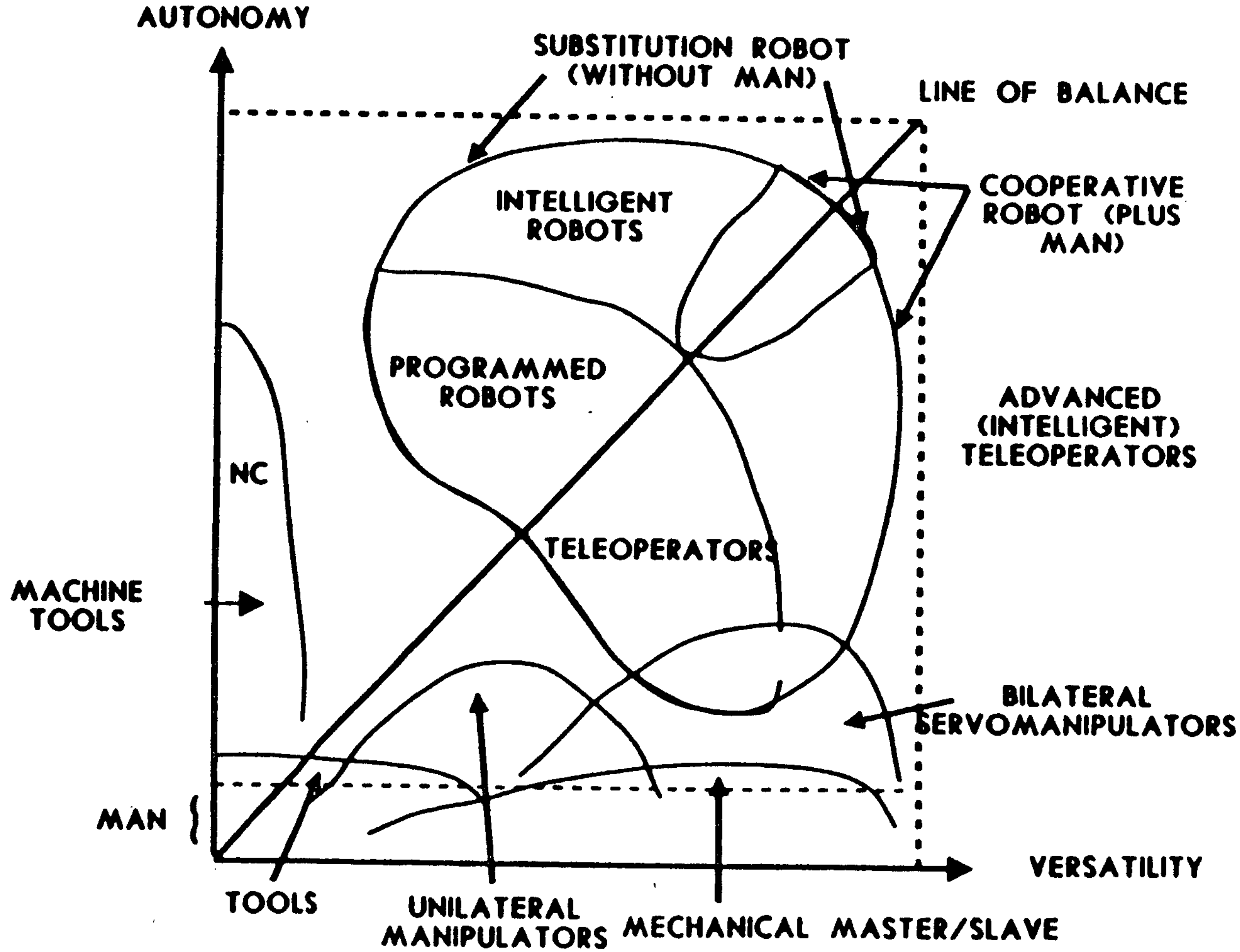
Hanford Purex Plant typical cross section.



Hanford Purex Plant remote canyon.

Historical Evolution of Teleoperators and Telerobotic Systems

RELATIONSHIPS BETWEEN ROBOTICS AND TELEOPERATORS
(AFTER JEAN VERTUT)



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Remote Systems and Telerobotics

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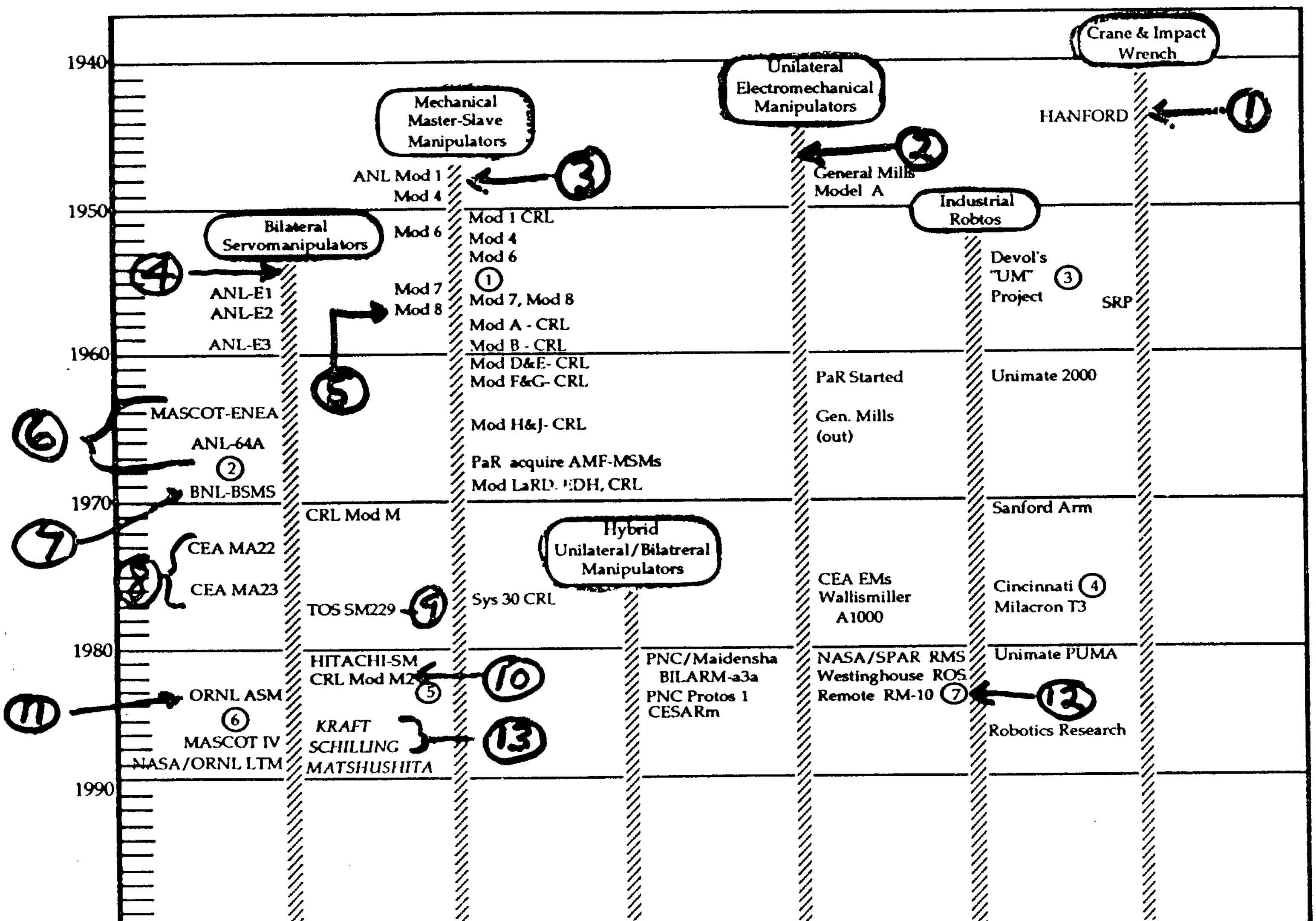
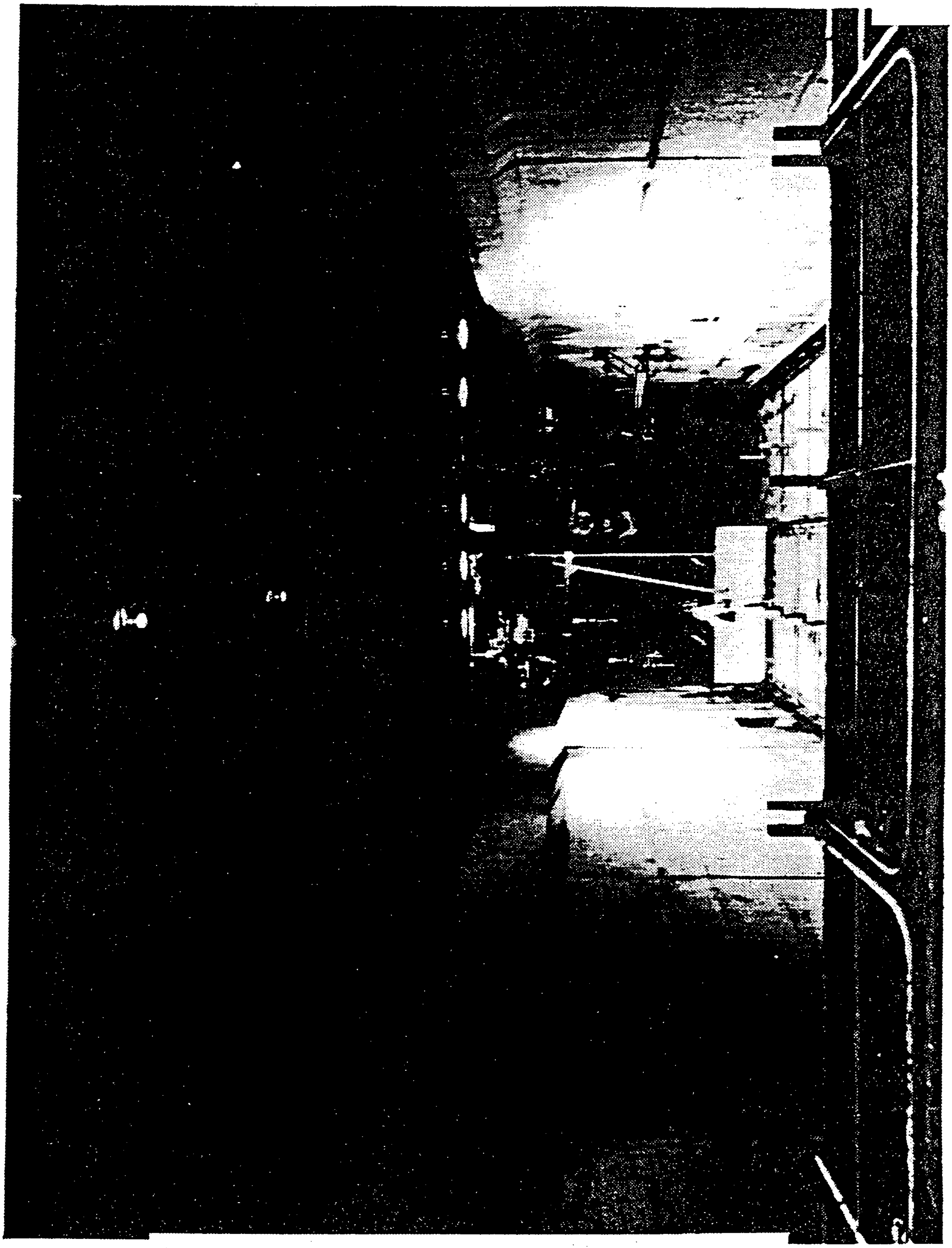


Government ← → Private

1. Technology Transfer ANL to CRL
2. ANL Program Ended
3. Robotics Begun
4. Microprocessor Control, Coordinate Transforms
5. Distributed Digital Control
6. Modularized for Remote Maintenance

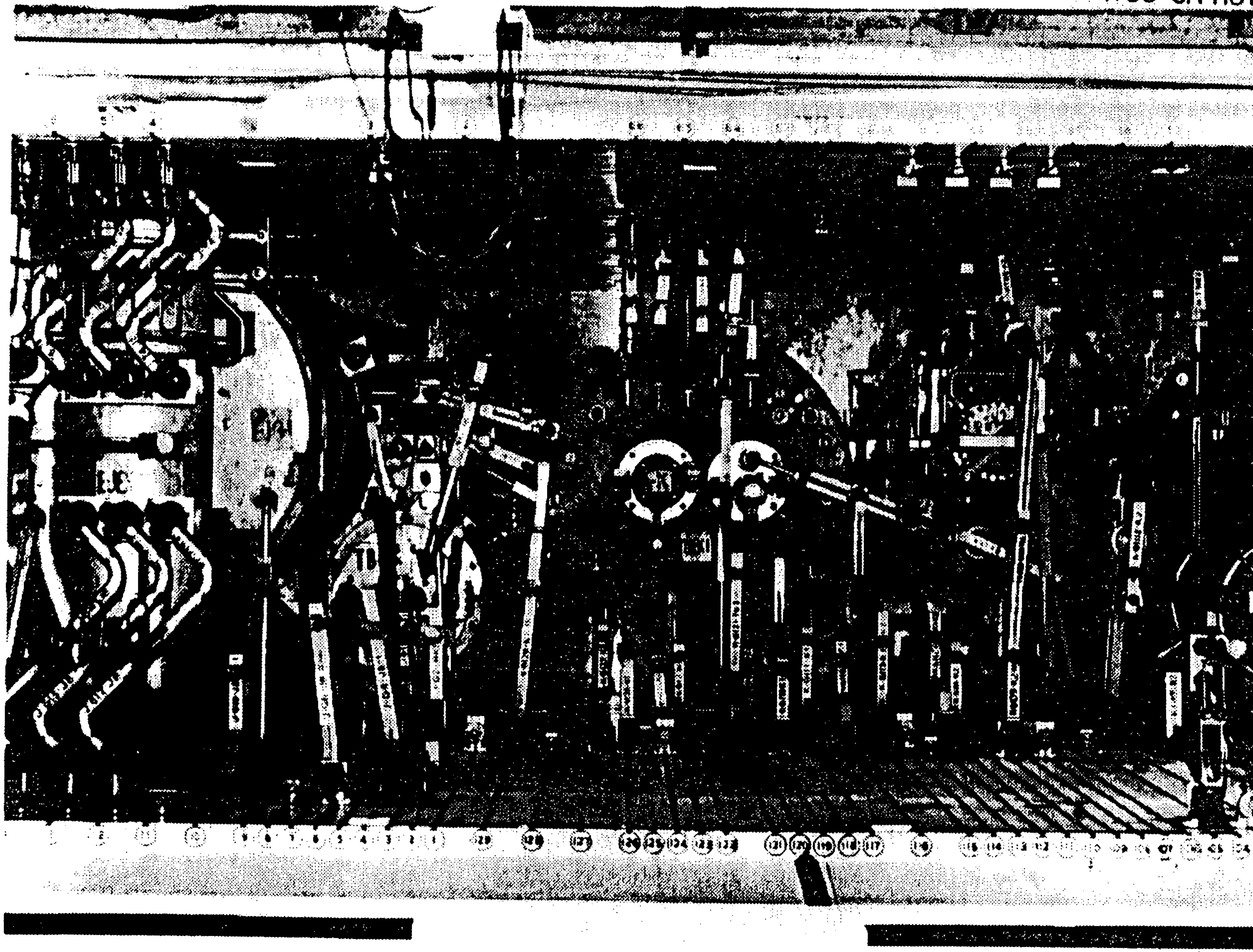
Typical remote manipulative capabilities of an overhead crane

Generalized manipulative features	System capabilities	Comments
Capacity/directions	Typically 45,000 to 90,000 kg; force can only be exerted in the lift direction.	Capacity is not limiting; the ability to exert forces in only one direction requires special design features.
Degrees of freedom/ kinematics	The hook can be positioned in any of the three translational degrees of freedom in space; two of the three rotational degrees of freedom are not provided.	Limits arrangement of equipment.
End effector speed capability	End effector speeds slow (about 0.05 to 0.5 m/s).	
Volumetric coverage	The entire cell volume can typically be covered; removable items must be accessible from overhead.	Tends to increase cell lengths and heights.
Envelope	The envelope for access to equipment tends to be small.	The overall equipment envelopes become large due to access only from overhead.
Weight/capacity	N/A.	
Ease of multi-joint operation in real time (inherent "naturalness" of control motions)	Poor.	Typically unilateral, rate controlled from a switch box.
Force reflection to sense and control forces	Not provided.	
Compliance/reversibility to minimize equipment damage	Very compliant; hook oscillations must be controlled to prevent damage.	
Index of overall task speed compared to man's hands-on capability	500:1.	Major vessel replacements typically require 48 hours or more



Hanford Purex Plant remote maintenance overhead crane.

1790-81 PHOTO



Hanford Purex Plant typical remote process equipment.

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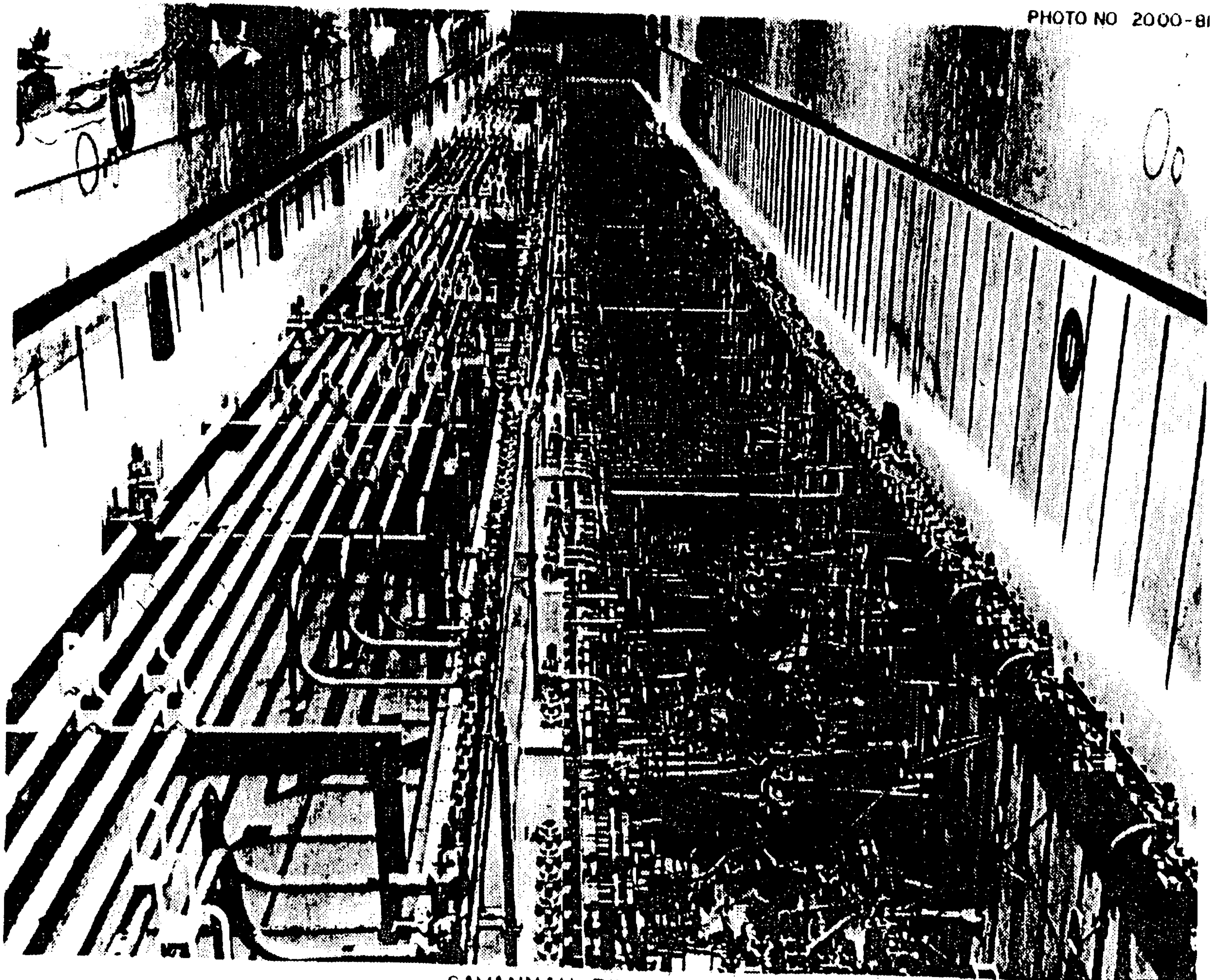
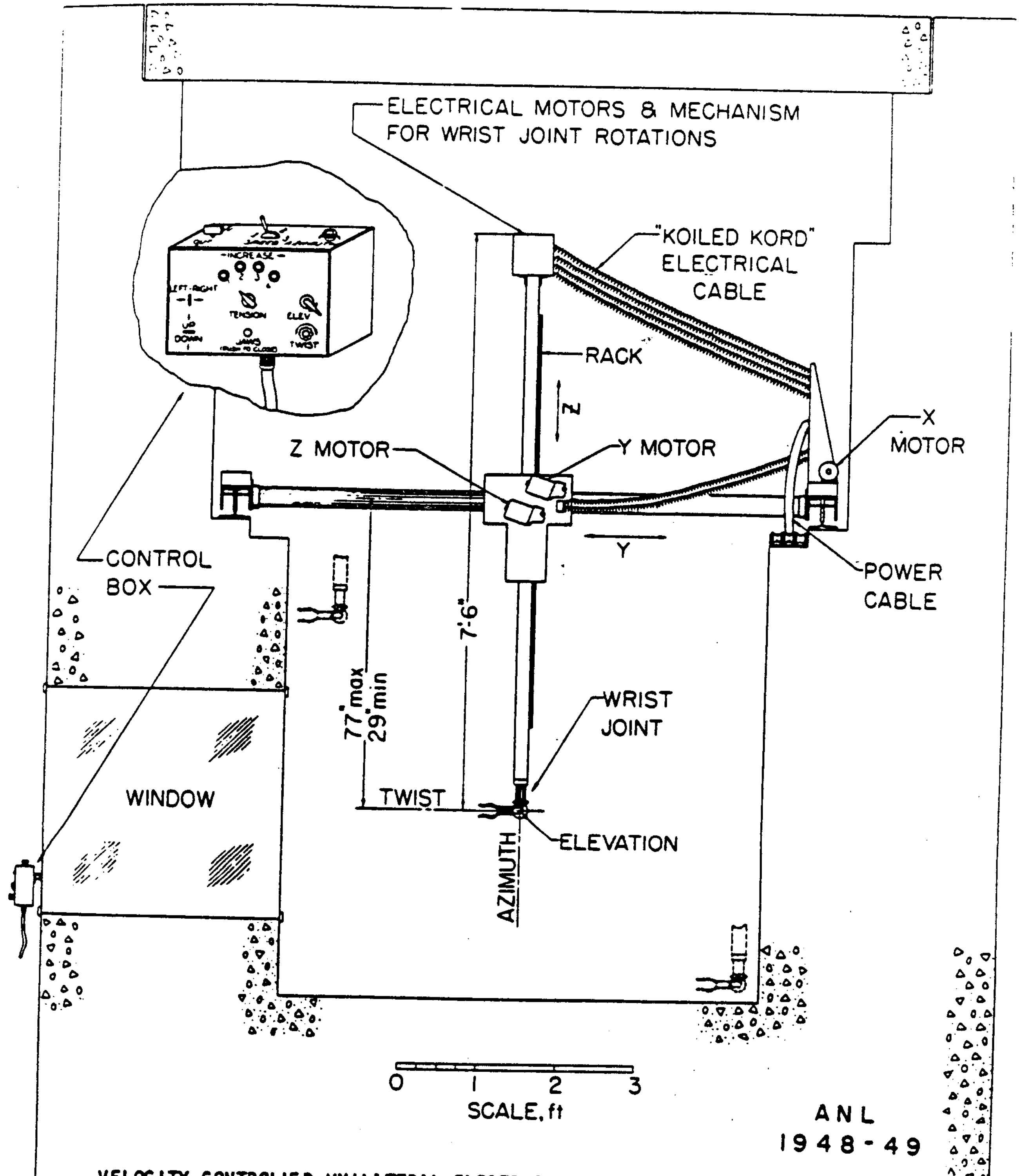


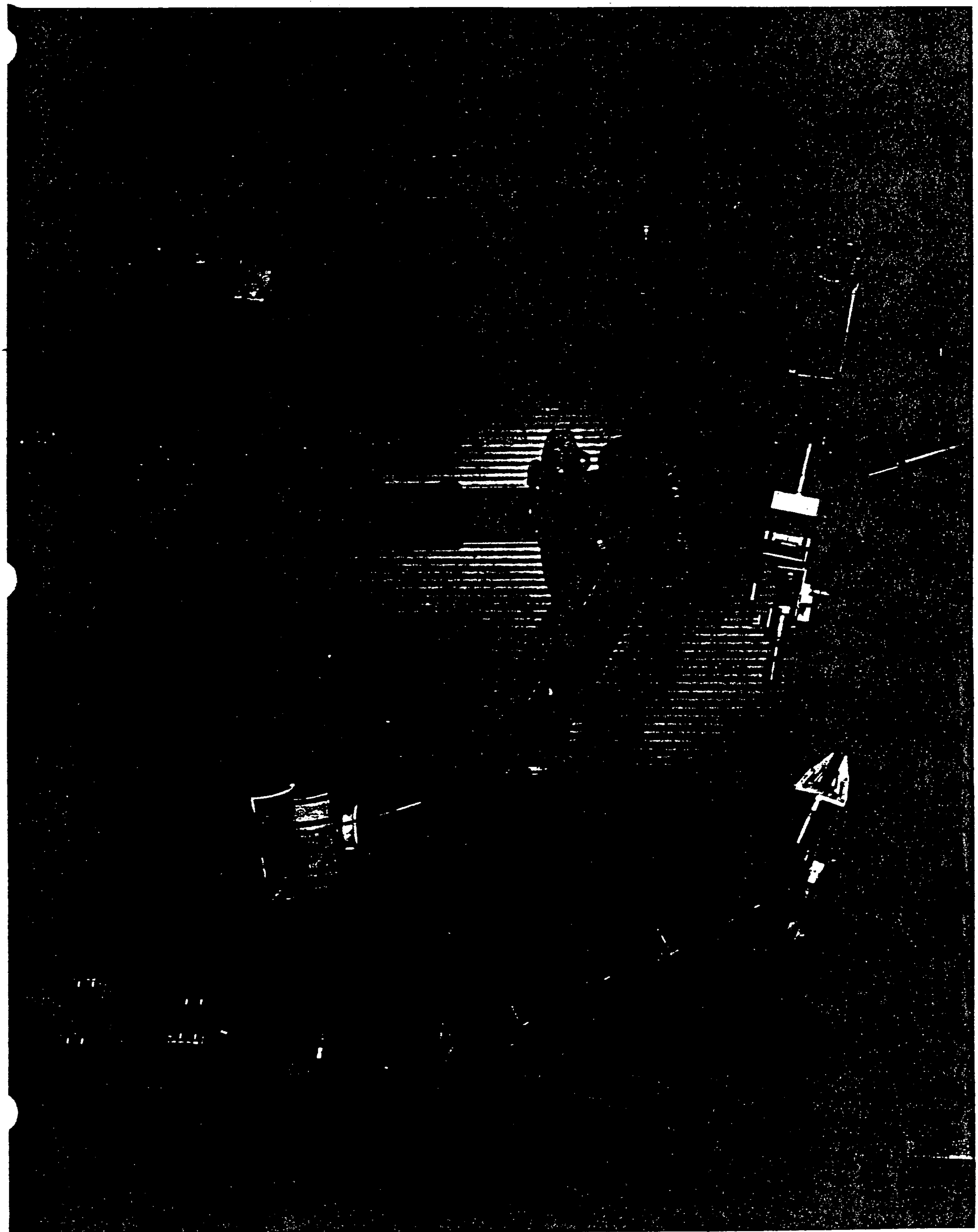
SAVANNAH RIVER PLANT

Typical capabilities of a power manipulator

Generalized manipulative features	System capabilities	Comments
Capacity/directions	60 to 180 kg, forces can be exerted in all directions (subject to transporter constraints).	
Degrees of freedom/ kinematics	Six degrees of freedom plus grip actuation; the grip cannot be positioned in any orientation in space without transporter movement unless a wrist pivot is provided (as in some models of a PaR 3000).	This tends to reduce the ability to perform general work in space and with spatial constraints.
End effector speed capability	0.05 to 0.1 m/s for the slower joints.	Rather slow compared to man's speed for performing translations.
Volumetric coverage	Essentially full cell volume coverage with transporter is feasible.	
Envelope	Relatively small.	
Weight/capacity	Very good (ranges from 1:0.8 to 1:1.5).	
Ease of multi-joint operation in real time (inherent "naturalness" of control motions)	Poor with switch control; better if joystick control used.	Unilateral rate control of individual motions by switches results in predominately "one joint at time" motion.
Force reflection to sense and control forces	None in most cases. Preselection of grip force available.	
Compliance/reversibility to minimize equipment damage	None.	Utilizes large gear ratios, not backdriveable.
Index of overall task speed compared to man's hands-on capability	500:1 with unilateral switch control; 40-80:1 with unilateral joystick control.	



VELOCITY CONTROLLED UNILATERAL ELECTRIC MANIPULATOR ANL MODEL 3 OR 4 DEVELOPED IN 1948-49. SEVERAL WERE PRODUCED, BUT THEY HAVE NOT BEEN PRODUCED FOR MANY YEARS. LOAD CAPACITY ABOUT 4 POUNDS.



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MEIDENSNA MODEL 83A BILARM

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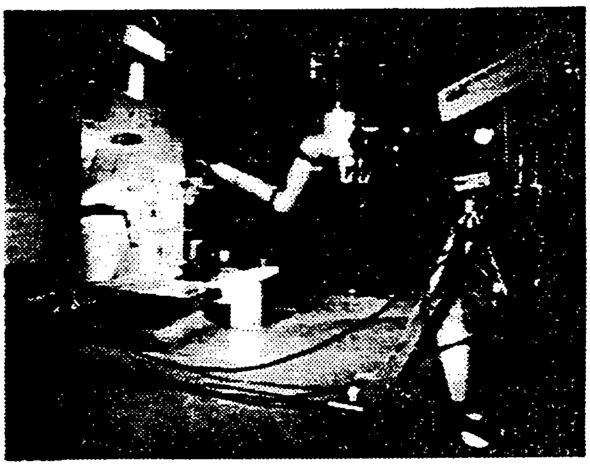
MASTER CONTROLLER



SLAVE

SWITCHBOX CONTROLLER

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Typical capabilities of a mechanical master/slave manipulator

Generalized manipulative features	System capabilities	Comments
Capacity/directions	Light duty - 4 to 9 kg heavy duty - 23 to 46 kg; forces can be exerted in all directions.	
Degrees of freedom/ kinematics	Typically six degrees of freedom and grip actuation; provides all six translation and rotation degrees of freedom in space.	
End effector speed capability	Capable of following a man's input motions in real time.	
Volumetric coverage	Limited to a 2.5 m by 2.5 m by 2.5 m work station adjacent to the shield wall.	Limits application in a reprocessing cell to activities which can be reached or brought close to the MSM.
Envelope	Rather compact.	
Weight/capacity	N/A	
Ease of multi-joint operation in real time (inherent "naturalness" of control motions)	Excellent.	
Force reflection to sense and control forces	Very good, as long as friction and inertia are kept fairly low.	
Compliance/reversibility to minimize equipment damage	Good to fair.	Can be abused by operators with resulting increased failure rates.
Index of overall task speed compared to man's hands-on capability	8:1.[1]	

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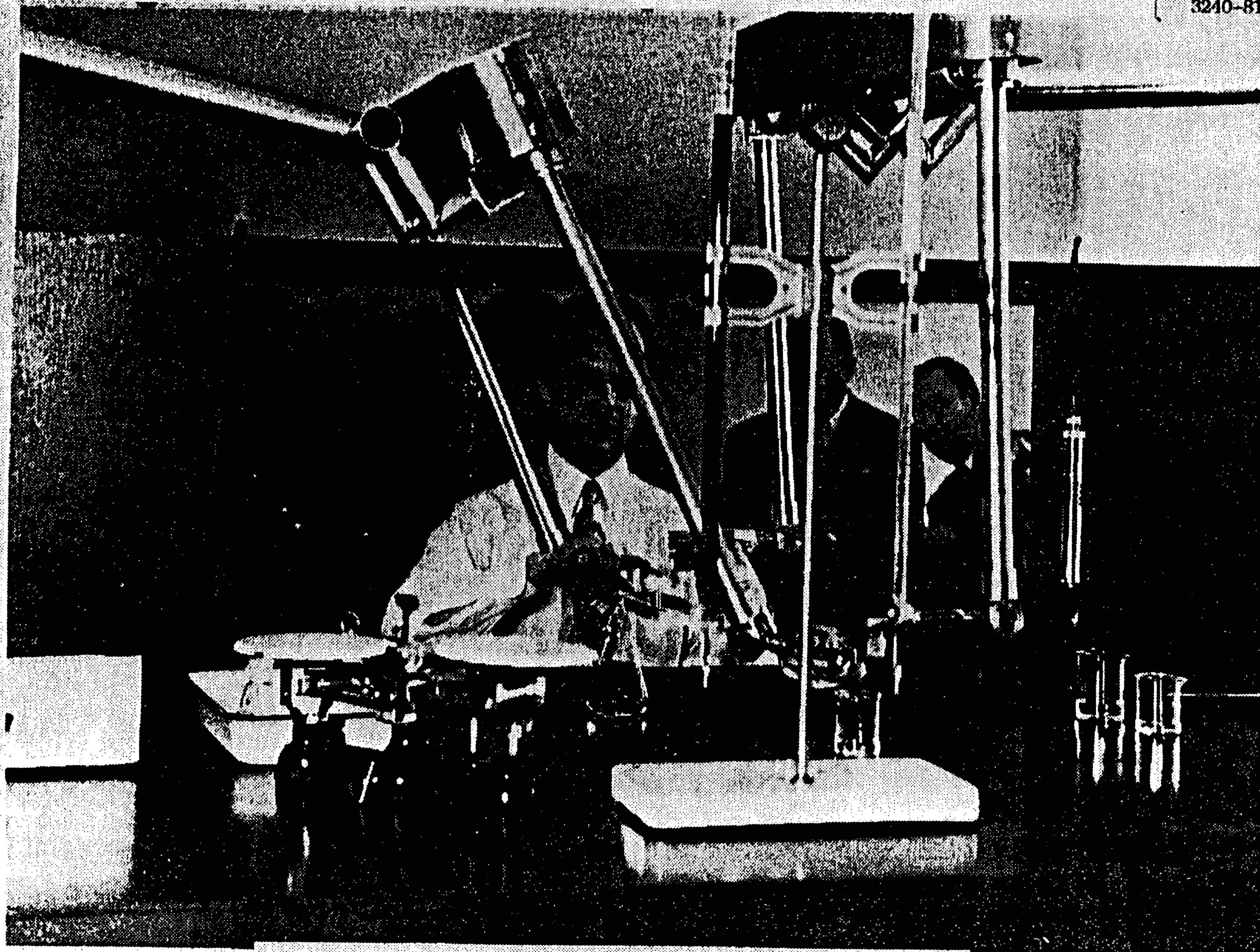
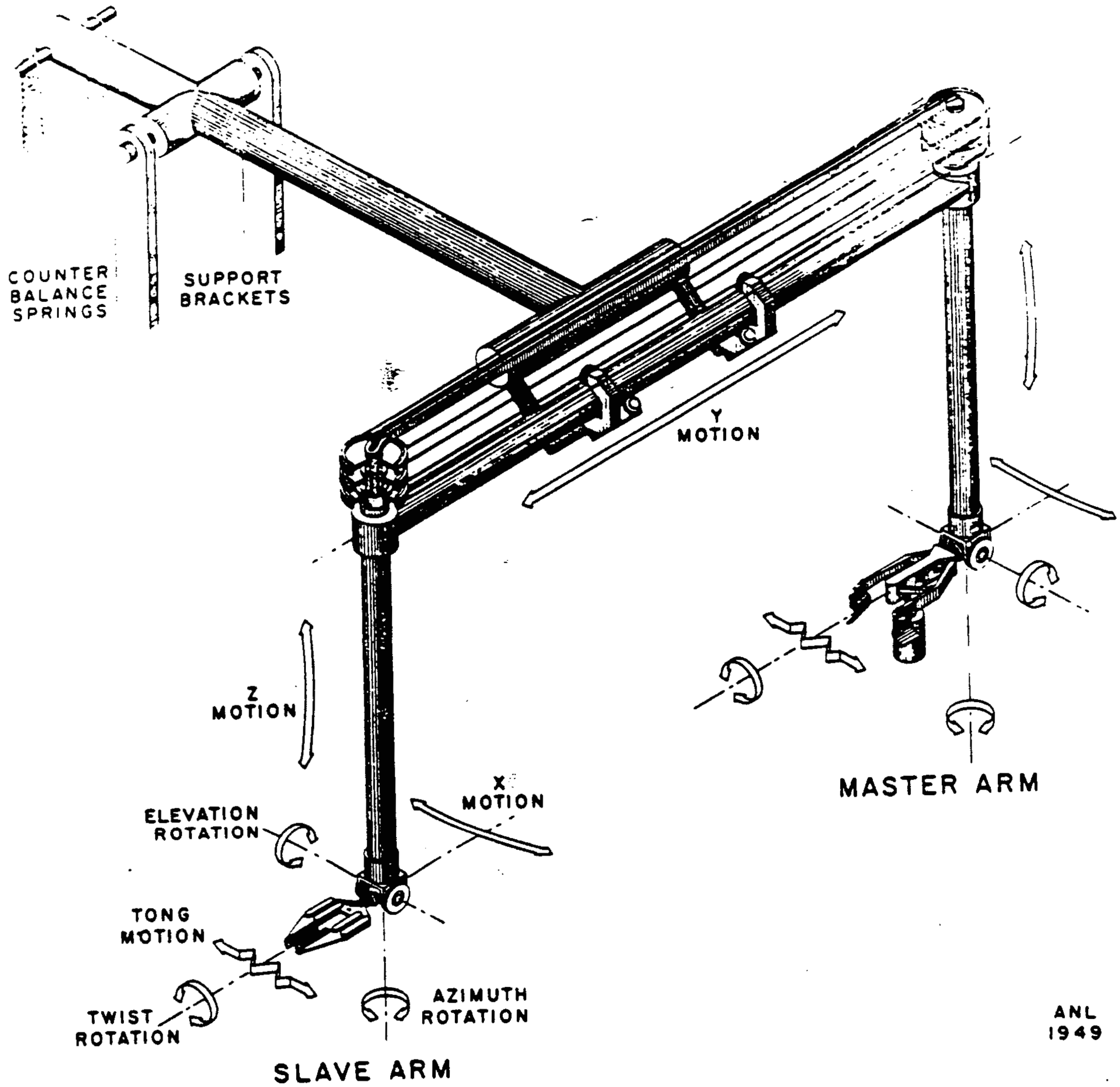
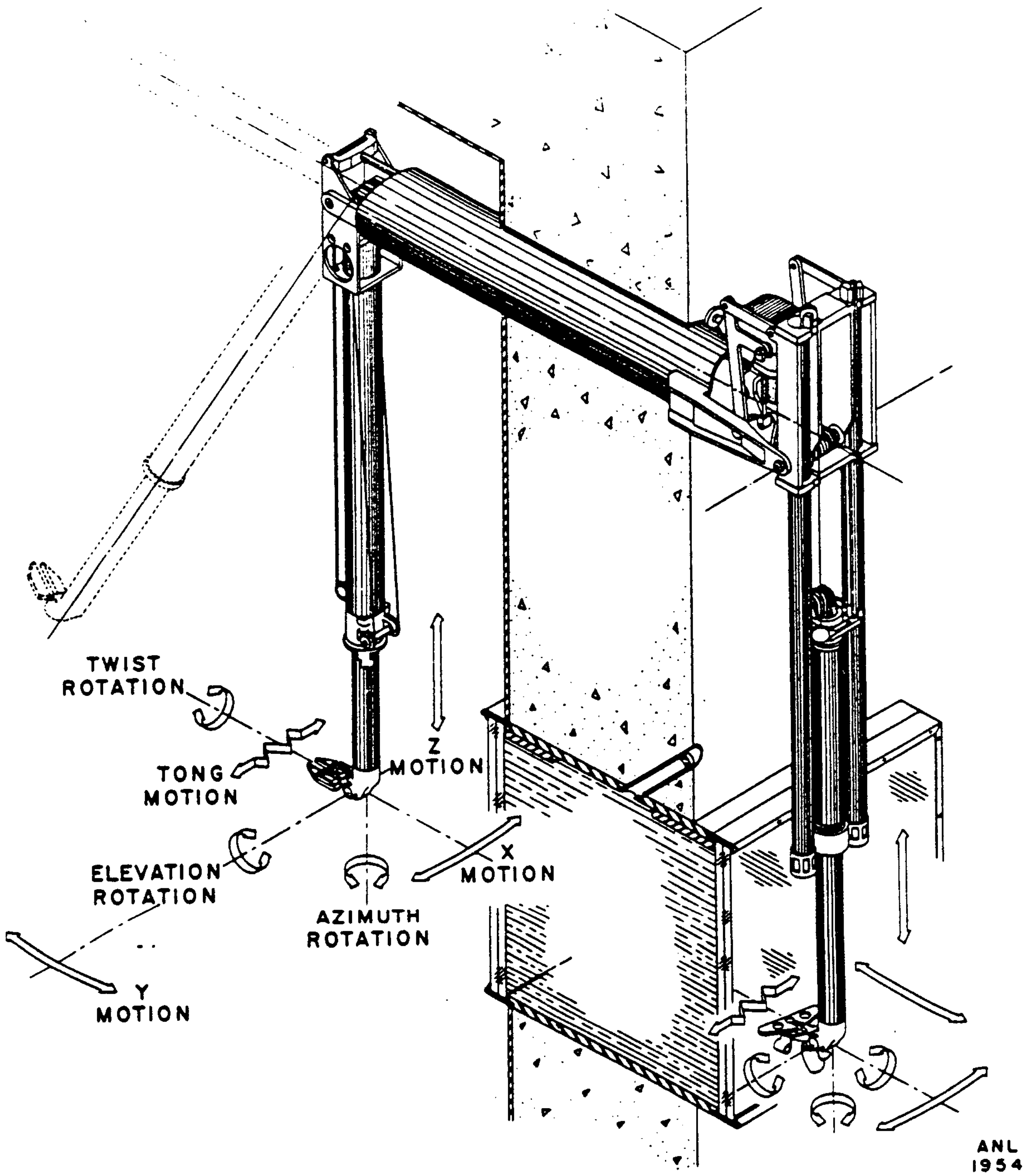


Ray Goertz operating Argonne National Lab Model 1 master slave.



MECHANICAL MASTER-SLAVE MANIPULATOR ANL MODEL 1 (EXPERIMENTAL MODEL)

DEVELOPED IN 1948-49 TO EVALUATE THE PRINCIPLES OF MASTER-SLAVE CONCEPTS. NEVER PRODUCED COMMERCIALLY.



MECHANICAL MASTER-SLAVE MANIPULATOR ANL MODEL 8

25 POUND LOAD CAPACITY. DEVELOPED IN 1954 AND HAS BEEN PRODUCED COMMERCIALLY AND WIDELY USED EVER SINCE.

ORNL DWG. 80-18747

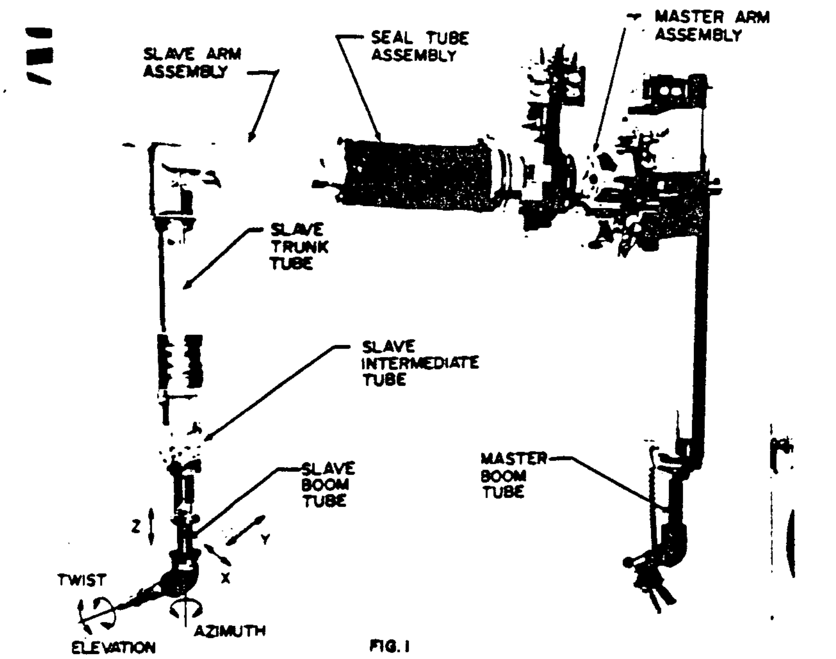


FIG. 1

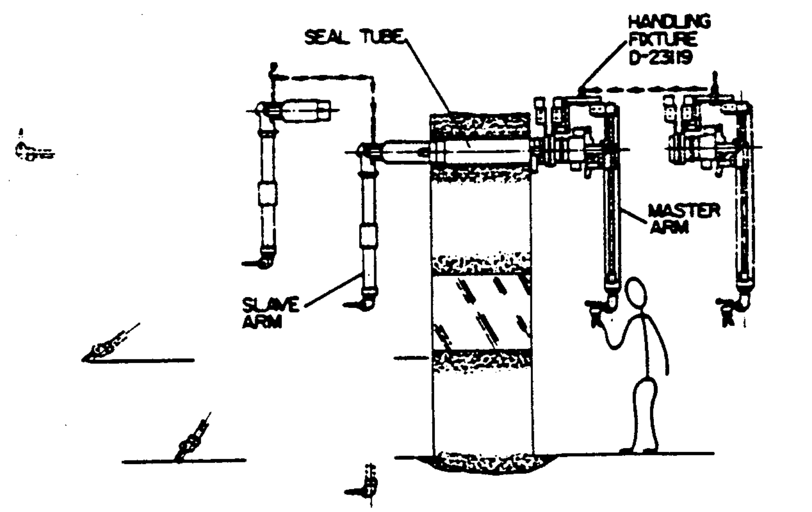
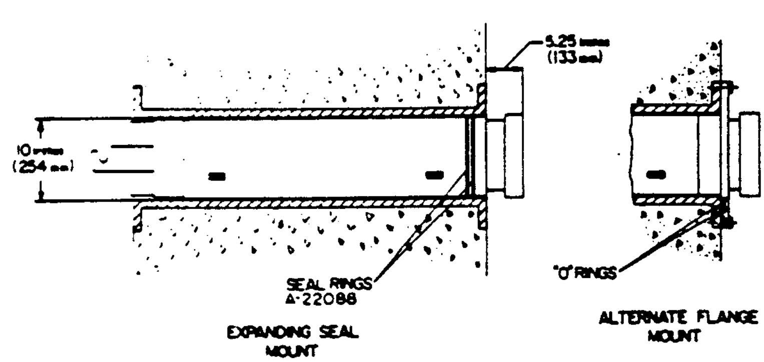


FIG. 2



Central Research Laboratories System 50 master slave.

Typical capabilities of a force-reflecting servomanipulator

Generalized manipulative features	System capabilities	Comments
Capacity/directions	10-46 kg; forces can be exerted in all directions.	
Degrees of freedom/ kinematics	Typically six degrees of freedom plus grip actuation; provide all six translation and rotation degrees of freedom in space.	
End effector speed capability	0.8-1.5 m/s.	This velocity capability allows for following a man's input motion in real time.
Volumetric coverage	Essentially total cell volume when mounted on a transporter.	
Envelope	Relatively small.	
Weight/capacity	Typically 3:1 to 12:1.	
Ease of multi-joint operation in real time (inherent "naturalness" of control motions)	Excellent.	
Force reflection to sense and control forces	Very good, as long as friction and inertia are kept fairly low; typical threshold of feel of 0.3 to 0.9 kg.	
Compliance/reversibility to minimize equipment damage	Excellent.	
Index of overall task speed compared to man's hands-on capability	8:1.	

ELECTRIC MASTER-SLAVE MANIPULATOR ANL MODEL 1
DEVELOPED IN 1954 - USED ONLY FOR EXPERIMENTAL PURPOSES.

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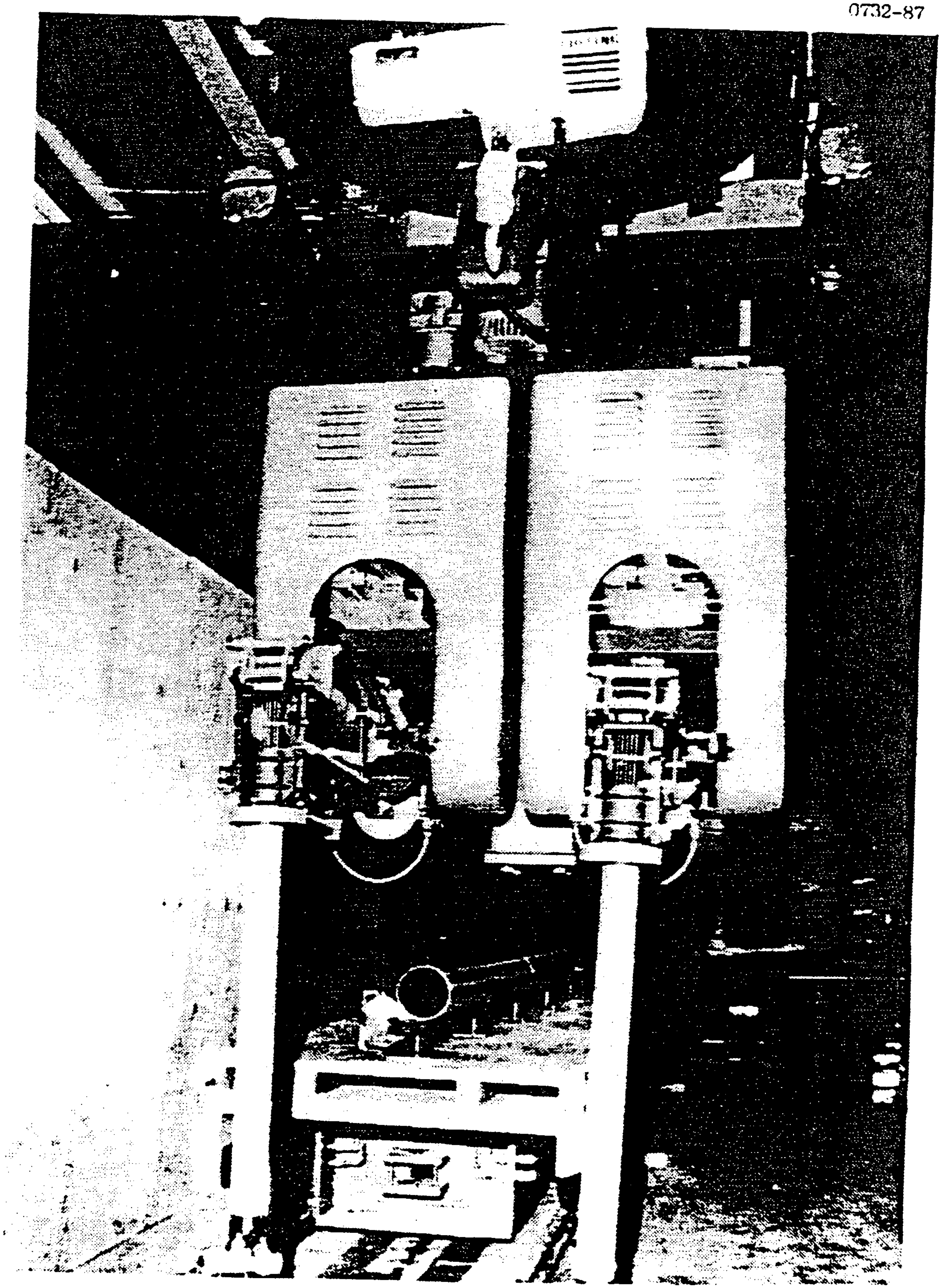

Central Research Laboratories [illegible]

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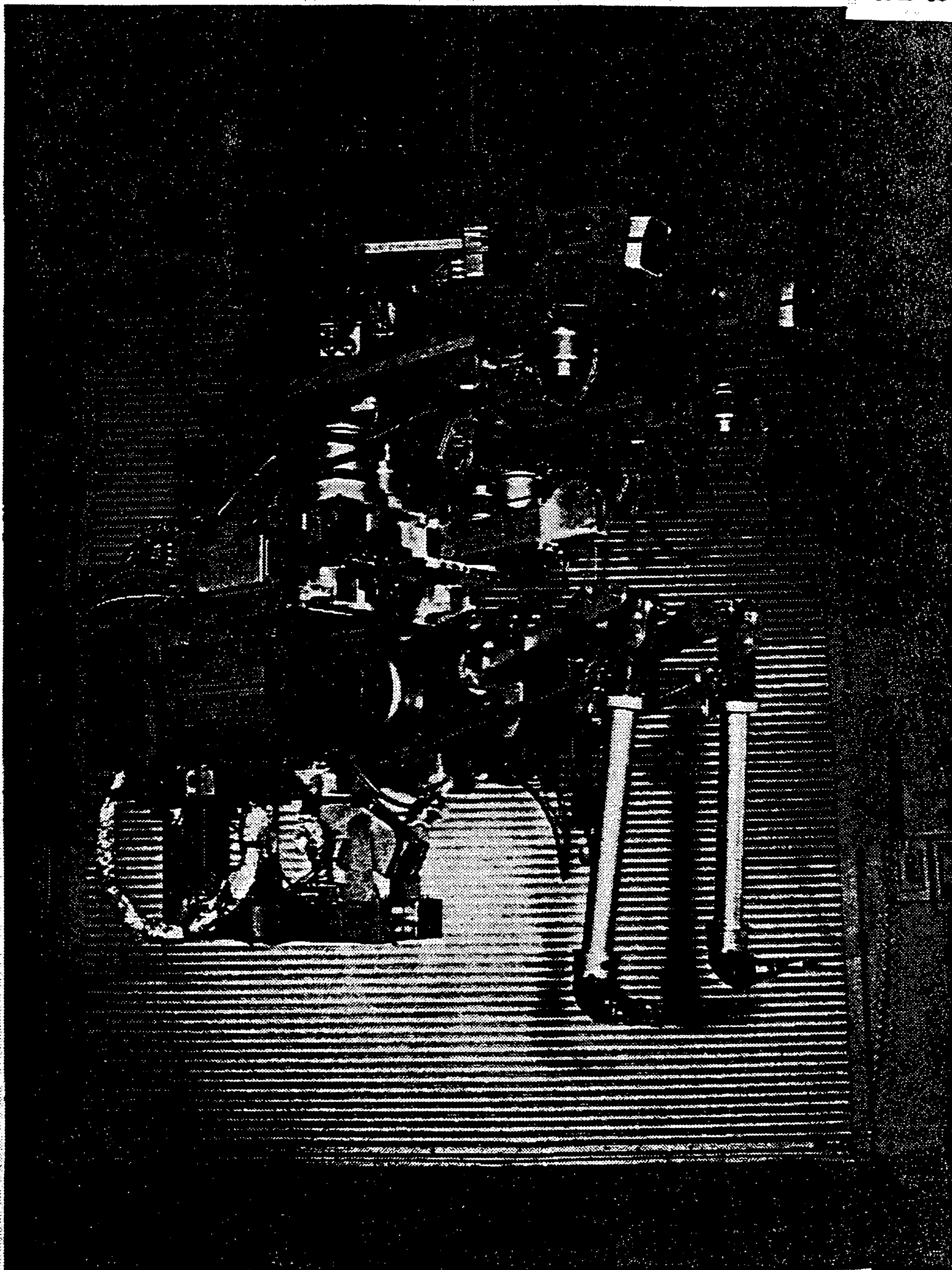

Central Research Laboratories Model M-2 Servomanipulators.

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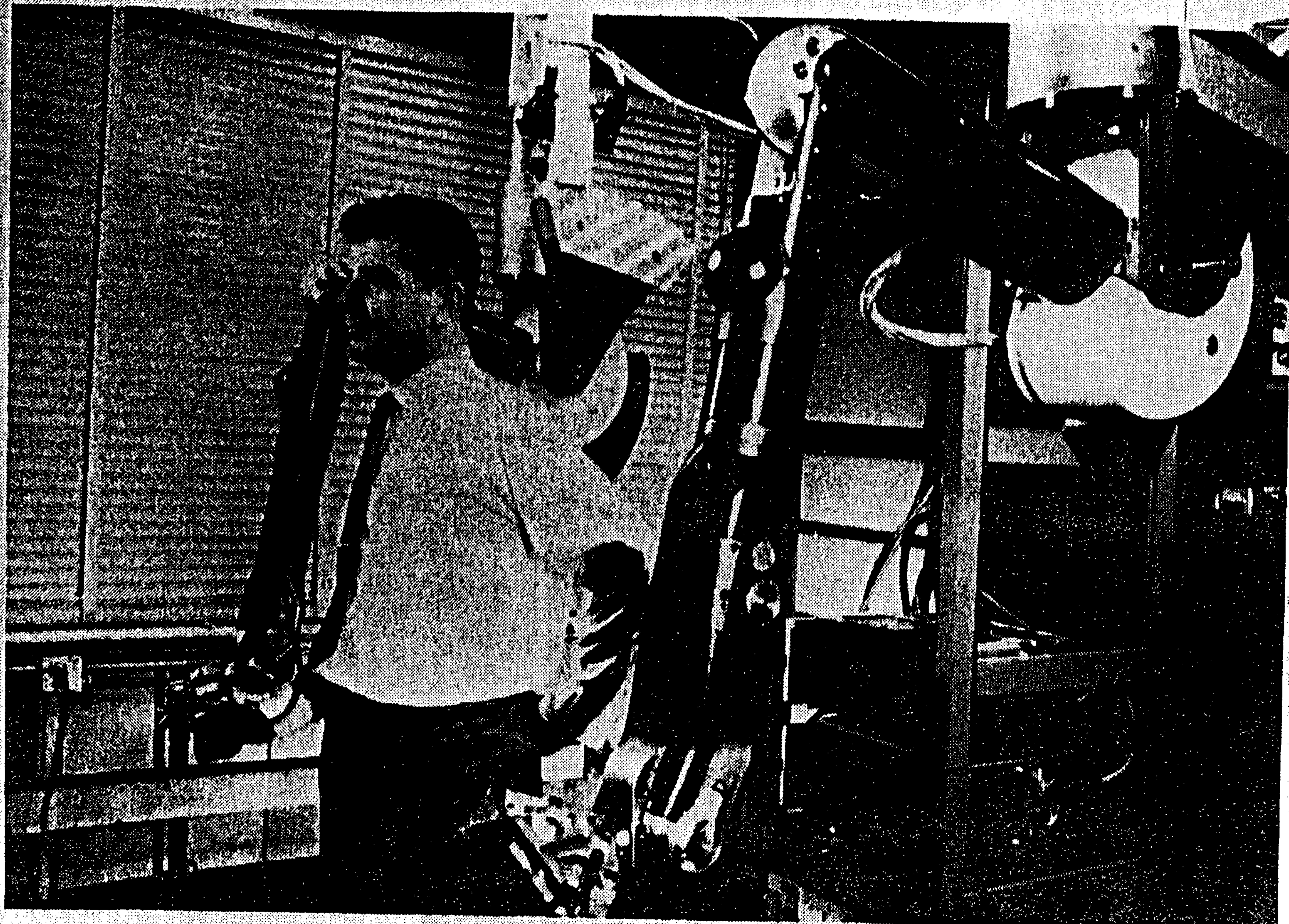

Carl Flatau with Brookhaven servomanipulator.

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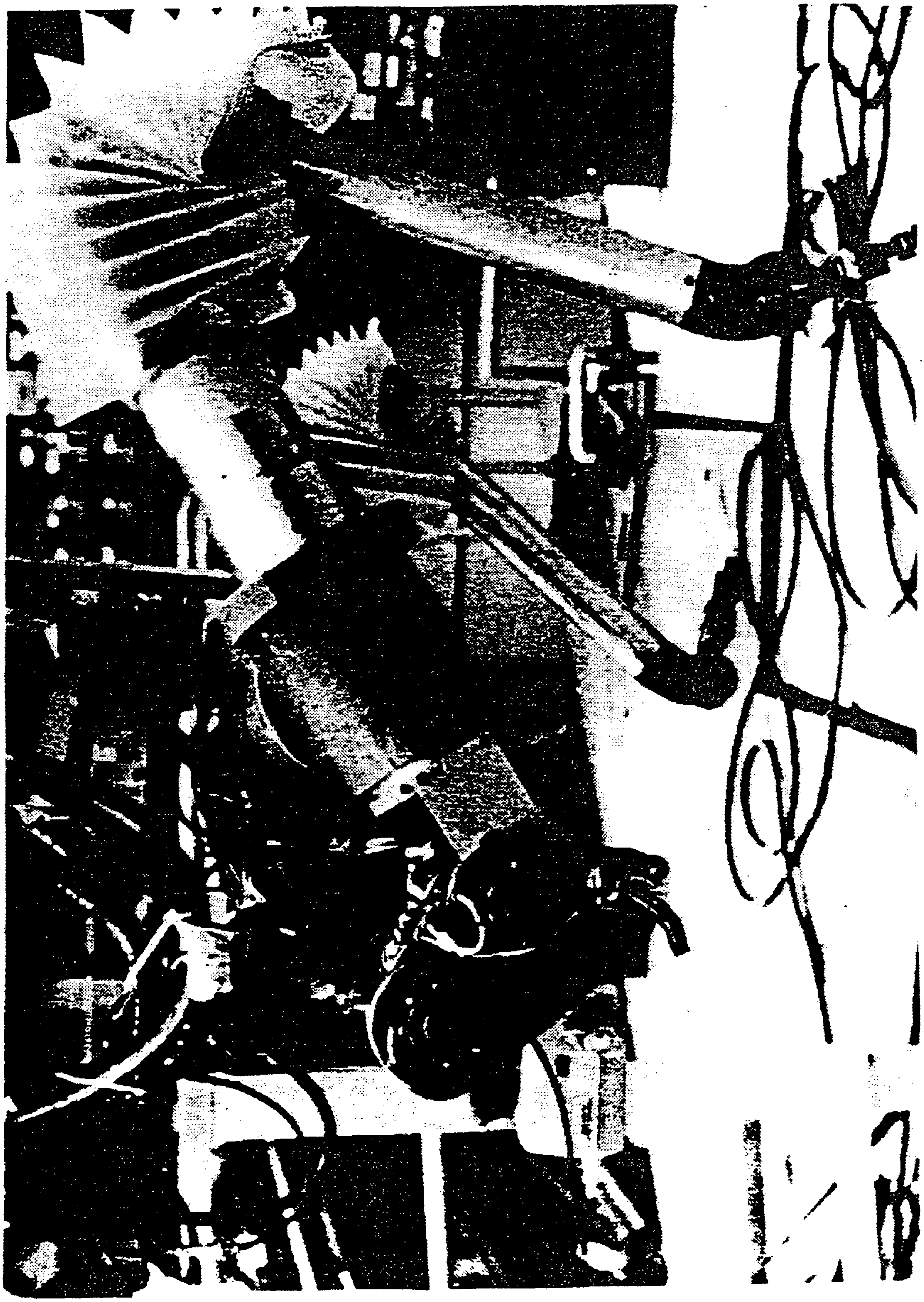
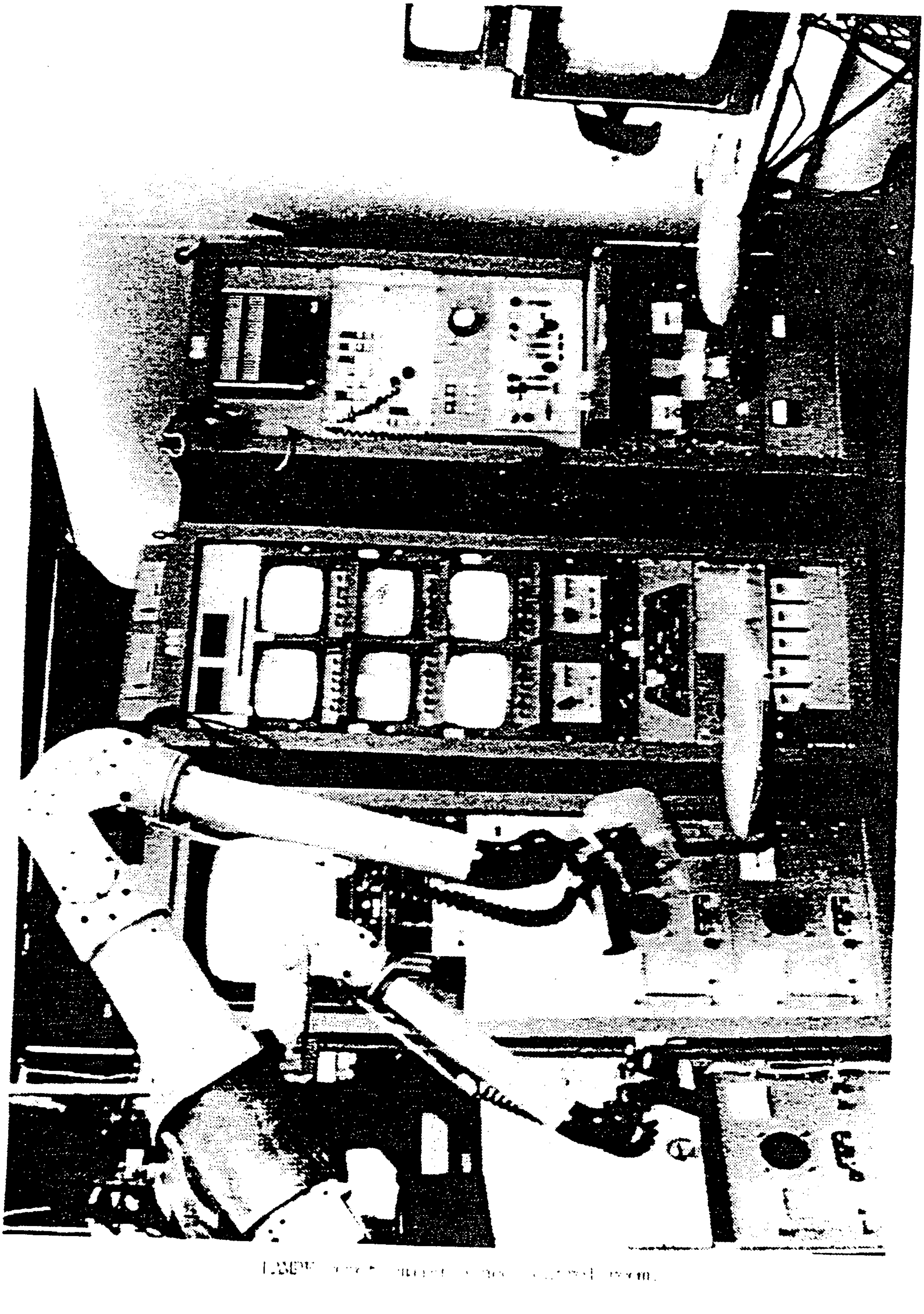
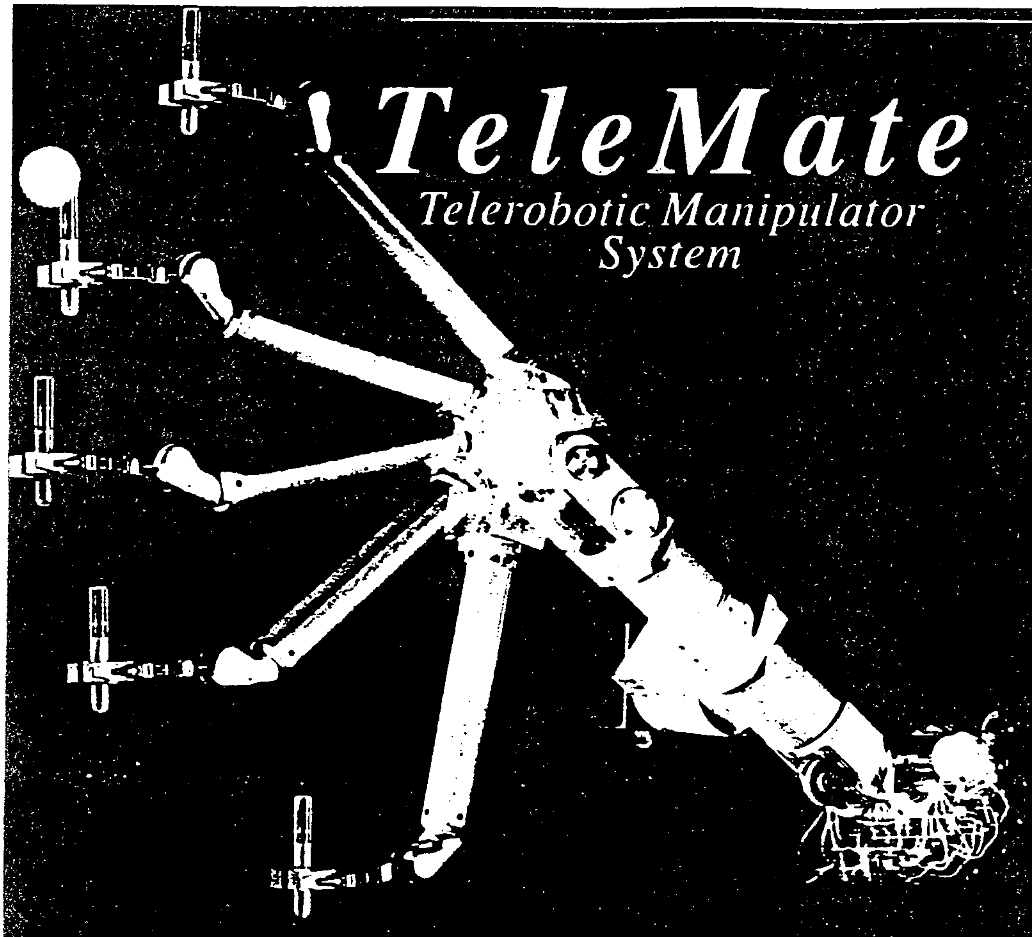




[illegible] room.



TRI

Realizing the Imaginable®

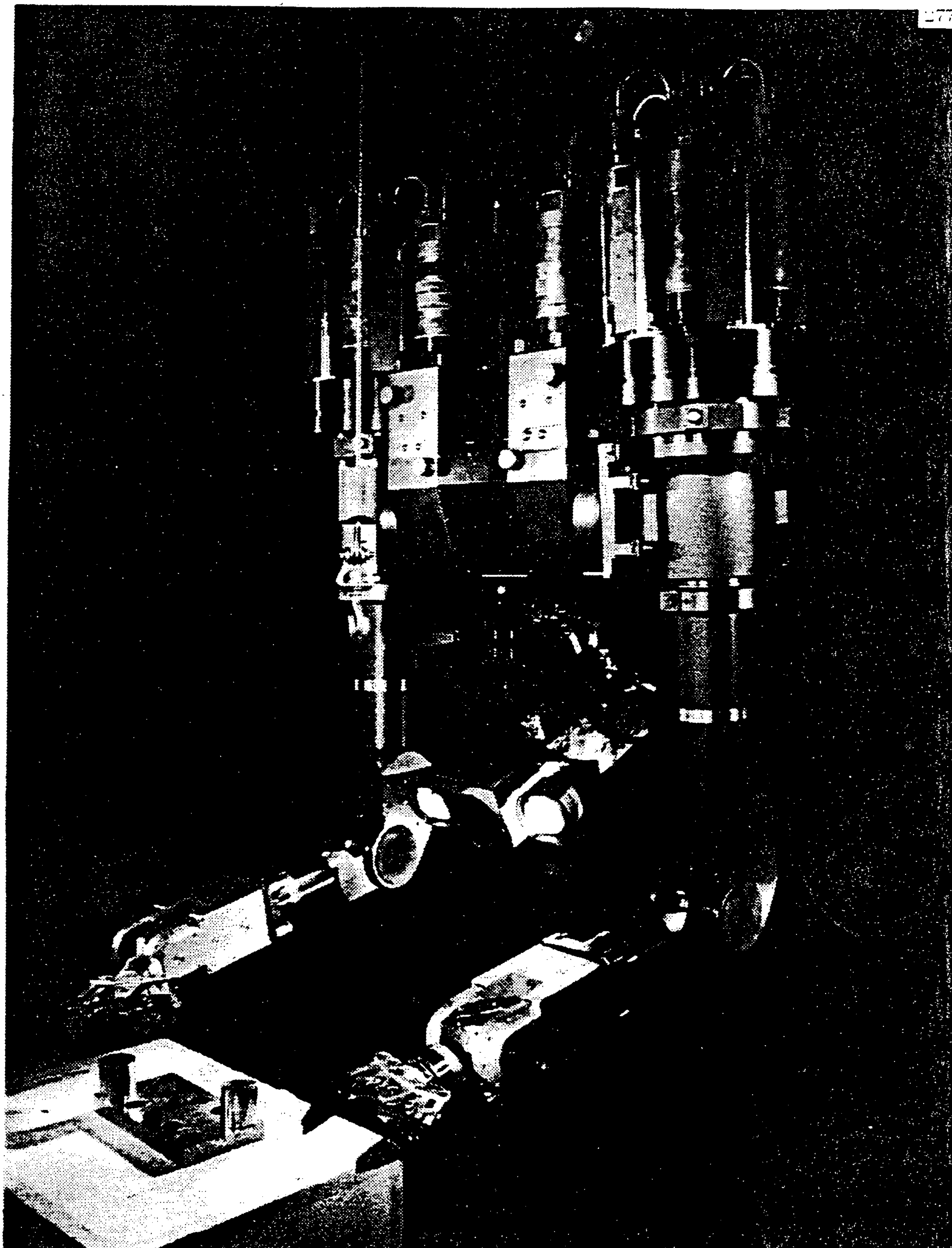
TeleRobotics International, Inc.

Remote Sensing and Manipulation Solutions

TeleMate extends your capabilities safely into remote and hazardous environments. By combining an exceptional strength-to-weight ratio with reliable, flexible digital control electronics, ***TeleMate*** becomes your operating partner by projecting your skills into hostile environments. Its real-time response and excellent force-reflection sensitivity provide man-like dexterity for complex operation and maintenance tasks. Its visual control language and fully integrated human/machine interface make ***TeleMate*** natural to use and easy to customize for special situations.

For any application with potential risk to human operators, ***TeleMate*** is ready to eliminate that risk, removing you from the hazard, yet still allowing you to accomplish your objectives. Remote operation and maintenance of nuclear process facilities, fusion devices, accelerators, rad waste storage facilities, and radioactive material handling are now all within your reach. Chemical and biological hazards can now be safely managed without compromising your operational capability. ***TeleMate's*** unique performance makes it ideally suited for waste cleanup activities, decontamination, and decommissioning efforts. The brushless motor/sensor technology in ***TeleMate*** supports use in near vacuum environments, or where explosive materials are present.

TeleMate - the next best thing to being there - maybe better!



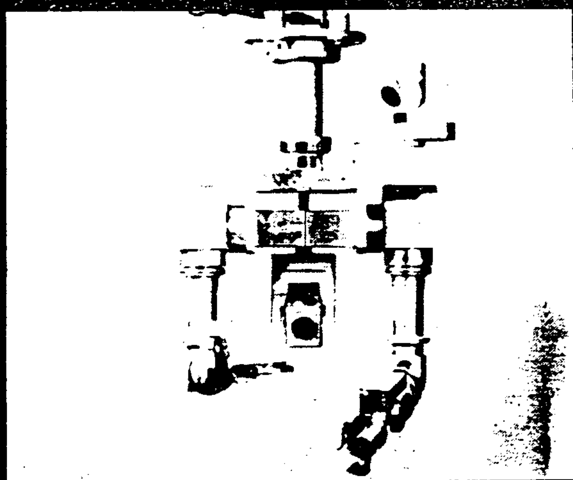
ORNL Advanced Servomanipulators.

RM-10A MASTER/SLAVE MANIPULATOR

Utilizes industrial robotic technology and components to provide a low cost, highly reliable maintenance tool for use in hazardous environments. Easily retrofitted into existing facilities on a crane hook, telescoping tube, power-arm manipulator, mobile vehicle, or fixed stand.

Control Features

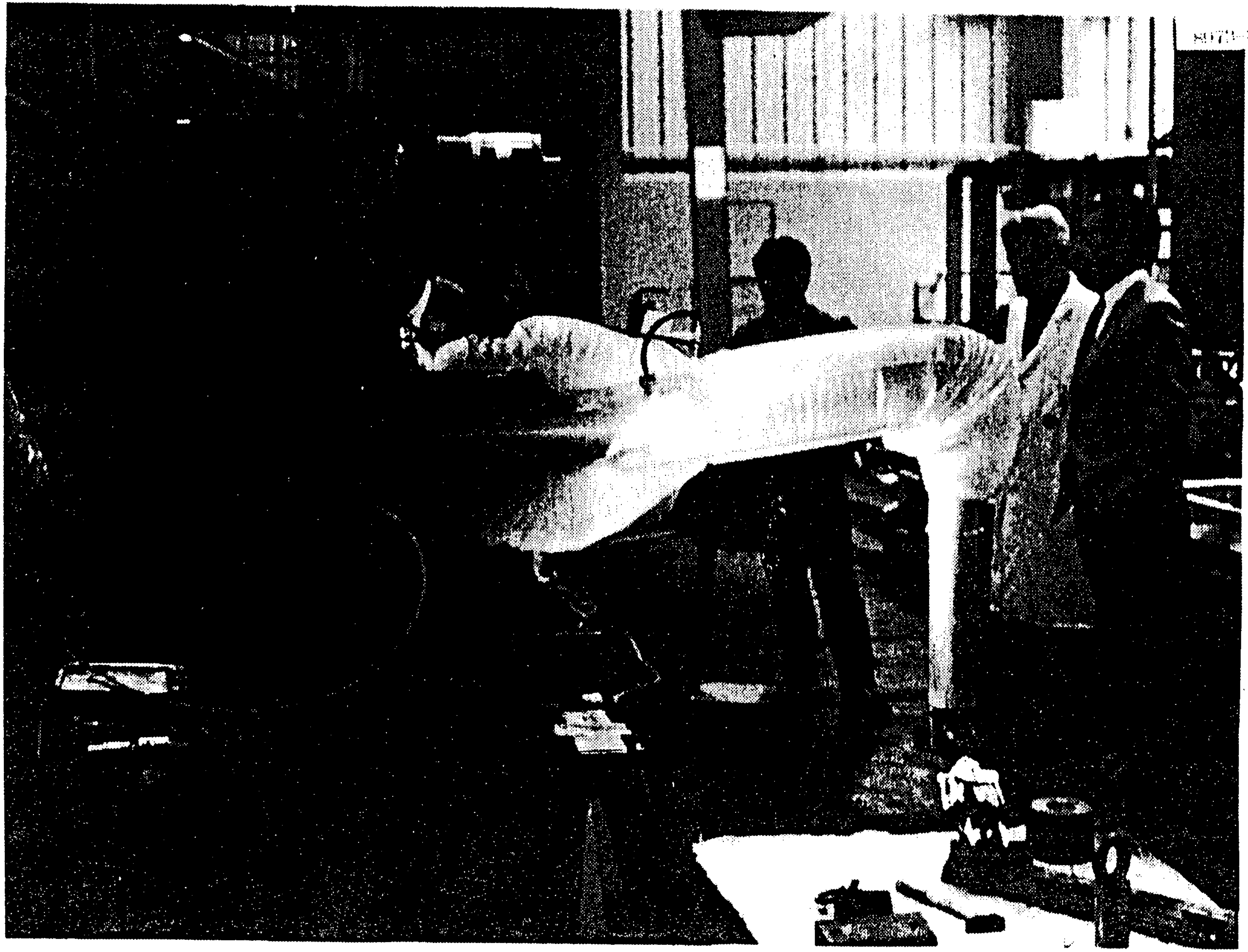
- Industrial Computer
- Teleoperator or Robotic Operation
- Touch Screen Control
- Adjustable Motion Ratio
- Adjustable Grip Force
- Commercially-Available Components
- Portable Console
- Indexable Motions



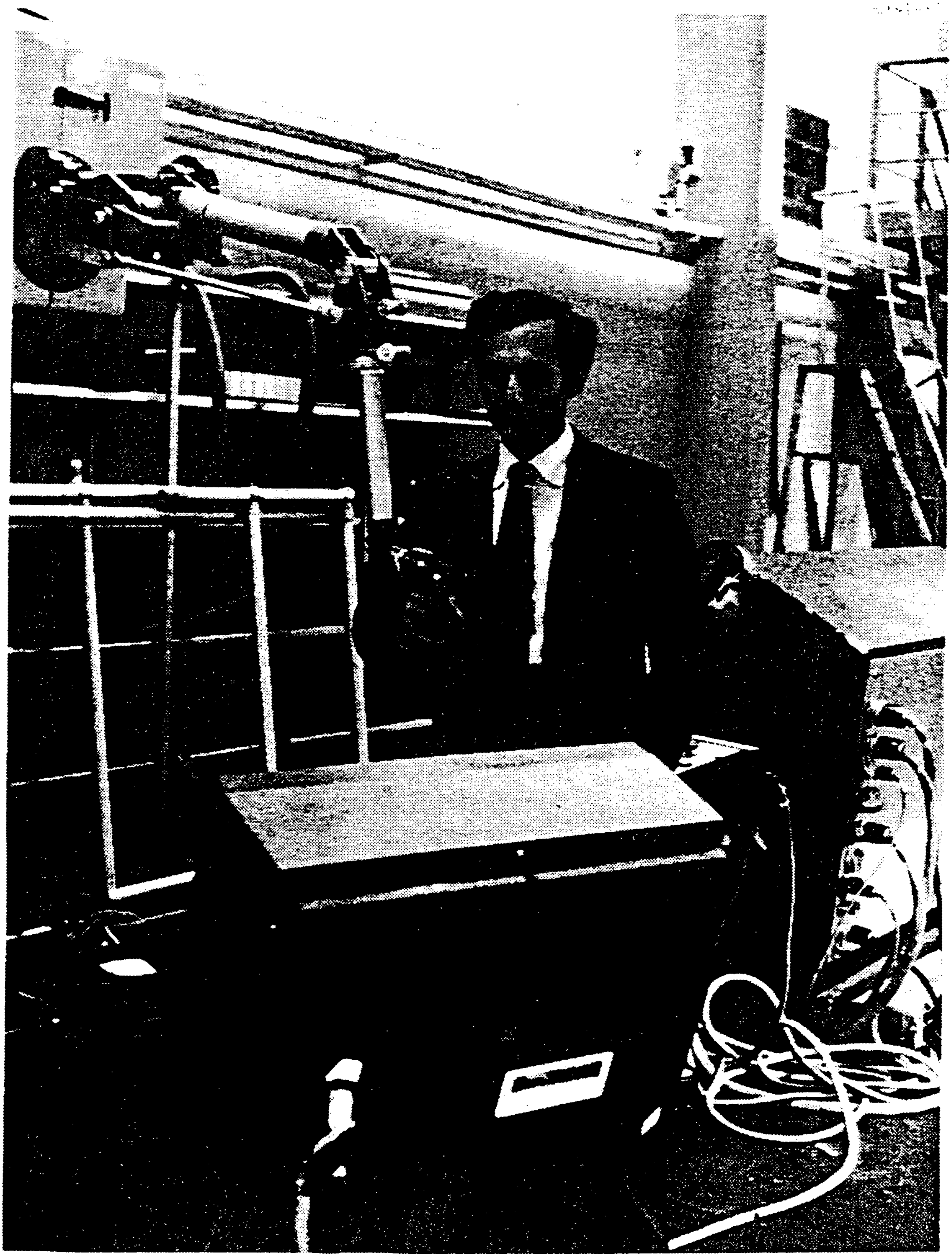
Slave Features

- Slave Assembly 175 lbs.
- Arm Weight 55 lbs.
- Arm Capacity 25 lbs.
- 42 in. Reach
- 7 Degrees of Freedom
- 360° Torso Rotate
- Remotely Repairable
- Radiation-Hardened Option
- Booting Option

REMOTEC®



French MA23 servomanipulator with booting.



French MA23 Master Controller.

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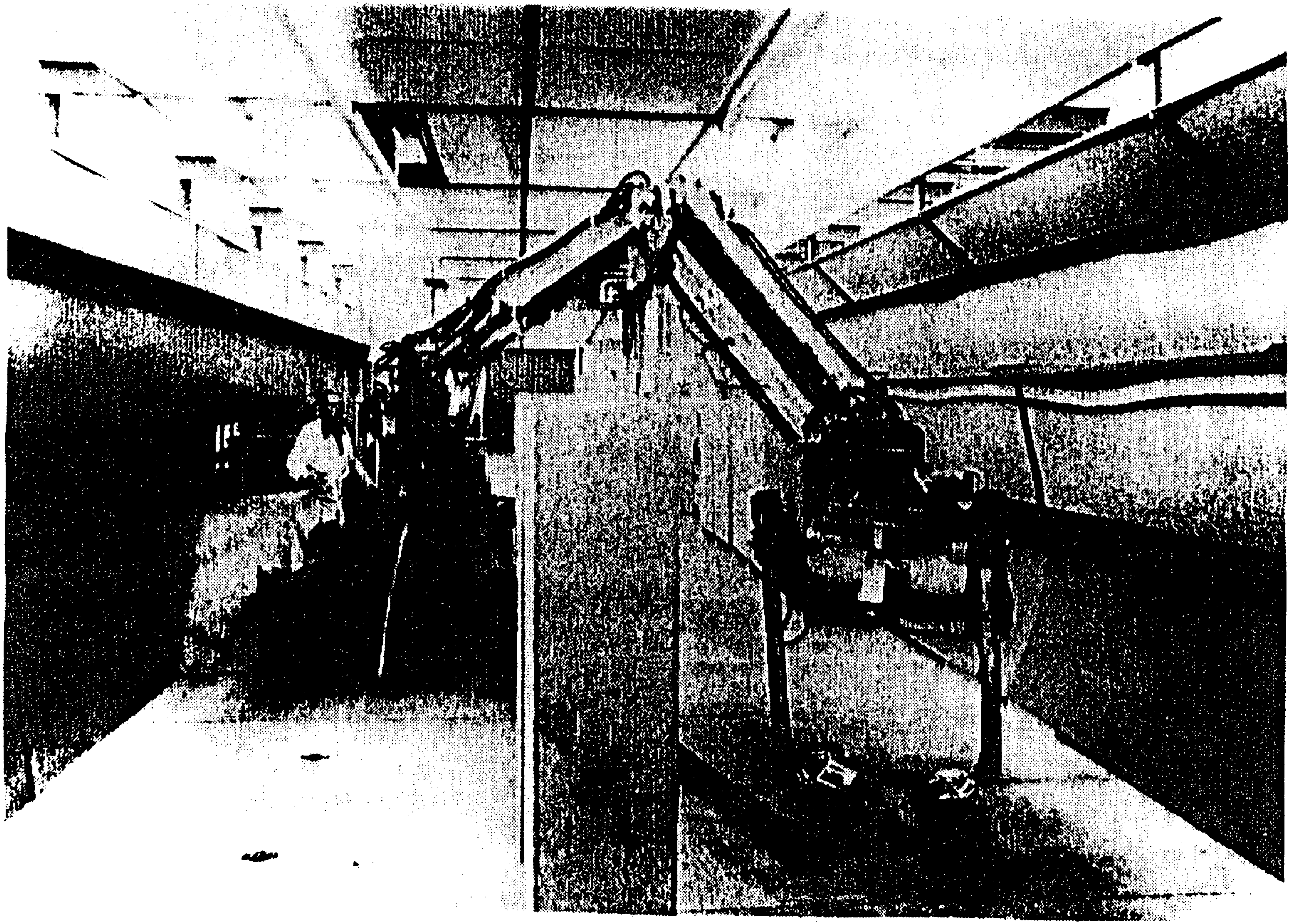
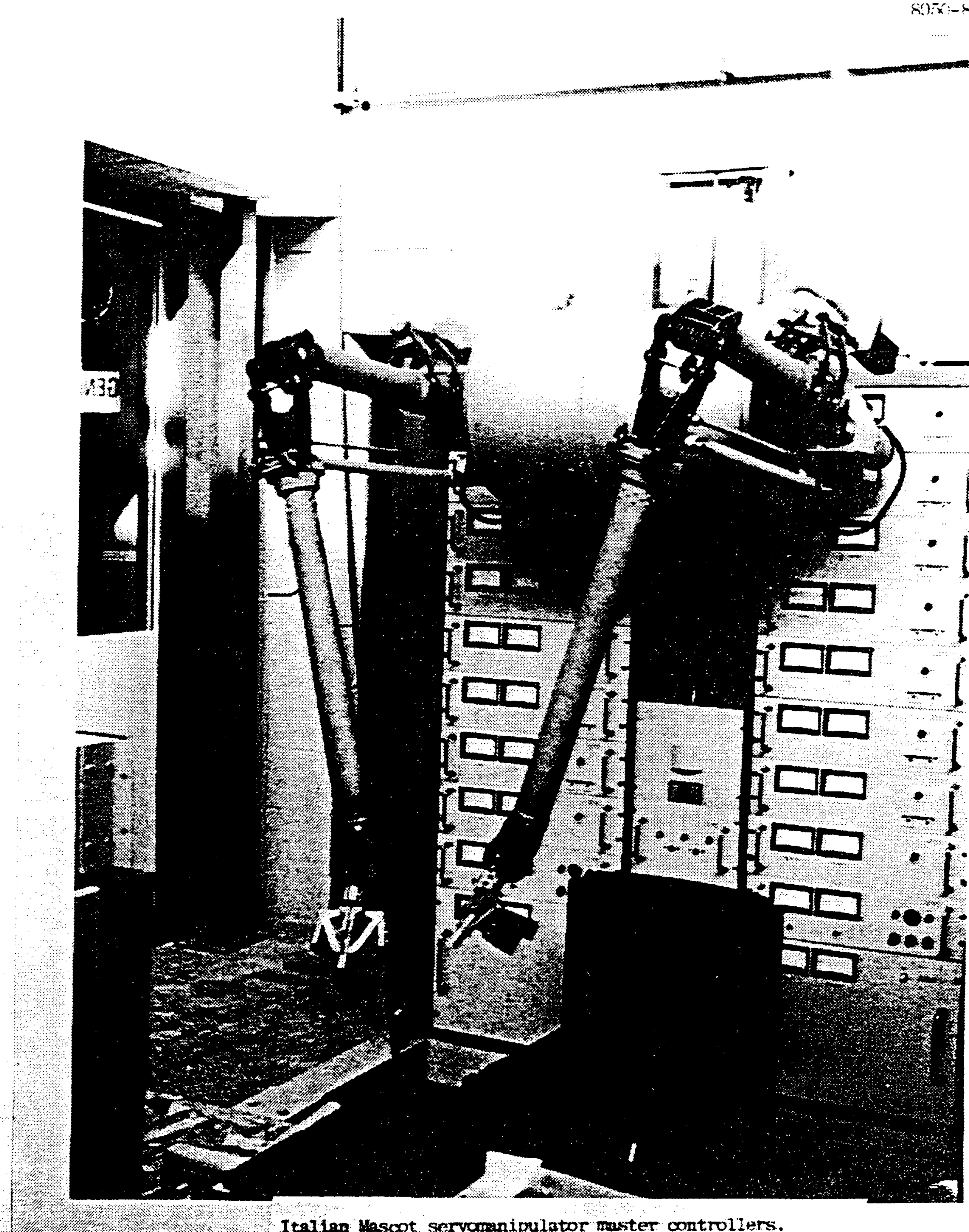
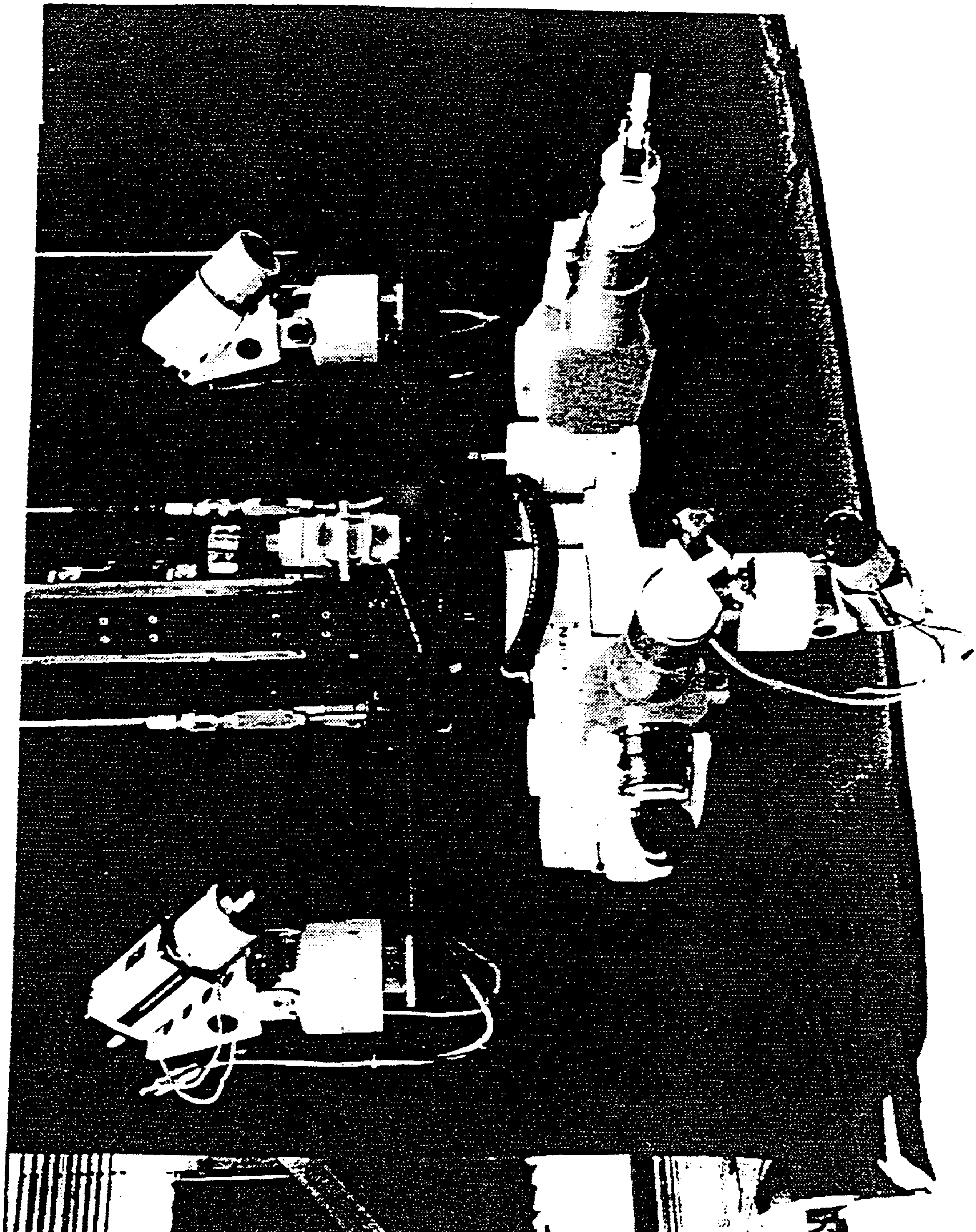
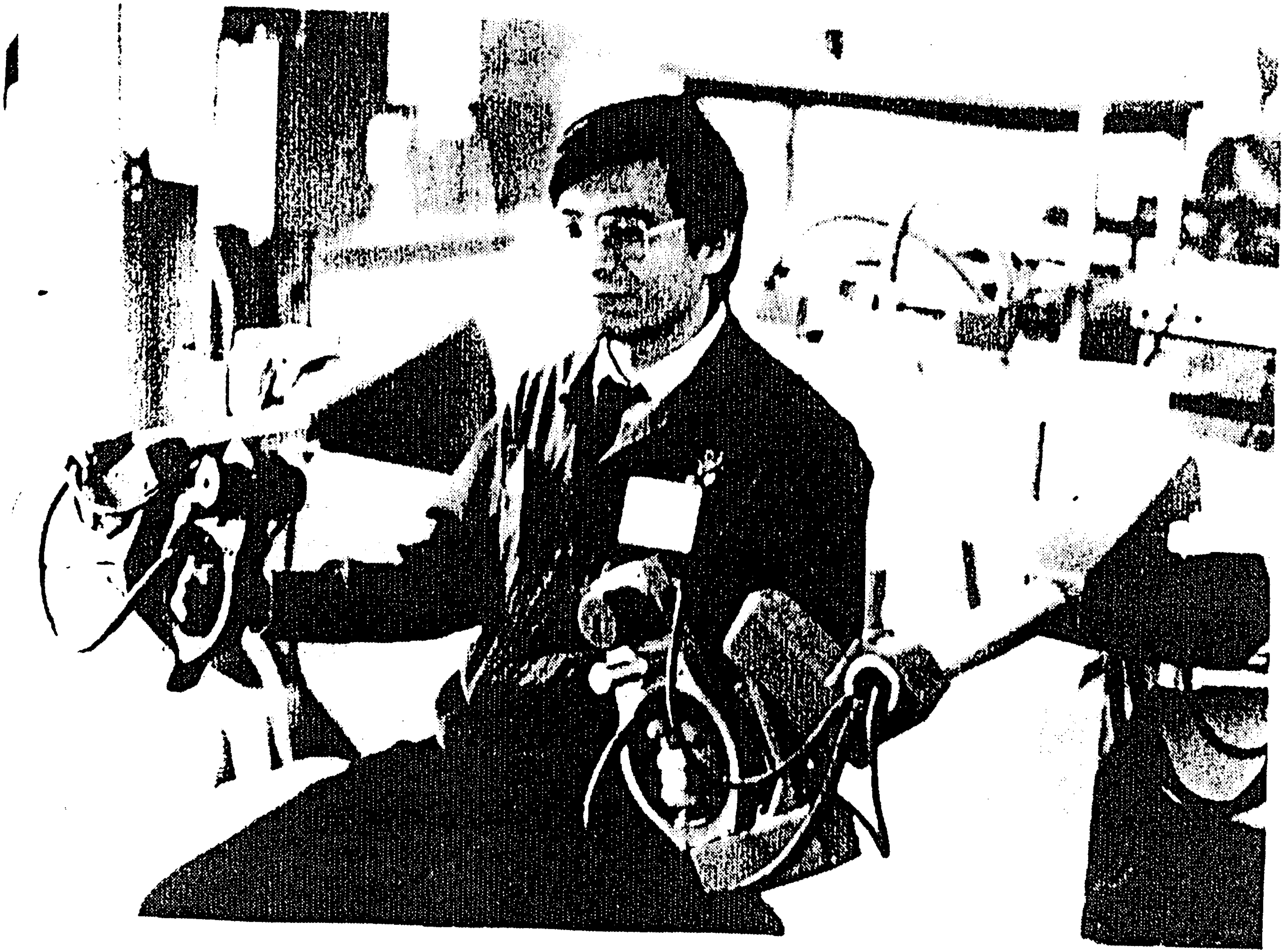


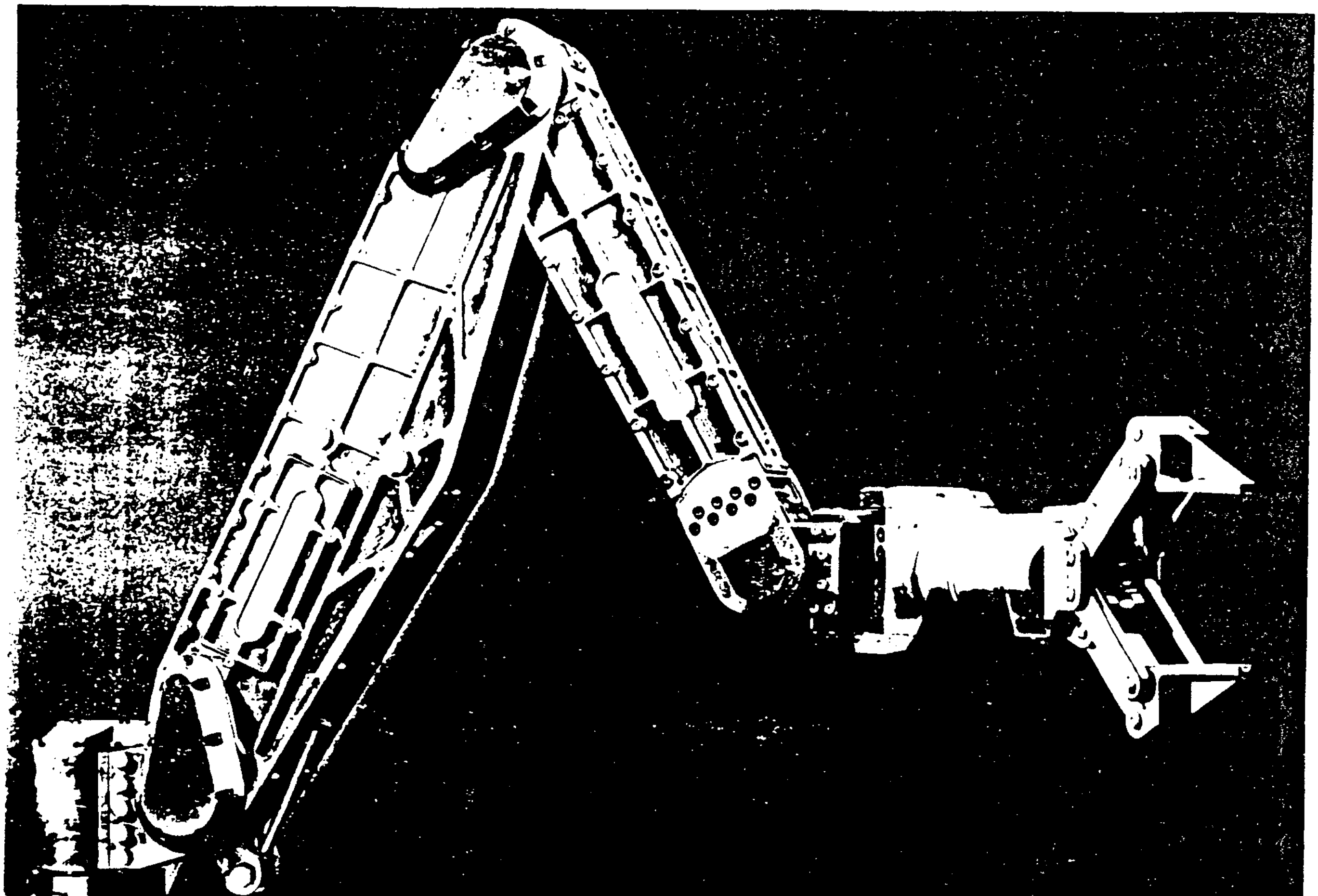
Mascot servomanipulators at CERN accelerator (Switzerland).

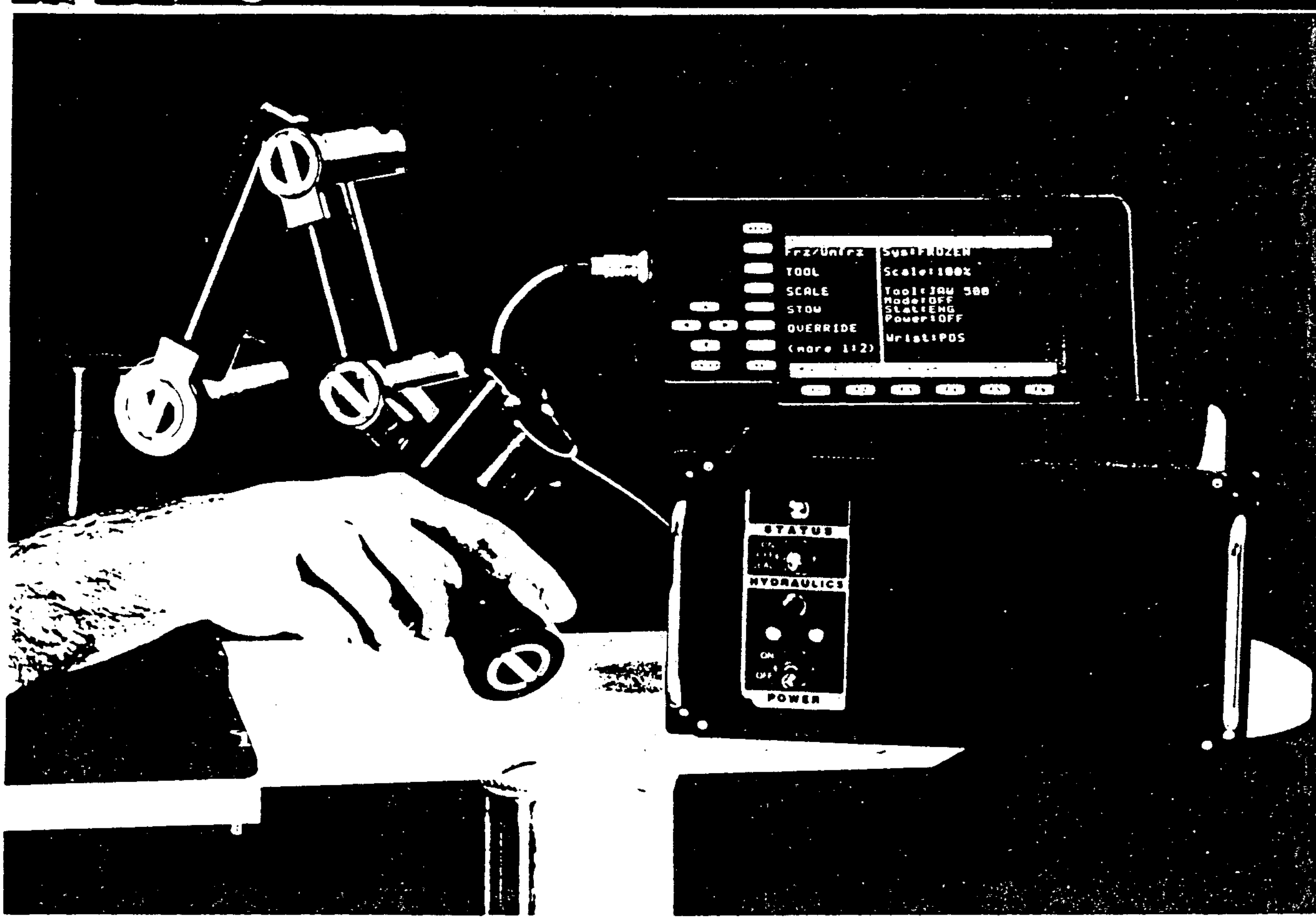


Italian Mascot servomanipulator master controllers.





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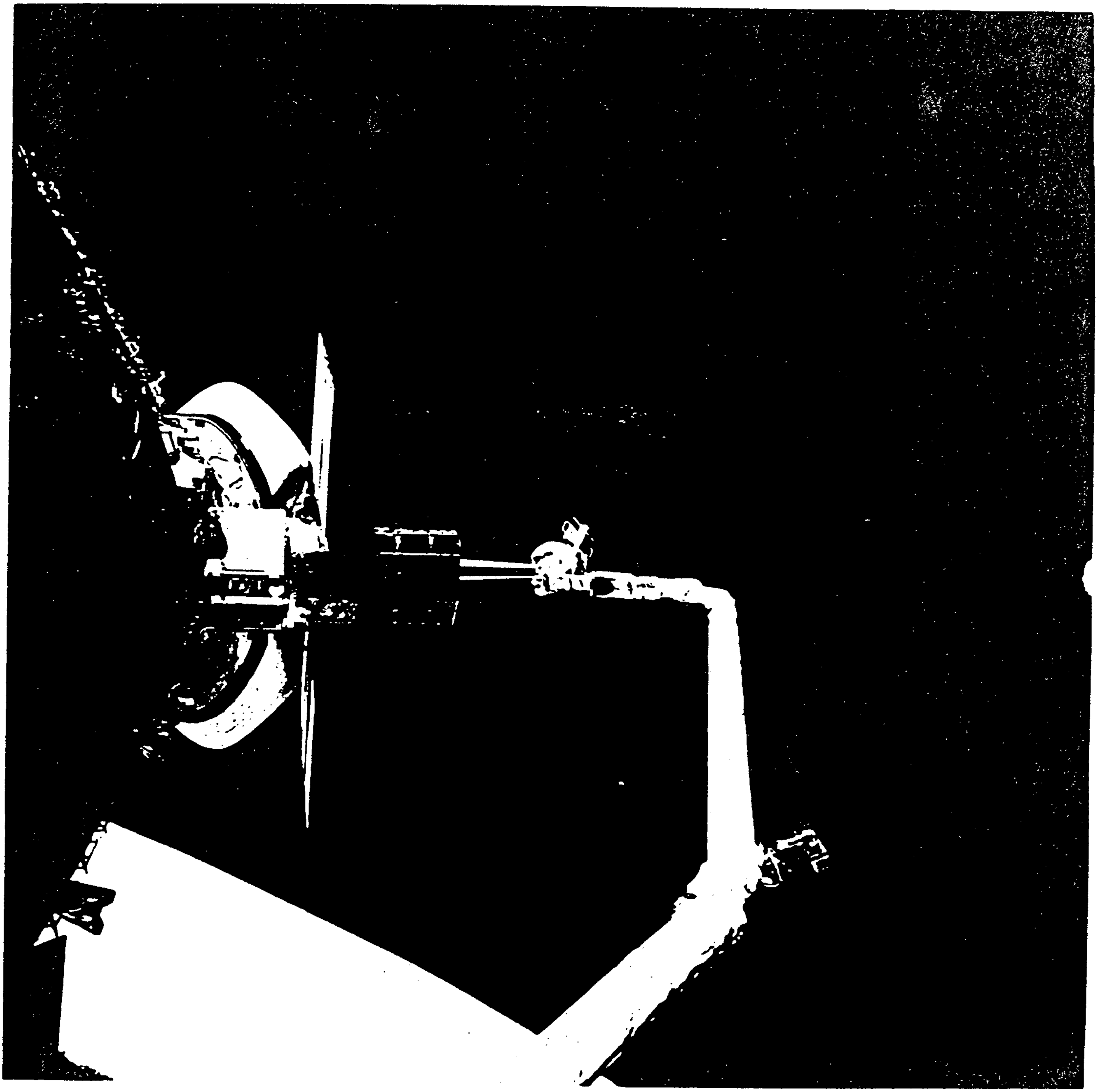
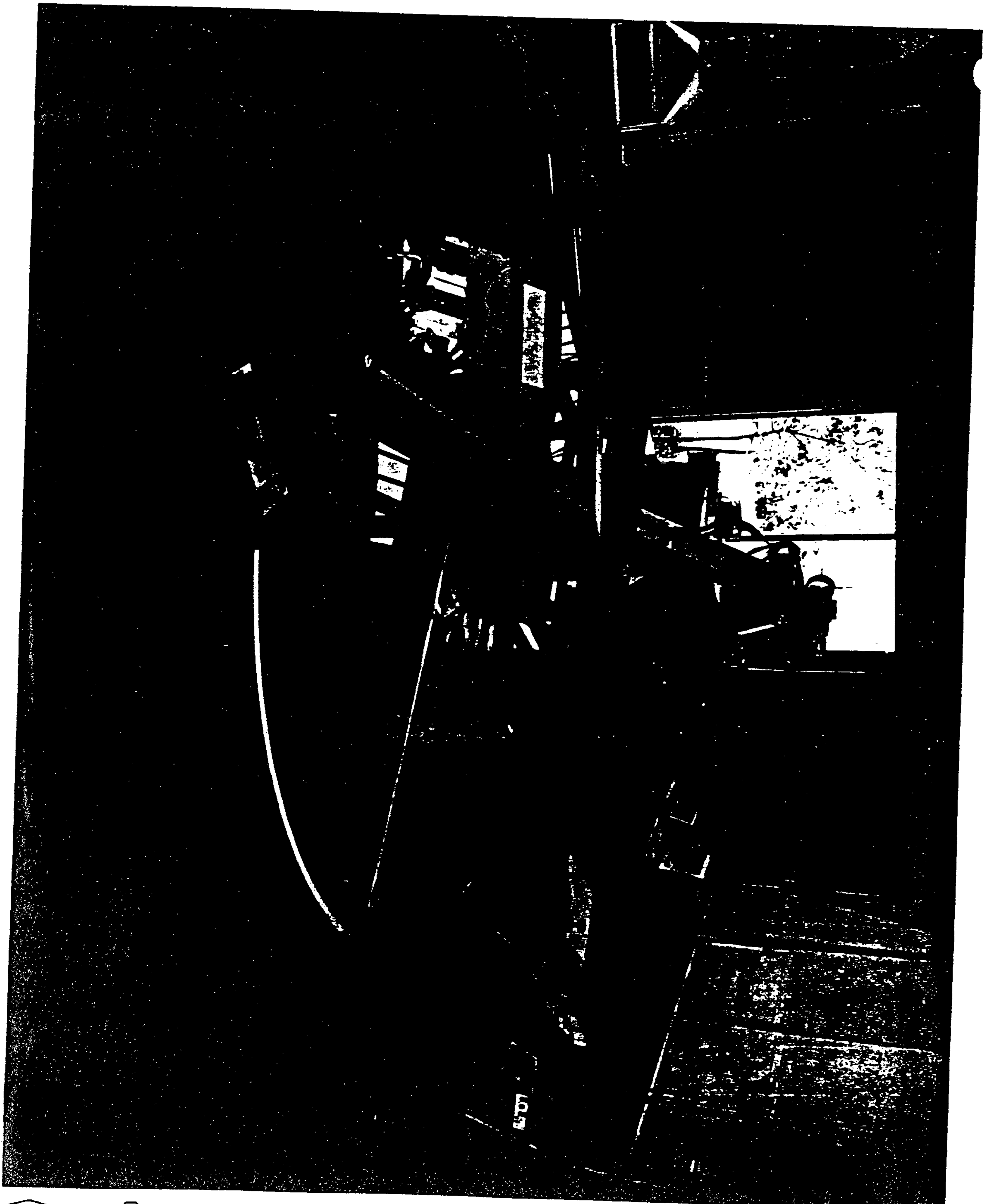
STOW
OVERRIDE
Wrist:POS
(more 1:2)
STATUS
HYDRAULICS
ON
OFF
POWER

NASA National Aeronautics and Space Administration

S 1 3 3 7 1 1 7 1 5

Lyndon B. Johnson Space Center
Houston, Texas 77058





Observations Regarding Remote Systems

Remote Technology Has Been Used Widely In The Nuclear Industry for Over 45 Years ... The Experience Shows That ...

- Maintenance system flexibility is essential to typical repair tasks because they are typically NOT repetitive, structured, or planned
- Very complex tasks can be successfully performed (even with remote crane-based maintenance)
- Work task efficiency is a strong function of the maintenance system elements
  - manipulation dexterity and transporter flexibility
  - remote sensing fidelity
  - human-machine interface efficiency
  - operator skill levels
- Fully remote design (manipulation, task provisions, remote tooling, and facility synergy) is essential to work task efficiency