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SAVANNAH RIVER SITE L REACTOR TESTING (U)

by

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John D Menna
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ABSTRACT

Flow tests were conducted in the Savannah River Site L reactor to evaluate the performance of the primary coolant system under simulated Loss of Coolant Accident (LOCA) conditions. Results were obtained with a prototypic cold fuel charge in the core. Core flows typical of normal and shutdown operation were studied. The tests consisted of measuring hydraulic parameters while lowering tank moderator levels to allow air entrainment from the reactor tank through operating coolant pumps. Data were collected continuously as the flows changed from single-phase to a two-component mixture of water and air. Minimum tank levels equivalent to those resulting from a hypothetical double-ended guillotine break of a coolant pipe were simulated. System pressures, water levels, densities, flows, and pump parameters were measured by over 200 instruments especially designed or adapted for in-reactor use. Special in-reactor video cameras provided visual observation of flow regimes and confirmed water levels in the reactor tank, plenum, and pump suction and plenum inlet pipes.

The tests provided a unique opportunity to study full-scale pump degradation and two-component flow distributions in the reactor under ambient temperature conditions. Results showed the different pump operating regimes and points of transition and some of the other key features of the reactor response system during a severe loss of coolant event.

INTRODUCTION

During the summer of 1989, tests were run to evaluate the performance of the reactor primary coolant system in the SRS L production reactor under conditions that simulated various Design Basis Accidents (DBA)[1]. The test program encompassed a spectrum of DBAs such as LOCAs and loss of pumping accidents. Special emphasis was placed on the LOCA resulting from a hypothetical double-ended guillotine break of a reactor coolant pipe.

The objectives of the test were to: (1) provide improved reactor coolant pump performance data under two-component (air/water) conditions, (2) obtain two-component flow regimes in the primary coolant system, (3) create a comprehensive system database to ascertain integral system performance and to assess the predictive ability of reactor system codes, (4) characterize system response during coastdown of reactor coolant pumps from AC to DC motor drive, and (5) evaluate two-component flow instrumentation for future tests. In order to meet these objectives, a large scale test program was organized and completed during 1988 and 1989. Data from over 200 instruments and eight cameras were collected during 29 separate tests. Preliminary results from the data analysis have confirmed some findings from previous tests and added new insights into the performance of the reactor system during abnormal operation.

The purpose of this paper is to give an overview of the test program and present a selection of results describing overall system performance under various flow conditions and regimes. The results presented will also deal , to some extent, with the second objective listed in the preceding paragraph. Future publications will detail results associated with the other objectives.

DESCRIPTION

Reactor System

The SRS reactors circulate heavy water through six primary loops to cool the reactor core (Figure 1). Each primary loop consists of a coolant pump, two heat exchangers in parallel, connecting piping, and three valves located at pump suction and at the outlet of each heat exchanger. The reactor coolant pump is driven by a 2535-kW (3400-hp) alternating current (AC) motor in parallel with a 75-kW direct current (DC) motor driven by a diesel generator. The reactor is normally operated with a helium gas blanket in the reactor tank, controlled at 34.5 kPa above atmospheric pressure (5 psig). Fuel and target components are aluminum-clad uranium/aluminum alloy or aluminum-clad uranium.

Heavy water is drawn from the bottom of the reactor tank by the coolant pumps, passed through the heat exchangers, and then directed to a water plenum that delivers the coolant to the assemblies. The plenum is located above the reactor tank and has a height of 222 mm (8.75 in.) and is about 5.3 m (17.5 ft) in diameter. Heavy water is delivered to several hundred fuel and target assemblies by the plenum. The coolant flows down through the assemblies and exits from the bottom into the reactor tank. Approximately 5.8 m (19 ft) of heavy water fills the tank moderator space of the reactor tank during normal reactor operation.

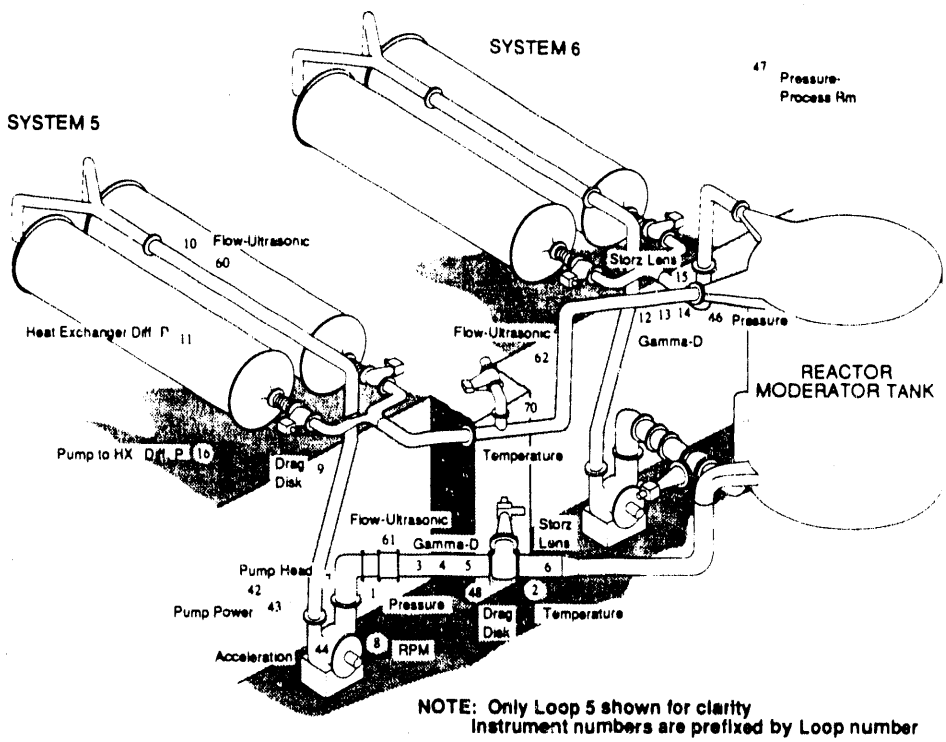


Figure 1. Instrumentation Locations for L Reactor Tests

In the event of a LOCA, the Emergency Coolant System (ECS) provides light water injection to four of the primary loops downstream of the heat exchangers. During the test program, the LOCA was simulated by removing the heavy water moderator coolant from the primary system without nuclear heating from the fuel assemblies. In a series of quasi steady-state steps, air drawn into the reactor tank through vacuum breakers replaced the coolant removed. Tests were performed without both blanket gas and ECS injection. The reactor tank was at approximately atmospheric pressure. Moderator fluid temperature was maintained at a value near ambient by light-water coolant pumped through the secondary side of the heat exchangers.

Instrumentation

The special use of L reactor for conducting full-scale tests imposed strict controls and functional requirements on the design and placement of the instruments in the reactor. Existing pipe penetrations and fuel positions were used for instrument locations. Instrument designs conformed to reactor geometry and dimensions. Instruments were also designed to operate in a radiation environment and were constructed of materials approved for in-reactor use.

Instrumentation was installed on all six primary loops, as well as inside the reactor tank and plenum (Figures 1 through 3). Loop instrumentation included pump suction pressure, pump DP (differential pressure), pump to heat exchanger inlet DP, heat exchanger DP, plenum inlet pressure (loops 1 and 5 only), pump rotational speed, pump motor power (AC and DC), pump acceleration, and total loop flow. Loop flow was measured on each loop by two ultrasonic flowmeters. The pump acceleration measurements were used to ensure that pump vibrations stayed within safe operating limits and were helpful in detecting two-component flow transition.

The ultrasonic flowmeters were placed upstream of the heat exchangers on a long horizontal run of pipe. Two types were used on each loop. One type was a transit-time instrument that operated in water flow

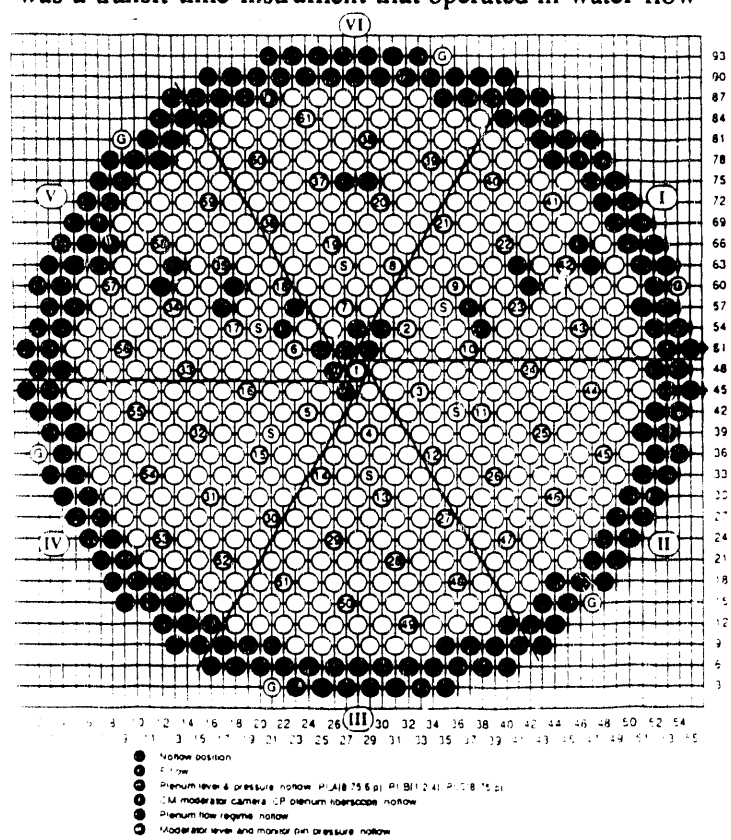


Figure 2. Reactor Core Instrumentation

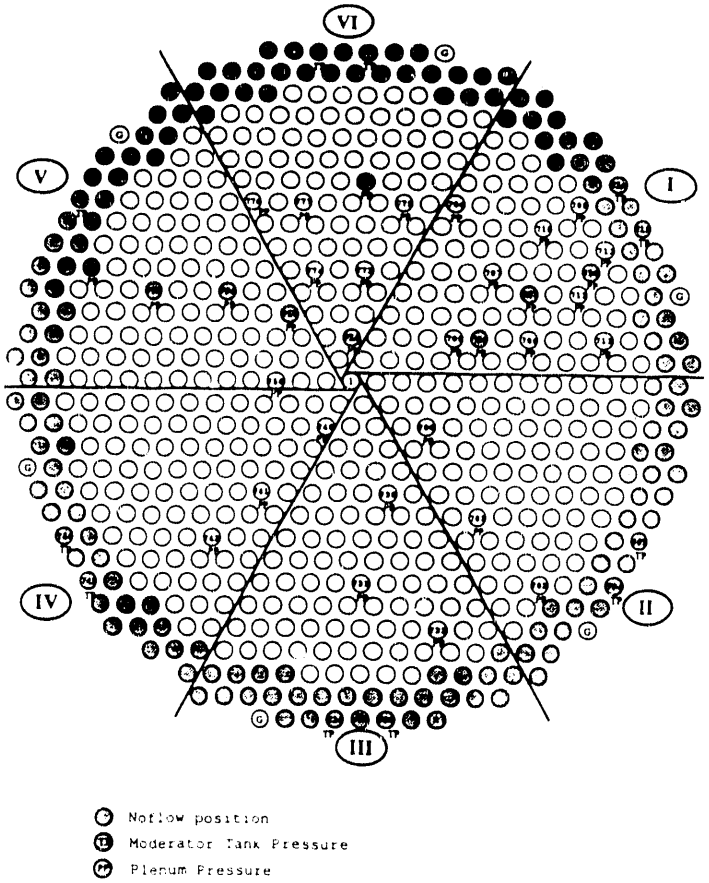


Figure 3. Reactor Core Instrumentation Plenum Pressure Measurements

and low-void-fraction, two-component flows. For higher-void-fraction flows, a Doppler ultrasonic flowmeter was used. The Doppler instrument responded whenever air was present in the flow, but it was unresponsive in pure water because of the low turbidity of reactor coolant.

In loop 5, special instruments were used for measuring fluid temperature, fluid density, and two-component flow (Figure 1). The pump suction region contained a Resistance Temperature Device (RTD), a gamma densitometer, a drag disk, and a Doppler ultrasonic flowmeter. The drag disk was located in the freestream and provided a measurement point for momentum flux near the center of the pipe. The plenum inlet region contained a gamma densitometer and a Doppler ultrasonic flowmeter. Plenum inlet temperatures were measured at the heat exchanger outlet.

The density measurements were made with gamma densitometers supplied by EG&G, Idaho. Each unit consisted of a cesium-137 source, collimated into three beams and three detectors located on the opposite side of the pipe (Figure 4).

Visual observations of the pump suction were made through a 150-mm (6-inch) acrylic plug placed in a vacant nozzle. Visual access to the plenum inlet was provided by a modified spacer ring placed in the plenum nozzle flange. The ring was constructed with three viewing windows which housed a borescope and two high-intensity light sources to observe the flow (Figure 5). Both instruments provided pertinent flow-regime information that has proved particularly helpful in

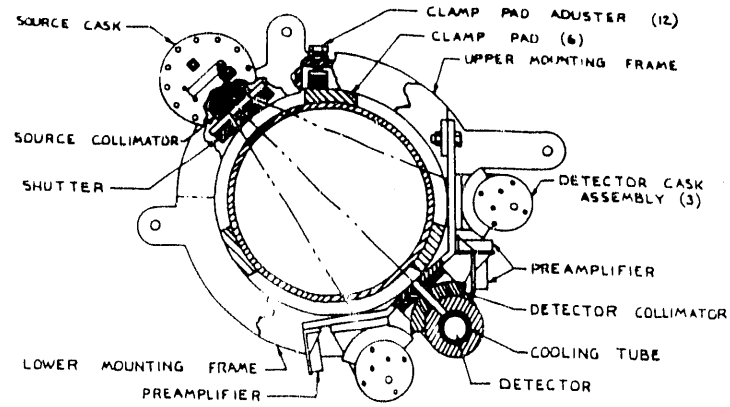


Figure 4. Gamma Densitometer Cross Section

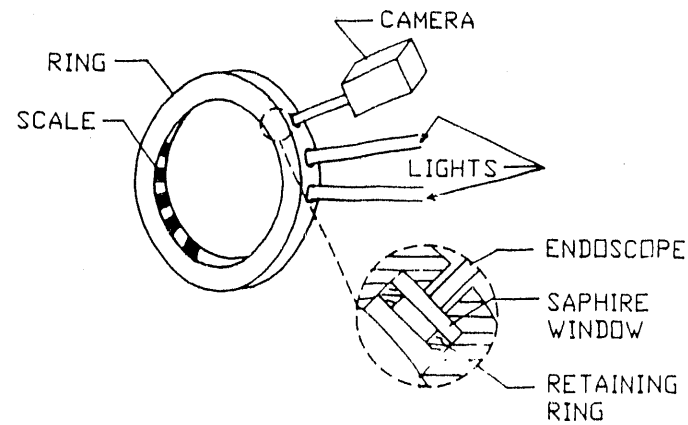


Figure 5. In-Pipe Viewing System Ring Configuration at Plenum Inlet

interpreting the results from the gamma densitometers and flow instruments.

The plenum was instrumented with pressure transducers at 33 locations (Figure 3). Plenum levels were obtained at each of 11 fuel positions by a capacitance assembly. The assembly consisted of insulated metal rods mounted vertically in a plug (Figure 6). When installed in a permanent reactor sleeve, the plug prevented flow-down into the fuel position, thereby creating a dormant region within the fuel tube. The capacitance between the rod and the surrounding metal were related to "collapsed" liquid level through direct calibration. Rods had active heights of 222 mm (8.75 in), 152 mm (6.0 in), 102 mm (4.0 in), 51 mm (2.0 in), and 25 mm (1.0 in.) and were coated to electrically insulate them from the moderator.

Two methods were used to determine flow regimes in the plenum space outside the assembly fuel positions at both the edge and the center of Sector 5 (Figure 2). The first method detected local flow stratification by measuring fluid capacitance at discrete locations along the plenum height. The capacitance probes consisted of a pair of closely spaced electrodes that penetrated the plenum flow stream (Figure 7). A rake of four electrode pairs was used to sense stratified flow at plenum heights of approximately 25 mm (1.0 in), 83 mm (3.25 in), 140 mm (5.5 in), and 197 mm (7.75 in). Because the dielectric constants of air and heavy water differ significantly, signals obtained in air were easily distinguishable from those obtained in water.

fraction sensor consisted of an insulated aluminum rod suspended within an aluminum cylindrical shell. Flow from the plenum was directed through the annulus between the cylinders before entering the turbine meter. The change in capacitance caused by the presence of air in the flow was correlated to void fraction in laboratory tests.

Sensor

Turbine Meter

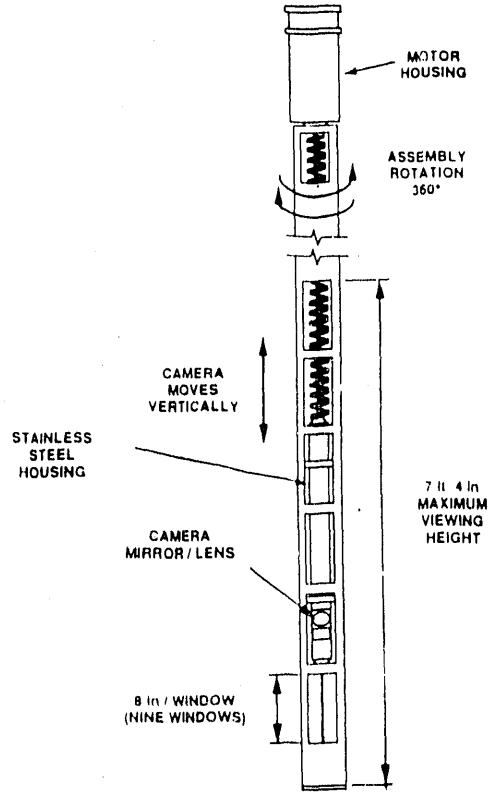
Drag Meter

Figure 10. Flow Package Showing Void Fraction Sensor

The combination of the drag plate (measuring ρV^2) and turbine meter (measuring velocity V) provided an accurate indication of total and liquid flow (to within ± 15 percent) over a range of approximately 1.6 to 6.3 liters per second (25 to 100 gpm). The turbine meter provided total flow measurements up to 25 liters per second (400 gpm).

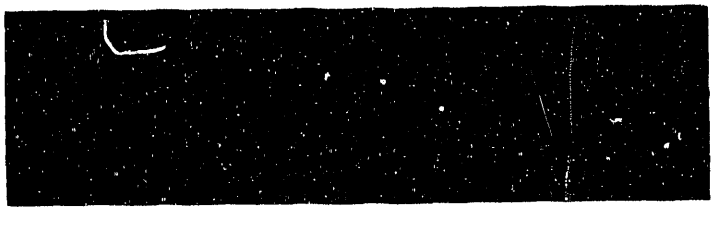
Extremely useful visual observation of the reactor tank was provided by four remotely operated underwater camera assemblies. A camera assembly consists of a thin-walled 10.4-cm- (4.1-in.-) diameter tube approximately 6.1 m (20 ft) long containing a radiation-resistant camera with a rotating viewing head, a retractable cable, and a drive train (Figure 11). Windows cut into the assembly allowed viewing of the bottom 2.1 m (7 ft) of the moderator space. A mesh covered each window to prevent loose parts from falling into the reactor. Two DC motors located at the top of the assembly provided vertical and rotational movement of the camera. Level marks were placed on the inside diameter of the assembly. One assembly was located at tank center, primarily for level verification and calibrations. The other three assemblies were located at the tank edge in front of the loop 5 effluent nozzle to determine level gradients and to observe flow regimes.

Approximately 220 hours of video recordings were made of the reactor tank, plenum, and system flows during the test.



Assembly

Rotating Viewing Head



View Windows With Protective Screen In Place

Figure 11. Moderator CCTV Assembly

Data were collected by a 192-channel NEFF Data Acquisition System (DAS) under the control of a Digital Equipment Corporation MicroVAX computer. Each instrument was sampled ten times per second for periods of up to eight hours. Data was reduced and "quick-look" plots were generated within one hour of the conclusion of each test segment using Macintosh work stations. Archival of data was also done after each test segment using optical Write Once Read Many (WORM) drives to store the 12 gigabytes of data produced during the test program. Two Frequency Modulation (FM) recorders provided backup data acquisition for critical channels as well as higher frequency recording capabilities.

CALIBRATIONS

All activities of the test program were governed by a rigorous quality assurance plan. Instruments providing qualified data were calibrated in accordance with approved procedures against standards traceable to the National Institute of Technology (formerly National Bureau of Standards). Exceptions were calibrated in-situ against other instruments that had traceable calibrations.

Level and assembly flow instruments were calibrated in the laboratory using prototypic hardware. The assembly flow packages were calibrated under two-component flow conditions in a prototypic fuel assembly. The laboratory facility consisted of a large tank connected to a recirculation loop with air injection. Reactor assembly flows were simulated by injecting known amounts of air into the water stream while lowering liquid level in the tank. Air and water flows were independently varied over a wide range to cover the conditions expected during the LOCA tests.

In-reactor calibrations of the drag disks using the loop flow meters and the calibration of all level instruments using plenum and tank-cameras were performed at regular intervals during the tests. The drag disk was calibrated in liquid flow by adjusting the positions of the heat exchanger outlet valves in steps to cover the full range of flow. Post-test calibrations of the drag disks and ultrasonic flow meters in a full-size loop facility will provide the direct calibration of the instruments under actual two-component flow conditions.

Measurement uncertainties are given with the plotted results except for the gamma densitometer uncertainties, which ranged from 1.6 (for low density flow) to 120 (for high density) kg/m^3 (0.1 to 8 pounds per cubic foot).

RESULTS

Simulated LOCA Tests

In the double-ended break of a plenum inlet line, water is released upstream and downstream of the break to ambient conditions. Backflow occurs through the affected plenum nozzle while normal pumping continues through the open loop from the recirculation pump.

Two pumping configurations were required to simulate these conditions with tank level used as the primary independent variable. One test simulated plenum conditions by allowing backflow in one loop. Backflow was set by turning off the pump and leaving the loop isolation valves open (five AC tests). An anti-rotation device prevented the pumps from rotating in reverse. A second test simulated tank conditions by keeping all six loops operating while the reactor was drained (six AC tests). Unless otherwise noted, the data presented in this paper are taken from tests performed with all six pumps driven by both AC and DC motors (six AC tests).

Each test began with normal AC flow and both AC and DC motors operating. Loss of coolant was simulated by slowly draining the reactor of inventory with the coolant pumps operating. Operating procedures allowed for a drain rate of about 25 mm (1 in.) per minute. Inventory recovery was simulated by refilling the reactor at approximately the same rate. A plot of tank level versus time is shown in Figure 12. Moderator tank levels were held at regular intervals (indicated by individual data points in Figure 12) to allow the reactor to reach steady state. Hold times varied between 5 and 15 minutes.

The amount of moderator removed or added to the reactor was recorded during the tests by measuring level changes in calibrated reactor moderator storage tanks. Minimum tank levels of 230 cm (9 in.) were achieved, which made it possible to study all the pump operating regimes.

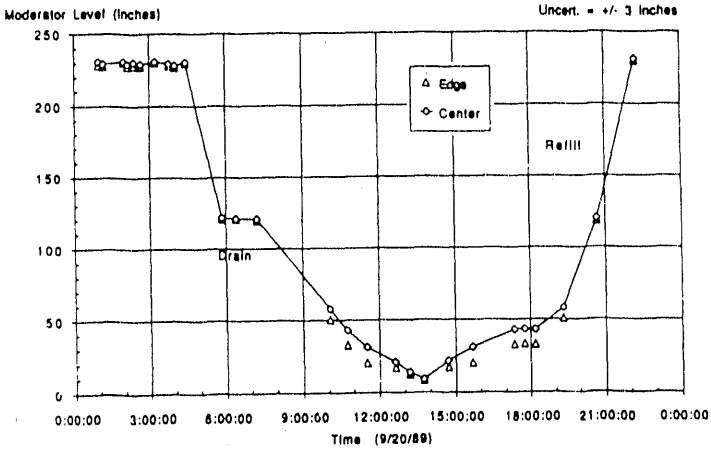


Figure 12. Moderator Level Versus Time

System Flow Characteristics

In SRS reactors, the two-component air/water flow characteristics of the pumps and the reactor coolant system are largely governed by the water level in the moderator tank. In describing system flow characteristics, it is, therefore, appropriate to present results as a function of moderator tank water level.

Previous studies[2,3,4] have characterized coolant flows during a LOCA by four distinct flow regimes of pump operation: single-phase, stable two-component, surging, and gravity flow. The initial regime is the normal single-phase pumping of coolant. Figure 13 shows that coolant is delivered at essentially a constant rate over a large range of moderator levels. In this range, the change in pump suction pressure shown in Figure 14 is directly proportional to the tank drain rate. At reduced tank levels, flow areas are reduced and circulation patterns in the moderator change and become more radial. The level

gradients across the tank, shown in Figure 12, are attributed to increased friction losses caused by higher radial velocities. When the level dropped below approximately 1.5 m (5 ft), air was entrained at the water surface and was ingested by the pump, as indicated by the pump suction gamma densitometer (Figure 15).

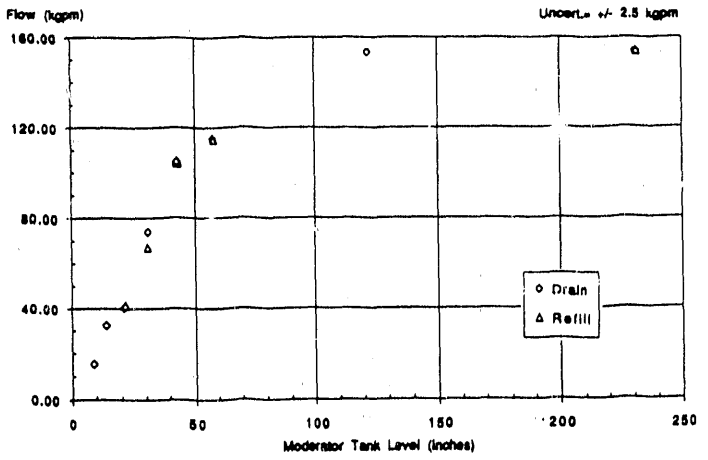


Figure 13. Total Core Flow Versus Tank Level

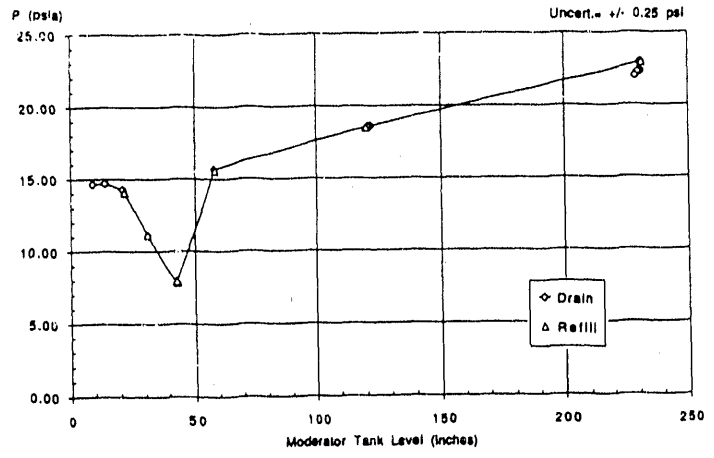


Figure 14. System 5 Pump Suction Pressure Versus Tank Level

The second operating regime is characterized by a progressive degradation in pump performance (Figures 13 and 15). Core flows decreased monotonically with tank level as well as the differential pressures across the pump (Figure 16) and heat exchangers. Results (Figure 17) show that plenum pressures also decrease across the core, which causes a corresponding reduction in assembly flow.

The fluid density at the pump suction and plenum inlet decreased indicating that larger amounts of air were entrained at lower tank levels as shown in the void fraction plots in Figures 15 and 18. Three densitometer beams giving similar readings (coincident points) suggested homogeneous flow. A change in flow regime was indicated by a deviation in the beam signals. Figure 15 shows such a change occurring in pump suction at about the 102-cm (40-in.) level. Pump suction pressure (Figure 14) reached a minimum near this transition. Stable pump operation continued through this regime with continuous recirculation of coolant.

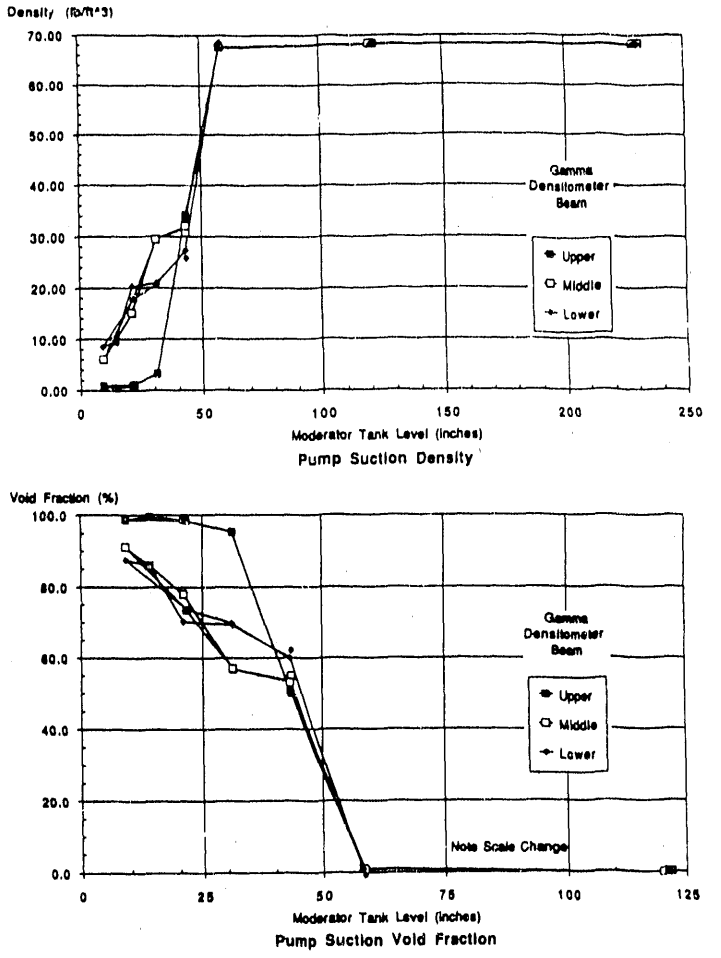


Figure 15. Pump Suction Density and Void Fraction Versus Tank Level

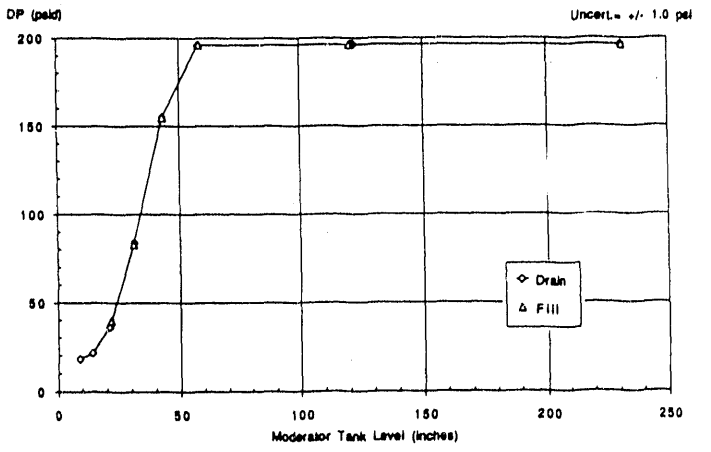


Figure 16. System 5 Bingham Pump DP Versus Tank Level

The third pump-operating regime was flow surging, which began at a tank level of approximately 71 cm (28 in.). At this level the water line was so close to the top of the tank outlet that venting of the suction pipe occurred and pumping was temporarily interrupted.

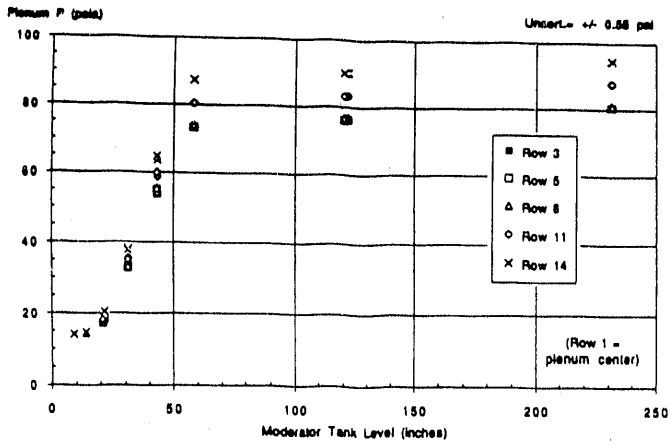


Figure 17. Plenum Pressure Versus Tank Level

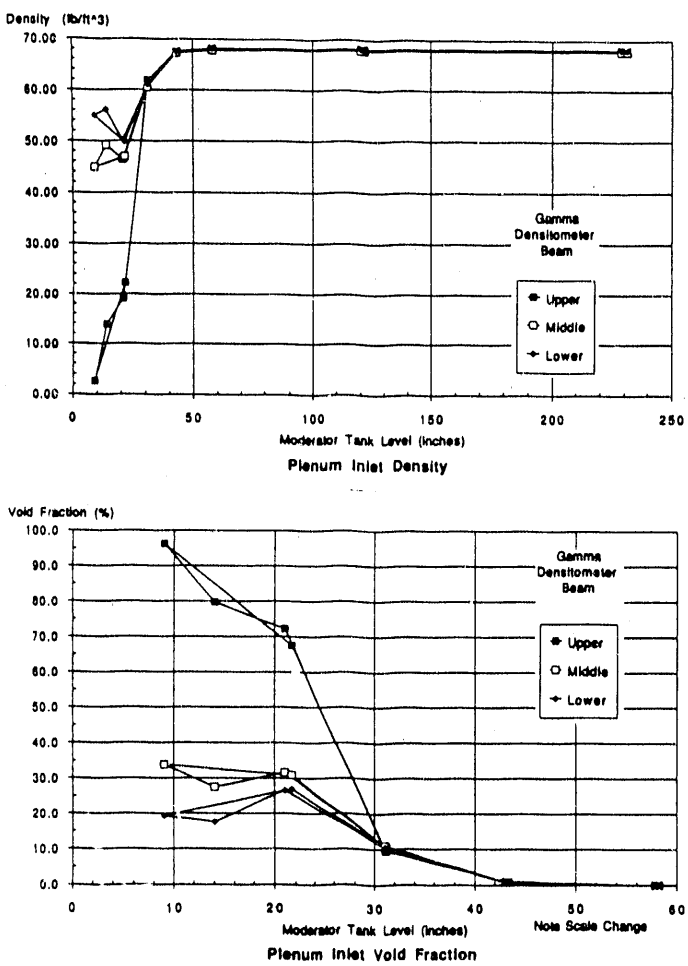


Figure 18. Plenum Inlet Density and Void Fraction Versus Tank Level

Venting reduced liquid flow to the pump to gravity flow, which is well below the capacity of the pump. Refilling of the suction line allowed pumping to resume but was again interrupted when the line vented. Figure 19 shows pump differential pressure oscillations occurring with regular 2.5-second periods. The period of oscillation is strongly dependent on the geometry of the piping leading to the pump. Similar oscillation behavior was observed during testing of the process water system in P reactor in 1970[2].

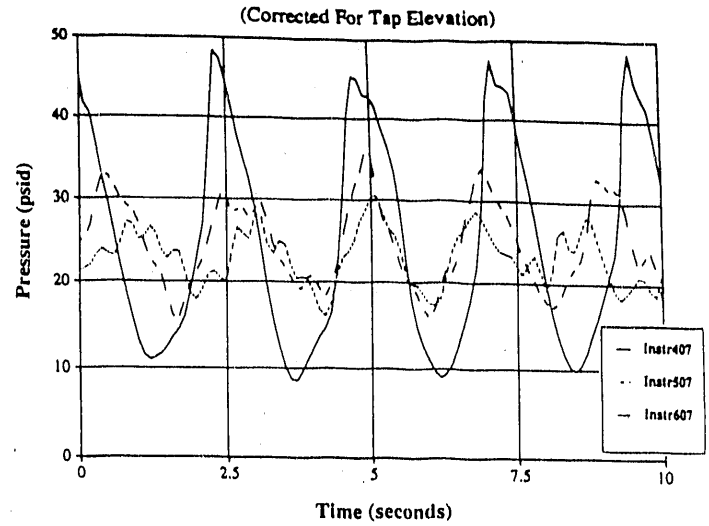


Figure 19. Pump Differential Pressure Oscillations

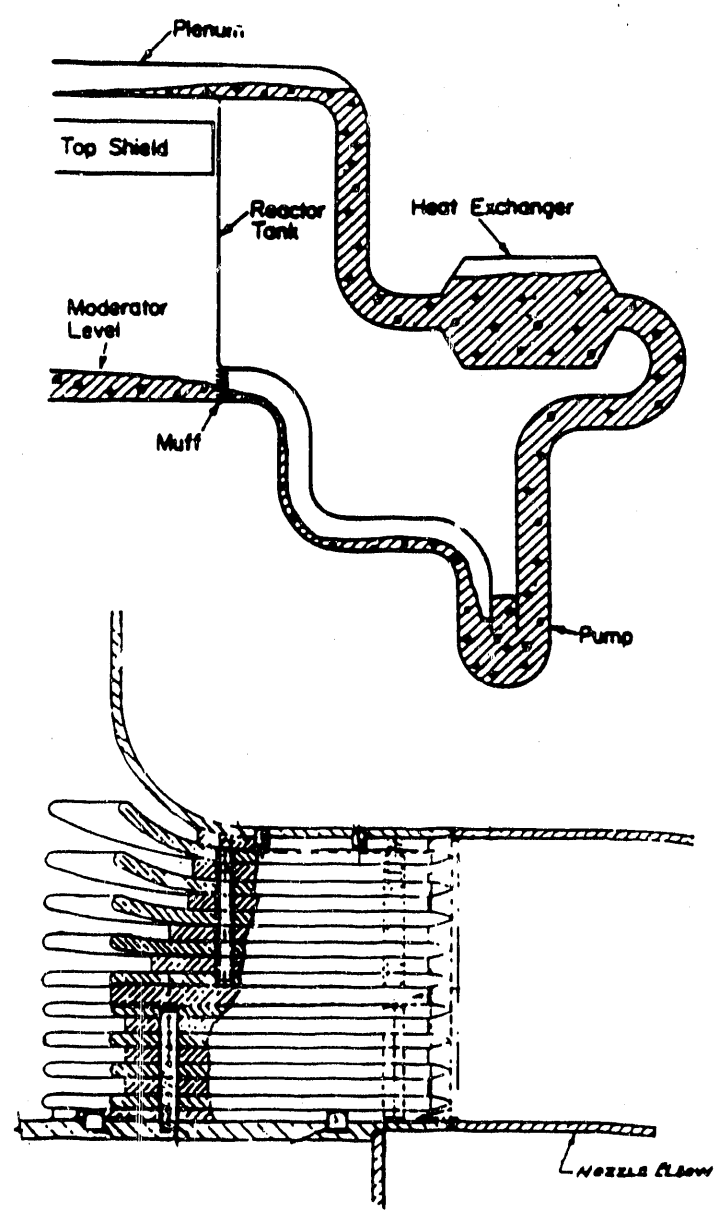


Figure 20. Flow Characteristics of the Effluent Nozzle

At moderator levels below approximately 56 cm (22 inches), a continuous vent path to the pump is established, and water drains to the pump under the control of gravity. This is shown by the atmospheric pressure measured at pump suction in the drain curves of Figure 14. Figure 13 shows a clear change in slope at the point of transition, making coolant flow more sensitive to tank level in this region.

The fourth operating regime amounts to a hydraulic decoupling of the tank from the rest of the system. Coolant flows appear to, almost exclusively, depend on the weir characteristics of the effluent nozzle. The flow characteristics of the nozzle (Figure 20) are dictated by its unique geometry. The nozzle is subdivided into ten flow passages by horizontal plates. At the nozzle entrance, the upper half of the plates are curved upward.

A water level between 56 and 58 cm (22 and 23 in.) is required to fully submerge the nozzle and keep the uppermost flow passage flowing full of water. At lower water levels, the plate acts like a dam restricting flow to the passage and eventually establishes the initial vent path. The lower plates create similar vent paths at reduced levels. Figure 21 presents two photographs taken from actual video footage showing gravity flow conditions in the reactor tank and pump suction piping.

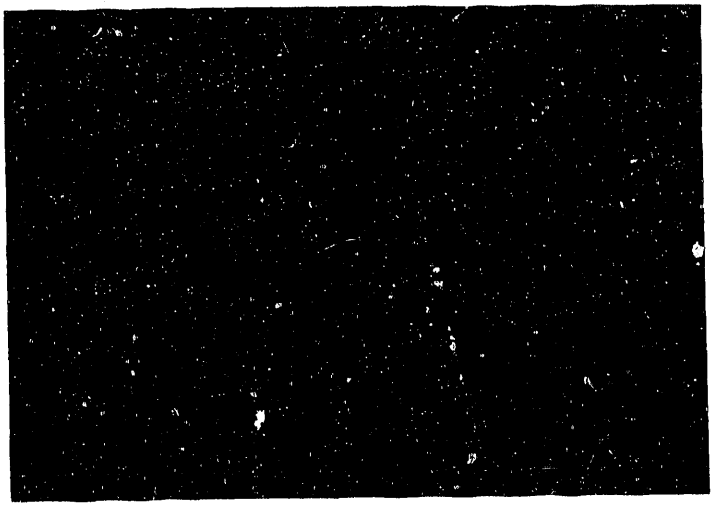
The plenum characteristics in the gravity flow regime are shown in Figures 22 and 17. Figure 17 shows that plenum pressure approaches atmospheric pressure and that this condition was established as gravity flow conditions were reached. At the same time, flow stratification was observed in the plenum. A typical plenum level distribution without loop backflow is shown in Figure 23, which also shows a symmetric profile across the core with a minimum occurring near the core centerline. Similar results are plotted in Figure 24 for a case with backflow, showing a shift in the minimum, which favors the affected loop. One would expect a similar asymmetric profile to exist in a LOCA.

SUMMARY

The reactor response during a LOCA becomes increasingly dependent on the moderator tank level when air entrainment by the pump begins. The flow regimes that develop at lower levels show a strong dependence on the geometry of the reactor effluent nozzle. At very low tank levels, the nozzle acts like a weir delivering to the pump under gravity control. The gravity flow condition at the nozzle was confirmed by visual observation during the tests.

The results presented can be viewed as a chronology of pump operating regimes and physical behavior for a severe LOCA. While the tests could not simulate actual transient conditions, the flow transitions, air entrainment, and gravity flow were full-scale characteristics of an actual LOCA. In this paper, only a small portion of the results obtained during the 1989 L reactor tests are presented. Much work remains to fully digest and analyze test results and post-calibration information still being generated as part of the test program.

Reactor Tank Effluent Nozzle



Pump Suction

Figure 21. Gravity Flow Conditions in the Reactor Tank and Pump Suction Piping

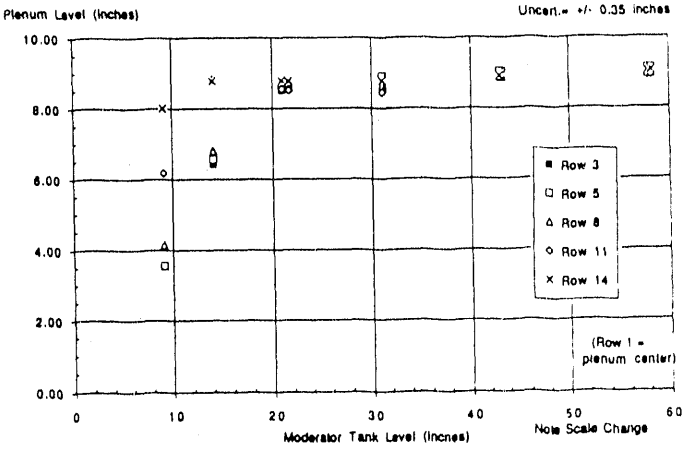


Figure 22. Plenum Level Versus Tank Level - Test AC4 Modified

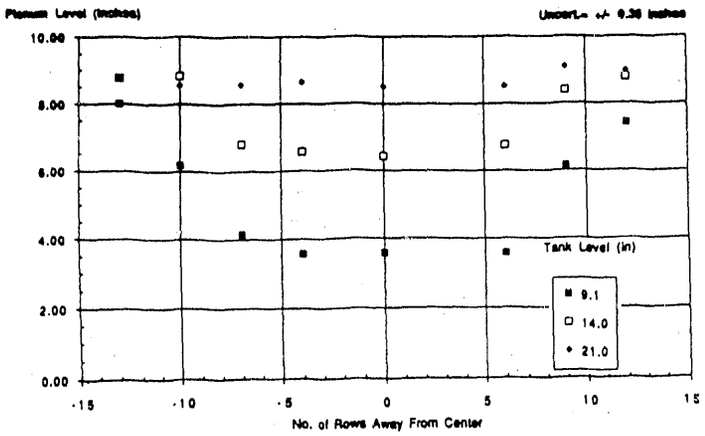


Figure 23. Plenum Level at Tank Levels of 9.1, 14.0, and 21.0 Inches

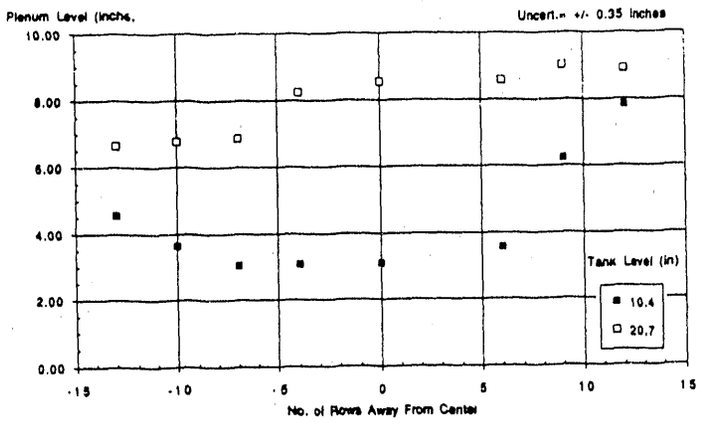


Figure 24. Plenum Level at Tank Levels of 10.4 and 20.7 Inches (5AC Motors on Loop 5 in Backflow)

The test program presented difficult challenges in designing instrument systems and test sequences to ensure the safety of personnel and reactor equipment. Literally hundreds of reactor manipulations, equivalent to several years of operation, were required to complete the tests.

The tests were successful in meeting program objectives. The results obtained provide an unprecendented database and a view of actual system responses that have proved invaluable in advancing our knowledge of the behavior of SRS reactors.

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3. D. R. MUHLBAIER, "Loss of Moderator Tests in the Cross Flow Tank," Memorandum to J. M. Boswell, DPST-69-514, Savannah River Laboratory, Aiken, SC 29808 (November 4, 1969).

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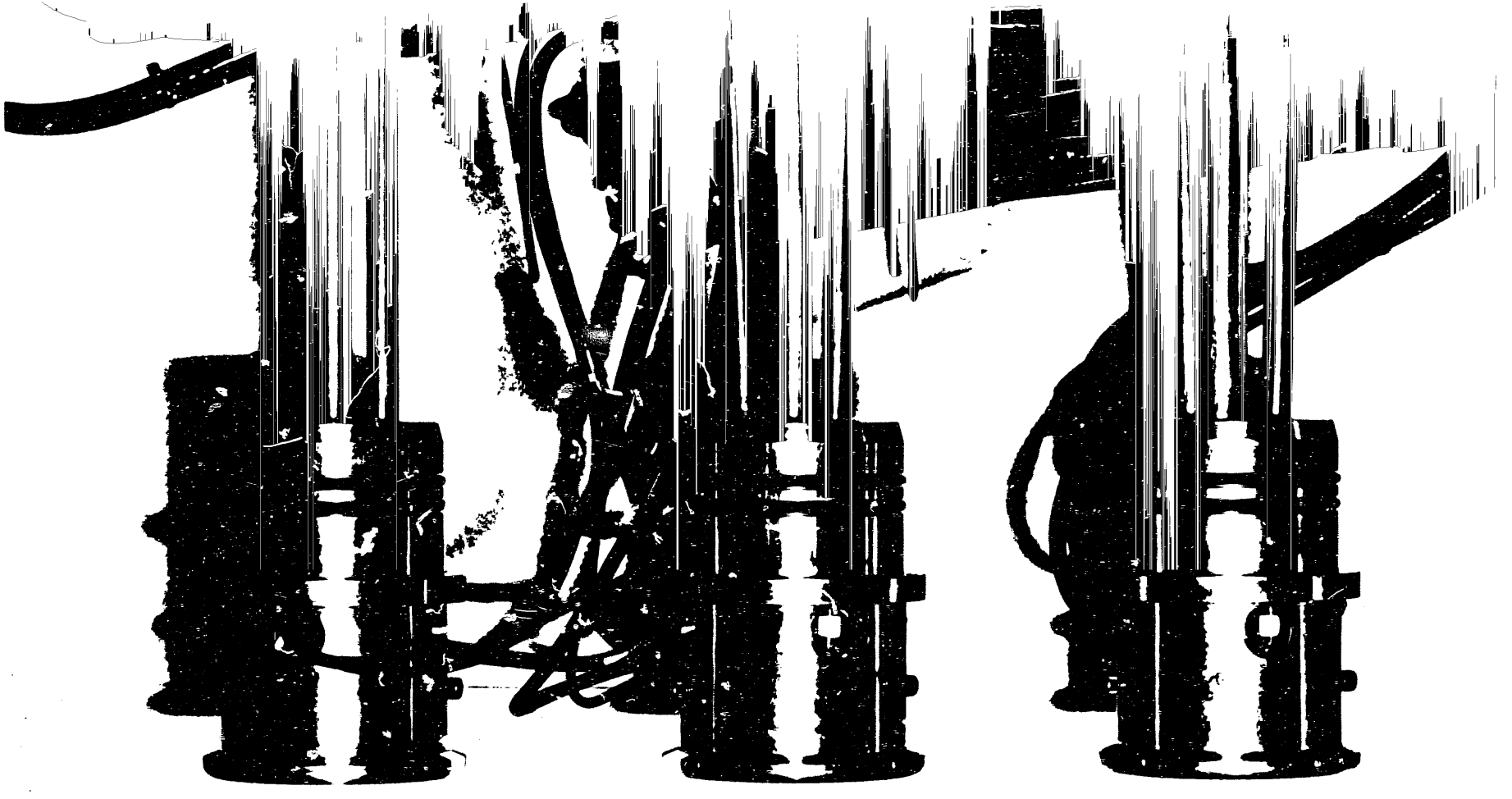


Fig. 7

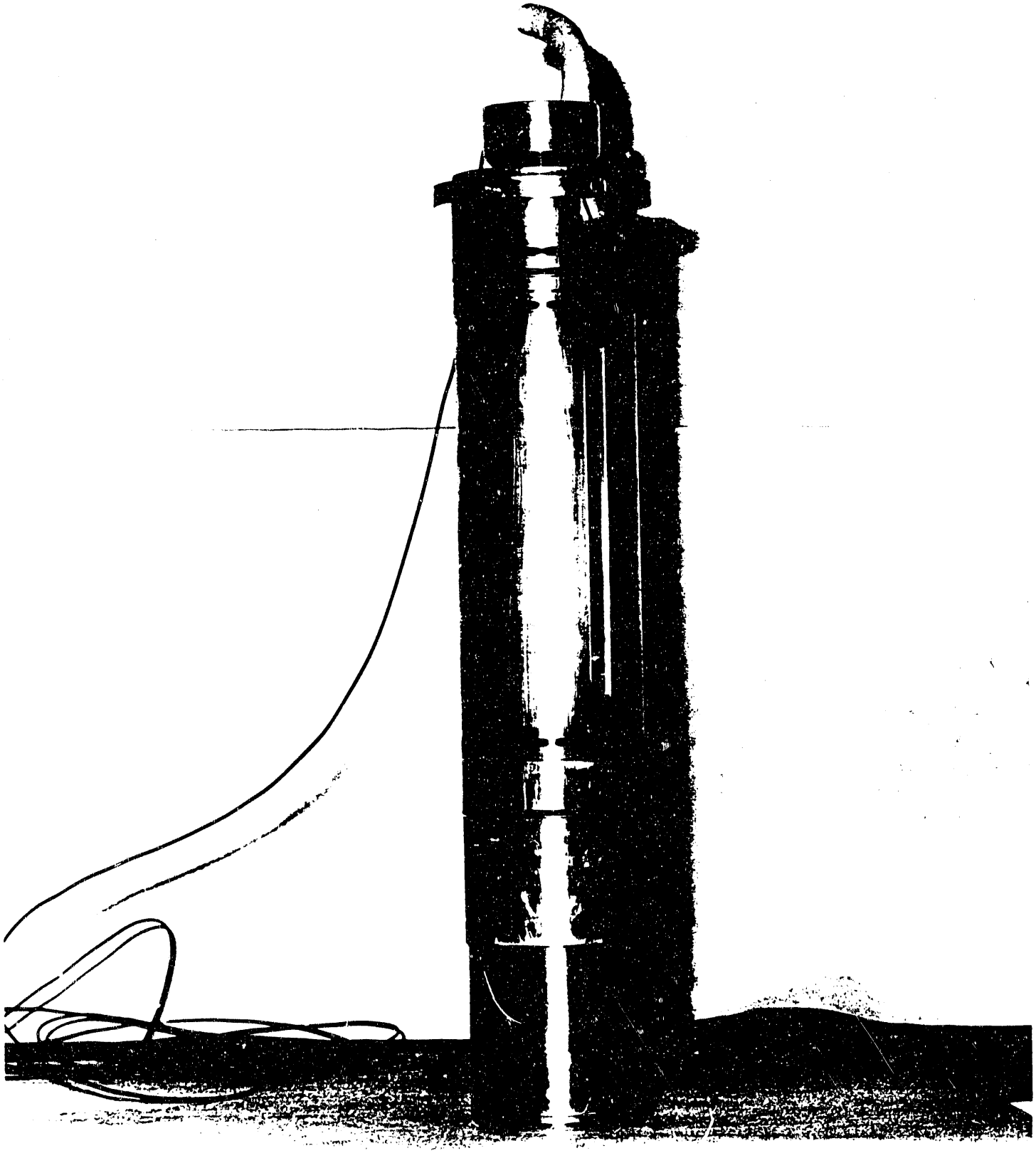
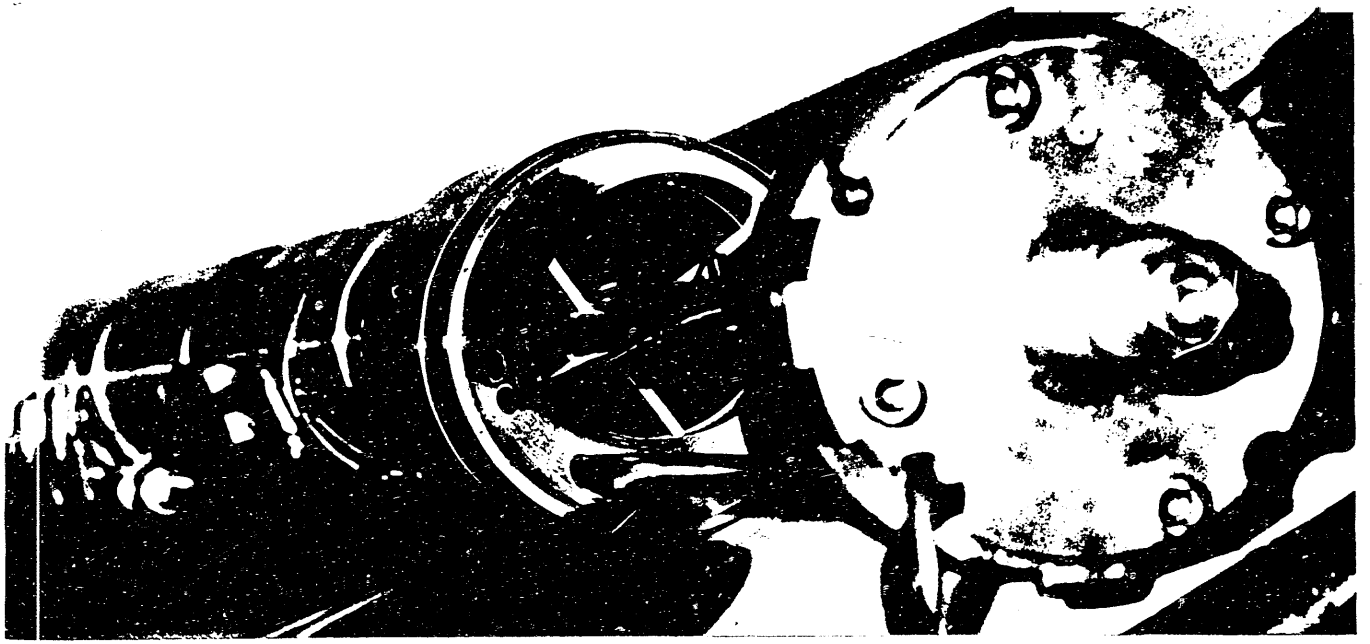


Fig. 4

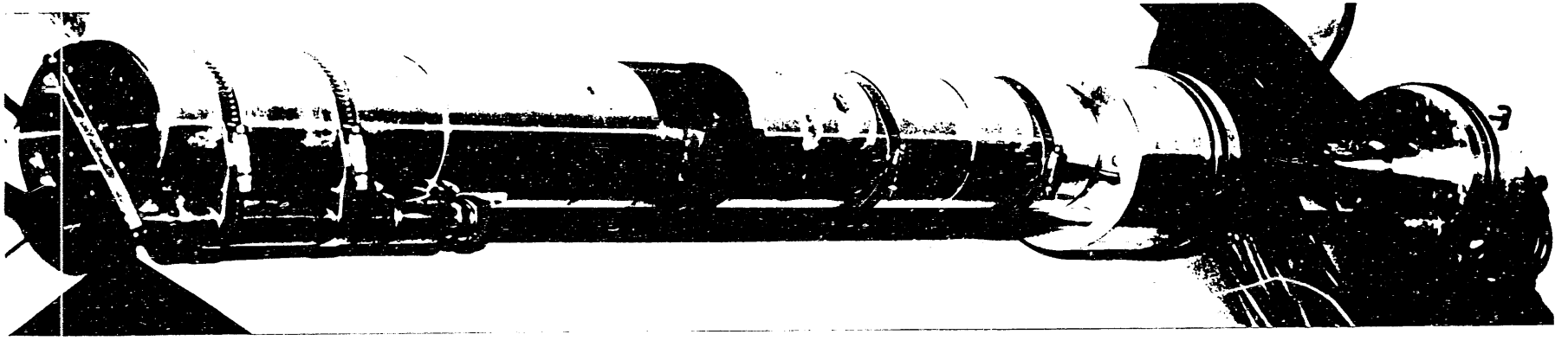


TOP

F10a (Sensor)

58%

50214-18

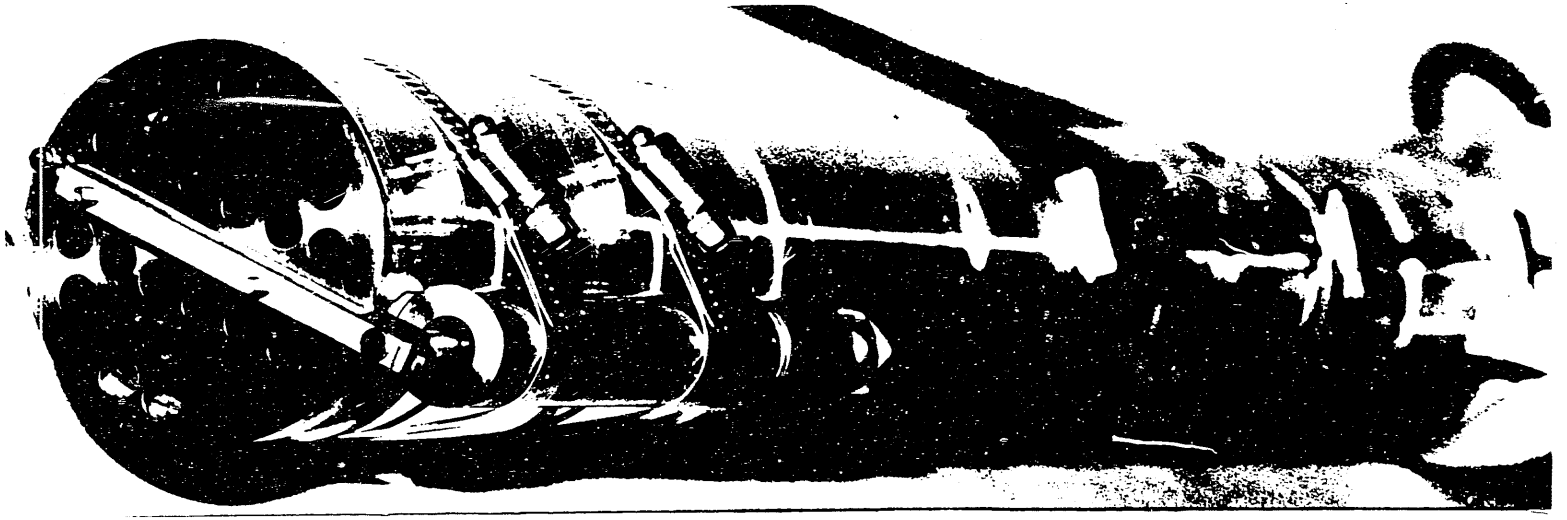


MIDDLE

F10b (Turbinometer)

44%

50214-15



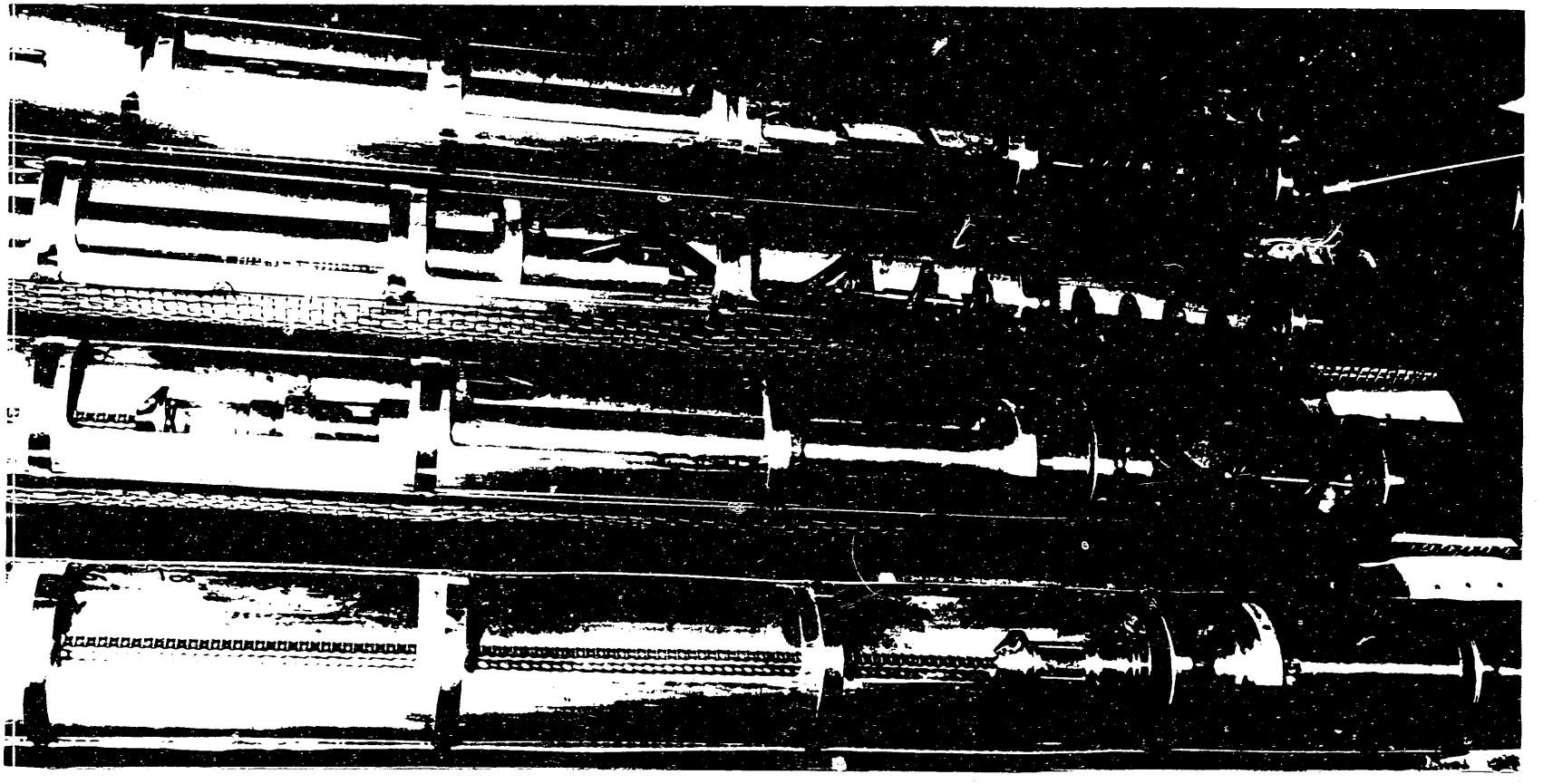
BOTTOM

F10C (Drag Meter)

50%

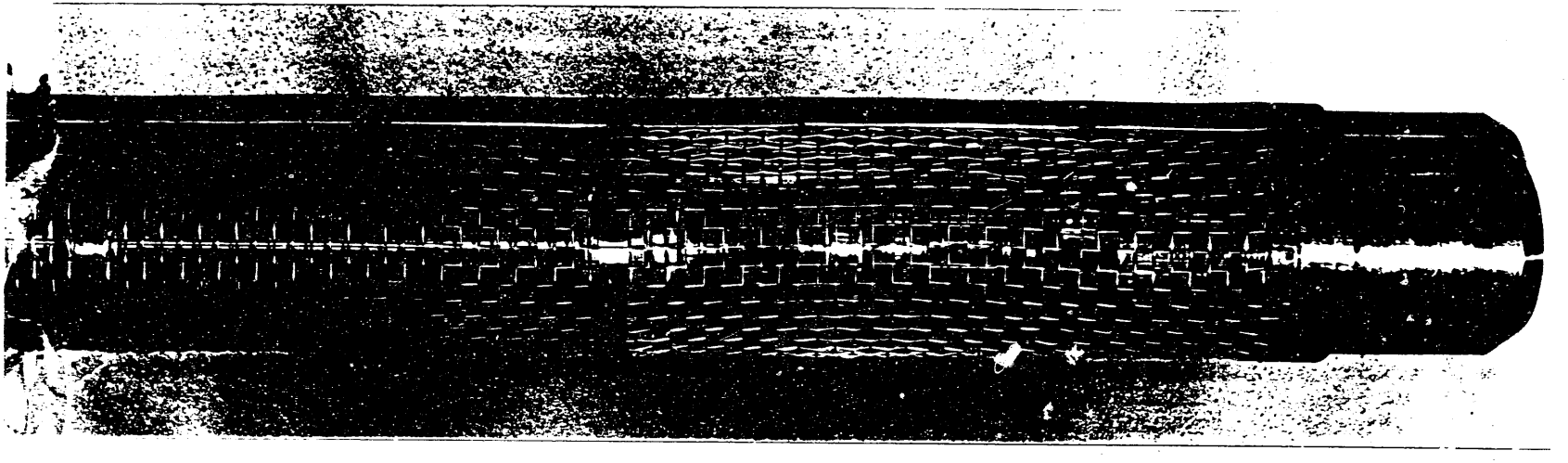
50214-16

Fig 10



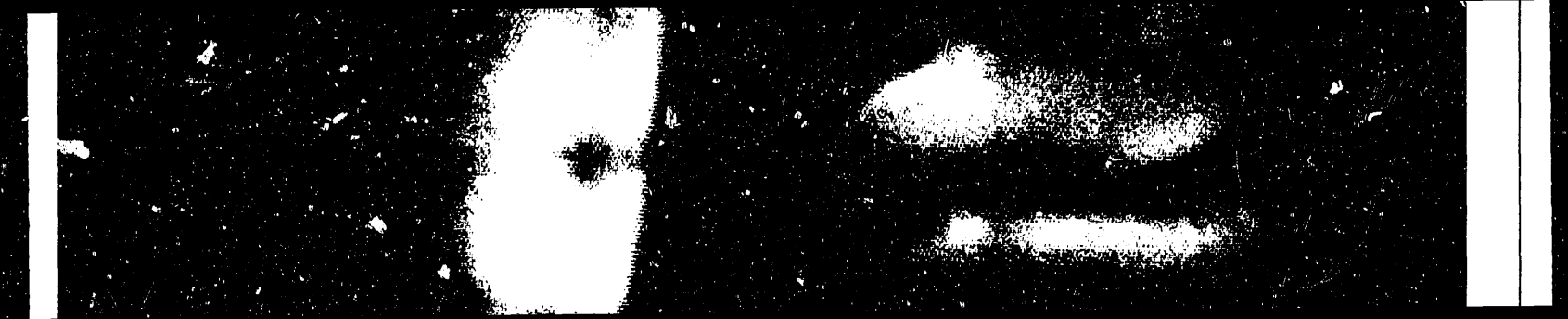
11b
(Rotating View Head)
50214-2
47%

P.5



11c
(View Window
89-
1193-4
47%

Fig. 11



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