CHARACTERIZATION OF FLOW IN A SCROLL DUCT

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Abstract

This work has been a qualitative, flow-visualization study on a partially elliptic cross-section, inward curving duct (scroll duct), with an axial outflow through a vaneless annular outlet. The working fluid was water, with a Re(d) of 40,000 at the inlet to the scroll duct, this Reynolds number being representative of the conditions in an actual gas turbine scroll.

Both still and high speed moving pictures of fluorescein dye injected into the flow and illuminated by an argon-ion laser were used to document the flow. Strong "secondary" flow, similar to the secondary flow in a pipe bend, was found in the bottom half of the scroll within the first 180 degrees of turning. The pressure field set up by the turning duct was strong enough to affect the the inlet flow condition. At 90 degrees downstream the large scale secondary flow was found to be oscillatory in nature. The exit flow was nonuniform (in the radial direction) in the annular exit. By 270 degrees downstream, the flow appeared unorganized with no distinctive secondary flow pattern. Large scale structures from the upstream core region appeared by 90 degrees and continued through the duct to reenter at the inlet section.

Introduction

An extensive field of literature on small (low power) gas turbines has grown up since the proven use of these engines shortly after WW II. Lately, as a result of improvement in materials for rotor construction, interest in small axial and radial flow gas turbines has produced a small body of detailed information on these types of machines. These research efforts are aimed at better component efficiency and improved overall performance.

There appear to be two sources of these studies: the aerospace industry, whose interest is in radial inflow turbines (REF 1-5), and the automotive industry, who are primarily concerned with small axial flow turbines to power turbo-chargers (REF 6,7,8: Note - REF 6 contains a small but detailed bibliography of the most recent applications-oriented papers.) The focus of much of the initial work in both areas has been on rotor design. However, it has been recognized that flow prior to the moving blades is of great importance. Until recently the flow was assumed to have uniform properties around the inlet to the turbine blades. Greater understanding of the inlet flow is necessary for improved performance of these engines. As some of the more recent studies from the University of Cincinnati on specific radial turbine scroll ducts have pointed out, the inlet flow conditions to the rotor (even in the case of stationary blades prior to the rotor) are highly three dimensional, and frequently nonuniform around the annular inlet to the turbo-machine blading.

The scroll duct passage directs the power fluid from a tangential direction (relative to the direction of rotation of the rotor) to the rotor, or stator, at some design condition. Axial and radial scrolls differ in the redirection of the power fluid. They also differ in that axial and radial moving blades have different inlet velocity requirements (relative to blade speed). However, both must deal with similar problems. Theoretically, they both should deliver flow through a tightly curved duct to a constant area exit passage which is normal to the "through" flow direction. Practically, scroll ducts have strict constraints on volume and geometry due to their component position in an operating assembly.

In an attempt to provide a better understanding of the fluid mechanics of flow in a scroll duct the present study has documented the downstream development of flow in an axial outlet, vaneless, scroll duct of partially elliptic cross section. Still photograpy and high speed movies have been used to map the wall and core flow from the inlet, downstream to its exit location. Particular flow patterns and exit conditions have been identified . The identification of certain flow phenomena will immediately provide the turbine designer with a realistic idea of inlet velocity conditions. Further, it will provide insight into the mechanisms controlling the "secondary" flow and help

Experimental Apparatus

A schematic of the flow system used is shown in Fig. 1. The water was at approximately 16 C. A centrifugal pump directed the flow to the plenum chamber then onto the test section. A line branched off the exit piping from the pump which allowed water to be recirculated back into the large supply tank. Both the test section flow and the recirculating flow had valves immediately after the branch to control the respective flows, thereby setting the flow conditions. A paddle wheel type flow meter was in place five meters downstream of the test section control valve. The flow entered a 53.3*30.0*30.5 cm3 (L*W*H) plenum chamber through a 7.5 cm line. Perforated plates were placed at 7.5 cm and 22.5 cm downstream of the inlet to the plenum to produce uniform flow.

From the plenum chamber the flow entered a 35 cm fiberglass transition piece which was connected by a flange to the exit of the plenum. The 15 cm circular exit of the plenum had smoothly rounded edges. The transition piece, from 0 to 17.5 cm downstream of the plenum chamber, changed from a circular cross section of 182.33 cm2 to the partially elliptic cross section of 113.49 cm2, in a converging manner. From 17.5 cm to 35.0 cm it remained a constant area duct having the same cross section as that of the scroll entrance.

The scroll duct model was mounted such that the "through" flow direction was in the horizontal plane. Being an axial flow turbine model, the scroll duct exited vertically into an annulus formed by a 15.0 cm inside diameter clear cast acrylic pipe, and an 8.9 cm outside diameter PVC pipe, these measurements having been the exit dimensions of the model provided. The vertical annular exit extended 20 cm. At that point the inside pipe wall became a conical hub and exited the annular flow into a 15.0 cm pipe. A 15.0 cm to 10.0 cm pipe reducer, immediately followed by a 90 degree elbow and a 3.5 m length of pipe, returned the exit flow to the large tank. See Fig. 2.

The scroll duct model was enclosed in a rectangular plexiglass tank. During operation the tank was filled with water, covering the scroll model and annular exit. This minimized optical distortion, making visualization and photographic documentation possible within the highly curved surfaces of the model.

Two fittings allowed the insertion of probes through which dye was added to the flow. One fitting was in the transition piece, 2.5 cm upstream of the entrance to the model. Probes inserted here allowed dye to be added at any location in the entrance plane of the model. The other fitting was in the 15.0 cm to 10.0 cm PVC reducer, located in the exit piping. The 0.17 cm diameter stainless steel tubing used for dye injection could be inserted through the fitting and be placed at any angular location around the scroll. This allowed access to the annular passage and most of the through passage of the model.

Scroll Geometry

A clear acrylic model fabricated by the Chrysler Corporation was provided by NASA Lewis for the present effort. The wall thickness of the model was approximately 0.16 cm. Its geometry was complicated. See Fig. 3. The shape of the cross section at the inlet to the scroll was an ellipse with its major axis rotated 45 degrees from the vertical. At 90 degrees the cross section of the through passage was nearly circular, except for the slight distortion on the inside walls due to the configuration of the annular exit. At 180 degrees the cross section was elliptic, with its major axis vertical, with even greater distortion due to the relative increasing exit dimension. By 270 degrees the exit dimension was approximately 1/2 the height of the duct. The cross section of the duct appeared as an elongated ellipse with a straight outer wall, cut along the vertical axis and matched to the exit walls. The duct continued around, diminishing in cross sectional area with the exit dimension remaining constant, until it joined into itself on the inside wall of the inlet section.

The scroll model had total visual accessibility. Photographic documentation of the model was primarily at angular locations of 0, 90,180,270 degrees.See Fig. 3. These cross sections provided minimal optical distortion and good representation of the flow as it developed.

Experimental Procedure

The scroll model was in a closed loop water system. The flow rate was controlled by opening or closing a gate valve in the supply line to the test section. The recirculating flow was controlled to minimize agitation of water in the pump and in the resevoir, thereby decreasing air bubbles in the flow to the test section.

After the system was filled with water, air purged from the plenum chamber and model, and the desired flow rate was reached, a line supplying fresh water to the reservoir was opened. An overflow drain maintained a constant level in the reservoir. This was done to minimize the build-up of dye concentration in the system.

An inlet Reynolds number, based on hydraulic diameter, of 40,000 was the condition at which the flow field in the scroll duct was investigated. With an inlet area of 113.49 cm2, this condition corresponds to a flow rate of 248.67 l/min and an average inlet velocity of 0.3660 m/sec. Still photographs and movies were taken at each of the five cross sections shown in Fig. 3, and for each dye injection point. Except for section 1, all photographs were taken looking downstream.

An argon-ion laser, at wavelength 488 nm, was used to illuminate flourescein dye injected into the flow. A cylindrical glass rod placed horizontally in the laser beam created a vertical plane of light in the test section of approximately 1 mm thickness. This plane of light was directed normal to the inside annular wall.

For sections 1 and 5 a mirror was required to direct the laser beam to the correct location. After the beam was reflected off the mirror and directed to the test section, the glass rod was placed in the beam to create the plane of light. Both the mirror and the glass rod were portable and could be moved to any location around the test section. The laser was on a movable table, providing optimum positioning of the lighting equipment with respect to the test section.

Dye injection was accomplished by use of a small, submerged, positive displacement pump with a needle valve to control the injection rate. The dye injector unit was designed specifically for flow visualization, and would deliver at steady, even rates.

Fluorescein dye was used for the visualization. Various dye concentrations were used in conjunction with different laser power settings in order to provide the best lighting conditions. Mixtures from 1:20 to 1:30 parts strong dye solution to water, with 3 watts (full) laser power, provided the best photographic lighting conditions. (Strong dye solution as recommended by Kodak: 2.5 g powdered dye, 1 tblsp alcohol, 1 l water.) Motion pictures required more light and ,therefore, use of the higher dye concentration mixtures.

Photography

A 35 mm camera, +1 and +2 close-up lenses, 400 ASA black and white film, and a number 15 Wratten filter (Kodak) were used to document the flow field by still pictures. The close-up lenses reduced the focal length of the standard 50 mm camera lens and provided slight magnification of the photograghic image. The number 15 Wratten filter allowed only fluorescent light through, eliminating most of the incident and reflected light and providing much better contrast of the dye image with the surroundings. (It also reduced the amount of light available, requiring slower shutter speeds and smaller f-stops. However, the improvement in picture contrast justified use of filtering.) Each combination of scroll section being photographed and dye injection point gave different light conditions, hence different camera settings. Standard light meters were of no use in determining the necessary camera settings (unless the user had a great deal of experience with laser fluorescent dye and filters). By bracketing - picking an f-stop and taking several pictures at different shutter speeds - the best settings were found. All pictures were taken using f-stops up to 5.6, and shutter speeds between 1/60 and 1/500 of a second. Typical camera settings were f-4 @ 1/125. A record of camera settings, scroll section and dye injection point were kept for each photograph taken. All illuminated scroll sections were normal to the still water box surrounding the model.

A 16 mm LOMAC, high speed, movie camera with a 12.5-75 mm zoom lens, a +1 diopter auxiliary lens, Eastman 7250 color video news film and number 15 Wratten filter were used to take motion pictures. The camera was capable of filming at rates to 400 frames per second. However, lighting conditions only allowed frame rates of between 100 and 125 frames per second. Camera angles were the same as those used for still pictures. Several filming sequences of four seconds each were taken at each of the five cross sections for the same inlet flow conditions and for each of the dye injection points. This provided a check for consistency of the gross and the secondary flow, and hence for pictures that were representative of the flow.

Results

Documentation of the developing turbulent flow (Re(d)=40,000 at entrance) in a geometrically complex, axial outlet, vaneless scroll duct has shown a highly three dimensional flow field. Large secondary flow patterns similar to the classic pipe bend flow were identified. Distinct smaller vortices were present in the flow. They were evident near the walls where they appeared to act as momentum transport mechanisms, interchanging the wall and core fluid. Large scale structures , on the order of the channel dimensions, were identified from 90 derees through and into the reentering flow.

The following is a description of the flow. All descriptions are of sections viewed in the downstream direction .

Section 1

All wall injection points showed strong secondary flow affects were present at, or immediately after the dye injection plane. The strongest crossflows were in the lower wall boundary layer. The cross flows were nearly as strong on the top and outer walls. The bottom wall (W3) had a relatively sharp corner in it, causing a build up of slow moving fluid; hence more fluid was moved inward off the bottom wall.

Flow from the knee was mixed by large scale action and moved further from the wall faster than at any other injection position on the wall. Although there was a noticeable amount of fluid which was caught in the top wall cross flow, the majority of the flow moved downstream, maintaining its relative position on the outer wall.

Both top wall injection points (W6,W8) showed the dye moving inward along the top wall. See Fig. 4A. The angle which the top wall cross flow made with the through direction centerline was not quite as drastic as the bottom wall cross flow angle
(20-25 degrees as vs. 25-30 degrees respectively). Dye injected from the five core points all appeared as "turbulent" streamlines at section 1. See Fig. 4B.

Section 3

At 90 degrees of turning the lower inner wall flow (W1) had moved up the inner wall to a position above midspan, and had partially exited on the inner annulus wall. The lower and outer wall (W3,W5) flow was driven in a consistent manner inward and up the inner wall. The lower wall flow had reached the exit level on the inner wall. The outer wall flow was very near, but not at the exit level on the inner wall. Some of the outer wall flow moved off the bottom wall and up into the lower 1/3 of duct, but still formed a continuous structure with the fluid on the wall. A rather consistent CCW vortex (on the order of 1.0 cm) had assmed a position on the lower inner wall. See Fig. 5A.

The knee flow had mixed to occupy 1/4-1/3 of the outer duct above midspan. Additionally, there was an obvious cross flow established across the top wall which transported fluid from the knee region to the exit on the outer wall of the annulus. There was a slight separation from the outer annular lip all around the annular exit, probably due to the sharp change in flow direction. The flow quickly reattached to the wall at approximately 0.5 cm downstream from the entrance to the annulus.

All of the top wall flow (W6,W8) had moved across the wall under the influence of the cross flow and had partially exited by here. The upper inner wall (W8) injection flow was covering the top wall from the outer annular position to 1/3 of the channel in the radial direction. The upper outer wall (W6) injection flow covered the top wall across the entire channel width with some large scale mixing into the upper 1/4 span of the channel. See Fig. 5B.

The core flow maintained its same relative position with respect to its positon at section 1. Flow from both upper and lower core injection points (C1,C3) remained close to a turbulent streamline in their respective relative positions. The lower inner core had stretched slightly in the radial direction, taking on an orientation parallel to the wall. See Fig. 5C. The upper inner core was exiting close to but off the outer wall of the annulus. The outer upper core flow structures which spanned the lower 1/2 of the channel. See Fig. 6C. The upper outer core (C4) had mixed well with the fluid from the knee and occupied a common area with the flow originating from the knee. The center core (C5) continued to occupy the center of the channel as a close grouping of stringy structures. See Fig. 6D.

Section 5

At 270 degrees of turning, flow from both wall and core points were well mixed and less organized in terms of their positions in the passage, even over a reasonable time average. The core flow maintained more distinct stringy-type structures compared to the wall flow i.e., when they were mixed in a common region the string type features distinguished the flow as having originated from the core. The flow from the lower inner wall (W1) had exited by here except for random appearances of vortical structures. The lower wall flow (W3) maintained its position from section 4, but more flow had exited and there was more mixing into the lower half of the channel. The outer wall flow (W5) had mixed evenly across the entire channel, but still contained large scale structures. See Fig. 7A. Flow from the knee appeared almost identical to the flow originating from the outer wall at this point. Flow from both top wall injection points (W6,W8) had completely exited by this location. See Fig. 7B.

The lower inner core (C1) appeared as linked stringy structures occupying the lower half of the channel. A small but distinct portion of this flow exited up the inner wall of the annulus. The lower outer core (C2) occupied most of the channel inconsistently but distinctly, except for the upper right quadrant. A small portion of the flow exited on the inner wall in the same inconsistent manner. See Fig. 7C. The upper inner core (C3) had completely exited by this point. The upper outer core (C4) appeared as randomly placed large scale structures, superimposed on small scale, diffuse structures throughout the passage. The center core (C5) was similar to the outer core except the large scale structures were more distinct, and there was less of the diffuse background fluid. See Fig. 7D.

Analysis of Results

Initially, a strong secondary flow similar to the classic pipe bend flow was seen to exist, particularly in the first 90 degrees. Between 90 and 180 degrees of turning a distinctly smaller scale vortex structure, which was particularly noticeable on the inside walls (approx 1.0 cm), was incorporated into the overall flow. By 180 degrees of turning the smaller vortices were strong and consistent, and the secondary flow had diminished slightly from its strong presence at 90 degrees. By 270 degrees, the overall secondary flow appeared to have weakened and become inconsistent. Large structures from the upstream core and small vortex structures persisted. Most of the large scale structures which had not exited by here reentered the scroll duct.

The comparison of flow in a pipe bend to the flow in a scroll duct shows many similarities. Fluid entering a bend sets up a pressure gradient by which the turning of the fluid occurs. There were obviously strong secondary flows on the top and bottom walls of the scroll duct immediately upon entry to the scroll, very similar to a pipe bend. By 90 degrees of turning there was a noticeable large scale CCW rotation set up in the bottom half of the scroll duct. The movies showed a tendency for the secondary flow to oscillate. (See REF 9,10)

Although there were strong qualitative similarities between flow in a pipe bend and flow in a scroll duct, there were also significant differences. The full secondary flow circulation in the upper half of a pipe bend never appeared in the scroll duct. There was never any obvious outward flow at the mid-span, even though the top and bottom wall cross flows were strong and consistent. The secondary flow in the scroll duct did not settle down to become steady, as in pipe bend flow. The fact that there was a mass flow exit normal to the "through" flow direction could not be addressed by pipe bend theory. The parallelism may even be misguiding because of the three dimensional "through" flow of scroll ducts.

The flow exiting through the annulus until 270 degrees of turning, was well organized into two major regions - the outer and inner regions (named with respect to the radial distance from the center of turning). The inner region, which spanned the greatest part of the annular exit (approximately 2/3), was swirling CCW. Entire vortex tubes appeared to exit on the inner wall, filling this region. The outer region could be separated into two easily recognized contributing regions. The outer wall contribution, which came from the top wall flow, and the upper inner core contribution. (Note - these are descriptions of the local contributing regions, not the origin of the flow.) Both of these outer region contributions showed little rotational motion. Within 0.5 cm downstream of the entrance to the annular passage the outer and inner region exit flows mixed to give an amazingly consistent gross flow exit angle around the scroll duct exit.

The flow which did not exit by 360 degrees came from the central core region. This flow, which contained random large scale structures at 270 degrees, reentered at section 1. However, the interaction of the reentering and the entering flows was not easily photographed, nor was it clear as to what was actually happening.

Conculusions

Optimizing performance of small axial or radial gas turbines requires specific knowledge of aerodynamic conditions at the inlet to the turbine blading. This flow visualization study has qualitatively verified the secondary flow pattern and identified conditions at the exit of a partially elliptic, axial outlet, vaneless scroll duct, with water as the working fluid, at Re(d)=40,000 at the entrance.

Qualitative agreement with three dimensinal flow in a pipe bend, particularly in the first 90 degrees of turning, has been verified. But increasing viscous effects in a narrowing duct, and the increasing ratio of axial mass exit to "through" mass exit for some finite volume, which requires the average flow to be described three dimensionally, present a unique problem to scroll designers.

The non-uniform radial mass flow distribution in the annular exit has been verified along with the identification of flow regions within the scroll which contribute to this exit condition.

A high degree of vorticity and vortex transport between the wall and core regions, particularly on the inner wall near the entrance to the annular exit has been observed. Large, unorganized, lengthy structures have been identified in the core flow region of the scroll throughout the 360 degree passage.

Recommendations for further work as a result of this study are :

1. Identify the relevant geometric parameters and their effects. Specifically, the location and the size (annular width) of the exit with respect to the through flow paasage. An experimental set-up for a simple geometry scroll duct could be fabricated which could easily be modified to allow the exit arrangement to be either axial or radial. Then documentation and analysis of the exit location-size problem could be done more generally, providing guidelines for designers of both axial and radial scrolls, and also provide information for verification of computational work based on the simplified geometry.

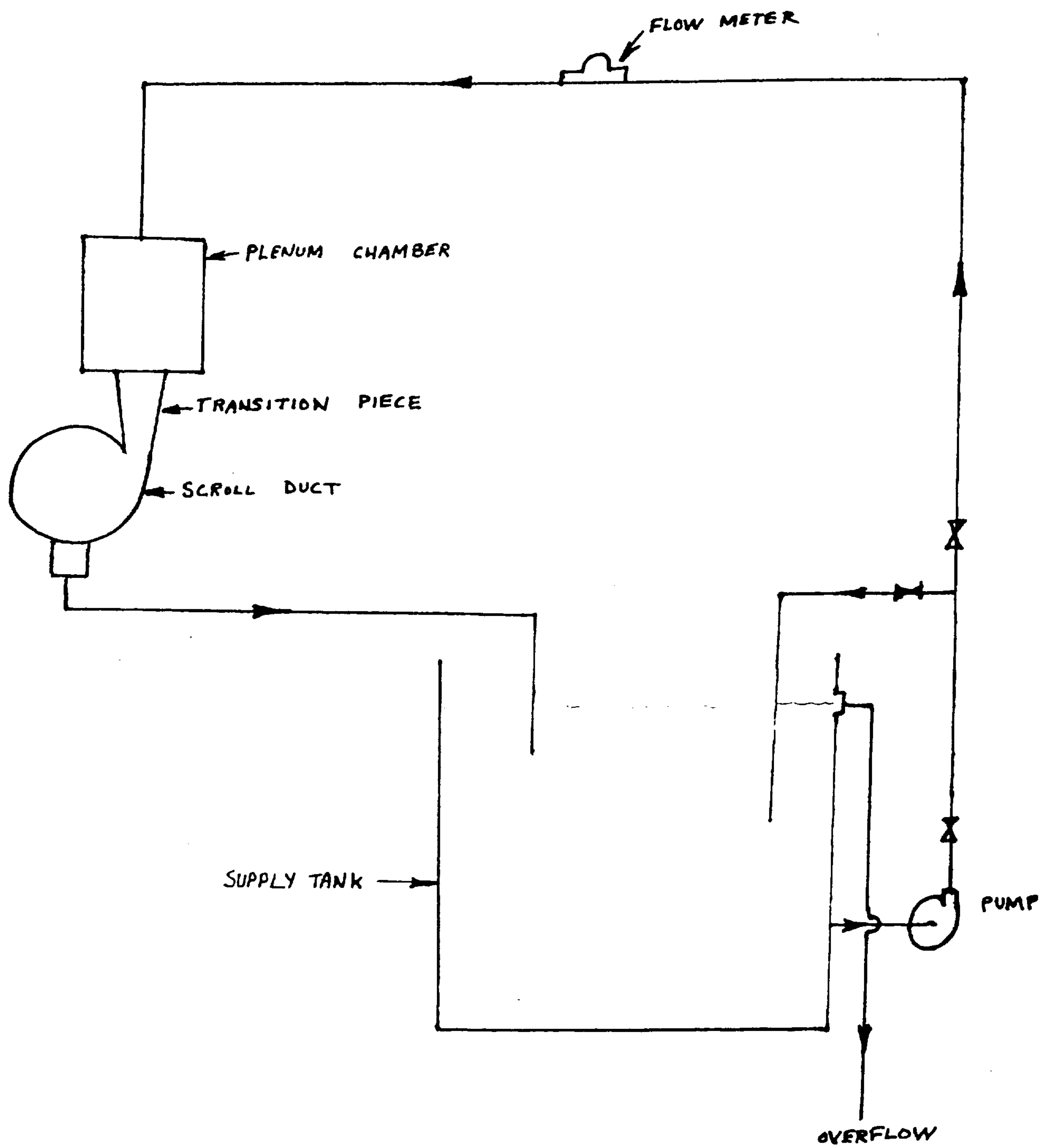
2. Identify the effect of different inlet velocity profiles on the secondary flow. Proper preconditioning of the inlet profile will effect the turning pressure field set-up in the scroll, possibly allowing for more uniform outlet conditions. It should be noted that because of the requirement of a tightly turning scroll, the pressure field in the scroll appears to effect the inlet velocity significantly.

3. Investigate Reynolds number dependence. This may be of interest in considering off design performance. Data from this may also be of use in verifying computational work.

4. Investigate the effect of blocking the reentering flow. The interaction of the entering and reentering flows was not clear. This work, in addition to being of value in isolating the mechanisms involved in the secondary flow, is of

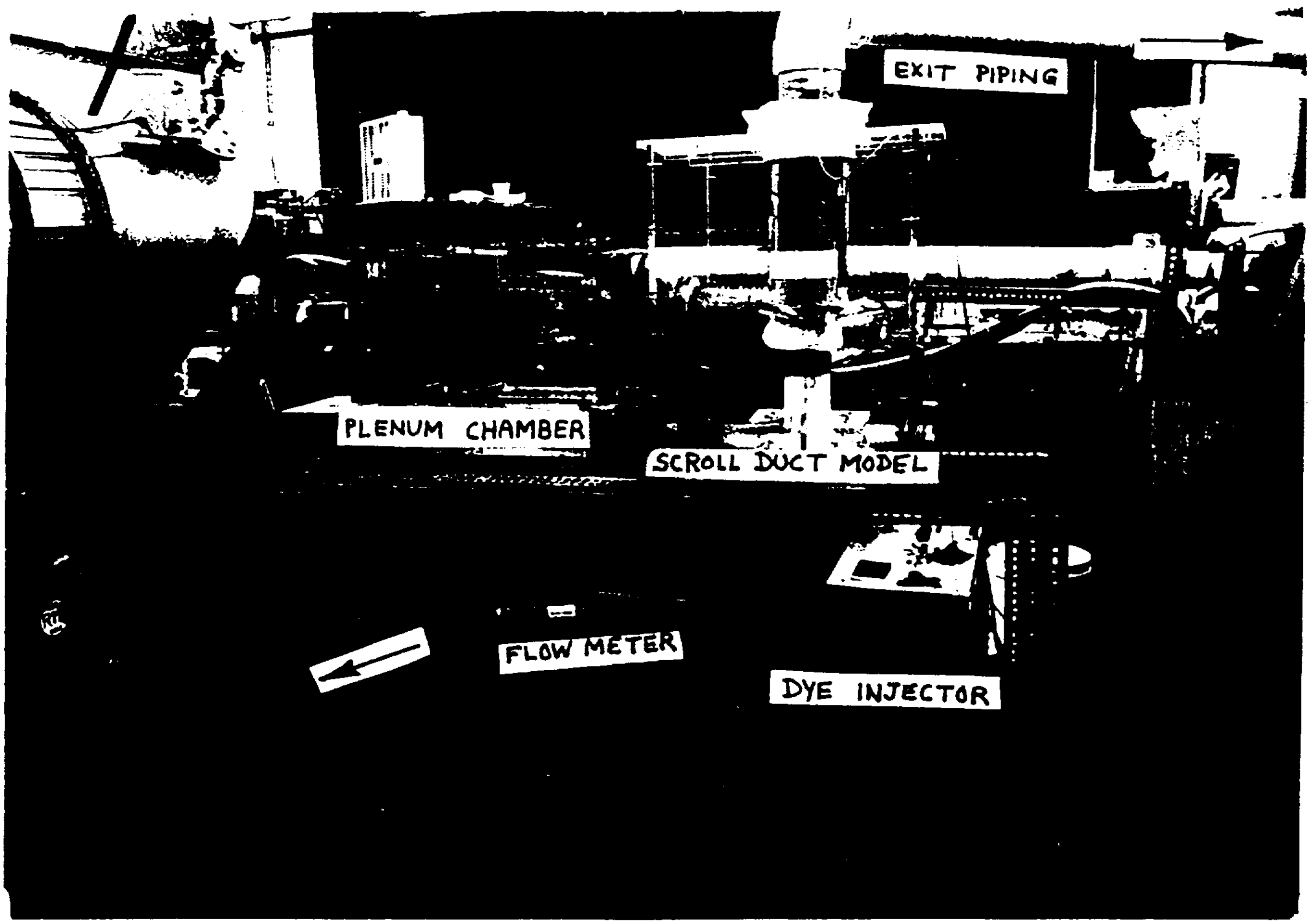
interest for comparison with existing codes at Scientific Research Associates.

FIG. 1



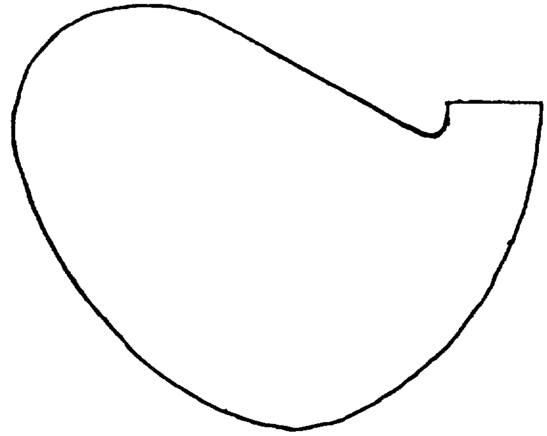
schematic of test system.

FIG. 2

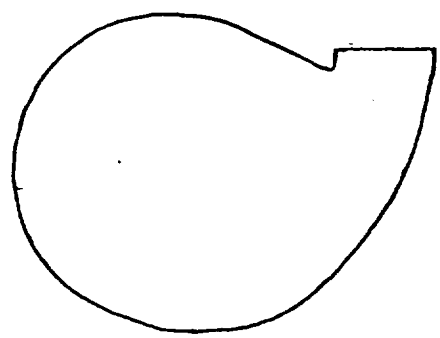


TEST SYSTEM

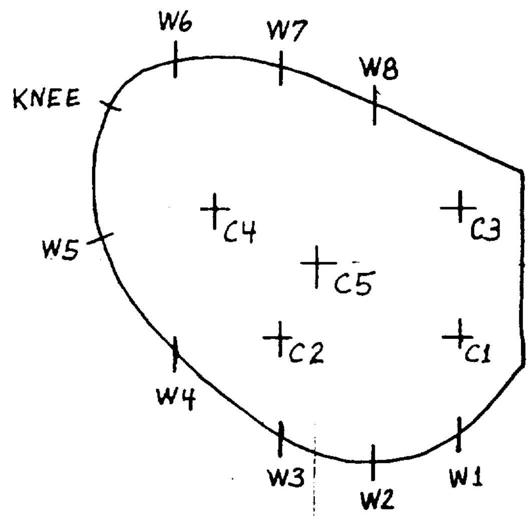
FIG 3



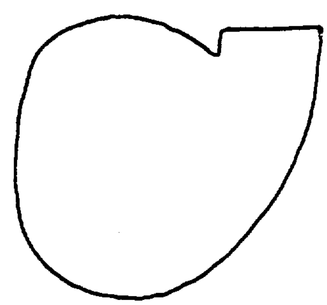
SEC. 1



SEC. 3

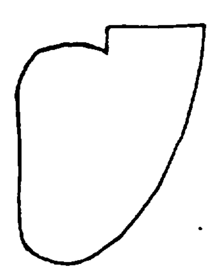


INLET PLANE & DYE INJECTION POINTS



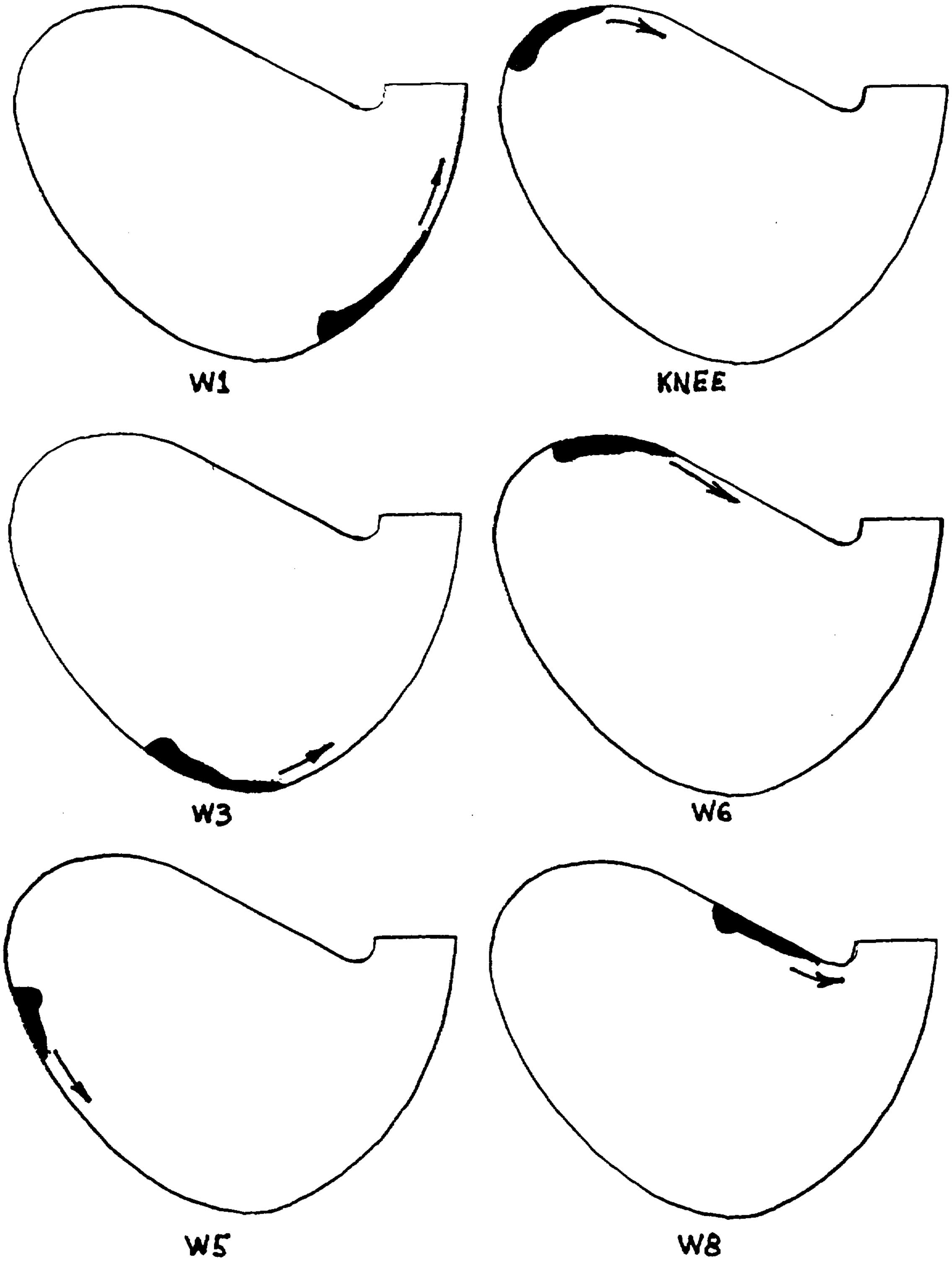
SEC. 4

NOTE - ALL CROSS SECTIONS VIEWED IN THE DOWNSTREAM DIRECTION.



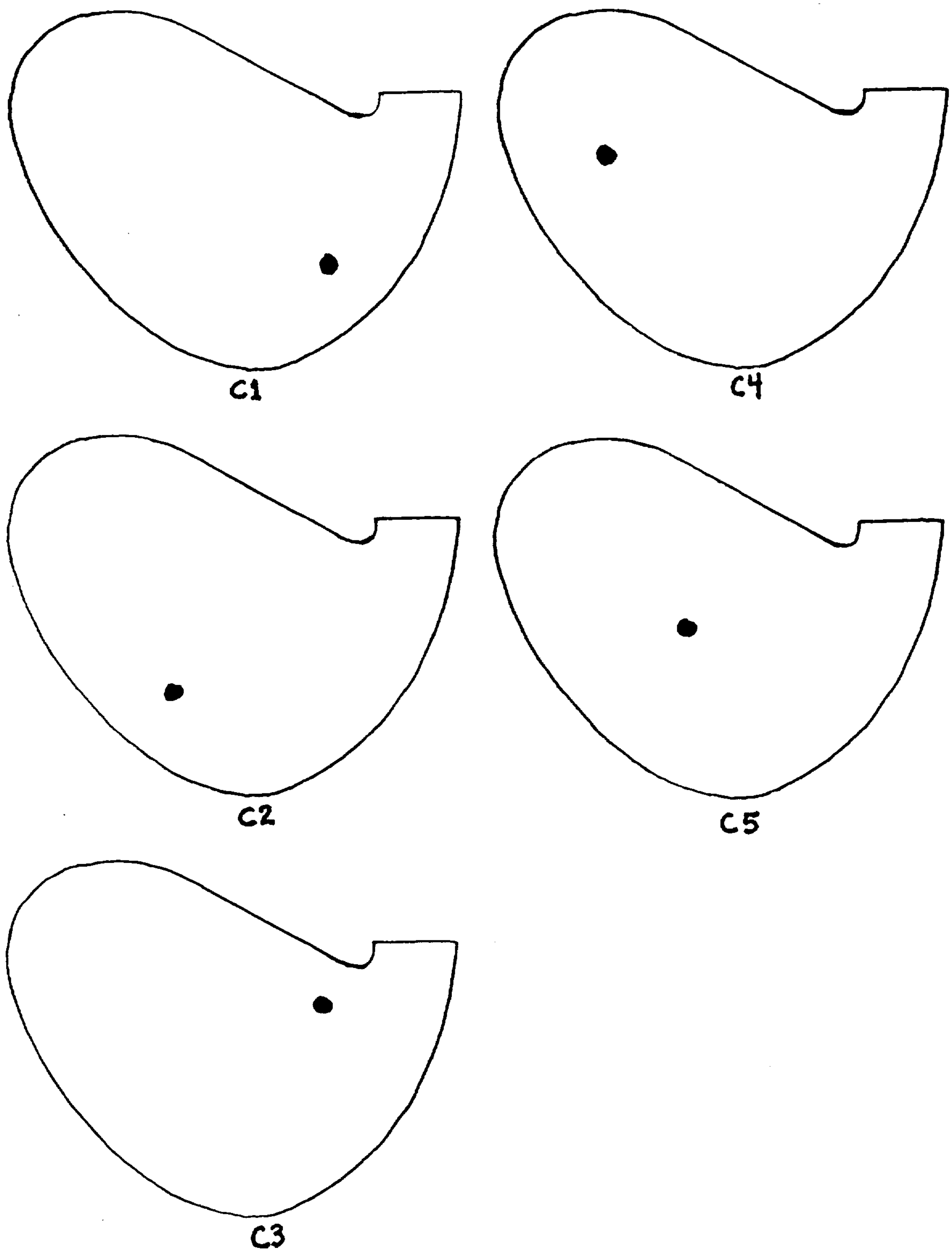
SEC. 5

FIG 4A



RESULTS

SECTION 1.



RESULTS

SECTION 1.

FIG. 5A

KNEE

W6

W8

FIG. 5B

C1

C2

C3

FIG. 5C

C4

FIG. 5D

C5

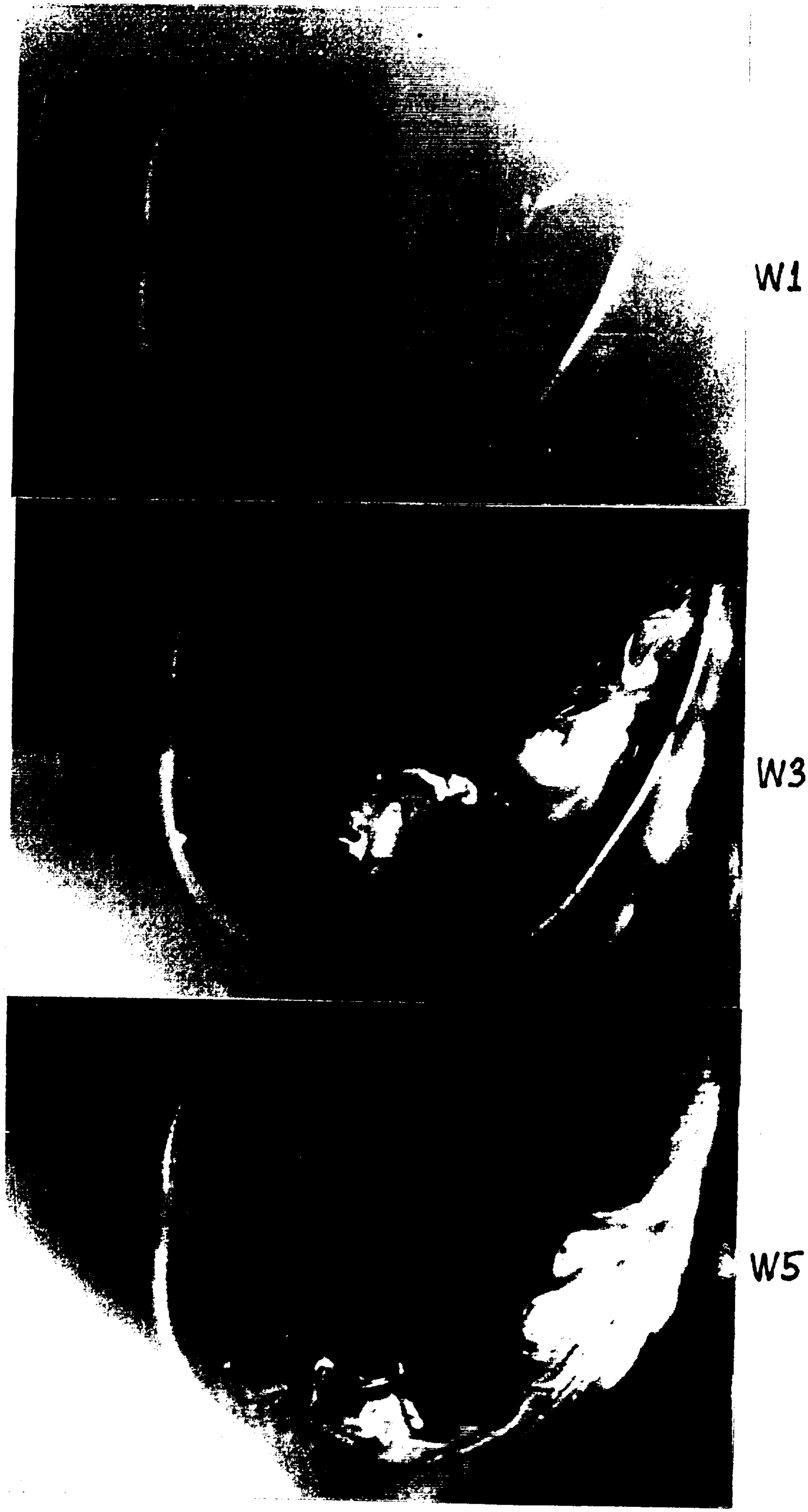
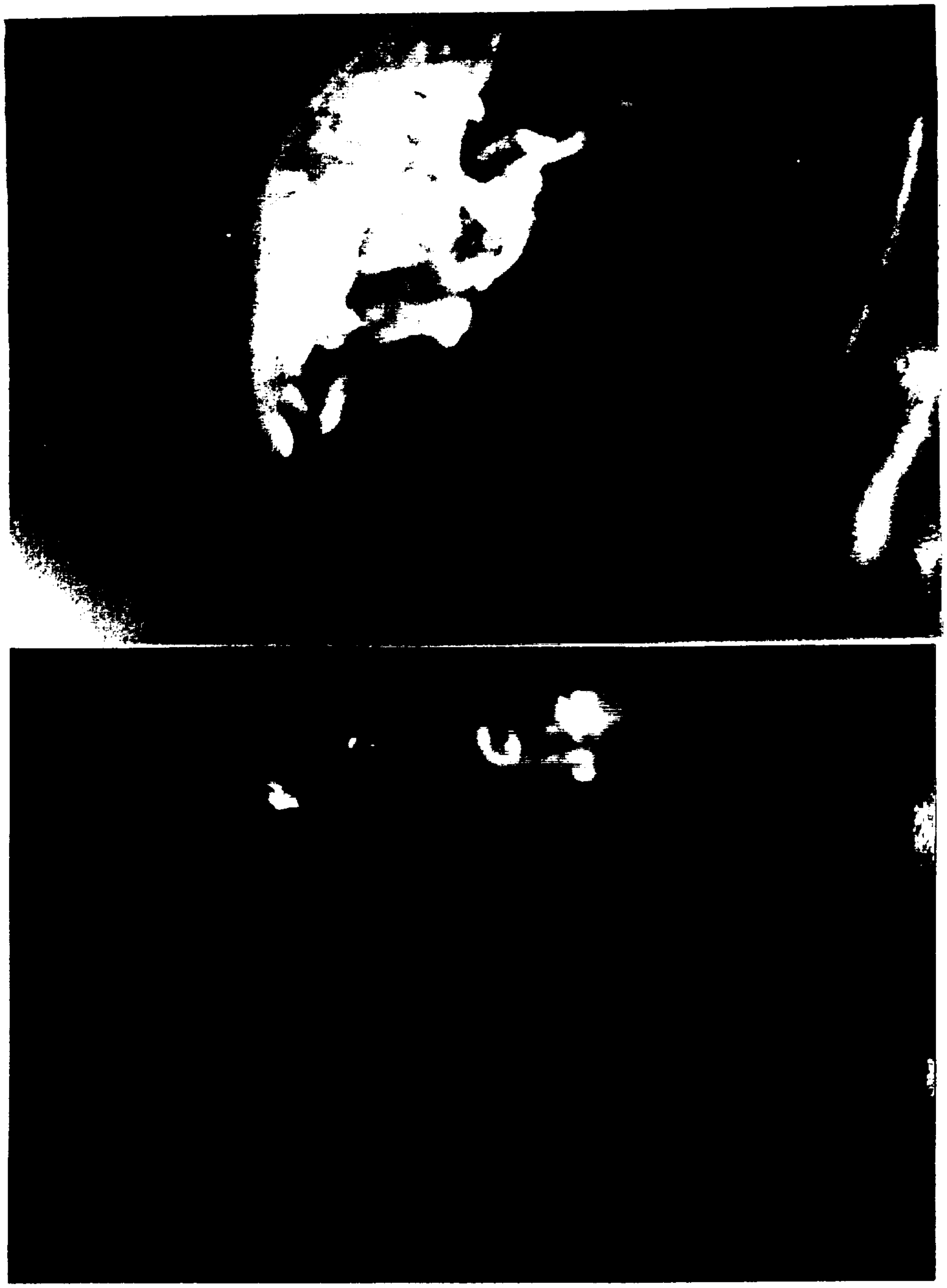


FIG. 6A

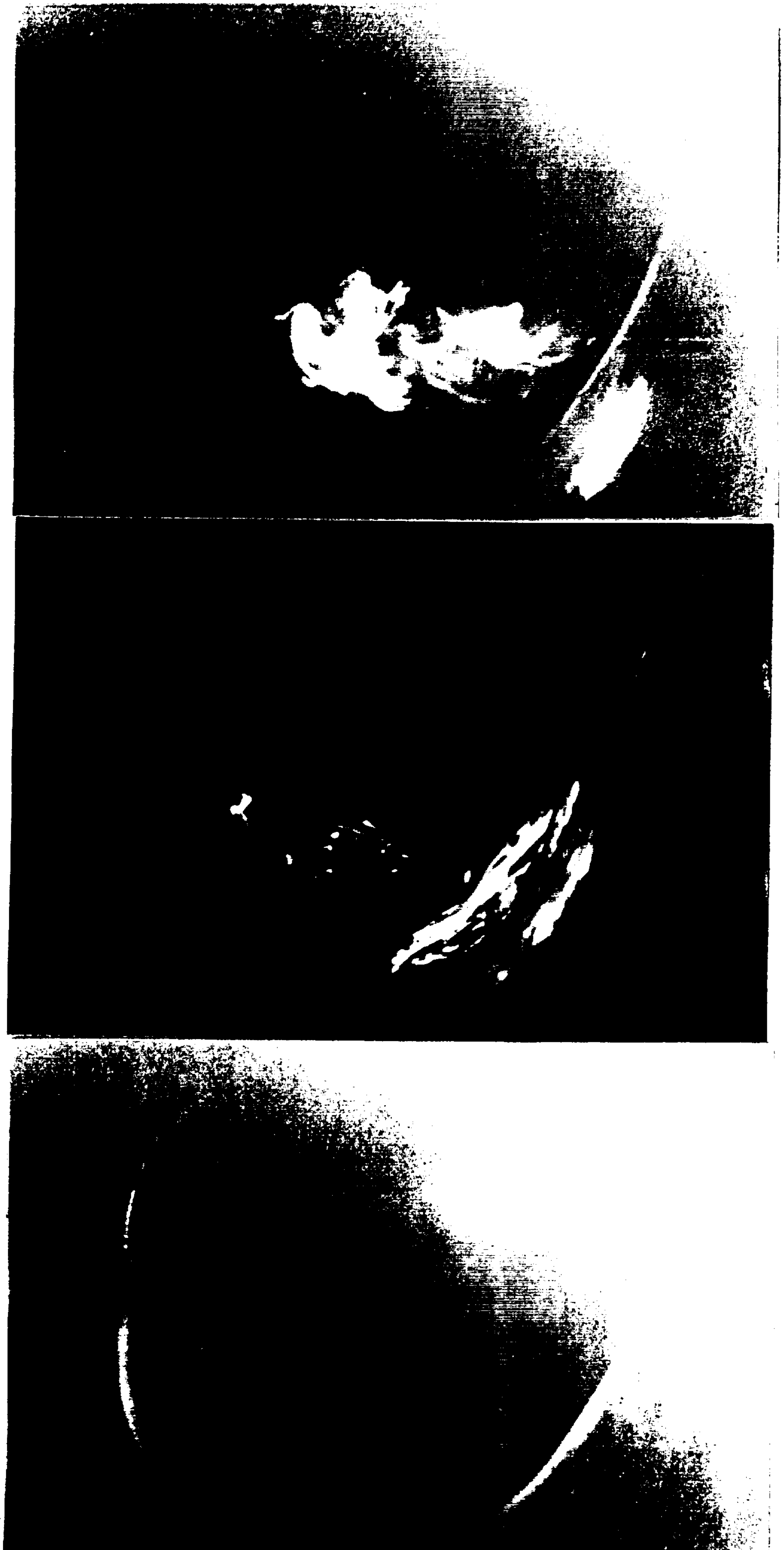
ORIGINAL PAGE IS
OF POOR QUALITY



KNEE

FIG. 6B

WG



C1

C2

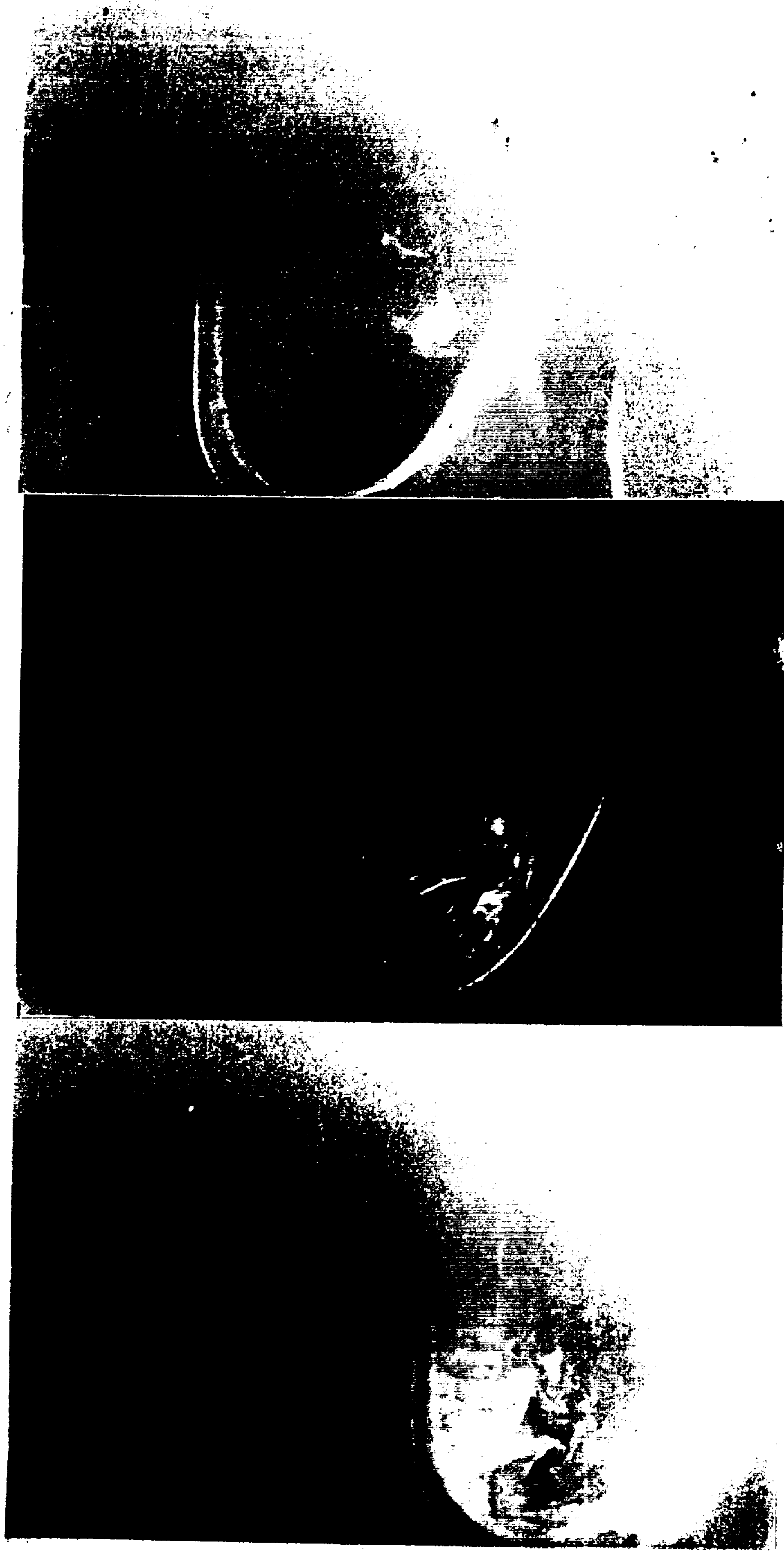
C3

FIG. 6C

C4

C5

FIG. 6D



W1

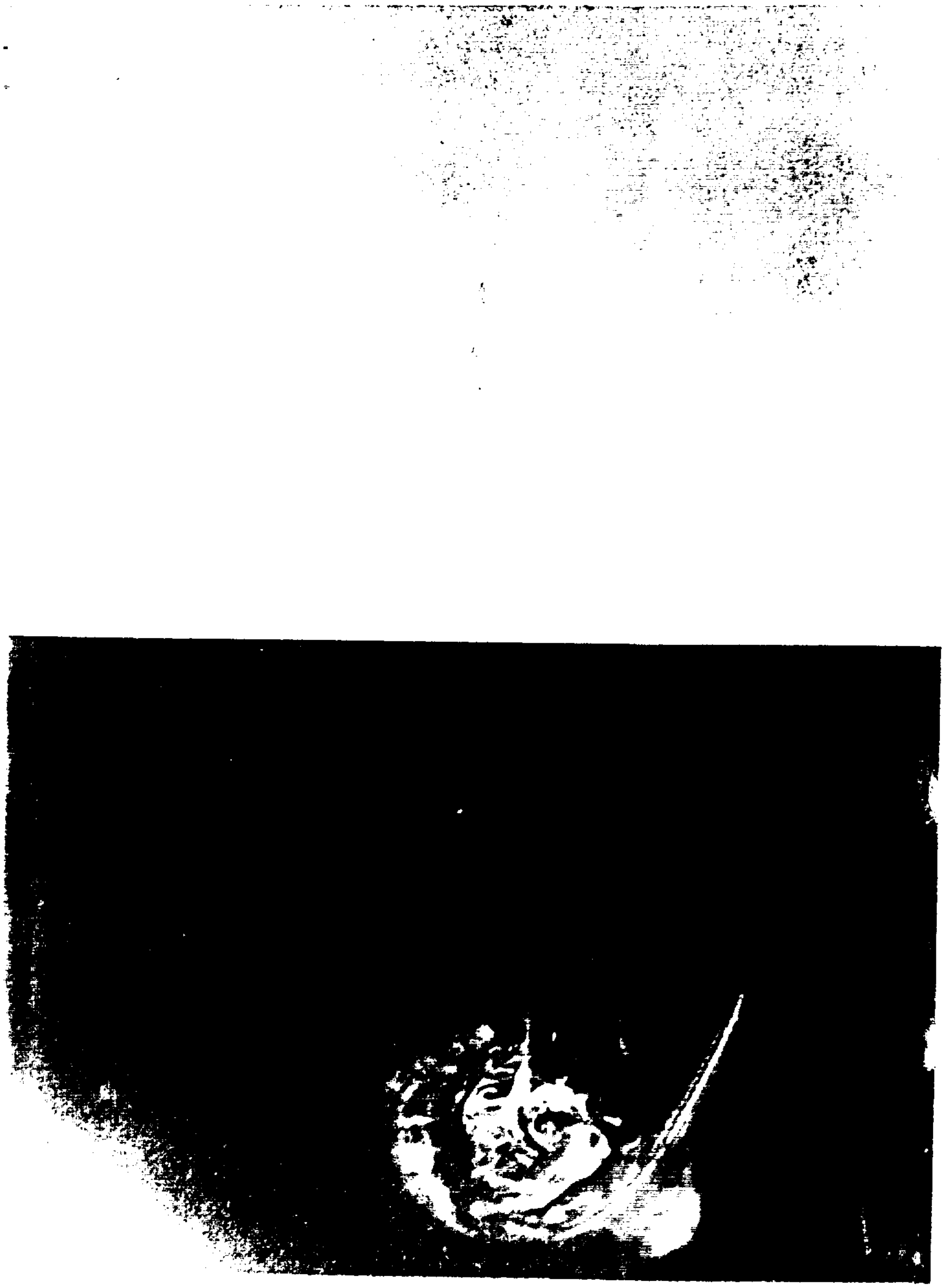
W3

W5

FIG. 7A

KNEE

FIG. 7B



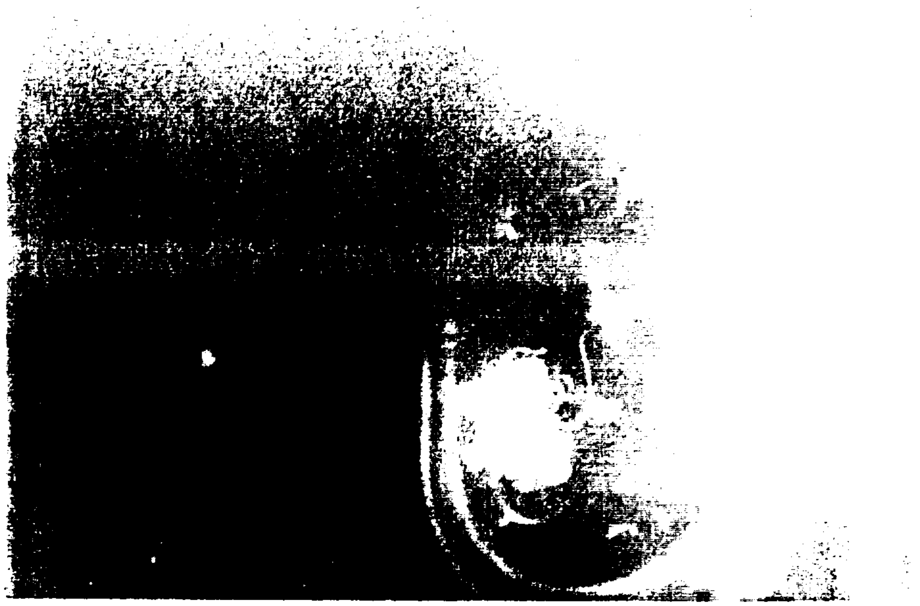
C1

C2

FIG. 7C

C4

FIG. 7D



C5

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