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PRELIMINARY REMOTE SENSING OF THE DELAWARE ESTUARY

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MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY
WASHINGTON, D.C. 20242

Interagency Report
NASA-128
October 1968

Mr. Robert Porter
Acting Program Chief,
Earth Resources Survey
Code SAR - NASA Headquarters
Washington, D.C. 20546

Dear Bob:

Transmitted herewith is one copy of:

INTERAGENCY REPORT NASA-128

PRELIMINARY REMOTE SENSING OF THE DELAWARE ESTUARY*

by

Richard W. Paulson**

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Sincerely yours,

William A. Fischer
Research Coordinator
EROS Program

*Work performed under NASA Contract No. R-146-09-020-011
Task 160-75-01-63-10

**U.S. Geological Survey, Philadelphia, Pennsylvania

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Contents

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ABSTRACT

Potential applications of remote sensing techniques for estuarine hydrology have been revealed by an analysis of infrared imagery and aerial photography of the Delaware estuary. It is clear that infrared imagery can be an important estuarine reconnaissance tool. In addition, the analysis indicates that estuarine circulation, reaeration, and dispersion might be effectively studied with remote sensors.

Introduction

Purpose of Program

The U.S. Geological Survey, in cooperation with the National Aeronautics and Space Administration, is seeking to determine the feasibility of using remote sensors for investigating estuarine hydrology. These sensors, which have been used in the NASA space program, are being evaluated in many earth resources studies. As part of a study of remote sensing application for estuarine hydrology, this progress report described the remote sensors used on the Delaware estuary, Test Site 142. The data on which this report is based were obtained by the USGS on April 13, 1967, and by NASA using their Lockheed Electra NP3A aircraft on Mission 53, July 12, 1967.

Remote Sensors

Two types of remote sensors were used to collect data on the Delaware estuary by NASA and the Survey; aerial photography and infrared imagery.

Aerial photography involves the focusing with a lens and recording on a sensitive film the light reflected from a part of the earth. In the Delaware estuary program, color film and infrared color film were used. Color film is sensitive to the spectral range detectable by the human eye, while infrared color film is sensitive to this range plus part of the infrared band not detectable by the human eye.

An infrared image of the earth's surface is a two-dimensional map showing the relative intensity of electromagnetic radiation that is emitted from the earth in the 8-14 micron band. The 8-14 micron band is measured because it is one of the so-called atmospheric windows where absorption of the radiation by water vapor and carbon dioxide in the atmosphere is low. An infrared imager is an electronic scanning device that can measure the intensity of radiation from an object and produce a point on a photographic film whose tone is a function of the measured radiation intensity. By mounting the imager in an aircraft and successively scanning lines on the earth perpendicular to the flight path and orienting the lines on the film similarly, one is able to produce a photographic image of a strip of ground along the flight path. Since the intensity at which energy is radiated from an object is proportional to the object's absolute temperature raised to the fourth power, according to the Stefan-Boltzmann law, and is also proportional to the emissivity, which is a property of the material emitting the radiation, high radiation intensity regions are lighter in tone on the positive film than low intensity regions. Hence, if one makes an infrared image of a water body, high radiation intensity regions, and therefore warmer regions, are lighter in tone than cooler, low intensity regions. With this device one is able to make a map of thermal patterns on the water surface. Such a map might give information about current patterns, mixing capabilities and other hydrologic characteristics of the water body.

The Delaware Estuary

The Delaware estuary, an 86-mile long water body located between Trenton, New Jersey, and Liston Point, Delaware, lies in a heavily industrialized and densely populated section of the Northeast. Since the estuary is extensively used as a municipal and industrial water source, several government agencies monitor the chemical and physical characteristics of the estuary. The U.S. Geological Survey, for example, in cooperation with local and state agencies maintains seven continuously recording water quality monitors in the Delaware Estuary. The substantial amount of data that has been collected during the past 25 years in the Delaware estuary makes this an excellent location to test the sensitivity of remote sensors.

POTENTIAL USE OF INFRARED IMAGERY IN ESTUARIES

Since infrared imagery is especially useful for detecting thermal contrasts in adjacent water masses and provides a nearly synoptic picture of a water body surface, the hydrologist can study spatial and temporal changes in an estuary with imagery taken periodically in time. However, studies that might be attempted with infrared imagery must be related to phenomena that are associated with thermal contrasts on the water surface. Such contrasts are produced by man and nature.

For Reconnaissance

Infrared imagery may well be the first piece of data collected in a well-planned estuarine sampling program. The imagery will help define how complex the hydrologic regime is and might indicate optimal locations for water-quality sampling stations.

In the Delaware, the imagery tended to confirm the previously held concept that the estuary was well mixed. The estuary has this classification because spatial changes of water-quality parameters in the vertical and lateral directions are thought to be small in comparison to changes in the longitudinal direction. For example, there generally is no more than a three or four degree Centigrade variation of temperature in the entire length of the estuary at any given time if one excludes areas in the immediate neighborhood of industrial outfalls. Natural thermal contrasts do exist in the Delaware, but often they are very subtle.

In contrast, Wiesnet and Cotton (1967) show imagery of the Merrimack Estuary, located in northeastern Massachusetts, that reveals a very complicated pattern of fresh and salt water interaction during the tidal cycle. In places in that estuary during August and September, when the data were collected, there are ten degree Fahrenheit differences between contiguous cold salt water and warm fresh water masses. Such thermal contrasts in two dimensions hint at the possibility of differences in the third (vertical) dimension.

If one is required to plan a water-quality data collection program or perform current studies to determine the hydrodynamics of an estuary, infrared imagery can give a preliminary estimate of the complexity of the problem.

For Studying the Water-air Interface

A major difficulty of using infrared imagery to determine the absolute temperature of a water body is that the sensor measures the radiation from a thin surface film on the water, which usually is not the same temperature as the water mass itself. While this is an obstacle to one who wishes to measure the temperature of the water at depth, it may be helpful in a study of the surface circulation.

During the day, when water is being heated from above, the thin thermal boundary layer is generally warmer than the water mass, while at night when the surface radiates energy to space, the layer is normally cooler. Temperature differences between the water mass and the boundary layer, which may be only a millimeter thick, are about one degree Centigrade. For a more complete discussion of infrared imagery constraints see Frank (1964) and Lyon (1965). Ewing (1964) and Franceschini (1964) also discuss some factors affecting the boundary layer.

If turbulence is induced in water moving past a stationary object, the surface boundary layer may be destroyed. Figure 1 is a pencil sketch of imagery taken at night of the estuary, which shows the local downstream disturbance near two sets of pilings. As the tidal current flowed past the pilings, the vertical circulation in the turbulence tended to remove from the surface the thin film of cooler water that resulted from radiational cooling. A thermal contrast between the disturbed region and the surrounding area resulted and was detected by the imager. As the turbulence attenuated, the vertical exchange lessened and, within about 5 minutes, the surface layer reformed. This phenomenon may also be seen around the piers of the nearby Delaware Memorial Bridge.

There are other potentially important mechanisms that may cause vertical motion in the surface water of the estuary. It is known that the stress of wind on the ocean surface produces "...a series of alternating right and left helical vortices in the water having horizontal axes parallel to the wind," as described by Langmuir (1938). Woodcock (1944) provides further description of this phenomena in the ocean. This wind-induced surface circulation produces alternating zones of water convergence and divergence on the surface that generally parallel the wind direction. If one were to conceptually follow an average water particle involved in this circulation from a starting point on the surface, it would move to a convergence zone, descend, drift back beneath a surface divergence zone, ascend, and then drift back across the surface to a convergence zone. This circular motion in a vertical plane is superimposed on a general horizontal movement of the surface water in the direction of the wind. An idealization of the circulation is presented in figure 2. If radiational cooling is taking place during this process, the divergence zones might be warmer because the water has recently ascended; the convergence zones might be cooler because the surface boundary might have begun to form. There is also a tendency for floating objects and organic and petroleum surface films to be swept into the convergence zones.

The differences in surface layer temperature or differences in surface emissivity due to these films can produce a streaked effect in infrared imagery. McLeish (1965) has excellent imagery of the ocean surface with this effect clearly visible. Imagery from the Delaware Estuary also appears to have a streaked appearance in some of the southern reaches of the estuary where the wind had a velocity of about six knots during the time the imagery was made. The streaks were also in the general direction of the wind. It seems reasonable to assume that there is a surface circulation induced in the estuary when the wind velocity is sufficient.

The wind-driven circulation previously described might play a role in the important process of reaeration, which introduces to the estuary oxygen that is consumed in the biological assimilation of carbonaceous and nitrogenous wastes.

From a study of the reaeration mechanism in streams and rivers by Langbein and Durum (1967) there is empirical evidence to show that the rate at which oxygen is taken up by the water is related to the stream geometry and water velocity. These two factors govern the water turbulence, which is the mechanism that transports water to and from the surface where the exchange takes place. In a tidal estuary there may be an ambient turbulence level imposed by geometrical and tidal factors plus a surface turbulence imposed by the wind, both interacting to produce reaeration. The vigorous surface circulation should be especially important in a polluted estuary like the Delaware because surface slicks of petroleum, which often are present, may be concentrated in convergence zones allowing film-free areas to exist. This might be important in light of evidence cited by Coon and Campbell (1967) that shows that oxygen transfer is inhibited by the presence of waste substances at the liquid-air interface.

If the ambient turbulence is not vigorous enough to destroy the surface boundary layer, or break up the petroleum films that often are present, oxygen may have to pass through the layer or films by molecular diffusion before coming in contact with subsurface oxygen-deficient water. If this is true, the reaeration mechanism should be more efficient when the wind is strong enough to induce the vertical circulation previously described. In addition, if the wind is strong enough to produce breaking waves, bubbles of air are forced into the water giving an increased surface area across which gaseous transfer can occur. This, combined with the surface turbulence, should make the reaeration mechanism most efficient.

Infrared imagery has detected small scale thermal variations on the surface of the Delaware estuary. If these thermal variations are traces of the circulation discussed above, infrared imagery can be a powerful tool for the study of the circulation.

<u>For Studying the Effects of Effluents</u>

The estuary's water is used extensively for cooling purposes. A pencil sketch of imagery of a heated effluent from a refinery is shown in figure 3. The shore is denoted by 1, the effluent by 2, and the estuary by 3. The tidal current is moving to the left and the contact denoted by 4 is very sharp. In the area of 5 the contact is very diffuse.

It is possible to detect more than 30 heated effluents from industrial and municipal sources in imagery of the Delaware. This is a conservative estimate of how many might be detected because, in some parts, the imagery did not completely cover the entire width of the estuary. In the narrow northern part of the estuary the effects of some effluents are seen across the entire width while in the wider southern parts this does not occur. Imagery might be used to determine the effect of an effluent in the immediate vicinity of its introduction and when taken periodically over a tidal cycle could indicate local dispersion patterns and tidal current variations.

POTENTIAL USE OF AERIAL PHOTOGRAPHY IN ESTUARIES

For Identifying Sources of Sediments and Measuring Dispersion

Color and infrared color aerial photographs of the Delaware estuary have been taken from altitudes of 3000, 4000, 5000, and 15,500 feet. Because the Delaware is turbid, these photographs provide information about a surface layer of water that may be two or three feet thick, as compared to the millimeter thick surface skin sensed by infrared imagery.

Man is very active in the Delaware estuary and its tributaries. Urbanization, spoil disposal and floods introduce suspended sediment to tributary flows. In addition, dredging, turbulence of tidal currents and river traffic contribute to sediment in suspension. Areas of apparent high concentrations of suspended sediment are easily seen in the aerial photographs. For example, figures 4a and 4b are color and infrared color photographs of the estuary near Wilmington, Delaware, taken from an altitude of 15,500 feet during the latter part of an ebb tide. The turbid tributary in the lower left hand corner of the photographs is the Christina River. The high altitude infrared color photographs generally show more detail in the water than the color photographs do because the low level atmospheric haze doesn't seem to interfere and produce a washed out effect as it does in the color photographs. From an examination of other photographs of the estuary, most tributaries do not appear to carry as much suspended sediment into the estuary as does the Christina River. The effects of dredging can be seen in figures 5a and 5b which are infrared color and color photographs taken from 3000 and 4000 feet, respectively. When the photograph in figure 5a was taken the tide was flooding and sediment put in suspension by the dredge was carried into Rancocas Creek, New Jersey. When the tide ebbs, as shown in figure 5b, the water from Rancocas Creek entered the estuary and appeared to be more turbid than the estuary water.

When water from a tributary or an effluent enters the estuary, it mixes with water in the estuary. The vigor of the mixing process is determined by the hydrodynamic regime of the estuary. In the Delaware, there is a strong semi-diurnal tide with a range of about six feet which produces tidal currents of up to five feet per second. Since the velocity decreases from a maximum near the center channel to zero at the bottom or sides of the estuary, strong velocity shears may result. These shears often are unstable and large scale turbulence results. In addition, velocity discontinuities between estuary and tributary flows may produce instabilities in the water. As described by Defant (1961), when two streams of water having different velocities flow together, there is a tendency for perturbations to grow on the interface between the two streams of water. These perturbations often distort the interface into a wavelike form. In figure 5b there is an obvious wavelike form to the interface, with wavelength of order 1300 feet and amplitude of order 200 feet. Further downstream the interface becomes more indistinct. Turbulence of this size is also seen in figure 6, which is a mosaic of two photographs of Florence Bend, located in the northern part of the estuary. The tidal current is from left to right. Note the two vortices near the shore on the inner side of the bend. On these and other photographs vortices that result from velocity shears near the shores of the estuary or from what may be called boundary layer separation at sharp bends in the estuary are easily seen. Most of these vortices are of order 100 and 300 feet in diameter.

Horizontal streaks of high sediment concentration water appear in the southern part of the estuary. The infrared color photograph taken at 15,500 feet shown in figure 7 hints at the possibility of vortex-like motion with horizontal axes which might be caused by vertical velocity shears. The streaks might be caused by sediment scoured from the bottom by the ebbing tidal current. The streaks appear to be from 100 to 500 feet wide. Infrared imagery was also taken of the part of the estuary, shown in figure 7, during an ebb tide. There is a streaked appearance in the imagery that corresponds to the streaks in the photographs.

The mechanism by which mixing and dispersion are accomplished might be revealed in the photographs. Velocity discontinuities between estuary and tributary flows and horizontal and vertical velocity shears could cause turbulence whose representative eddy size is between 100 to 500 feet. This might be the most important mechanism for dispersion in the estuary.

Since dispersion depends upon both spatial and temporal scales of motion, repetitive flights during a tidal cycle would allow an intensive study of mixing in a reach of the estuary to determine the time dependency of the turbulent eddies.

For Velocity Estimates

It is often possible to discern surface wave patterns on low level aerial photographs. Information about the water velocity might be obtained from these patterns.

An aerial photograph of a part of the estuary where there is a tidal current moving from left to right is shown in figure 8. The movement of the water past the docked ships in the top of the picture could be setting up the waves seen at locations 1 and 2. Note the shorter wavelength of the waves at 2 as compared to 1. If a stationary object sets up a wave disturbance of a constant frequency in the water moving past it, it can be shown that the velocity of the water V is where L_1 is the larger wavelength,

$$V = \frac{\sqrt{\frac{g\, L_1\, L_2}{2\pi}}}{(L_1 + L_2)} \left(\sqrt{L_1} - \sqrt{L_2}\right)$$

L_2 is the smaller wavelength, g is the acceleration of gravity, and $\pi = 3.14$. A necessary condition for this equation to be valid is that L_1 is less than twice the depth of water. In this photograph the depth is about 40 feet, the longer wavelength is about 40 feet and the shorter is about 30 feet. Using these crude estimates in equation 2, V is about one foot per second. The average flood tidal velocity for this reach of the estuary is roughly one and one half to two feet per second.

Cameron (1965) discusses a method for measuring the relative motion of a moving object with respect to stationary objects using stereoscopic aerial photography. If the relative position of a moving object changes with respect to a stationary one during the time elapsed between consecutively taken stereo photographs, the object will appear to have a false "topographic position" when the photos are viewed stereographically. Thus, a drogue carried by the current will appear to be above or below the water surface, depending upon the direction of movement, if stationary shoreline features are aligned in a stereo viewer.

For Identifying Sources of Petroleum Pollution

If the sun is near the zenith and the photography is taken from directly above, surface slicks of petroleum are very easily seen, especially with low level infrared color photographs. An example of this is shown in figure 9. This might be used to identify sources of petroleum pollution.

CONCLUSION

Infrared imagery and aerial photography give the hydrologist a new approach to understanding estuarine hydrology by providing virtually synoptic representations of estuarine conditions. When taken periodically in time, they give a qualitative respresentation of estuarine hydrodynamics, which could be very useful in reconnasisance studies.

It might be possible to use imagery in quantitative studies of the effect of wind on the reaeration mechanism in estuaries. An analysis of imagery of the Delaware estuary indicates that there is a variation of surface temperature that may reflect the presence of a wind-induced surface circulation.

It also appears feasible to estimate the dispersion characteristics of an estuary by measuring the time rate of change of effluents detected by imagery or the time rate of change of turbid eddies seen in the aerial photographs. The size of effluent plumes ranges from a few feet in width where they enter the estuary to many hundreds of feet in width well away from the point of entry. The lower limit of the size of turbid eddies appears to be of the order of 100 feet.

This study has revealed that remote sensors can detect many water quality variations that exist in estuaries. Looking to future data obtained from earth orbital platforms, a spatial resolution of less than 100 feet on IR imagery would be desired for hydrologic study on an estuary similar to that of the Delaware River. Future studies using remote sensors in the Delaware will pursue further some of the possible avenues of approach discussed in this report.

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ILLUSTRATIONS

6. A black and white mosaic of two color aerial photographs that shows two vortices, denoted by arrows, which may be an important part of the mixing mechanism in the estuary.
7. Infrared color photograph taken from an altitude of 15,500 feet of the Delaware estuary near Pea Patch Island, Delaware. The tidal current is ebbing to the lower left corner of the photograph.
8. An aerial photograph of a surface wave pattern.
9. An aerial photograph showing surface petroleum slicks.

Delaware River Estuary; Technical Letter NASA 128

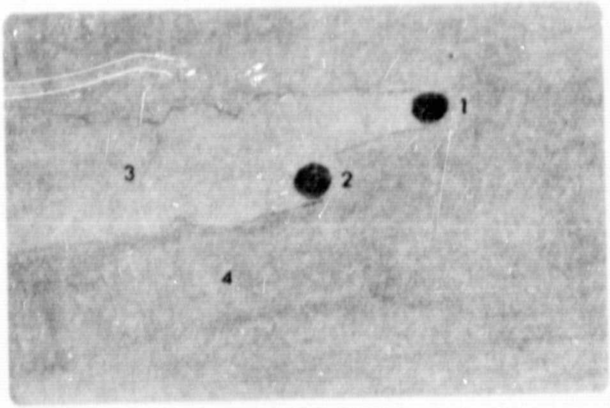


Figure 1.

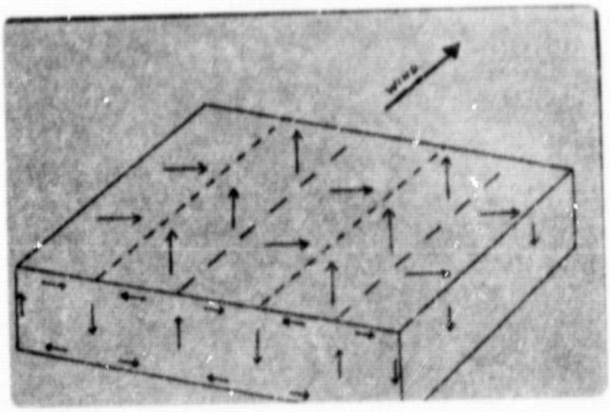


Figure 2.

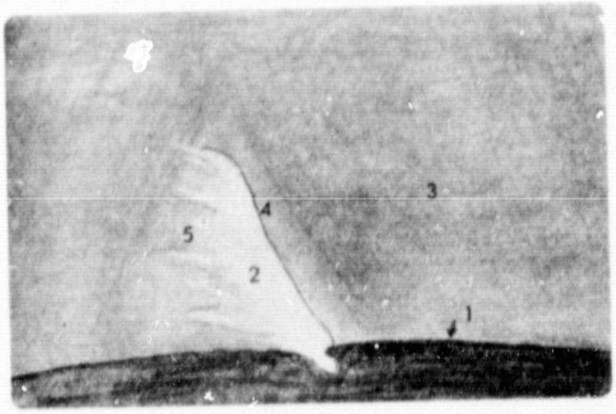
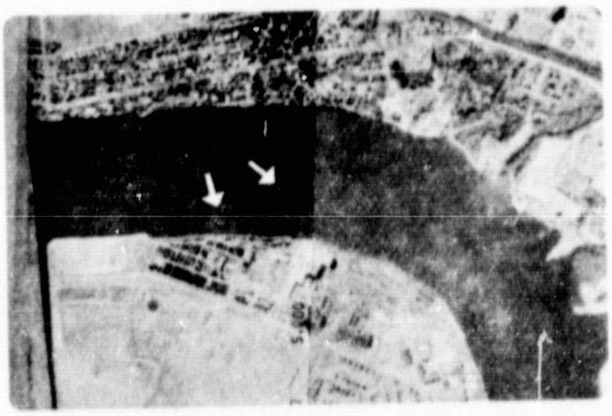


Figure 3.



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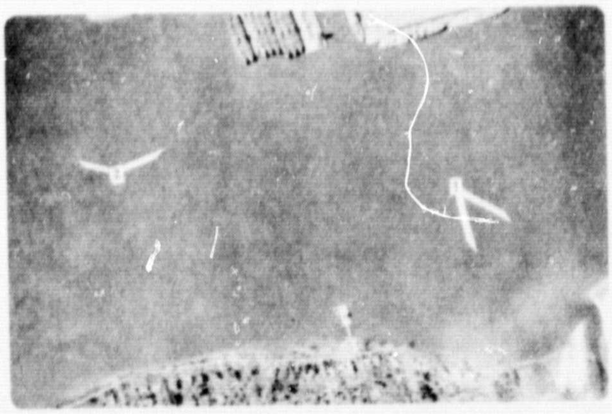

Figure 8.

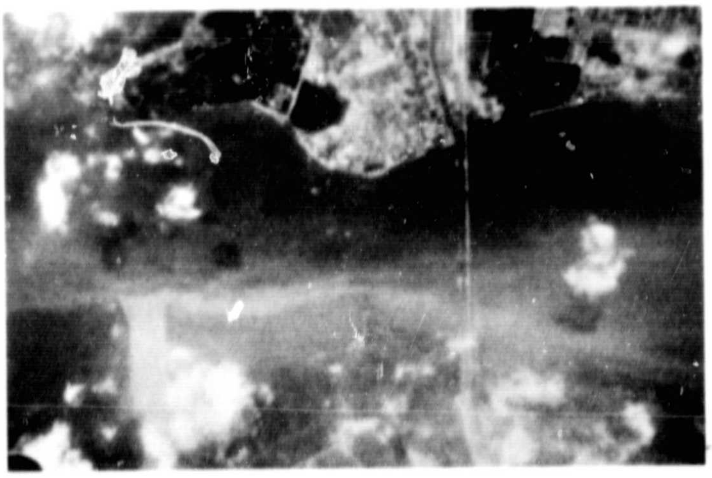

Figure 4a.

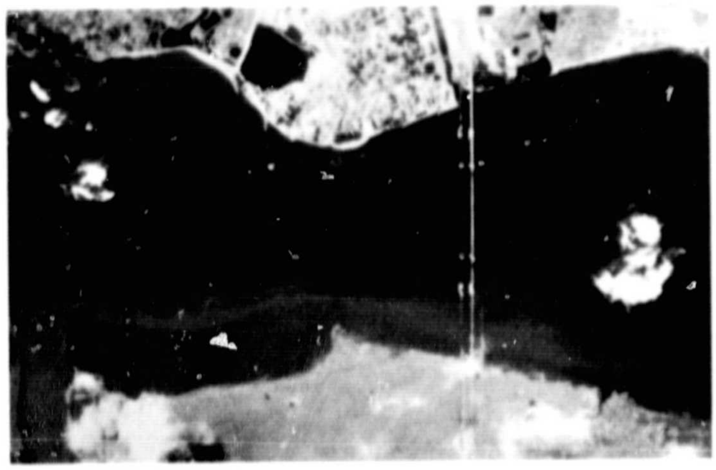

Figure 4b.

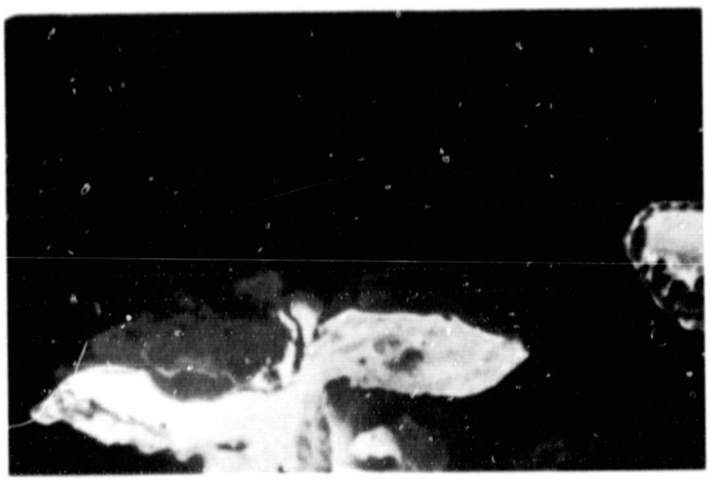

Figure 5a.

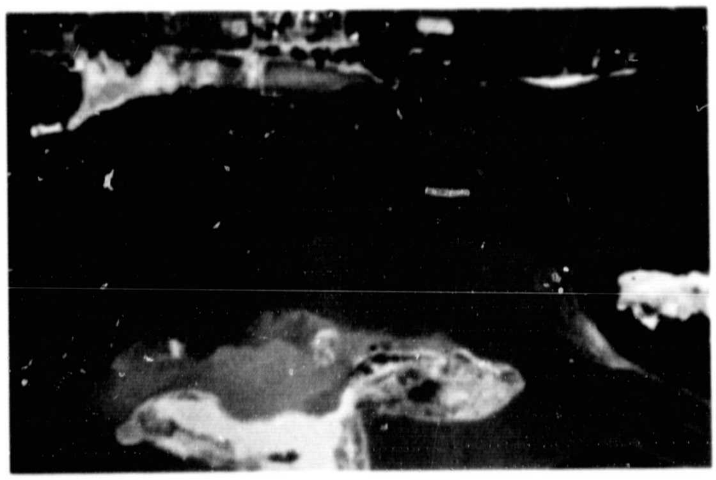

Figure 5b.

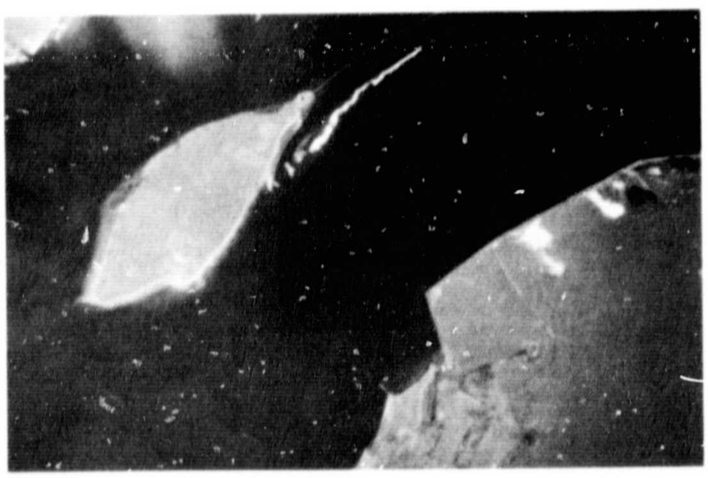

Figure 7.

Figure 9.